Principles of Reinforced Concrete

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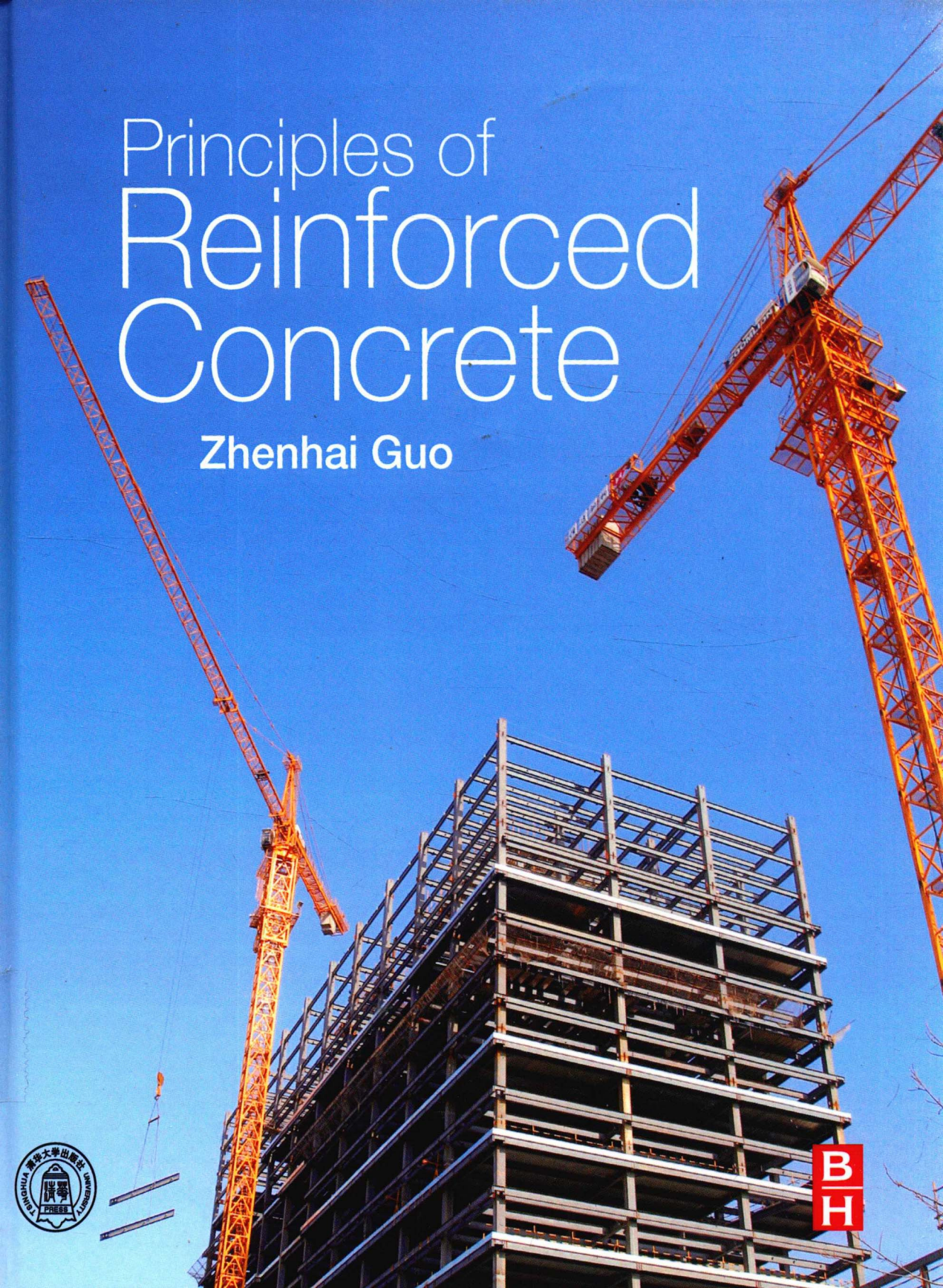

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Preface

The courses "Theory of Reinforced Concrete Structures" [1-1] and "Strength and Constitutive Relation of Concrete" [1-2] were started in early 1980's for the post-graduate students in structural engineering and related fields in Tsinghua University. The lectures, and the syllabus and contents of both courses are varied during the teaching practice. Two courses are composed and named "Principles of Reinforced Concrete" in 1990's. The author gave a lecture on this course for several years and wrote the textbook of same name [1-3], based on the teaching draft.

After the book was published in 1999, it is also adopted as the textbook or main reference for similar courses of both post- and under- graduates of many universities in China. And, it is helpful as well for the university lecturers. In addition, sometimes the book is used by the structural engineers during their scientific or technical work.

In 2001, Education Committee of Beijing decided to establish "the elite textbooks for university education of Beijing', and the textbook was selected after appraisement. The new textbook is renamed as "Principle and Analysis of Reinforced Concrete" [1-4] and published in 2003. The new textbook or the second edition contains most contents of the original one, but some chapters and sections are reformed and two new chapters, i.e. general analysis method of structural member and durability, are added. In addition, the exercises are attached to its text.

This book is the English version of textbook "Principle and Analysis of Reinforced Concrete" (in Chinese), but some contents are modified and slightly abridged to reduce its length. There are four parts including twenty chapters in this book.

In Part One, the strength and deformation behavior and its variation regularity of concrete are introduced in detail, based on its basic characteristic and failure mechanism. The main mechanical behaviors of various structural concrete, i.e. high-strength, light-weight, and fiber concrete, are presented as well. And, the multi-axial strength and constitutive relation of concrete are briefly contained.

The combination function of reinforcement and concrete is a special problem with importance, when reinforced concrete is considered as a composed structural material and is distinguished from a single structural material. So, bond and deformation deference between reinforcement and concrete, and confined concrete are discussed in Part Two.

In Part Three, the strength, crack, and deformation of flexural and compressive members, and shear- and torsion-resistances of structural members of reinforced concrete are introduced in detail based on the corresponding experiments. And, the general regularities, working mechanisms, and analysis methods of them are concluded.

A reinforced concrete structure may experience some extreme circumstances during its long life, e.g. earthquake, explosion, fatigue, high temperature (fire), or long-term damage (durability). So, the special behaviors of reinforcement and

concrete materials, and the mechanical responses and analysis methods of the structural members under these conditions are introduced briefly in Part Four.

"Reinforced Concrete Structures" or the similar [1-5] is a course for the undergraduate students of Structural Engineering in Chinese university. The main objective of it is to help them to conduct the structural design. Therefore, the main contents of the course include: the mechanical behaviors of reinforcement and concrete are briefly introduced, the behavior, calculation method, and requirement of design and construction of the basic structural members under various internal forces are presented in detail, and the concept and method of structural design and relevant design codes are introduced and explained.

This book is used for the post-graduate students in structural engineering. The main contents are research and analysis of the mechanical behavior and its regularity of reinforced concrete structural members, and the main objective is to solve various questions occurred in engineering practice. Therefore, the general regularities of strength and deformation of concrete under uni- and multi-axial stresses, even under several extreme circumstances, are introduced systematically, as this is the basis for understanding and analyzing the structural members. When the mechanical behavior of the structural members under various conditions are discussed, the results of corresponding experimental investigations are emphasized, the stress and deformation states, cracking and failure process, and influences of important factors are analyzed in detail, and the working mechanism, the principle and method of calculation, and the determinations of the technical indices are concluded. It is hoped that the reader not only knows the general regularities of the materials and members of reinforced concrete, but also understands the general way and reasonable method for analyzing and solving the practical problems in reinforced concrete structural engineering, after reading this book.

When this book is sent to press, the author sincerely thanks the professors of elder generation, who worked in the Department of Civil Engineering, Tsinghua University. They worked and studied seriously and their teaching experiences [1-5][1-6] and research achievements in reinforced concrete structure field enrich my knowledge, which partly composes the basis of this book. My colleagues, including technicians and workers, and post- and under-graduate students, who worked together within the processes of experimental and theoretical researches within many years, are appreciated as well. Their cooperation with effort helps to bring about the research achievement, which substantiate and improve the contents of this book. In addition my special thanks is due to my wife, retired professor Suying Qian, who not only patiently typed and input the entire manuscript of this book to form the original computer text, but also takes care thoughtfully of my life. Of course, the print and publication of this book is relied on the efforts of Tsinghua University Press, it is also appreciated.

Zhenhai Guo
September 2013

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CHAPTER

Introduction 1

CHAPTER OUTLINE

1.1 Development and features of reinforced concrete structure

Since the first product of reinforced concrete was manufactured and used in structural engineering, only about one hundred years have passed. Compared with soil and timber structure, which is the earliest on earth, used by the original mankind, the masonry structure of stone or brick appeared in the early society of ancient civilizations, and steel and other metal structures developed after the Industrial Revolution, reinforced concrete structure is the youngest one among the structure family. However, the performance and manufacture technique of reinforced concrete structure are continuously improving and being enhanced, structural configuration and construction get more variety, and the application scope is widely expanded. Now, reinforced concrete structure is the most prosperous one in structural engineering in many countries, especially in China.

Now, the engineering fields using widely reinforced concrete structure are as follows.

Building engineering – various civil and public buildings, single- and multi-storey industrial buildings, high-rise and long-span buildings …
Bridge and communication engineering – slab, beam, arch, and truss upper structures, abutments, piers, and foundations, slope protection, retaining walls, highway pavements, railway sleepers …
Hydraulic and harbor engineering – dams, hydropower stations, coasts and docks, offshore platforms, ponds and pipelines, aqueducts …
Underground engineering – tunnels, railways, mines, caissons, piles, foundations of heavy equipment, military defense works …
Special engineering – television towers, transmission poles, viaducts, silos, chimneys, pavements and parking aprons of airports …. Even reinforced concrete structures enter into the machine building field, e.g. reactor vessels and

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containment of nuclear power plants, hydraulic presses, shipbuilding, lathes, etc., which are occupied traditionally only by steel structures.

The inherent certainty of a combination of reinforcement and concrete is due to the mutual compensation of the behavior of both materials and the advantage of each material is fully utilized. Concrete is the main body of the structural material and has some advantages, e.g. easy manufacturing, utilizing local materials, low investment. However, concrete has lower tensile strength and is fragile and cracks easily. Therefore, only when the reinforcement of a proper type and quantity is put into the concrete, the strength and ductility of the reinforced concrete structure is improved and enhanced to satisfy the necessary safety and service conditions. In the meantime, the disadvantages of reinforcement, e.g. poor environmental stability, and corrosion and fire resistance, will be overcome when it is buried into concrete. So, reinforcement and concrete can effectively be composed of a structural material with high strength, good integrity, corrosion and fire resistances, and flexible uses.

In addition, concrete is a shapeless substance and can be made into any structure of complicated shape and different sizes, when a proper mold is manufactured and installed. There are so many different reinforced concrete structures which include not only the one-dimensional members, e.g. beam, slab, column, of solid and hollow sections of different shapes, but also the two-dimensional members, e.g. flat plate, slab, wall panel, shear-wall, folded plates, and the three-dimensional, e.g. thin and thick shells and irregular solid, structures.

Reinforced concrete itself is composed of two materials and can also be used as a kind of structural material and combined with other structural materials to compose various composite structures, such as reinforced concrete-steel and reinforced concrete-masonry structures. Then, more varieties of structure scheme are developed and the adaptability and application scope of it are expanded.

As reinforced concrete structure is widely used in engineering practice, the requirement of production accelerates the research work in all aspects. The plentiful research results on structural scheme and configuration, kind and quality of material, construction technique, mechanical behavior of structural members, design concept and calculation method, construction measures, etc., are achieved and great progress is made as below.

Some disadvantages of concrete material, such as higher dead weight, lower cracking resistance, strength increasing slowly, and seasonal limitation of construction, have been improved or overcome, when the technical measures, which include selection of raw materials, mix and cure technique, construction management, reinforcement construction, prestressing, and improvement of calculation method, are utilized.

In order to enhance the performance of concrete and to reduce its self weight, high-strength (>C50), light-weight ($\gamma = 500-1900$ kg/m^3), fiber, and high-performance concretes of various categories are developed successively and applied in engineering practice.

When various chemical additives are mixed into concrete during its mixing, the higher workability, freezing resistance, high strength, and earlier coagulating of

concrete are achieved, even heat-resisting and acid-resisting concrete can be obtained. And, pumping, spraying, and self-compacting concrete may be used to improve the manufacturing technique. All kinds of these concretes are suited to different construction and application conditions of reinforced concrete structures.

The strength of the steel reinforcement used for reinforced concrete structure is gradually increased from low value into medium and high values. The steel reinforcements of low relaxation and with anticorrosion coating are used frequently. Various resins and carbonic fiber bars (or sheets) of high strength and anticorrosion are also used successfully now to replace the steel reinforcement.

The behavior of concrete under uni- and multi-axial stress states and its failure criterion and constitutive relation have been investigated experimentally and theoretically, and great progress has been made. The strength and deformation of concrete under various conditions, e.g. repeated load, high-speed loading, sustained load, at elevated temperature, are also tested and many results are reported.

The bond behavior between reinforcement and concrete, including working mechanism, characteristic values of bond strength and slip, shape and calculation model of τ-s cure, have been investigated for many years. The anchorage of reinforcement is important in engineering practice and an effective measure is available now.

The mechanical behaviors of various structural members under static and dynamic loads are always the key topics of research on reinforced concrete. Most of them already have definite conclusions and ripe calculation methods. The mechanical responses of them under extreme circumstances, e.g. earthquake, explosion, fire accident, also have plenty experimental and theoretical results.

In the initial stage of application, the design concept and calculation method of a reinforced concrete structure are based on the allowable stress and elastic analysis, which follow that of the steel structure. Then, they were changed into single safety coefficient and ultimate strength analysis respectively. Now, the limit state design method, based on the probability statistics and reliability analysis, is used worldwide. In the meantime, the calculation method of the structural internal forces is also developed from the classical elastic analysis into the ultimate equilibrium method considering plastic deformation, and again into the non-linear analysis along loading history. The combination of the finite-element analysis method and the computer technique is a very powerful means for accurate and quick analysis of a complicated reinforced concrete structure and is widely used now in engineering practice.

The progress of experimental method and high technicalities of experimental equipment and measuring instrument raise the capability and accuracy of structural testing. Various environmental and loading conditions of the structures can be simulated better and more and meticulous information and data can be obtained in the testing. These are helpful for understanding correctly the responses of the testing structure and discovering its new physical phenomena and regularity.

All of these research achievements promote deeper understanding of the behavior regularities of reinforced concrete materials and structures and raise the