高等学校土木工程专业系列规划教材

Fundamentals of Reinforced Concrete Structures

钢筋混凝土结构基本原理

·平台课课程群·

主编 刘素梅 杨宗元

主审 叶建乔

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高等学校土木工程专业卓越工程师教育培养计划系列规划教材

丛书序

土木工程涉及国家的基础设施建设，投入大，带动的行业多。改革开放后，我国国民经济持续稳定增长，其中土建行业的贡献率达到 1/3。随着城市化的发展，这一趋势还将继续呈现增长势头。土木工程行业的发展，极大地推动了土木工程专业教育的发展。目前，我国有 500 余所大学开设土木工程专业，在校生达 40 余万人。

2010 年 6 月，中国工程院和教育部牵头，联合有关部门和行业协（学）会，启动实施“卓越工程师教育培养计划”，以促进我国高等工程教育的改革。其中，“高等学校土木工程专业卓越工程师教育培养计划”由住房和城乡建设部与教育部组织实施。

2011 年 9 月，住房和城乡建设部人事司和高等学校土建学科教学指导委员会颁布《高等学校土木工程本科指导性专业规范》，对土木工程专业的学科基础、培养目标、培养规格、教学内容、课程体系及教学基本条件等提出了指导性要求。

在上述背景下，为满足国家建设对土木工程卓越人才的迫切需求，有效推动各高校土木工程专业卓越工程师教育培养计划的实施，促进高等学校土木工程专业教育改革，2013 年住房和城乡建设部高等学校土木工程学科专业指导委员会启动了“高等教育教学改革土木工程专业卓越计划专项”，支持并资助有关高校结合当前土木工程专业高等教育的实际，围绕卓越人才培养目标及模式、实践教学环节、校企合作、课程建设、教学资源建设、师资培养等专业建设中的重点、亟待解决的问题开展研究，以对土木工程专业教育起到引导和示范作用。

为配合土木工程专业实施卓越工程师教育培养计划的教学改革及教学资源建设，由武汉大学发起，联合国内部分土木工程教育专家和企业工程专家，启动了“高等学校土木工程专业卓越工程师教育培养计划系列规划教材”建设项目。该系列教材贯彻落实《高等学校土木工程本科指导性专业规范》《卓越工程师教育培养计划通用标准》和《土木工程卓越工程师教育培养计划专业标准》，力图以工程实际为背景，以工程技术为主线，着力提升学生的工程素养，培养学生的工程实践能力和工程创新能力。该系列教材的编写人员，大多主持或参加了住房和城乡建设部高等学校土木工程学科专业指导委员会的“土木工程专业卓越计划专项”教改项目，因此该系列教材也是“土木工程专业卓越计划专项”的教改成果。

土木工程专业卓越工程师教育培养计划的实施，需要校企合作，期望土木工程专业教育专家与工程专家一道，共同为土木工程专业卓越工程师的培养作出贡献！

是以为序。

2014 年 3 月于同济大学四平路校区

Preface

The purpose of this textbook is to provide students majoring in Civil Engineering with an alternative reference and theory for the course of Reinforced Concrete Structures based on the provisions of the 2011 *American Concrete Institute (ACI) Building Code*. It can act as a supplementary material for students' understanding of fundamentals in accordance with *The Code for Reinforced Concrete Structures* (GB 50010-2010). The contents in it are organized and structured according to the system of GB 50010-2010. This textbook can serve as a reference for the course of reinforced concrete structure in Chinese universities and colleges, which can be used in class by "bilingual teaching".

The textbook consists of eight separate chapters, which are written by several editors. It includes: Chapter 1, Introduction; Chapter 2, Design Process; Chapter 3, Properties of Concrete and Reinforcement; Chapter 4, Flexural Analysis and Design of Beams; Chapter 5, Shear in Beams; Chapter 6, Columns; Chapter 7, Torsion; Chapter 8, Serviceability Requirements. Chapters 1, 2 and 3 are written by Tony Yang of the University of British Columbia, in Canada; Chapters 4, 5 and 6 are written by Liu Sumei of the University of Wuhan, in China; Chapter 7 is written by Li Qian of Department of Design and Construction of New York Government, in America; Chapter 8 is written by Li Yanqiang of Changjiang Institute of Survey, Panning, Design and Researd, in China.

The textbook was reviewed for accuracy by Ye Jianqiao of Lancaster University, in Britain. The editors would like to appreciate their valuable suggestions as well as contributions in professional proof-reading, which have led to a significant improvement of the quality of the textbook.

Editors

2017.9

Contents

1 Introduction

1.1 Basic Concepts of Reinforced Concrete

1.1.1 Mechanics of Reinforced Concrete

Plain concrete is a construction material composed primarily of cement, water, fine and coarse aggregates. Cement, water and fine aggregates form the mortar, which acts as a binding agent for the material, while coarse aggregates provide the necessary compressive strength. Concrete possesses many desirable characteristics, such as high compressive strength, durability and geometric flexibility. However, it is weak in tension and is susceptible to brittle failure. Under low tensile stresses, plain concrete will experience sudden failure as the material cracks.

Reinforced concrete is a composite material utilizing the relatively high tensile strength and ductility of reinforcing steel bars to complement the properties of plain concrete. Reinforcing steel is typically placed where tensile stresses are expected, such as the underside of simply supported beams and slabs under flexural bending. Concrete forms a strong bond with the reinforcing steel, allowing stresses to transfer efficiently between the two materials. When a reinforced concrete element is subject to tensile stresses, concrete cracks and transfers the tensile stresses to the reinforcing steel. The steel deforms gradually under increasing tensile load, hindering further cracking of the concrete and preventing abrupt failure of the element to provide a ductile failure mechanism. The difference in behaviour between a plain concrete beam and a reinforced concrete beam is illustrated in Figure 1-1.

Concrete and reinforcing steel are able to form strong bonding with each other, allowing stresses to be transferred efficiently between the two materials. Furthermore, concrete and reinforcing steel exhibit similar coefficients of thermal expansion. Steel has a coefficient of thermal expansion of $1.2\times10^{-5}℃^{-1}$, while concrete has a coefficient of thermal expansion varying generally from $1.0\times10^{-5}℃^{-1}$ to $1.5\times10^{-5}℃^{-1}$. This eliminates internal stresses result from thermal expansion or contraction of the materials.

1.1.2 The Reinforced Concrete Construction

Construction of traditional reinforced concrete elements begins with the placement of a reinforcing steel cage. Figure 1-2 shows a reinforcing steel cage for two types of structural elements — a beam and a slab. In beams, reinforcements typically consist of longitudinal bars, used to carry tensile forces along the beam as a result of bending moments, and stirrups or ties used to resist shear forces in the beam. In slabs, reinforcements typically consist of longitudinal bars in both orthogonal directions.

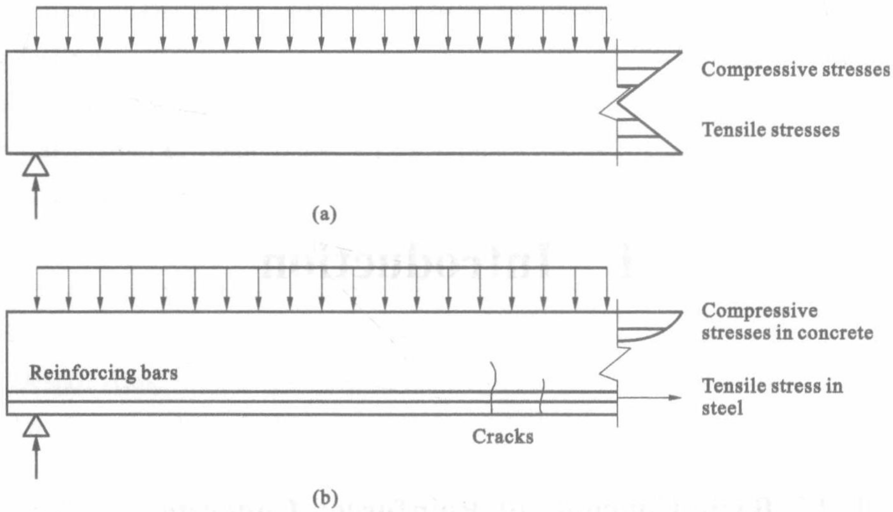

Figure 1-1 Behaviour of unreinforced and reinforced concrete beams

(a) Plain concrete beam; (b) Reinforced concrete beam

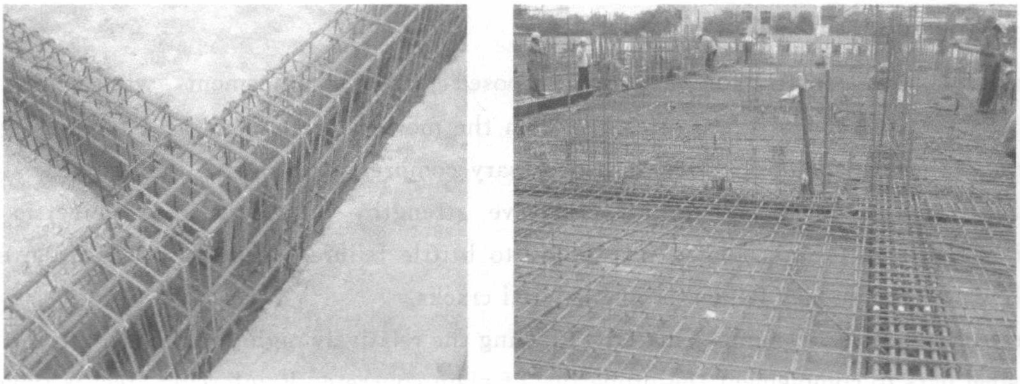

Figure 1-2 Reinforcing steel cage for a beam and a slab

Formwork is then placed around the perimeter of the element to dictate the geometry of the element, as shown in Figure 1-3. The components of concrete are combined to form fresh concrete, which is poured within the formwork. The concrete is left to cure for approximately 28 days to gain the desired structural properties. During this time, the formwork is removed, and props or shores are installed to support the weight of the concrete before it hardens and develops the required strength.

Figure 1-3 Formwork for concrete pour

Two types of concrete construction techniques are commonly used: cast-in-place construction and pre-cast construction. For a cast-in-place concrete construction, the element is formed and poured at its intended location on the project site, as shown in Figure 1-4; for pre-cast construction, components are formed and cured separately within a shop environment before it is transported to the project site and assembled to form the complete structure, as shown in Figure 1-5.

Figure 1-4 Concrete pour for a cast-in-place concrete construction

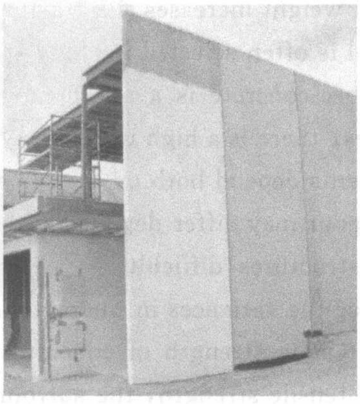

Figure 1-5 Erection of pre-cast concrete wall panels

1.2 Characteristics of Reinforced Concrete

1.2.1 Advantages of Reinforced Concrete

Reinforced concrete inherits many of the benefits of plain concrete, such as flexibility in the shape, size and finishing of the structural elements, high compressive strength, high stiffness, high durability and low maintenance requirements.

Unlike other common construction materials such as steel and timber, the size and shape of reinforced concrete elements is not governed by the availability of standard manufactured shapes. Fresh concrete can be poured within forms to create members of any shape and size. The surface texture of the element can also be customized to provide an architecturally pleasing finish. This versatility allows concrete to be used in virtually any structural application.

Because of high rigidity of concrete, it is less susceptible to vibration under wind or live loads. This property is significant both in the design of long span bridges and high-rise buildings.

Reinforced concrete is a highly durable material. While steel is susceptible to corrosion under chloride attack and timber is susceptible to decay under moisture and insect attack, concrete offers great durability when exposed to weather and deterioration. When proper cover is provided and dense, air-entrained concrete is used, and concrete protects the reinforcing steel within from the atmosphere. Concrete also offers great fire resistance, which is particularly important to the design of buildings, where the structure's integrity must be maintained while occupants are evacuated. Reinforced concrete buildings inherently offer a fire protection rating from 1 to 3 hours, without additional fire protection. Concrete is also inherently resistant to impact and blast loads. Because of its great durability, concrete generally requires less maintenance than timber and steel.

1.2.2 Disadvantages of Reinforced Concrete

Compared with steel, concrete has a relatively low strength to self-weight ratio. The density of concrete is approximately 30% that of steel, but it only offers approximately 10% of steel's compression capacity. As a result, a larger volume of material is required to provide the same structural capacity. This additional weight increases the gravity load demands on the structure as well as seismic demands. Based on this, steel is often selected for long-span structures.

Because concrete is a non-homogeneous material formed through a mixture of cement, water and aggregates, there is a high uncertainty in the material properties. The strength and durability of the resulting elements depend both on the material composition and construction practices. The properties of each concrete pour may differ depending on the consolidation and curing conditions, making quality control of concrete structures difficult. As a result, greater tolerance must be applied in designing concrete to account for the variances in the material properties.

The tensile strength of concrete is very low. Although steel reinforcement is used to provide the necessary tensile strength, the surrounding concrete is still susceptible to cracking. The size of cracks is dependent on quality of design and detailing. Large cracks may be both aesthetically unpleasing and allow moisture and other harmful chemicals to penetrate the structural element, which results in corrosion inside the reinforcing steel.

Concrete construction typically involves long curing periods for the concrete to gain its desired structural properties. This may impose restrictions in the construction process. Furthermore, the quality of concrete is affected by environmental conditions during the pouring and curing stages. As a result, concrete construction may be governed by seasonal restraints. Methods to alleviate such restraints include the use of prefabricated members to eliminate the need for on-site curing, and the use of admixtures to accelerate the curing process.

1.2.3 The Material Selection for Structures

When selecting a material to use for any structure, overall construction cost will often be a driving factor. The cost of construction consists of three components—material cost, labour cost, and cost due to construction time. Materials required for reinforced concrete construction involve sand, gravel or crushed rock, water, cement and reinforcing steel, all of which are generally readily available. Because the materials can be transported to site individually before forming the structural element, logistics of the material is also easier than structural steel, which must be fabricated in a shop environment, making reinforced concrete preferable for construction in remote locations.

However, reinforced concrete construction involves a large amount of detailing and placement of reinforcing steel and construction and erection of formwork. As a result, the economy of this construction method depends greatly on the detailing and construction planning involved. During design, measures can be taken to standardize member sizes, which allow cost savings from the re-use of formwork.

1.3 Applications of Reinforced Concrete >>>

Because of its various beneficial characteristics such as strength, durability and flexibility, reinforced concrete is used in a wide variety of applications, including industrial and civil buildings, hydraulic buildings, traffic projects, nuclear structures and other unique structures. Figure 1-6 shows Sydney Opera House. Figure 1-7 shows Three Gorges Dam. Figure 1-8 shows Bruce Nuclear Power Plant.

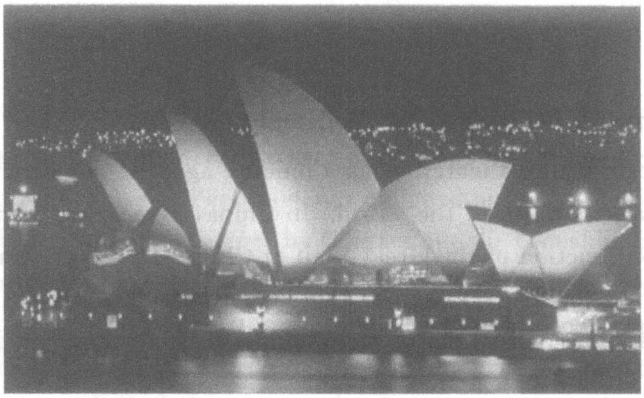

Figure 1-6 Sydney Opera House

Sydney Opera House was designed by a Danish architect, Jorn Ulzon.
The twenty-storey building is 60m high and took 15 years to construct.

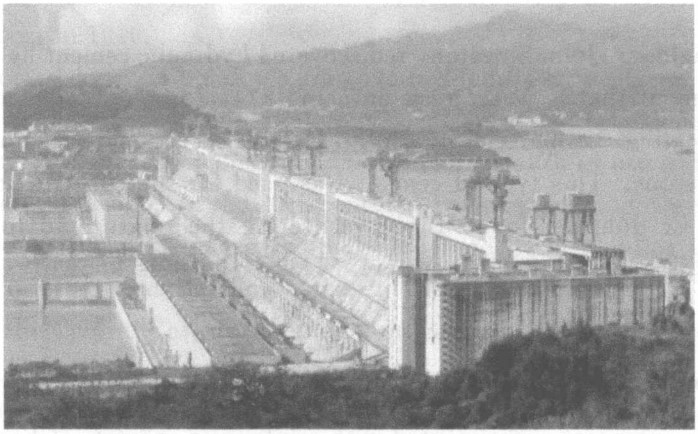

Figure 1-7 Three Gorges Dam in China

Three Gorges Dam is the largest electricity-generating plant in the world, with a length of 2,309m and a height of 101m.
Walls of the dam are constructed with reinforced concrete, with a thickness of 115m at the bottom and 40m of the top.
The project used 27 million cubic meters of concrete and 463,000t of steel.

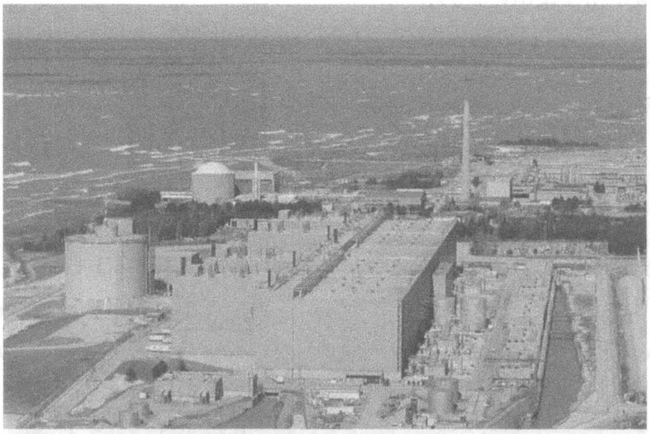

Figure 1-8 Bruce Nuclear Power Plant in Ontario

Bruce Nuclear Power Plant located in Ontario, Canada is the largest nuclear generating station in the world.
It consists of two plants and eight reactors, with each reactor housed within reinforced concrete containments.

1.4 The History of Reinforced Concrete Structures

1.4.1 The Development of Cementitious Materials

The concept of using cementitious materials as a binding agent in construction materials was adopted as early as 3000 B. C. in various parts of the world. In China, cementitious materials were used to hold bamboos together in the construction of the Great Wall of China. In Egypt, lime and gypsum mortar was used as a binding agent in the construction of pyramid structures. However, there were shortcomings in the mortar of those days, as lime mortar dissolves gradually in water and could not be used in structures exposed to moisture.

In 300 B. C., the Romans mixed fine sandy volcanic ash with lime mortar to create a concrete material that is stronger and more resistant to water. This was used widely as a construction material by the Romans for centuries. With the fall of the Roman empire in 400 A. D., the art of concrete construction was almost lost.

In 1756, a British engineer, John Smeaton, rediscovered hydraulic cement by mixing burned limestone and clay to produce a cement that is water resistant. In 1824, Joseph Aspdin made cement by grinding limestone and clay and heating the material in a kiln. He named the material Portland cement due to its resemblance to Portland stone. This type of cement was used for the construction of tunnels and bridge structures. In 1845, I. C. Johnson found that overheating the mixture to form a hard clinker, and grinding this clinker yields a higher quality cement. This is what is known as the Portland cement of today.

1.4.2 The Development of Reinforced Concrete Structures

In the 1850s, various engineers experimented with reinforcing concrete slabs and beams with different forms of metal reinforcement, and a number of patents were developed. In 1850, J. L. Lambot, a French engineer, constructed a small boat by reinforcing concrete using a mesh of iron rods. In 1875, the first reinforced concrete building in the United States, William E. Ward House, was constructed in Long Island, New York (as shown in Figure 1-9).

Figure 1-9 William E. Ward House

1.5 Building and Design Codes

As the use of reinforced concrete in structures became more widespread in the late 19th century, much research was also conducted to give engineers greater knowledge on the behaviour and mechanics of reinforced concrete. Many books, articles and codes were published on the theories behind reinforced concrete design between 1890 and 1920. In 1894, a paper by Coignet and de Tedeskko on the working stress design method for flexural design was published. This method was used by all engineers between 1900 and 1950.

In 1904, the first set of building regulations pertaining to reinforced concrete design was issued in Prussia. Similar regulations were issued by Britain, France, Austria and Switzerland in subsequent years. In 1904, the American Society of Civil Engineers, the American Society for Testing and Materials, the American Railway Engineering Association and the Association of American Portland Cement Manufacturers established a joint committee on Concrete and Reinforced Concrete design, which later became the American Concrete Institute (ACI). The committee carried out numerous studies and research, and published a final report in 1916.

The design of reinforced concrete buildings are governed jointly by bridge or building codes and design specifications specific to reinforced concrete. Building codes, regulated by municipal bylaws for each city, dictates requirements for the design and construction of buildings such as use and occupancy, fire, heating and ventilation and structural design. In the 20th century, primary building codes in North American consist of the Uniform Building Code, Standard Building Code and Basic Building Code. In 2000, the codes were replaced with the International Building Code. In Europe, the CEB-FIB Model Code for concrete structures published by the Comité Euro-International du Béton in 1978 was used in place of the Building Code. For highway bridge structures, designs are governed by the *Load Resistance Factor Design* (LRFD) *Bridge Design Specifications*, published by the American Association of State Highway and Transportation Officials (AASHTO). Design using reinforced concrete in North America is dictated by the ACI 318-14, the Building Code Requirements for Structural Concrete and the corresponding Commentary, ACI 318R-14.

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