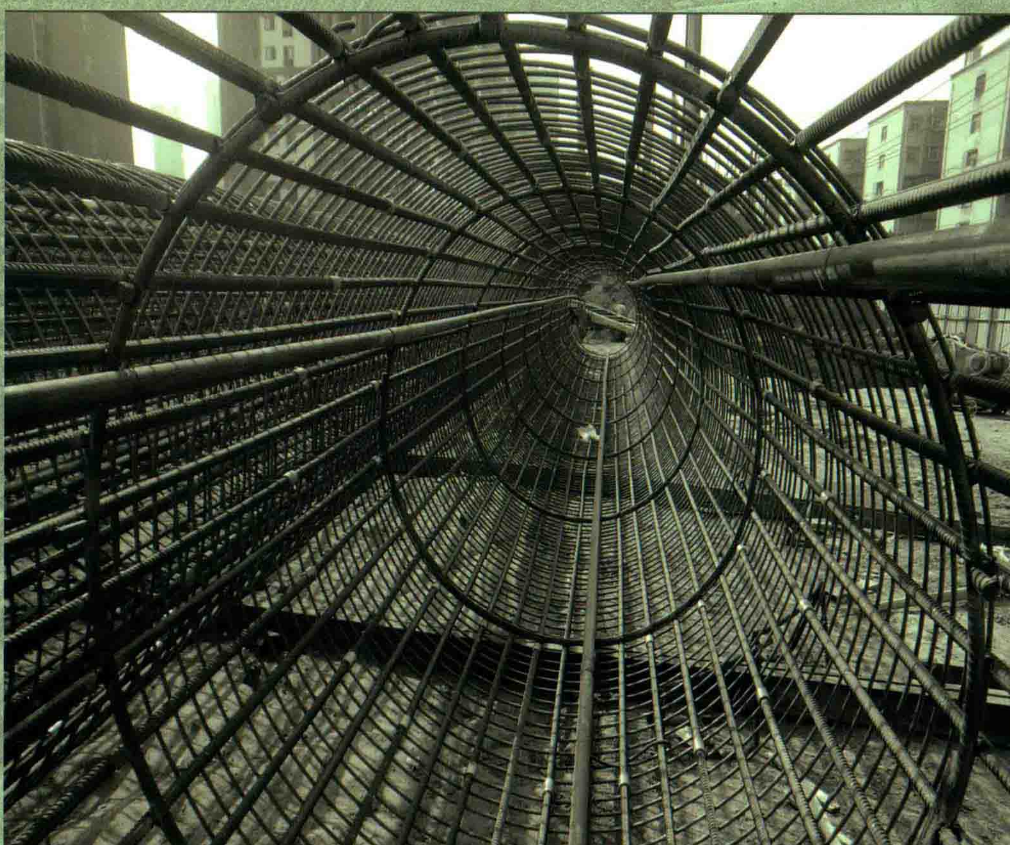
混凝土结构基本原理

（英文版）

Reinforced Concrete Fundamentals

赵 军 王新玲 楚留声 钱 辉 李 乐 编著



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前　　言

Concrete structure fundamentals is the professional basic course of civil engineering in colleges and universities. This book is a bilingual textbook under the guideline of the new code "Instructive professional code for colleges and universities undergraduate of civil engineering" established by College and University Instructive Committee of Civil Engineering Discipline. The book totally carries out the guiding ideology of cultivating qualified engineers, which not only pay attention to cultivate professional foundation knowledge and engineering concept of students, and pay attention to students' application ability in professional English.

This book is based on the code in China "Code for design of concrete structure" GB 50010—2010 and other related newly reviewed Codes. The main contents include: mechanical properties of concrete structure materials, design method of concrete structure, calculation method for flexural capacity、shear capacity、compressive capacity、tensile capacity and torsional capacity of reinforced concrete members, crack and deflection control and durability of reinforced concrete members and prestressed concrete members. Besides the basic concept, the calculation theory and design method of concrete structure are explained in each chapter, the typical examples are calculated according to "Code for design of concrete structure" GB 50010—2010.

The book can be served as a textbook for the undergraduate and graduate students of civil engineering and related majors in colleges and universities, also can be as a useful reference book for technicians of civil engineering. For the students and technicians of civil engineering in foreign countries, this book can be as a reference to learn and practice the current Chinese design code.

Some colleagues have taken part in the editorial work. They are: Zhao Jun and Wang Xinling (chapter 1, 2), Wang Xinling and Qian Hui (chapter 3, 4, 5, 6), Zhao Jun and Chu Liusheng (chapter 7), Chu Liusheng (chapter 8), Li Le (chapter 9), Zhao Jun and Chu Liusheng (chapter 10).

Due to the limited knowledge of the authors, some mistakes and errors in the book may exist. The suggestions for improvement will be gratefully accepted.

Content

Chapter 1

Introduction

1.1 Fundamental Concepts of Reinforced Concrete Structures

Plain concrete is formed from hardened mixtures of cement, water, fine aggregates, coarse aggregates such as crushed stones or gravels, air, and other admixtures often used. The plastic mixtures are placed and consolidated in the formwork, then cured to accelerate the chemical hydration of the cement mixtures and results in hardened concrete. It is generally known that concrete has a high compressive strength and a low tensile strength. The tensile strength is approximately one-tenth of its compressive strength. For plain concrete member such as a beam is subjected to bending moment. The compression in the top and the tension in the bottom are produced. The beam must therefore be able to resist both the tensile and compressive stresses. But the inability to resist tensile stresses of concrete results in the failure of the beam and the cracking in concrete simultaneously. The load-carrying capacity is very low and the beam is of very brittle failure. The relatively higher compressive strength of concrete cannot be used effectively. So the drawback must be overcome for concrete structures.

The steel reinforcing bars have high compressive and tensile strength which means that the steel reinforcing bars can help concrete resist compression and tension. Especially when the steel reinforcing bars are embedded at the tensile area in a concrete member, they can resist the tension instead of concretes after the concretes crack. Then steel reinforcing bars and concretes can work cooperatively to provide the resistance of a member. Reinforced concrete is the result of the suitable combination of steel bar and concrete and can be designed and constructed properly to have adequate resistant capacity. Hence tensile reinforcements in the tensile zones are generally provided to supplement the tensile strength of the reinforced concrete section.

For example, a plain concrete beam under a uniformly distributed load q is shown in Fig. 1.1(a), when the distributed load increases and reaches a value $q = 1.37\text{kN/m}$, the tensile region at the mid-span will be cracked and the beam will fail suddenly. A reinforced concrete beam of the same size but has two steel reinforcing bars (2Φ16) embedded at the bottom under a uniformly distributed load q is shown in Fig. 1.1(b). The reinforcing bars bear the tension which generated from the external loads and transferred from the concrete being cracked. When the load q is increased, the width of the cracks, the deflection and the stress of steel bars will increase. When a reinforcing steel bar approaches its yield stress f_y, the deflections and the crack widths of a beam offer some warning that the beam is going to fail. The failure of a beam is characterized by the crushing of the concrete in the compression zone. The failure load $q=9.31$kN/m, is approximately 6.8 times that for the plain concrete beam.

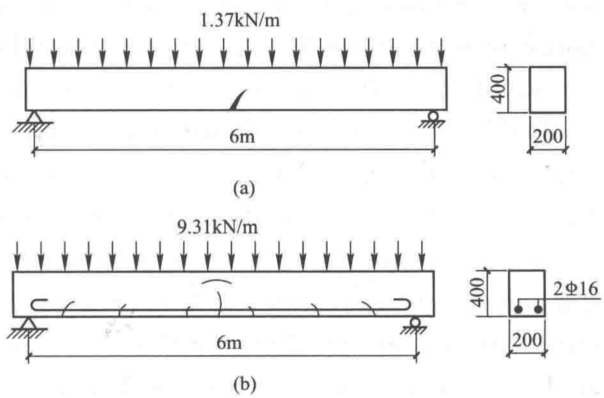

Fig. 1.1 Plain concrete beam and reinforced concrete beam

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

Evidently, concrete and steel bars can work together effectively. The main reasons are as follows. First there is a sufficient strong bond between the concrete and steel bars, which can make no relative slip between the steel bars and the surrounding concrete before being cracked. Next the thermal expansion coefficients of the two materials are 1.2×10^{-5}/K for steel and $1.0\times10^{-5}\sim1.5\times10^{-5}$/K for concrete, so they have almost the same length change with the temperature variation and the bond failure due to the temperature variation is avoided. In addition, the surrounding concrete can protect the bars from corrosion.

Generally speaking, reinforced concrete is a composite material in which concrete's relatively low tensile strength and ductility are counteracted by the inclusion of steel bar having higher tensile strength and/or ductility. The steel bar is usually embedded passively in the concrete before the concrete sets. Reinforcing schemes are generally designed to resist tensile stresses in particular regions of the concrete that might cause unacceptable cracking and/or structural failure. Reinforced concrete structures possess the following features:

(1) Ability to be cast in almost any shape. Because the mixture of cement, water and aggregate is in plastic state before it sets. It may have good fluidity to meet the requirement of construction by the suitable mix proportion design. Theoretically, concrete can be cast to form many members with any shape made by formwork in construction.

(2) Durability. Because the reinforcing steel bars are protected by concrete, reinforced concrete is perhaps one of the most durable materials for construction. It does not rot or rust, and is not vulnerable to efflorescence.

(3) Fire resistance. Both concrete and steel are not inflammable materials. Reinforced concrete would not be affected by fire below the temperature of 300℃ when there is a moderate amount of concrete cover giving sufficient thermal insulation to the embedded reinforcement bars.

(4) High stiffness. Most reinforced concrete structures have comparatively large cross sections. As concrete has high modulus of elasticity, reinforced concrete structures are usually stiffer than structures of other materials, thus they are less prone to large deformations. This property also makes the reinforced concrete less adaptable to situations requiring certain flexibility, such as high-rise buildings under seismic loads, and particular provisions have to be made if reinforced concrete is used.

(5) Locally available resources. It is always possible to make advantage of the local resources of labors and materials such as fine and coarse aggregates. Only cement and steel bars need to be brought in from other regions.

(6) Cost effective. Comparing with steel structures, reinforced concrete structures are low in cost.

(7) Large dead mass. The density of reinforced concrete may reach 2400～2500kg/m^3. Compared with structures of other materials, reinforced concrete structures generally have a heavy dead mass. However, this may not be always disadvantageous, particularly for those structures which rely on heavy dead weight to maintain stability, such as gravity dams and other retaining structures. To a certain extent, the developments and uses of light weight aggregates make concrete structures lighter.

(8) Curing period of long time. It normally takes a curing period of 28 days under specified conditions for concrete to acquire its full nominal strength. This makes the progress of reinforced concrete structures construction subjected to the seasonal climates. The development of prefabricated members alleviates this disadvantage. The development of prefabricated members used and the application of metal formworks also reduce the use of timber formwork materials.

(9) Easily cracked. Concrete is weak in tension and is easily cracked in the tension zones. Reinforcing bars withstand tensile forces and are not provided to prevent the concrete from cracking. So most of the reinforced concrete structures in service is behaving in a cracked state. This is an inherent weakness of reinforced concrete structures. The concrete in prestressed concrete structures is subjected to a compressive forces before working loads are applied. Thus the compressed concrete can bear some tensions from the loads.

1.2 Historical Development of Concrete Structures

Although concrete and its cementitious(volcanic) constituents, such as pozzolanic ashes, have been used since the days of Greek, the Romans, and possibly earlier ancient civilizational time, the use of reinforced concrete for construction purposes was relatively recent events. In 1801, F. Coignet published his statements of principles of construction, recognizing the weakness of concrete in tension regions of a member. The beginning of reinforced concrete is generally attributed to Frenchman J. L. Lambot, who in 1850 constructed, for the first time, a small boat with concrete for exhibition in the 1855 World' s Fair in Paris. In England, W. B. Wilkinson registered a patent for reinforced concrete floor slab in 1854. J. Monier, a French gardener, used metal frames as reinforcement to make garden plant containers in 1867. Before 1870 Monier had taken a series of patents to make reinforced concrete pipes、slabs and arches. But Monier had no knowledge of the working principle of this new material; he placed the reinforcement at the mid-depth of his wares. Then little construction was done in reinforced concrete. It is until 1887, when the German engineers Ways and Bauschinger proposed to place the reinforcement in the tension zones, the use of reinforced concrete as a material of construction began to spread rapidly. In 1906, C. A. P. Turner developed the first flat slab without beams.

Before the early twenties of 20^{th} century, reinforced concrete went through the initial stage of its development. Considerable progress occurred in the 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 established. Various structural elements, such as beams、slabs、columns、frames、arches、footings, etc. were developed by using this material. However, the strength of concrete and that of reinforcing bars were still very low. The common strength of concrete at the beginning of 20^{th} century was about 15MPa in compression, and the tensile strength of steel bars was about 200MPa. The elements were designed according to the allowable stresses.

By the late twenties, reinforced concrete entered a new stage of development. Many buildings、bridges、liquid containers、thin shells and prefabricated members of reinforced concrete were constructed by 1920. Reinforced concrete, because of its low cost and convenient availability, has become the main material of construction all over the world, especially after the wide acceptance of prestressing technology in the 1950s. Up to now, the quality of concrete has been greatly improved and the ranges of its utility have been expanded. The design approaches have also been innovative to giving the new role for reinforced concrete in the construction fields.

Today, the concrete commonly used has a compressive strength of 20 ～ 50MPa. For concrete used in pre-stressed concrete, the compressive strength may be as high as 60 ～ 80MPa. The reinforcing bars commonly used has a tensile strength of 500MPa, and the ultimate tensile strength of prestressing wire may reach 1570 ～ 1960MPa. The development of high strength concrete makes it possible for reinforced concrete to be used in high-rise buildings、off-shore structures、pressure vessels, etc. In order to reduce the dead weight of concrete structures, various kinds of light weight concrete have been developed with a density of 1400 ～ 1800kg/m^3. With a compressive strength of 50MPa, light weight concrete may be used in load bearing structures.

In the design method of reinforced concrete structures, the ultimate state design concept has replaced the former allowable stresses principle. Reliability analysis based on the probability theory has recently been introduced to put the ultimate state design on a sound theoretical foundation. That is to say, the ultimate state design method based on probability theory is now in use. The elastic-plastic analysis of continuous beams is established and is adopted in most of the design codes. Methods of finite element analysis are extensively used in the design of reinforced concrete structures and non-linear behaviors of concrete are taken into consideration. Recently, earthquake disasters prompted the research in the seismic resistance of concrete structures. Significant results have been achieved.

1.3 Special Features of the Book

Reinforced concrete is a widely used material for construction. As a minimum requirement, each civil engineer must have a basic understanding of the fundamentals of reinforced concrete. The primary objective of the book is to make the readers understand the basic concepts of materials composing of concrete structures and the behavior and design methods of reinforced concrete members under flexure、compression、tension、torsion, etc.

Design is the determination of the general shape and all specific dimensions of a particular structure so that it will perform the function for which it is created and will safely withstand the influences which will act on it throughout its useful life. The design of reinforced concrete requires some prerequisites of principles of engineering mechanics, structural analysis, behavioral knowledge in structures and materials.. In some courses, with the exception of Strength of Materials to some extent, a structure is discussed in the abstract. For instance, in the theory of rigid frame analysis, all members have an nominal $\frac{EI}{L}$ value, regardless of what the actual value may be. But the theory of reinforced concrete is different. It deals with specific materials, concrete and steel bar. The values of most parameters must be determined by experiments and can no more be regarded as some abstract values. Additionally, due to the low tensile strength of concrete, the reinforced concrete members usually work with cracks, some of the parameters such as the elastic modulus E of concrete and the moment of inertia I of section are variable with the loads.

The theory of reinforced concrete is relatively not long but has developed quickly. Although great progress has been made, the theory of reinforced concrete is still empirical in nature instead of rational. Many formulas can not be derived from in a strict mechanical theory. Besides, due to the differences in different countries, most countries base their design methods on their own experience and experimental results. Consequently, what one learns in one country may be different in another country. Besides, the theory is still in a stage of rapid development and is subjected to revision according to new research advances.

In China, the Code for design of concrete structures undergoes major revisions in about every 10 years and with minor revisions in between. This book is based on the latest current code in China "Code for Design of Concrete Structures" GB 50010—2010 (hereinafter referred to as the Code), which serves as a design standard and can be used as a companion reference to the book. The readers must keep in mind that this book cannot give them the knowledge which is universally valid regardless of time and places, but the basic principles on which the current design method is established.

The absolute precision of designing a concrete structure is not necessary due to the man-made and composite material of concrete and some semi-empirical formulas. The 10% consistency in quality is remarkably good. Reinforcing bars are rolled on factories, yet variation in strength may be as high as 5%. Besides, the position of bars in the formwork may deviate from their design positions. In fact, computing accuracy is adequate for almost all the cases, rather than carrying the calculations to meaningless precision. The time and effort of the designer are better spent to find out where the tension may occurs and the tension is resisted by placing reinforcement there.

For any design of the reinforced concrete members of a structure is achieved by trials and adjustments: assuming a section, determining the loads that are going to be applied to the structure, evaluating the internal forces, taking account of the properties of materials, checking the dimensions of members of the structure for adequacy of safety and serviceability. It is necessary to combine the theory with experience. The book is to offer the readers a basic training in every aspect of the process, together with Engineering Mechanics, Strength of Materials, Theory of Structures, Materials of Construction, etc.

Chapter 2

Mechanical Properties of Reinforced Concrete Materials

2.1 Steel Reinforcement

2.1.1 The Type of Steel Reinforcement

The main mechanical properties of steel reinforcements mainly depend on its chemical components, particularly on the contents of the elements of iron (Fe), carbon (C), manganese (Mn), silicon (Si), sulphur (S), and so on. Generally, with the increase of the contents of manganese and silicon, the strength of steel reinforcement is higher, and the elongation remains almost unchanged. With the increase of the contents of carbon, the strength of steel reinforcement is higher, while the elongation and weld-ability are lower. Based on carbon content, steel reinforcement is classified as low carbon steel when the carbon content is less than 0.25%, and high carbon steel when the carbon content is more than 0.6% and less than 1.4%. The elements of phosphorus (P) and sulphur (S) are categorized as harmful elements because the steel reinforcement's elongation will be reduced obviously as long as their contents are more than certain values.

Appending some elements to steel, such as manganese (Mn), silicon (Si), vanadium (V), titanium (Ti), and so on, the mechanical properties and other working properties of the steel reinforcement (generally called low alloy-steel) will be obviously improved.

The steel reinforcements for concrete structures may be classified as hot-rolled steel bars, heat-treated steel bars, cold-working steel bars, steel wire and so on. Among them the hot-rolled steel bars are the most commonly used in civil engineering structures.

In China, the hot-rolled steel bars are classified as HPB300, HRB335, HRBF335, HRB400, HRBF400, RRB400, HRB500 and HRBF500 according to their strengths. Among them only HPB300 bar has a plain surface, all other grades have lugs or indentations rolled on the surface of bars (shown in Fig. 2.1). Usually, the sizes of the steel bars used in concrete structure range from 6mm to 32mm at an interval of 2mm, in order to distinguish steel bars from each other easily