国家级精品课程双语教材
21世纪交通版高等学校教材

Principle of Structural Design

结构设计原理

Jianren Zhang, Xiaoyan Liu
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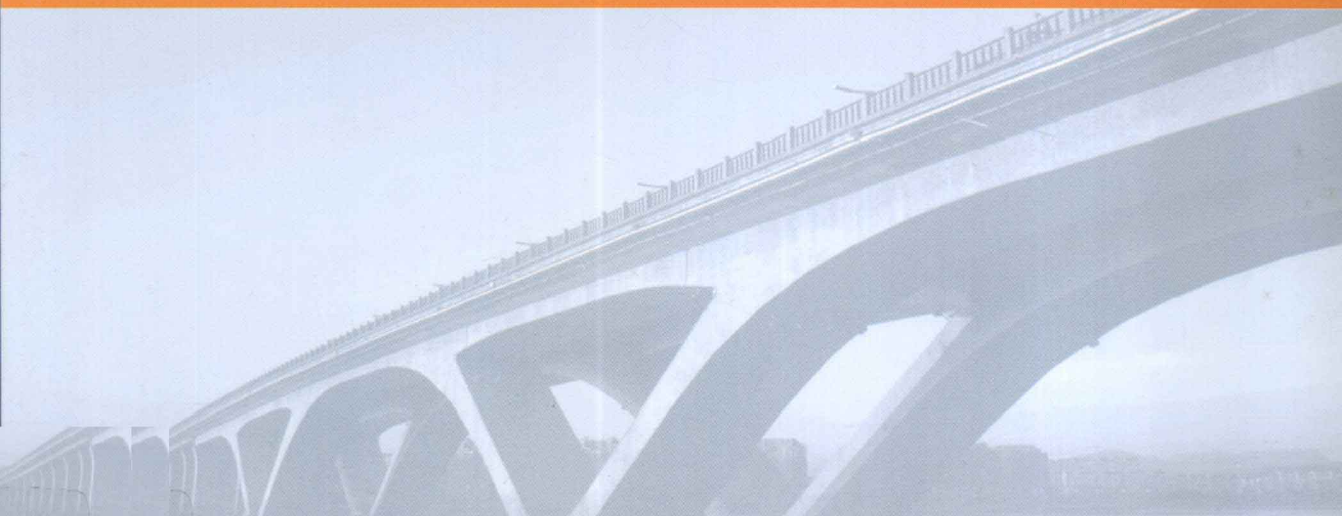

人民交通出版社
China Communications Press

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Preface

Reinforced concrete is widely used to many structures in infrastructure engineering as a good performance architecture material. As for civil engineering technicians, it is the basic requirements to master the design principles of reinforced concrete structures, prestressed concrete structures and masonry structures.

The book was edited based on the requirements of teaching advisory committee of civil engineering or road, bridge and crossing engineering professions and in accordance to the latest standards of P. R. of China and provisions of Ministry of Transportation, such as ***General Code for Design of Highway Bridges and Culverts*** (***JTG D60—2004***), ***Code for Design of Reinforced Concrete and Prestressed Concrete Highway Bridges and Culverts*** (***JTG D62—2004***) and ***Code for Design of Masonry Highway Bridges and Culverts*** (***JTG D61—2005***). This book is a bilingual textbook adapted to related professional technicians home and abroad including Hong Kong and Macau.

This book was completed based on long-term teaching practices of authors, National Advanced Course of the Principles of Structural Design and existed Chinese and English textbooks all over the world. This book has characteristics of clear concepts and concise content. All symbols and units conform to the national standards.

There are many contributors who undertake to edit this book as: Prof. Zhang Jianren and Dr. Peng Jianxin contribute the General Introduction, Chapters 1, 2 and 3; Dr. Xu Xiaoxia and Dr. Xiao Dan contributes the Chapters 4, 5 and 8; Dr. Wang Lei contributes the Chapters 6 and 7, Dr. Peng Hui contributes the Chapters 9 and 10; Dr. Yuan Ming and Prof. Liu Xiaoyan contribute the Chapters 11, 12 and 13, and Dr. Yin Xinfeng contributes the Chapters 14, 15 and 16.

The professional help provided by Prof. Steve-C. S. Cai, who is a professor of Civil Engineering at Louisiana State University, USA, is gratefully appreciated. The English revisions by Prof. Xiong Lijun, College of Foreign Language, and Associate Prof. Wang Yan, Department of International Communications, Changsha University of Science & Technology, are much acknowledged.

There are some unavoidable errors in this book due to the limit time and authors' abilities. Any corrections by readers are welcome.

Jianren Zhang

12/2010

前　言

钢筋混凝土作为一种优质的建筑材料被广泛应用于土木工程的各种结构中，作为土木工程专业的技术人员，掌握钢筋混凝土结构、预应力混凝土结构、圬工结构的设计原理是专业的基本要求。本书基于高等院校土木工程专业、道路桥梁工程专业教学指导委员会的要求，按照中华人民共和国国家标准和现行的交通运输部行业标准与最新设计规范《公路桥涵设计规范》(JTG D60—2004)、《公路钢筋混凝土及预应力混凝土桥涵设计规范》(JTG D62—2004)、《公路圬工桥涵设计规范》(JTG D61—2005)进行编写的，适应于包括香港、澳门等地的国内外相关的专业技术人员使用。

本书是在作者长期教学实践和创建“结构设计原理”国家精品课程、充分汲取国内外优秀中英文教材精华的基础上完成的，在内容编排上，由浅入深，循序渐进，注重理论联系实际。符号和计量单位按国家标准。

参加编写的人员及分工为：总论、第1、2、3章由张建仁和彭建新撰写，第4、5、8章由徐晓霞、肖丹撰写，第6、7章由王磊撰写，第9、10章由彭晖撰写，第11、12、13章由袁明和刘小燕撰写，第14、15、16章由殷新锋撰写。

在书稿的撰写过程中，得到了美国路易斯安那州大学蔡春生教授的指导，得到了长沙理工大学外语部熊丽君教授、国际交流处王燕副教授的审核，特此表示衷心感谢。

由于编写时间短促和编者的水平有限，书中错误在所难免，恳请读者批评指正。

张建仁

2010年12月

Contents

General Introduction

0.1 Introduction

Human beings took advantage of soil, stone, wood and other natural materials for construction activities in earlier age.

Civil engineering has experienced three breakthroughs in human history.

First breakthrough: 11 ~ 3 century BC, brick and tile, compressive human-made materials were invented. This was an era of widely use of wood and brick (stone) structures, such as: the Great Wall, the Pyramids and Metrical.

Second breakthrough: the 17th century cast iron, 19th century wrought iron, and the mid-19th century high-quality steel (tensile and compression resistant material) appeared. This was an era of steel works, for example, 300m high Eiffel Tower, steel structures with a main Cross of 512m of the Fox Channel.

Third breakthrough: the 19 ~ 20 century, reinforced concrete structures occurred. After the invention of steel and cement, until this century, the reinforced concrete structure calculation theory and stress loss and anchorage of prestressed concrete structure and reinforced concrete structure had been solved. This dominated in the field of civil engineering.

"Principle of Structural Design" is an important and technical base course, which studies structural element combined bridge engineering after learning "mechanics of materials" and "road construction materials". Therefore, it is a very practical subject.

0.2 Basic Concepts

1) Component

Its function is to carry loading and play a role as skeleton. According to mechanical characteristics, typical component includes flexural members (beams and plate), compression members, tensioned members and torsioned members, etc.

2) Structure

Structure means a space or plane system consists of several components made of construction materials. For example: beam of a bridge, pier and foundation compose of bridge's load-bearing system, which is called structure.

3) Structural category

(1) According to the construction materials, structures are divided into concrete structures,

masonry structure, steel structure and wood structure. Concrete structures include plain concrete structure, reinforced concrete structure, prestressed concrete structure, and concrete-filled steel tubular structure.

(2) Based on the use and function of structures, structures include bridge structures, building structures, underground structures, hydraulic structures, and special structures. Bridge structures can be divided into following types according to mechanical characteristics of load-carrying components as beam bridge (flexure), arch bridge (compression), rigid frame (beam and column combination), suspension bridge (in tension) and cable-stayed bridge (combined stress).

4) Reinforced concrete structure

Reinforced concrete structure, consisting of steel reinforcement and concrete, is a kind of architecture component that takes advantage of the merits of steel reinforcement and concrete.

Its advantages are:

(1) Local resources;

(2) Low cost;

(3) Durability;

(4) Fire resistance;

(5) Good adaptability.

Its disadvantages are:

(1) Large self-weight;

(2) Construction impacted by season;

(3) Cracking;

(4) Not suitable for high-strength material.

Reinforced concrete structures is mainly applied to small and medium span beams, plates, piers, arches, towers.

5) Prestressed concrete structures

Prestressed concrete structure is a kind of structure that a stress is imposed to concrete to improve stress condition of concrete. Its advantages include use of high-strength material, light weight, capacity of large span and good cracking resistance. Its disadvantages are complex workmanship and more equipments required. It is mainly applied to the bridge span that is more than 50m.

6) Masonry structures

Masonry structure consists of brick and stone such as masonry block according to certain rules of construction materials made of the structure. Its advantages are a wide source of materials, high compressive strength, durable and simple construction. Its drawbacks are that it is only suitable for compressive member.

7) Steel structures

The advantages of steel structures are light weight, high strength, material uniformity, large elastic modulus, and ideal elastic material. In addition, the construction is convenient and fast. The disadvantages are high cost and poor durability, regular maintenance, and poor fire resistance. Steel structure is mainly suitable for long-span steel bridge superstructures and light steel buildings.

0.3 Characteristics of the course and guidance for how to learn the course

1) Main tasks of this course

(1) To learn basic concepts and theories of reinforced concrete and prestressed concrete structures;

(2) To learn the principles of design and calculation of various engineering materials;

(3) To master working performance, failure modes, computation theory, design and construction requirements and other issues under various loading condition of reinforced concrete structures, prestressed concrete structures, masonry and steel structures. Through course design project, the entire beam design is mastered, and it provides a basis for graduation design and future engineering design.

2) Features of the courses

(1) The course is transition curriculum, transiting from the basic courses to technical courses. Research methods inherit from previous courses and but differ each other.

(2) Reinforced concrete design method is based on experimental investigation. Design method of reinforced concrete members depends heavily on experimental tests, and we should pay attention to application scopes and conditions of theoretical analysis.

(3) Design has a character of variation. Structural design should obey principles of safety, adaptability, economy and reasonability. When a load is given, the same design elements have various answers. A reasonable selection is made based on comprehensive analysis and comparison.

(4) For this course, design process and steps of analysis are needed to understand.

(5) Learning how to use design specifications.

The following codes are associated with this course:

①*General Code for Design of Highway Bridge and Culverts* (*JTG D60—2004*).

②*Code for Design of Reinforced Concrete and Prestressed Concrete Highway Bridges and Culverts* (*JTG D62—2004*). This is abbreviated by the *CHBC*.

③*Code for Design of Masonry Highway Bridges and Culverts* (*JTG D61—2005*).

④*Uniform Standard for Engineering Structural Reliability* (*GB 50153—2008*).

⑤ *Uniform Standard for Highway Engineering Structural Reliability* (*GB/T 50283—*

1999).

⑥*CEB-FIP*.

The mentioned codes are necessary to be understood during the study.

3) Problem needed to be solved

(1) Selection of structural material;

(2) Selection of section type;

(3) Pre-design sectional dimensions;

(4) Reinforcement Computing;

(5) Checking strength conditions, stiffness, stability, cracking resistance.

4) Ways to learn the course

(1) Learning contents on class well, and grasping internal relations and nuances of content system.

(2) Combining theory with practice, and addressing on testing, experience and meeting design standard requirements.

(3) Understanding the material properties, because the structure features are determined by the material properties.

(4) Structural design features in diversity, and it is possible to search optimal design strategy.

(5) Familiar with the provisions and addressing construction requirements.

Part 1 Reinforced Concrete Structures

Chapter 1 Basic Concepts of Reinforced Concrete Structures and Physical and Mechanical Properties of Materials

1.1 Basic concept of reinforced concrete structures

1) Definition of reinforced concrete structures

Concrete is a non-homogeneous materials with high compressive strength and very low tensile strength. However, steel is a kind of material with very high tensile and compressive strength, being able to bear the tensile stress. The combination of steel and concrete is used to work together. Concrete is in pressure and to withstand tension. Steel rebar bears tensile. This will be able to use their strengths fully, and hence produce a reinforced concrete structure. Therefore, reinforced concrete structure is made of concrete configured by the ordinary mechanical steel rebars or skeleton of reinforcement.

2) Example

The following examples illustrate the stress state of a pure concrete member and a reinforced concrete structure.

Example: a span is 4 m, the concentrated load is placed at the middle of test beam, beam section size is 200mm × 300mm. The grade of concrete is C20. The details are shown in Figure 1-1.

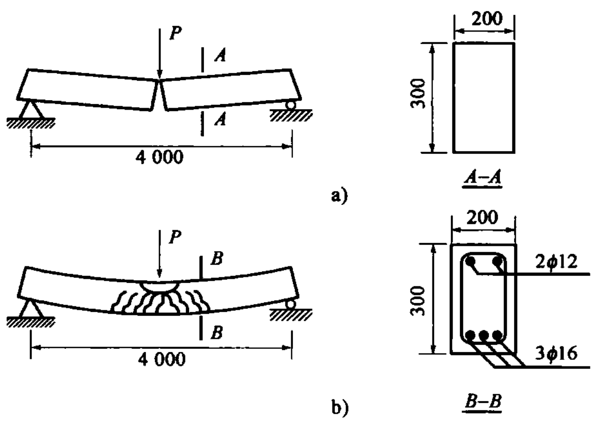

Figure 1-1 Concrete and reinforced concrete beams (unit: mm)

(1) Experimental results

①As shown in Figure 1-1a), for concrete beams, load P is 8kN and is controlled by the concrete tensile strength and failure mode was brittle;

②As shown in Figure 1-1b), the ultimate load of reinforced concrete beams P is 36kN, and the steel is in tension reaching yielding and concrete is in compression. The failure mode is plastic failure.

(2) Experimental findings

The combination of steel and concrete improves the bearing capacity and the mechanical properties of the structure.

3) Reasons for working together of steel and concrete

The reasons for working together of steel reinforcement and concrete are as follows:

(1) Good bonding between the concrete and steel. Hence the two can be reliably combined into an integrity, and it deform well under load together to complete the structural function.

(2) Temperature expansion coefficient of rebar $\alpha_{st} = 1.2 \times 10^{-5}$, temperature expansion coefficient of concrete $\alpha_{ct} = (1.0 \sim 1.5) \times 10^{-5}$. Both have a similar temperature coefficient of linear expansion, and so there is not a greater temperature stress and relative deformation and destruction of bond strength because of no temperature changes.

(3) Sufficient cover thickness. Reinforcement in concrete can be protected against corrosion and so concrete in alkaline environment can ensure that concrete can work with reinforcement.

4) The main advantages and disadvantages of RC structures

(1) Advantages

①Using local resources and saving reinforced concrete material;

②Good durability and fire resistance;

③Good modulability, easy implementation of structural type;

④Good structural integrity for casting in site or prefabricated, enough stiffness.

(2) Disadvantages

①High self-weight (improvement measures: use of lightweight aggregate concrete);

②Poor crack resistance (improvement measures: prestressed concrete);

③Construction influenced by climatic conditions;

④Difficult strengthening and reconstruction, poor performance of heating and noise.

As mentioned above, it is realized that RC structures have advantages and disadvantages, and so structural engineers may use its advantages in design practices. In engineering light aggregate is used to reduce self-weight and so enhance its span.

1.2 Concrete

1) Introduction

Concrete is made from cement, stone, sand, water and so behaviors a certain mix of different grades. Concrete quality is high strength, workability(easy bleeding), durability, economy and so on. Its performance characteristics are: a. compressive strength is high and tensile strength is low; b. many factors affect its strength, such as: cement grade, aggregate properties, concrete age, production methods, curing conditions and test methods; c. concrete compressive strength is conditional-the compressive strength of concrete depends on the lateral deformation constraints.

2) Concrete Strength

Strength of concrete has three indicators: cubic compressive strength f_{cu}, axial compressive strength f_c, and tensile strength f_t. There are various factors affecting its strength indices, including: physical performance of materials, concrete mix, curing environment, construction method, the shape and size of specimen, test methods, loading conditions and the loading model of the sample.

(1) The cubic compressive strength (f_{cu}) -basic strength index

Concrete cubic compressive strength is the basic strength index, making the standard cure method (temperature 20℃ ±3℃, relative humidity of not less than 90% of the moist air curing 28d) of side length of 150mm cube specimens. Standard Test Method is that (test lubricant coated surface is not the whole cross-section pressure, loading speed is 0.15 ~ 0.25MPa/s) concrete cubic compressive strength is measured in the 28d age with a 95% guarantee rate of compressive strength (in MPa unit) and with the symbol of f_{cu}. The factors affecting cube strength are sample size and test methods.

$$\left.\begin{aligned} f_{cu}(150) &= 0.95 f_{cu}(100) \\ f_{cu}(150) &= 1.05 f_{cu}(200) \end{aligned}\right\} \qquad (1\text{-}1)$$

Concrete strength changes from C15 ~ C80 divided into 14 grades. The middle incremental is 5MPa. For lower than C50 concrete is named as ordinary strength concrete. For C50 and above C50 is high strength concrete.

According to the ***CHBC***, RC structures, strength should not be less than C20. When steel types with HRB400, KL400-class are used, its strength should not be less than C25. But for prestressed concrete members, strength should not be less than C40.

It is worthy to mention that concrete cylinder compressive strength is often used abroad, such as the United States, Japan and Europe Concrete Association with diameter of 6 inches (152mm) and height of 12 inches (305mm) standard cylinder compressive strength of specimens as a index of axial compressive strength, denoted by f'_c. For concrete lowering than C60, concrete cylinder compressive strength and the standard value of f_{cu} have a relation, it can be converted as.

$$f'_c = 0.79 f_{cu,k} \qquad (1\text{-}2)$$

When $f_{cu,k}$ exceeds 60MPa with an increase of compressive strength , and the ratio of f'_c and $f_{cu,k}$ (that is, the coefficient in the formula) also increase. For CEB-FIP code, for C60 concrete the ratio is 0.833 and for C70 concrete ratio is 0.857. For C80 concrete the ratio is 0.875.

(2) Axial compressive strength (f_c)

Axial compressive strength is able to reflect mainly the compressive strength of concrete structure, which is 150mm × 150mm × 300mm prism as the standard sample measured compressive strength. The standard value of axial compressive strength (f_{ck}) has a relationship with standard value of cubic compressive strength ($f_{cu,k}$), and so the relationship is

$$f_{ck} = 0.88 a f_{cu,k} \quad (1\text{-}3)$$

Where for C50 concrete and below, $a = 0.76$, For C55 ~ C80 concrete $a = 0.78 \sim 0.82$. For C40 ~ C80 concrete the discount factor of 1.0 ~ 0.87 should be considered and interpolation method is used.

(3) Axial tensile strength (f_t)

Concrete tensile strength is much smaller than the compressive strength of concrete with 1/8 ~ 1/18 of the compressive strength. Axial tensile strength is also a basic strength index. The main test methods:

①Face-to-face tensioned test method

As shown in Figure 1-2, specimen is a cylinder with 100mm × 100mm × 500mm. Reinforcing bars are placed at geometric centroid of member, and tension force is acted by using tools to tension steel rebars. When the central specimen destroys and transverse concrete cracks, the average axial tensile stress of damaged cross section shall be the average axial tensile strength f_t.

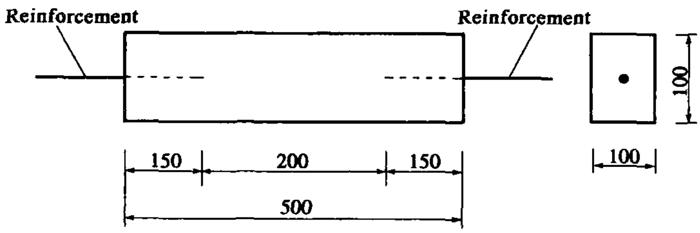

Figure 1-2 Concrete tensile strength of test specimens (unit: mm)

②Splitting test method

As shown in Figure 1-3, 150mm cubes are used as a standard specimen of concrete to measure splitting tensile strength, and splitting tensile strength of concrete f_{ts} can be measured as

$$f_{ts} = \frac{2F}{\pi A} = 0.637 \frac{F}{A} \quad (1\text{-}4)$$

Where f_{ts} is the concrete splitting tensile strength (MPa); F is the splitting fracture load, and A is split area for the sample surface (mm^2).

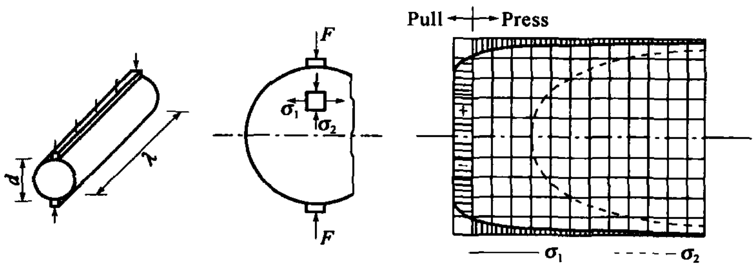

Figure 1-3 Splitting test

It is noted that measured value of concrete splitting tensile strength converted into axial tensile strength should be multiplied by the conversion factor of 0.9 by the above test method, that is $f_t = 0.9 f_{ts}$.

The standard value of axial tensile strength (f_{tk}) has a convension relationship with standard value of cubic compressive strength ($f_{cu,k}$) is

$$f_{tk} = 0.88 \times 0.395 \beta f_{cu,k}^{0.55} (1 - 1.645 \delta_f)^{0.45} \tag{1-5}$$

Where δ_f is coefficient of variation of cubic compressive strength.

(4) Concrete strength under complex stress

①Bi-directional normal stress

As shown in Figure 1-4, When σ_1 and σ_2 (compression-compression) act, concrete strength increases. When σ_1 and σ_2 (tension-compression) act, concrete strength decreases. When σ_1 and σ_2 (tension-tension) act, concrete strength remains unchangeable.

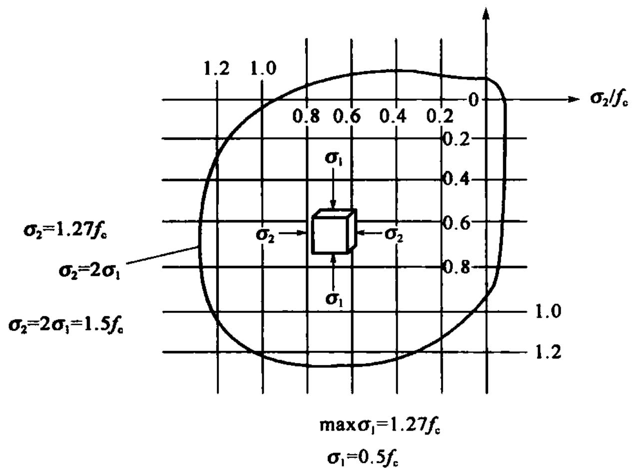

Figure 1-4 Concrete strength curves under biaxial stress

②Normal stress and shear stress

As shown Figure 1-5, when $\sigma/f_c < (0.5 \sim 0.7)$, the concrete shear strength increases with an increase of compressive stress. When $\sigma/f_c > (0.5 \sim 0.7)$, the concrete shear strength decreases with an increase of compressive stress.

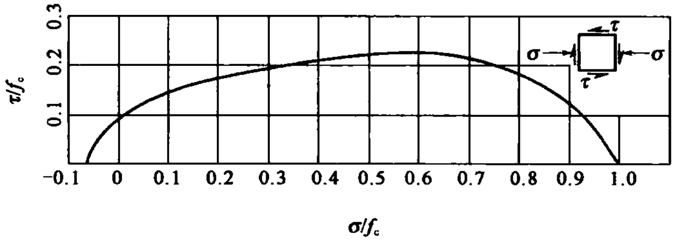

Figure 1-5 Strength curve under combination of normal stress and shear stress

When the compressive stress is about $0.6 f_c$, the shear strength increases to the maximum value, and compressive stress continues to increase significantly. Due to the development of internal cracks, the shear strength will decrease with an increase of compressive stress. For compression-shear element, the ratio should be considered.

③Concrete triaxial compression

As shown in Figure 1-6, for the three-compressed concrete, its compressive strength is:

$$f'_{cc} = f'_c + k'\sigma_2 \quad (1\text{-}6)$$

Where σ_2 is the lateral compressive stress, and f'_c is the cylinder compressive strength.

Application of the three-compressed concrete appears concrete-filled steel tubular concrete and reinforced concrete column with screwed stirrups (see Figure 1-7).

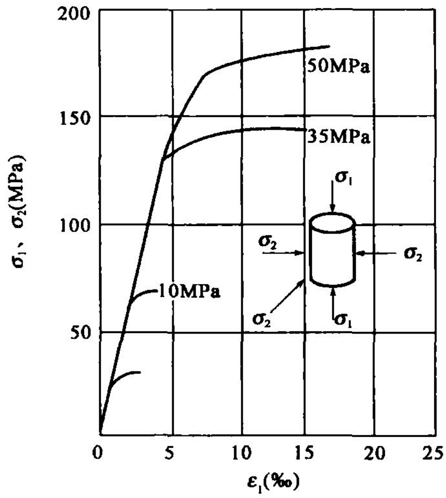

Figure 1-6 Three-compressed concrete under compression

3) Deformation of concrete

(1) Characteristics of deformation properties of concrete

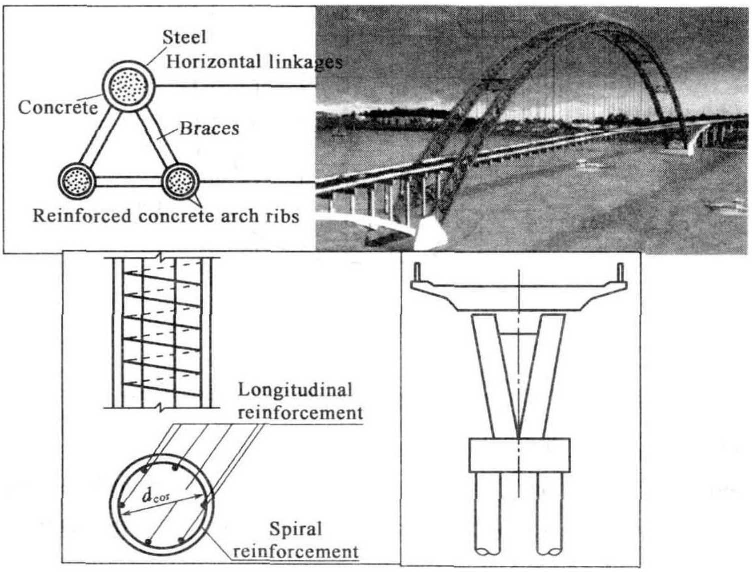

Figure 1-7 Application-steel tube, close with spiral reinforcement

Deformation factors of concrete include loading methods, loading time, temperature, humidity, test size, shape and strength of concrete. The main deformation is the deformation and volume deformation. Deformation includes deformation under monotonic loading short-term, long-term deformation under loading, and repeated deformation under loading. Volume deformation is related to shrinkage deformation and deformation caused by temperature changes.

(2) Concrete deformation performance under monotonous and short-term load

The experimental conditions of concrete under monotonous and short-term load are: a. uniaxial compression; b. loading under equal strain rate, etc.; c. test specimen and the high-elastic component attached to the specimen together under in compression.

Concrete stress-strain test σ-ε curve is shown in Figure 1-8.