21世纪土木工程专业双语教材

混凝土结构基本原理

CONCRETE STRUCTURAL FUNDAMENTALS

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武汉理工大学出版社

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CONCRETE STRUCTURAL FUNDAMENTALS

（混凝土结构基本原理）

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SUMMARY

This book is based on the newly reviewed code in China "Code for design of concrete structure" (GB50010—2002) and the teaching program for civil engineering. It containts: mechanical properties of reinforced concrete materials, basic principles for the design of reinforced concrete structures, flexural strength of members, shear strength of members, torsional strength of members, compressive strength of members, tensile strength of members, crack and deflection control of reinforced concrete members and prestressed concrete members. The velevant introduction in Chinese is attached at the end of the book.

The book can not only be served as bilingual textbook of "Concrete Structural Fundamentals" for university and college students of civil engineering, but book may be also served as a reference for technicians, researchers and foreign students of civil engineering.

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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 rudimental requirement, a basic understanding of the fundamentals of reinforced concrete structure. This book is written with the purpose of being used as a reinforced concrete textbook for Chinese universities and colleges which use "bilingual teaching"(English and Chinese) in their lectures.

This book is based on the newly reviewed code in China "Code for design of concrete structure"(GB50010—2002) and made up of ten separate sections: introduction, mechanical properties of reinforced concrete materials, basic principles for the design of reinforced concrete structures, flexural strength of members, shear strength of members, torsional strength of members, compressive strength of members, tensile strength of members, crack and deflection control of reinforced concrete members and prestressed concrete members.

The book may be also served as a useful reference book for engineers and designers. For students and engineers in Hong Kong, Macao, and foreign countries, this book may be used as a reference to the current Chinese design code.

The writer is grateful for the careful revision received from Dr. K. S. Law(City University of Hong Kong) and Dr. Louis. Lam(Vocational Education Institute of Hong Kong).

Many colleagues have taken part in this edition work. They are: Liu Lixin (editor in chief, chapter 1, 3, 5), Guan Pinwu (chapter 2, 6), Wang Xinling (chapter 4, 8), Yang Weizhong and Chen Meng(chapter 7), Song Jianxue(chapter 9), Zhao Zhuo and Guan Gang (chapter 10), Chen Meng(introduction in Chinese).

The writer also wishes to thank his postgraduate students Zhang Ting, Mao Daling, Lv Yanmei, Li Xiaofen, Kong Qin, Peng Gang and Xue Pengfei for their contributions to the introduction in Chinese of the book.

As this book is written in a relatively short time, and not in the writer's native language, some errors may have slipped the writer's notice. The writer would be grateful to any constructive comments or criticisms that readers may have and for notification of any errors that they will inevitably detect.

Liu Lixin
Zhengzhou University
January 2004

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CHAPTER 1

INTRODUCTION

1.1 BASIC CONCEPTS AND CHARACTERISTICS OF REINFORCED CONCRETE

Plain concrete is formed from 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 accelerate of the chemical hydration of the cement mix and results in a hardened concrete. It is generally known that concrete has high compressive strength and low resistance to tension. Its tensile strength is approximately one-tenth of its compressive strength. Consequently, tensile reinforcement in the tension zone has to be 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 (2 Φ 16) embedded at the bottom under a uniformly distributed load q is shown in Fig. 1.1(b). The reinforcing bars take up the tension there after the concrete is cracked. When the load q is increased, the width of the cracks, the deflection and the stress of steel bars will increase. When the steel approaches the yielding stress f_y, the deflection and the crack width are so large offering some warning that the beam is going to fail. The failure of the beam is characterized by the crushing of the concrete in the compression zone. The failure load $q=9.31\text{kN/m}$, is approximately 6.8 times that for the plain concrete beam.

Concrete and reinforcement can work together because there is a sufficiently strong bond between the two materials[①], there are no relative movements of the bars and the surrounding concrete before cracking. The thermal expansion coefficients of the two materials are $1.2\times10^{-5}\text{K}^{-1}$ for steel and $1.0\times10^{-5}\sim1.5\times10^{-5}\ \text{K}^{-1}$ for concrete.

Generally speaking, reinforced concrete structure possess the following features:

(1) Durability. With the reinforcing steel protected by the concrete, reinforced concrete

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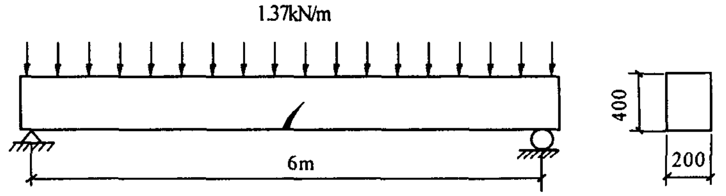
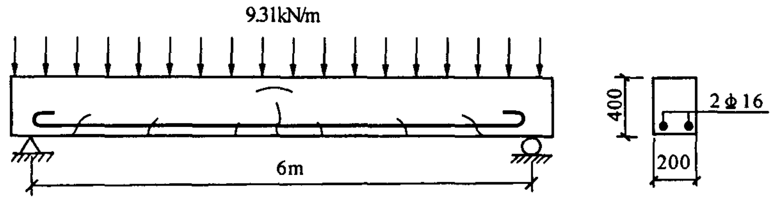
① Making the two materials acting monolithically.



(a)Plain concrete beam



(b)Reinfoced concrete beam

Fig. 1. 1 Plain concrete beam and reinforced concrete beam

is perhaps one of the most durable materials for construction. It does not rot or rust, and is not vulnerable to efflorescence.

(2)Fire resistance. Both concrete and steel are not inflammable materials. They would not be affected by fire below the temperature of 200℃ when there is a moderate amount of concrete cover giving sufficient thermal insulation to the embedded reinforcement bars.

(3)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 load, and particular provisions have to be made if reinforced concrete is used.

(4)Locally available resources. It is always possible to make use of the local resources of labour and materials such as fine and coarse aggregates. Only cement and reinforcement need to be brought in from outside provinces.

(5)Cost effective. Comparing with steel structures, reinforced concrete structures are cheaper.

(6)Large dead mass. The density of reinforced concrete may reach 2400～2500kg/m^3. Compare with structures of other materials, reinforced concrete structures generally have a heavy dead mass. However, this may be not always disadvantageous, particularly for those structures which rely on heavy dead weight to maintain stability, such as gravity dam and other retaining structure. The development and use of light weight aggregate have to a certain extent make concrete structure lighter.

(7)Long curing period. It normally takes a curing period of 28 day under specified conditions for concrete to acquire its full nominal strength. This makes the progress of reinforced concrete structure construction subject to seasonal climate. The development of factory prefabricated members alleviates this disadvantage. The development of using prefabricated members and investment in metal formwork also reduce the consumption of timber formwork materials.

(8)Easily cracked. Concrete is weak in tension and is easily cracked in the tension zone. Reinforcing bars are provided not to prevent the concrete from cracking but to take up the tensile force. So most of the reinforced concrete structure in service is behaving in a cracked state. This is an inherent weakness of reinforced concrete structure. The concrete in prestressed concrete structure is subjected to a compressive force before working load is applied. Thus the compressed concrete can take up some tension from the load.

1.2 HISTORICAL DEVELOPMENT OF CONCRETE STRUCTURE

Although concrete and its cementitious (volcanic) constituents, such as pozzolanic ash, have been used since the days of Greek, the Romans, and possibly earlier ancient civilization, the use of reinforced concrete for construction purpose is a relatively recent event. In 1801, F. Coignet published his statement of principles of construction, recognizing the weakness of concrete in tension. 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 Wayss and Bauschinger proposed to place the reinforcement in the tension zone, 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 20th 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 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 20th century was about 15MPa in compression, and the tensile strength of steel bars was about 200MPa. The elements were designed along the allowable stresses which was an extension of the principles in strength of materials.

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. The era of linear and circular prestressing began. Reinforced concrete, because of its low cost and easy availability, has become the staple material of construction all over the world. Up to now, the quality of concrete has been greatly improved and the range of its utility has been expanded. The design approach has also been innovative to giving the new role for reinforced concrete is to play in the world of construction.

The concrete commonly used today has a compressive strength of 20～40MPa. For concrete used in pre-stressed concrete the compressive strength may be as high as 60～80MPa. The reinforcing bars commonly used today has a tensile strength of 400MPa, and the ultimate tensile strength of prestressing wire may reach 1570～1860MPa. 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. One of the best examples is the gymnasium of the University of Illinois which has a span of 122m and is constructed of concrete with a density of 1700 kg/m^3. Another example is the two 20-story apartment houses at the Xi-Bian-Men in Beijing. The walls of these two buildings are light weight concrete with a density of 1800 kg/m^3.

The tallest reinforced concrete building in the world today is the 76-story Water Tower Building in Chicago with a height of 262m. The tallest reinforced concrete building in China today is the 63-story International Trade Center in GuangZhou with a height of 200m. The tallest reinforced concrete construction in the world is the 549m high International Television Tower in Toronto, Canada. The prestressed concrete box-section cable-stayed bridge over the Red-water River in China has a main span of 90m. The main span of the highway bridge at Mao-Gang in Shanghai is 200m. The prestressed concrete T-section simply supported beam bridge over the Yellow River in Luoyang has 67 spans and the standard span length is 50m.

In the design of reinforced concrete structures, limit state design concept has replaced the old allowable stresses principle. Reliability analysis based on the probability theory has very recently been introduced putting the limit state design on a sound theoretical foundation. Elastic-plastic analysis of continuous beams is established and is accepted in most of the design codes. Finite element analysis is extensively used in the design of reinforced concrete structures and non-linear behavior of concrete is taken into consideration. Recent earthquake disasters prompted the research in the seismic resistant reinforced of concrete structures. Significant results have been accumulated.

1.3 SPECIAL FEATURES OF THE COURSE

Reinforced concrete is a widely used material for construction. Hence, graduates of every civil engineering program must have, as a minimum requirement, a basic understanding of the fundamentals of reinforced concrete.

The course of Reinforced Concrete Design requires the prerequisite of Engineering Mechanics, Strength of Materials, and some if not all, of Theory of Structures. In all these courses, with the exception of Strength of Materials to some extent, a structure is treated of in the abstract. For instance, in the theory of rigid frame analysis, all members have an abstract EI/l value, regardless of what the act value may be. But the theory of reinforced concrete is different, it deals with specific materials, concrete and steel. The values of most parameters must be determined by experiments and can no more be regarded as some abstract. 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 inertia I of section are variable with the loads.

The theory of reinforced concrete is relatively young. Although great progress has been made, the theory is still empirical in nature instead of rational. Many formulas can not be derived from a few propositions as in mechanics, and may cause some difficulties for students. Besides, due to the difference in practice 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 findings from research. In China, the design code undergoes major revision in about every fifteen years and with minor revision in between. This book is based on the latest current code in China "Code for Design of Concrete Structures"(GB50010—2002). The students must keep in mind that this course can not give them the knowledge which is universally valid regardless of time and place, but the basic principles on which the current design method in the country is established.

The desk calculator has made calculations to a high degree of precision possible and easy. Students must not forget that concrete is a man-made material and a 10% consistency in quality is remarkably good. Reinforcing bars are rolled in factory, 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, two figure 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 occur and to resist it by placing reinforcement there.

Any design of the reinforced concrete members of a structure is achieved by *trial and adjustment*: assuming a section, collecting the loads that are going to act on 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 course is to offer the students a sound training in every aspect of the process, together with Engineering Mechanics, Strength of Materials, Theory of Structures, Materials of Construction, etc. The course of Reinforced Concrete Design serves that purpose.

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 reinforcement mainly depend on its chemical content, particularly on the content of the elements iron (Fe), carbon (C), manganese (Mn), silicon (Si), sulphur (S), and so on. Generally with the increase of the content of manganese and silicon, the strength of steel is higher, and the elongation remains almost unchanged. With the increase of the content of carbon, the strength of steel is higher, while the elongation and weld-ability are lower. With respect to 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 content is more than a certain value.

Appending some elements into 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 distinctively improved.

The steel reinforcements for concrete structure 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 is the most commonly used in civil engineering structures.

In China, the hot-rolled steel bar is classified as HPB235, HRB335, HRB400 and RRB400 according to their strength. Among them only HPB235 bar has a plain surface, all other grades have lugs or indentations rolled on the bars (shown in Fig. 2.1). Usually, the size of the steel bars used in concrete

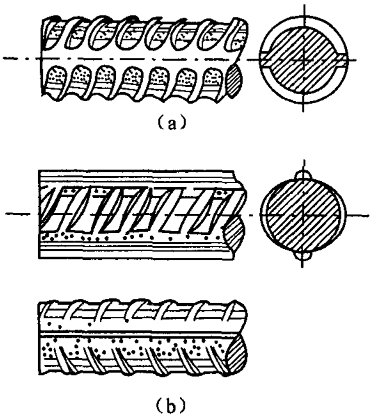


Fig. 2.1 Surface-shapes of deformed bars

structure is between 6mm to 32mm at an interval of 2mm, in order to distinguish from each other easily.

The hot-rolled bars are named according to their manufacturing process, surface shape and yield strength. So HPB235 means for hot-rolled and plain-shaped bars with characteristic value of yielding strength 235 MPa, HRB335 means hot-rolled and ribbed bars with the characteristic value of yielding strength 335 MPa, HRB400 means hot-rolled and ribbed bars with the characteristic value of yielding strength 400 MPa, and RRB400 means remained heated treated ribbed steel bars with the characteristic value of yielding strength 400 MPa.

Heat-treated steel bars are a grade of hot-rolled steel bar by certain technics (as shown in Fig. 2. 2). Cold-working bars are cold-stretched bars and cold-drawn bars. Steel wires can be classified into carbon element steel wires, high strength steel wires, indentation steel wires and steel strands. They are usually applied in prestressed concrete.

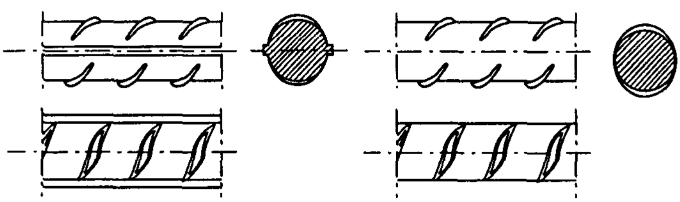


Fig. 2. 2 Surface-shapes of heat-treated bars

2. 1. 2 The Mechanical Properties of Steel Reinforcement

2. 1. 2. 1 The Stress-strain Relationship of Steel Bars

The steel used for reinforcement in reinforced concrete is generally classified into mild steel with a clear yielding strength, and hardening steel without a clear yielding strength.

Take a mild steel rod with an initial cross-section area of A_s and subject it to a tension pull of T. If the elongation in a gauged length l of the bar is Δl, the stress σ_s and strain ε_s can be defined as

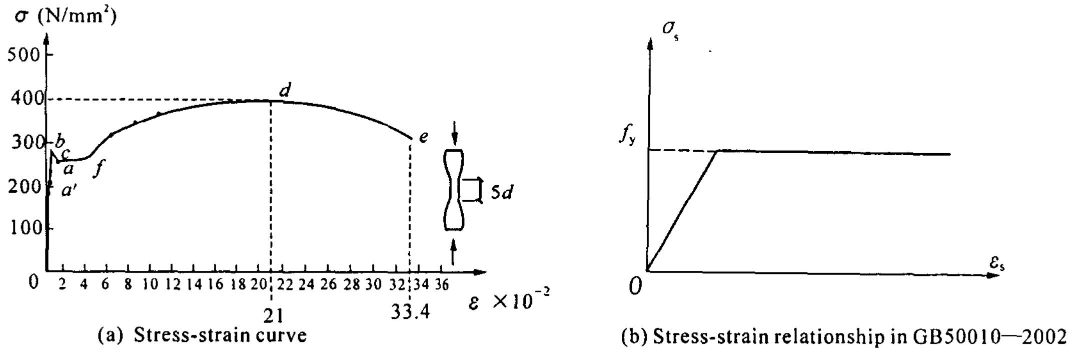
$$\sigma_s = \frac{T}{A_s} \tag{2.1}$$

$$\varepsilon_s = \frac{\Delta l}{l} \tag{2.2}$$

then the curve of stress against strain will be as shown in Fig. 2. 3(a).

As showed in Fig. 2. 3, the steel starts to yield when the stress exceeds the proportional limit and enters into the stage of flow, which is marked by a pronounced increase of strain with the stress kept constant. Beyond the stage of flow, the steel will pick up stress. The strain then increases and enters into the strain hardening stage.

For mild steel, the increase of strain in the stage of flow is more than 10 times the strain attained before yielding. This property is of utmost importance in structural design involving



(a) Stress-strain curve

(b) Stress-strain relationship in GB50010—2002

Fig. 2. 3 Stress-strain curve of mild steel bars

steel as the material① makes the redistribution of stresses in steel structures possible. Because of the large deformation during the flow, the strength of the steel beyond the yielding strength cannot be utilized and the yield stress f_y is all the strength available for structural design. The stress-strain relationship of mild steel bars is regarded as an ideal elastic-plastic material in the Chinese Code (GB50010—2002), the stress-strain relationship can be described as

$$\sigma_s = E_s \varepsilon_s \quad (\text{for } \varepsilon_s \leqslant \frac{f_y}{E_s}) \tag{2.3}$$

$$\sigma_s = f_y \quad (\text{for } \varepsilon_s > \frac{f_y}{E_s}) \tag{2.4}$$

where E_s is the modulus of elasticity of steel.

For hardening steel bars the stress-strain curve is shown in Fig. 2. 4. The curve shows that the hardening steel has no pronounced yielding strength and stage of flow. For similarity the pronounce increasing point of the plastic deformation in stress-strain curve is named as simulated yielding point, where the strength is regarded as simulated yielding strength. For simplicity, the simulated yielding strength, whose symbol is $\sigma_{0.2}$, is defined as the stress with residual strain of 0. 2%, and is approximately equal to 0. 8 times of the ultimate tensional strength σ_b in the Chinese Code.

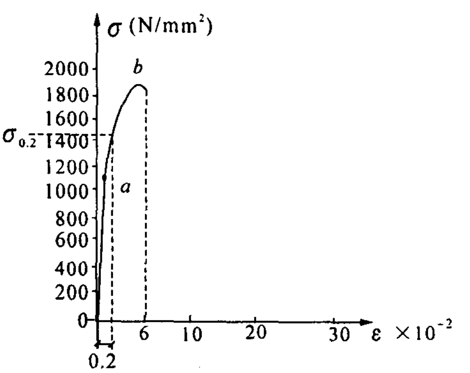


Fig. 2. 4 Stress-strain curve of hardening steel bars

2. 1. 2. 2 Other Material Properties

Besides strength and elongation, other material properties are about the properties concerning cold-bent, weld-ability, fatigue, stress relaxation and so on. Fig. 2. 5 shows the cold-bent test of steel bar by the method suggested by

① The ductility of steel that other materials do not have.

GB/T 232—1988.

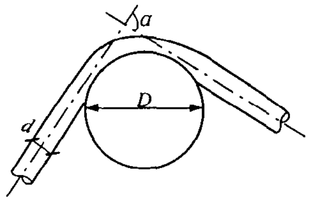


Fig. 2. 5 Cold-bent test of steel bars

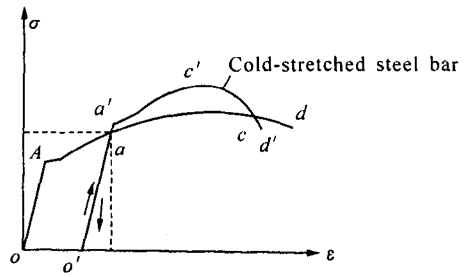


Fig. 2. 6 Stress-strain curve of cold-stretched steel bar

2. 1. 3 Cold Working of Steel Reinforcement

Before a tensile bar is stretched to its yielding strain, its elongation will completely recover when the tensile stress is released. If the bar is strained into or beyond its stage of flow, as shown at point a in Fig. 2. 6. When the stress is released a residual strain oo' will remain and cannot be recovered as shown in Fig. 2. 6. If the bar is immediately stretched again, the stress-strain curve will follow $o'acd$ and the ultimate strength of the bar will remain unchanged. However, if the bar is stretched again after a period of time, say 24 hours, then the stress-strain curve will follow $o'aa'c'd'$ as shown in Fig. 2. 6. Here, the yielding stress and ultimate stress is increased. At the same time the stage of flow is shortened or disappeared. In other words, the material becomes stronger but less ductile by the cold stretching. The result of cold stretching after a period of time is also named as the time effect of cold stretching.

The amount of stretching can be singly controlled by the elongation or can be doubly controlled by both the elongation and the stretching stress. Tab. 2. 1 gives the values of the control parameters.

Tab. 2. 1 Control parameters of cold stretching of steel

Grade of steel		HPB235	HRB335	HRB400	RRB400
Single control	Elongation strain (%)	10	4~6	3. 3~5. 5	2. 5~4
Double control	Elongation strain(%)	5. 5	5	4	
	Stretching stress (MPa)	450	530	750	

Small diameter plain bars can be cold drawn into wires. The cold drawn wires do not have a clear yielding stage. The tensile strength and compressive strength is much increased but the material becomes very brittle.

The cold rolling and cold twisting also belong to the scope of cold working of steel. The results of cold rolling and cold twisting of steel is similar to cold stretching or cold drawing of steel, which makes the steel stronger in strength but less ductile in elongation.

Because cold working of steel can raise the design strength of the steel and thus leads to a saving of material, it becomes a popular practice in China in the 20th century.