Optimization and Selection of Reinforced Steel Bar Applicable in the Code for Concrete Structures of P. R. China

——Discussion about the Performance of the Reinforced Steel Bar in Wenchuan Earthquake Disaster

Xu Youlin

（China Academy of Building Research）

1 Problems with the reinforced steel bar in Wenchuan earthquake disaster

1.1 Performance of the reinforced steel bar in Wenchuan earthquake disaster

The 2008 Wenchuan earthquake resulted in collapse of many buildings and loss of lives and personal injuries. It was found that the collapse of many structures was correlated to the failure modes, which were largely dependent on the reinforced steel bars used in the structures. Therefore, it is significant to examine the behavior and performance of various steel bars in Wenchuan earthquake disaster.

Strictly speaking, the earthquake impact is not a force but a forced displacement. Therefore, the earthquake resistance is greatly affected by the deformability (ductility) of the structures. Most of the structures with brittle brickwork collapsed in the earthquake (Fig. 1), but in most cases the buildings with ring beam-column cracked but did not collapse in the earthquake (Fig. 2). The reason is that the ring beam-column structure benefited from the hot rolled steel bars with good ductility which generated a kind of hooping-restraint effect. As a result, the brickwork walls could suffer less deformation, thus exhibiting some extent of ductility.

Fig.1 Brittle brickwork buildings without restraint effect collapsed in the earthquake

Fig.2 Brickwork buildings with reinforced ring beam-column under hooping-restraint effect cracked but did not collapse in the earthquake

For concrete structures, whether there will be a brittle failure or structure collapse caused by fracturing of reinforced steel bars depends on mechanical properties of the rebars applied in the structure-primarily strength and ductility. Details will be discussed in the following.

1.2 The brittle failure of cold finished reinforced steel bars

The major reason for loss of lives and injuries in the earthquake was fracturing, disintegrating, and falling of fabricated floor systems in the brick and concrete structures. The fall of precast slabs is caused by collapse of supporting brick walls and disintegration of fabricated floor systems while fracturing of precast slabs is caused by the pulling-apart of the cold finished rebars due to their poor ductility once they are struck by falling objects. Fig. 3 shows the fractured cold-drawn low-carbon wire concrete hollow floor slab. Though measures for structural connection have been taken to improve the integrity of floor systems and their anchorage connection with supports and cold rolled ribbed steel bars have been used as pre-stressed reinforced bars since the end of last century, disasters have not been avoided. Fig. 4 shows the fractured cold rolled ribbed bar concrete hollow floor slab. The precast slabs hanging in rows indicate that the integrity of floor systems and their anchorage connection with supports have been improved, but their fracturing shows poor ductility of cold rolled ribbed steel bars. Fig. 5 shows fractured cold rolled twisted steel bar stair treads . The inclined stairs suffered a kind of pulling–pressing force during the earthquake. The major reason for fracture of this structure is also the bad ductility of cold rolled twisted steel bars.

In the era of underdeveloped economy and shortage of supply, cold finished process cold drawn, cold rolled and cold twisted) was widely used in our country to improve the strength of reinforced bars, thus saving their consumption. However, the limited increase of strength is at the expenses of decreasing ductility, which tends to cause brittle failure of bars.

Fig.3 Fracture of cold-drawn low-carbon wire concrete hollow floor slab-falling

Fig. 4 Fracture of cold rolled ribbed bar concrete hollow floor slab-hanging

Fig. 5 Fracture of cold rolled twisted steel bar stair treads

Experiments and investigations indicate that: the overall elongation ratio δ_{gt} (uniform elongation ratio) of hot rolled steel bar HPB235 is about 20% under the maximum force, but down to about 2% after cold finished process. Substantial loss of ductility will cause brittle failure of steel bar even under a small deformation. This is the primary reason for the frequent fracture of structures using cold finished reinforced steel bars (destructive symbol 3).

Especially for the pre-stressed reinforced steel bar, prior to being loaded, about 70% of its strength has been lost due to stretching . After being loaded, it is likely to lead to an unpredicted brittle failure as a result of limited capacity for stress–strain increase and poor ductility (deformability-elongation) of the steel bars. Therefore, cold finished steel bars used as pre-stressed reinforced bars has not been documented abroad. In addition, redistribution of internal plastic force is based on the capacity for dramatic deformation (plastic strand) of the applied rebar; therefore, the applicability of cold finished reinforced steel bars is still in doubt.

1.3 Collapse-resistant capacity of hot rolled steel bars

Hot rolled steel bars HPB235 (Q235), HRB335 (20MnSi), HRB400 (20MnSiV) exhibit good ductility with uniform elongation ratio δ_{gt} exceeding 15% actually, much greater than the stipulated standards of 10.0% and 7.5%. Therefore, even after the steel bars have yielded, the potential for increase of strength and deformation is enough to prevent fracturing. Thus seismic capacity of the rebar structure is dramatically improved to avoid fracture of concrete structure and collapse of buildings. The investigations into Wenchuan earthquake disasters indicate that the hot rolled steel bars, though its strength not being so high, exhibited good seismic capacity. Under the same circumstances, ie, repeated strong pulling-pressing force which resulted in fracture of concrete in the structures, the stair tread which used the hot rolled steel bars did not break, thus collapse was prevented.

Fig. 6 Stair treads withstanding earthquake

The concrete cross beam shown in Fig. 7 used some hot rolled steel bars. After the supporting brick walls had collapsed, the cross beam was still under loading force without fracture or collapse. There are two earthquake hit buildings shown in Fig. 8 and Fig. 9. Some hot rolled steel bars were introduced in the ring beams, and continuous reinforced bars without lap joints were anchored at the support. Therefore, when the lower structure collapsed without support, in spite of great deformation of the structure, the ring beam still under loading force in the form of “suspension wire” and “suspension beam” did not fracture or collapse. These are examples of the beam –tie bar model, suspension wire –tie bar model, and suspension beam –tie bar model. From the above examples, it can be found that the hot rolled steel bars with good strength and ductility played an important role in collapse resistance when the structure was under great deformation during the earthquake.

Fig. 7 Collapse-resistant model of beam-tie bar

Fig. 8 The collapse-resistant model of suspension wire – tie bar

Fig. 9 The collapse-resistant model of suspension beam– tie bar

A partly collapsed brick and concrete structure is shown in Fig. 10. It can be found that the brickwork structure fractured and collapsed, but the hot rolled steel bars embedded in the ring beam were still unfractured. This phenomenon can be found everywhere in earthquake-stricken region which indicates that the hot rolled steel bars enjoy very good ductility.

Fig. 10 Unfractured hot rolled reinforced steel bars in the collapsed structure

1.4 The restraint effect of hooping steel bars

The hooping-restraint effects of the reinforced ring beam-structural column on the seismic capacity of the masonry structure are discussed above (Fig. 2). Similarly, the reinforced hoop can improve seismic capacity of concrete columns. The ground column of a high rise building is shown in Fig. 11. Thanks to repeated impacts from the earthquake, the concrete at the foot of column had been cracked and broken. However, due to hooping-restraint effect of dense reinforced hoops, the concrete was broken but did not fall apart. Therefore, in spite of great loading from the upper structure, the column did not overturn or collapse. However the hoop with hooping-restraint effect was pulled apart as a result of great loading force.

There were quite a many vertical reinforced steel bars in the column shown in Fig. 12, but there were not enough reinforced hoops to restrain the center concrete effectively .The concrete cracked and broke in the earthquake and its fragments without hooping-restraint were disintegrated and fell apart. As a result, columns without support crushed. Crush of ground columns is likely to cause collapse of concrete framework (Fig. 13).

Fig.11 The restraint concrete was broken but did not collapse

Fig.12 The concrete structure without restraint collapsed

Fig.13 The frame collapsed due to collapse of ground column

In traditional concept, the reinforced hoop was used only to fix vertical bar and bear shearing force, Therefore, only steel bar with low strength was used. However, experiments and investigations into earthquake disaster indicate that the hooped steel bar with hooping-restraint effect can greatly strengthen the supporting capacity and ductility (deformability) of the column. It acts like loose sands, which will generate a kind of resistant force after being put into a can and compacted. It is a new trend to develop concrete structure with greater seismic resistance by making use of the hooping-restraint steel bars, and new requirements for steel bars are put forward accordingly.

2 The failure mode and safety of concrete structures

2.1 Failure criteria of concrete structures

There are strict definitions for failure of concrete structure resulting from lack of bearing capacity. The failure criteria and mode of concrete structures are listed in Table 1. The structural properties are identified based on these criteria during experimental research, and these criteria also serve as the design basis for concrete structures. There are three modes of structural failures: ductile, inductile, and brittle. Different modes generate different results.

It should be noted that: the “Brittle failure” (criteria 3, 12, and 14) is correlated to the interruption of force transfer caused by fracture of bar and failure of anchorage and joint. And the deflection and crack width of "ductile failure" (criteria 1, 2, and 9) are correlated to the deformability of the steel bars.

Table 1 The failure criteria and mode of concrete structures

Status	No	failure criteria	Failure mode
bent and large eccentrically loaded	1	The bending defection has reached 1/50 of the structure span.	Ductile
	2	The width of crack at the tensioned main bar has reached 1.50 mm.	Ductile
	3	The tensioned main bar of the structure has fractured.	Brittle
	4	The concrete at the bent and loaded area has broken.	Inductile
Under shearing force.	5	The width of inclined crack at the web of structural component has reached 1.50 mm.	Inductile
	6	The concrete at the end of inclined crack has broken.	Inductile
	7	The concrete along the inclined section of structural component has cracked and broken.	Inductile
	8	Sheared cracks appear along the superposed and joint parts of the structure.	Inductile
Under twisting force.	9	The width of inclined crack at the web of structural component has reached 1.50 mm.	Ductile
Under punching force.	10	Ring cracks appear at the top and bottom of the punching cone surface.	Inductile
loaded	11	The concrete of the loaded structure has cracked and broken.	Inductile
Anchoring and connection	12	The tensioned main bar has slipped at the end, or the other kind of anchorage has failed.	Brittle
	13	The tensioned main bar has slipped at the joint, and its force transfer has failed.	Inductile
	14	The tensioned main bar has fractured at the welding and mechanical joints, and the force transfer has been interrupted.	Brittle

2.2 The failure mode and safety of structural components

The "ductile failure" is characterized by excessive deformation (deflection) and cracks of the structure, which will generate adverse effect make users unconfident. But there is still a long way toward disintegration and collapse of the structure. The "Brittle failure" happens suddenly, which grows rapidly without distinct signs resulting in fracture and collapse of structures. The" inductile failure" is between the two modes mentioned above, which grows rapidly, but there is a certain length of time before it develops to the failure mode. It is usually characterized by distinct cracks, breaking down, and excessive deformation of concrete, and generally will not cause fracture of structures and collapse of buildings.

In recent years, there have been many accidents resulting in fracture of structures, which led to disintegration and collapse of buildings, loss of lives and properties. Much attention has been paid to the influence of the whole structure stability (Rubustnees) on safety. In addition, further research on performance of structural materials (especially ductility) and failure modes of structures is in progress.

2.3 Strength and ductility of materials

Concrete is a kind of brittle material which can not bear pulling force but compressive force, being easy to crack, break and fracture. All pulling force is born by reinforced steel bars. It is the hooping-restraint reinforced bars that enable the concrete structures to bear all kinds of loadings and internal forces. Therefore, mechanical properties of reinforced bars have decisive influence on the performance and failure mode of concrete structures.

Much importance has been attached to the strength of reinforced steel bars in traditional structural design, and the yield strength has been considered as design basis of strength. However, investigations into structural collapse in recent years show that ultimate strength f_t and the overall elongation δ_{gt} under maximum stress, namely ductility (deformability) of reinforced steel bars also have important and direct impacts on the safety of the structure. Yielding of reinforced bars can only lead to excessive deformation of the section, and even possibly function as plastic strand to support the structure without fracturing. But fracture of steel bars may cause disintegration of structures, which usually gives rise to collapse of building.

2.4 The restraint effect of hoop on concrete

In traditional concept, only the strength of concrete under uniaxial stress is taken into account. Actually, the concrete is always under multiaxial stress in engineering practices. Researches on concrete mechanics in recent year indicate that: if side pressure in triple axial stress is considered, the compressive strength of concrete will substantially increase, while the ductility (deformability) will be improved. For example, when the side pressure is 0.1, o.2 and 0.3 of axial force, the strength of concrete will increase 1.8, 3 and 5 times respectively (see Fig. 14).

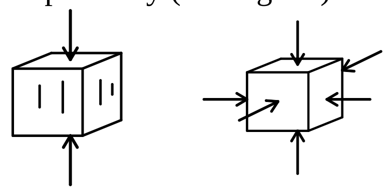


Fig. 14 The stress and strength of concrete

If the concrete column is not hooped, the column will be squashed quickly under the axial pressure. When the reinforced hoop is used, the lateral expansion (the Poisson′s ratio) caused by axial pressure will be resisted by the hoop. The core concrete is under triple axial stress, thus the resistance (strength and ductility) will increase dramatically (Fig. 15). This is the reason why many hooped columns cracked but did not collapse in the earthquake.

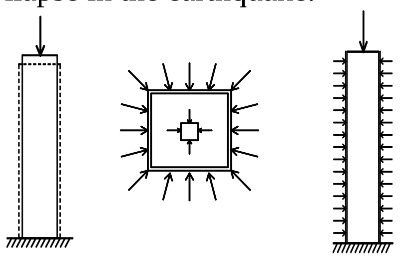
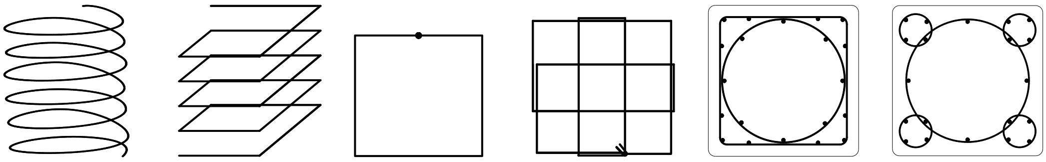


Fig. 15 The mechanism of hooping – restraint effect of hooped concrete column

Hooped bars with high strength have been used in recent years, and the hooping-restraint effect has been intensified through various close hoops (continuous spiral hoop or welded hoop). Positive results have been achieved in experimental researches and engineering practices (Fig. 16). More advanced concrete kinetic theory is needed to maximize restraint effect on concrete. At the same time, more stringent requirements are placed on the properties of steel bars used for hoops.



Circular spiral hoop, square-rectangular spiral hoop, welded close hoop, multiple continuous spiral hoop, circle inside and rectangular outside hoop, multiple spiral hoop

Fig.16 Continuous spiral hoop and welded close ring hoop

3 Reinforced bar properties required by concrete structures

3.1 The effects of reinforced bar properties

Strength: The high strength steel bars is helpful to increase bearing capacity of concrete structure at the expense of lower ductility; moreover the strength will be restricted by the rigidity and cracks.

Ductility: The deformability has significant influence on failure modes and safety of concrete structure. Brittle failure without sign is dangerous, but ductile failure is relatively safe.

Anchorage property: The anchor is the basis for bearing force jointly by steel bar and concrete. The anchorage property is decided by the appearance of steel bars and needs to be improved..

Performances of pre-stress transferring: Pre-tensioning method is used to create pre-stressing capacity through self anchorage, which shall affect the transfer length of pre-stressed steel bar.

Weldability: The weldability of steel bars is correlated to the carbon content in the steel. When carbon content is high, the steel bar is hard to weld, and when carbon content exceeds 0.55, the steel bar can not be welded.

Fitness for mechanical connection: The surface of steel bars whose strength is concentrated on surface is too hard to make connection threads, and is easy to cause strength loss.

Thermo stability: The strength of steel bars can be increased by cold working and heat treatment, but it will decrease after it is reheated (welding, fire disaster).

Fatigue properties: Under repeated loadings, the strength of steel bars will decrease. The fatigue properties are related to the materials and appearance of steel bars.

Durability: The electro chemical erosion will affect the service life of steel bars. The durability of steel bars will decrease when they are cold worked or in pre-stressing state .

Cold bending properties: The cold worked steel bars are easy to crack and break off after being bent or repeatedly bent. The construction fitness is bad.

Quality stability: The quality of steel bars manufactured in large scale is stable. The quality stability of steel bars after secondary processing is bad. The quality of steel bars manufactured in simple workshops is very bad.

Specification: Thin steel bars, thick steel bars, and some specific steel bars are always in shortage during construction, which will cause inconveniences.

Marking: Steel bars are easy to be mixed mistakenly during construction. Visible marks are needed to identify steel bars of different brands.

Delivery status: The straight bars must be cut and connected. The wire rods must be straightened. Cut-to-length bars can reduce construction amount.

Additional procedures: The plain steel bar must be supplied with hook, which is inconvenient for construction. The wire rod must be straightened. Abutting joints should be used when straight bars are reused after surplus parts are cut off.

Product rigidity: The thin steel bars are easy to deform and shift during construction. The rigidity of welded netting and precast frame is high, and the shape is accurate.economical efficiency: The economical efficiency is decided by the strength to price ratio (MPa.kg / yuan). Generally, high strength steel bars have price advantages.

3.2 The effect of strength on the bearing capacity of concrete structure.

The steel bars in concrete structure will bear all of the tensile force, therefore, higher strength of steel bars means greater bearing capacity of concrete structure. However, as the strength increases, the ductility will decrease. With the same deformation modulus, tensile deformation caused by high stress is restricted by the crack width and deflection of concrete structure. Therefore, there is a limit to increase the strength of steel bars. Only the high strength of pre-stressed bar can be used conditionally through pre-tensioning.

3.3 The effect of elongation ratio on the energy consumption of fracture.

The traditional elongation at break can only reflect the residual elongation of necking zone, but is not the real indicator of deformation capacity (ductility) of steel bars. Only the overall elongation ratio δ_{gt} (uniform elongation ratio) under the maximum stress before fracture is the real indicator of the ductility of steel bars. The fracture of steel bars will cause disintegration and collapse of concrete structure, which is the utmost threat to the safety. The actions of earthquake and subsidence is not a force (loading) but an enforced displacement. Therefore, ductility (deformation capacity) of steel bars has decisive effect on the safety of concrete structure. The importance of ductility is no less than the strength.

Considering the effects of both strength and deformation, it is found that energy consumption of fracture W presented by the integral area in the constitutive curve shown in Fig. 17 is the real indicator of the resistance of steel bars. The energy consumption of fracture of hot rolled steel bars is about 7000 Nm/kg, the energy consumption of fracture of pre-stressed steel wire and steel strand is about 6000~7000 Nm/kg, and the energy consumption of fracture of cold worked steel bars is about 1000~1500 Nm/kg. This is the reason why so many cold worked steel bars with high strength (hard steel–dotted line in the figure) fractured due to poor ductility, causing collapse of buildings. However many hot rolled steel bars with lower strength but better ductility (soft steel – active line in the figure) maintained integrity of the structure, and stood through the disaster.

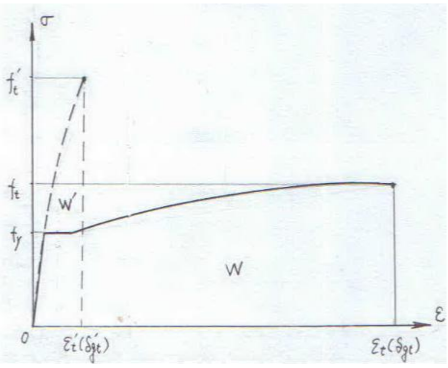


Fig.17 The strength, elongation ration and energy consumption of fracture of steel bars.

3.4 The effect of yield to tensile ratio on the failure modes

Besides the elongation ratio, the ratio of tensile strength f_t to yielding strengthf_y –tensile to yield ratio (f_t/f_y) has significant effect on the failure modes (ductility) of concrete structure. The yield to tensile ratio of hot rolled steel bars (soft steel) is above 1.20 generally; with excellent ductility and distinct signs there is a long length of time from yield to fracture.

But there is no distinct yielding point in the constitutive curve of cold worked steel bars and pre-stressed steel bars (hard steel). The constitutive curve of two kinds of steel bars which have similar tensile strength f_t and elongation ratio δ_{gt} is shown in Fig. 18.The nolinear section of the steel wire and strand tends to change gradually (active line). Generally, 0.85 times of tensile strength is taken as the offset yield strength, so that the yield to tensile ratio is high. The steel bar shall be pulled apart when the tensile strength f_t is reached shortly after yield strength f_y has been reached (dotted line). The yield to tensile ratio is relatively lower, a bit more than 1. This kind of steel bar, though exhibiting rather high strength, overall elongation and energy consumption of fracture, shall fracture after yielding and developing quickly under loading force. Without distinct signs, brittle failure generally occurs suddenly. Therefore, this kind of steel bars with poor ductility is considered insecure. Therefore, the tensile to yield strength ratio (f_t /f_y) is also an important indicator of ductility of steel bars.

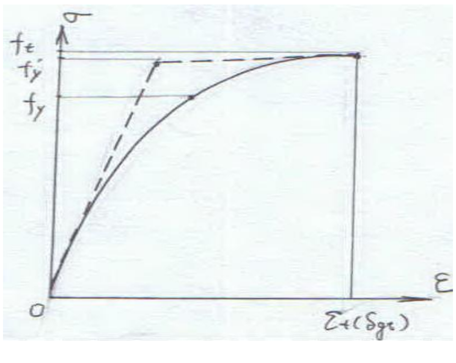


Fig.18 The constitutive relation and yield to tensile strength ratio of steel bars.

3.5 Effect of construction fitness

From the viewpoint of engineering practice, the construction fitness of steel bars has significant influence on the structure safety. The quality reliability, cold bending property, weldability, mechanism connection property, thermal stability (welding, fire disaster), additional working procedures (hook, straightening and butt joint) and durability are all related to the mechanical properties of steel bars and failure modes of concrete structure. Therefore, these parameters are also factors to the safety of structures.

Above all, many requirements for steel bar properties are placed by concrete structure. Among them strength and ductility are the most critical factors to the safety of concrete structure. The concept which takes strength into account but ignores ductility in traditional theory must be rectified. Steel bars with higher strength should exhibit necessary deformability–ductility, which is expressed as overall elongation ratio and tensile to yield strength ratio under maximum stress.

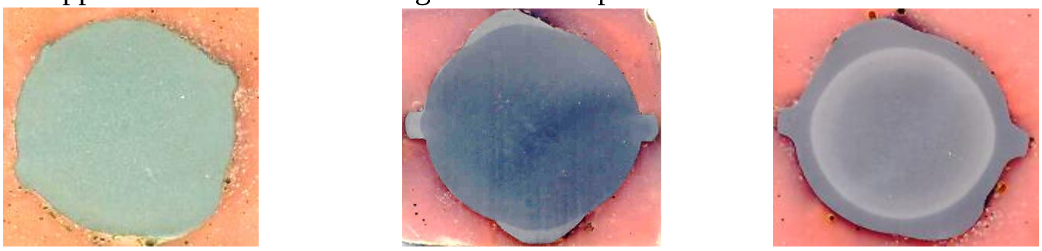
4 The optimization and application of steel bars

4.1 The approaches to increase strength of steel bars

To increase the strength of steel bars is the common goal pursued by both metallurgical and construction sectors. However, different kinds of steel bars exhibit different effects.

Low alloying treatment: The addition of manganese (Mn), silicate (Si), vanadium (V), niobium (Nb), and other elements can increase the strength of carbon steel while ductility and construction fitness are well maintained. Fig. 19 shows that the metallographic structure is uniform, which made up of ferrite and pearlite and there is no presence of any other harmful structure.

Fine graining: Control rolling and cooling is used to obtain grains no coarser than level 9, which can improve strength while maintaining a certain extent of ductility. The metallographic structure is shown in Fig. 19 (2), which indicates ferrite–pearlite as the prevailing structure surrounded with discontinuous partially tempered martensite.



(1) Low alloyed common hot rolled steel bar HRB. (2) Fine grained hot milled steel bar HRBF. (3) Residual heat treated steel bar RRB.

Fig. 19 The metallographic structures of different kinds of steel bars

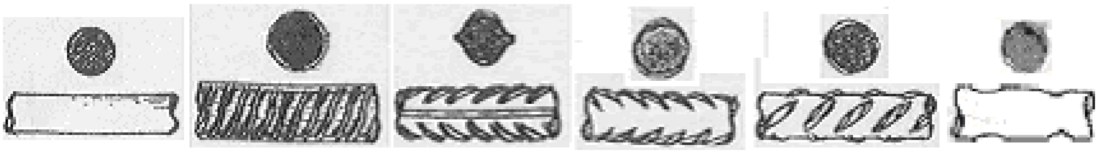
Residual heat treatment: The strength of steel bars can be increased through hardening – residual heat treatment during rolling, which will bring loss of ductility and downgrade construction fitness. The metallographic structure is shown in Fig. 19 (3), where it can be found that the high strength tempered martensite structure is hard and brittle, and is concentrated on the surface of steel bars.

Cold working: The strength of steel bars can be increased by cold drawing, cold rolling, cold twisting and cold upsetting processes. But the ductility and construction fitness of the steel bars will be decreased at the same time.

Overall treatment: The drawn (rolled) steel wire strength can be increased while a certain extent of ductility maintained through heat treatment for a short time. It can be used as pre-stressed steel wire, or made into steel pre-stressed steel strand.

4.2 Analysis and optimization of physical forms of steel bars

The physical parameters contributing to the properties of steel bars are: base circle area ratio, relative rib height, relative rib spacing, rib area ratio, teeth to rib ratio, circumference of horizontal ribs, and symmetry of horizontal ribs. Physical forms of various kinds of steel bars are shown in Fig.20, which will be analyzed in the following:



(1) plain round, (2) contour ribbed, (3) crescent ribbed, (4) cold rolled ribbed – double faces, (5) cold rolled ribbed – three faces, (6) indented – double faces.

(7) indented – three faces, (8) spiral ribbed, (9) spiral grooved, (10) cold rolled twisted, (11) 3-stranded wire, (12) 7-stranded wire.

Fig.20 Physical forms of different kinds of steel bars.

Plain round steel bars: It features the largest base circle area ratio (1.00) but poor anchoring property. The hook is needed to bear force, so it will be eliminated gradually.

Contour ribbed steel bars: With base circle area ratio less than 0.90, excessive strength loss and poor physical form, it has been eliminated.

Crescent ribbed steel bars: With base circle area ratio of 0.94, good anchoring property and oriented, it is in prevailing use for force bearing bars.

Pre-stressed steel strand and **spiral ribbed steel wire**: With large base circle area ratio and good anchoring property, they are in prevailing use for pre-stressed bars.

Pre-stressed spiral grooved steel bar: With weak occlusion tooth of concrete and poor anchoring property, its physical form should be improved toward the spiral ribbed bar.

Cold rolled ribbed steel bar: The base circle area ratio should be further increased. To improve its anchoring property, its physical form should be modified toward the spiral ribbed bar.

Cold rolled twisted steel bar: Its physical form should be improved toward the spiral ribbed bar.

Indented steel wire: The cross section is weakened with shallow occlusion tooth and poor anchoring property. It tends to be eliminated.

The physical form of steel bars in China should be optimized. The spiral ribbed rebar has the greatest advantage in terms of the base circle area ratio and anchoring property.

4.3 The optimization and selection of steel bars.

Based on the actualities of steel bars used for concrete structures in China and the investigation results of Wenchuan earthquake disaster, the existing steel bars should be further optimized. The general trend is to improve strength, ductility and construction fitness, Different steel bars should be selected for different application areas.

Vertical force bearing steel bars should use 400 and 500MPa HRB common hot rolled ribbed rebar and HRBF fine grained hot rolled ribbed rebar. Main rebar for anti-earthquake buildings should adopt high ductility seismic grade steel bar suffixed **"E",** which has an overall elongation ratio under maximum stress no less than 9% and tensile to yield strength no less than 1.25. The ductility of steel bars RRB treated with residual heat is poor and can be used in secondary structure, infrastructure or large volume components whose requirement for ductility is not critical, so that less alloy can be used. The HPB235MPa plain steel bar with lower strength should be eliminated and replaced by 300 MPa steel bar. The 335 MPa strength grade steel bar should be combined into ribbed steel bar and used as supplementary steel bar. The strength grades of 300, 400, 500 MPa should be established eventually.

Pre-stressed reinforced bars should use high strength spiral ribbed steel wire and strand with strength of 1570 MPa above and overall elongation ratio under maximum stress no less than 3.5%. The indented steel wire should be eliminated. The ductility and the physical form of pre-stressed reinforced bar (PC) should be improved. In addition, middle strength grade steel wires with a strength of 1000 MPa and below can be used for middle and small spanned pre-stressed structures. And experimental research and engineering practice should be employed to identify if they can be used as rebar for concrete restraint.

The cold worked steel bars used as thin diameter force-bearing and supplementary rebar should be kept and optimized. The shape tends to be spiral ribbed steel bar to increase base circle area ratio and improve anchorage property. The reduction of area of cold working should be reduced to minimize loss of ductility. According to the experience of Wenchuan earthquake disaster and other brittle failures, the cold worked steel bars should not be used as pre-stressed rebar. Design of plastic internal force redistribution should not be considered, because pre-stressed and plastic strands require great deformability-ductility of steel bars. Fundamental solution is to eliminate the "cold working" effects and recover necessary ductility through appropriate heat treatment (tempering), Obviously, the steel bar treated in this way should not to be classified into 'heat treated' rebar instead of "cold worked" one. And this kind of steel bar is actually a fine grained rebar.

4.4 Characteristic and superiority of vanadium containing steel bar.

Above all, the low alloying treatment is the most effective way to improve combined properties of steel bars. A few hundredths of a percentage point of vanadium (V), titanium (Ti), and niobium (Nb) added into hot rolled steel bars is sufficient to increase their strength substantially while maintaining good ductility and construction fitness (welding, cold bending, and mechanical connection). This concept provides a major route to development of steel bars for concrete structures in China.

There are abundant vanadium and titanium resources in Panzhihua and Chengde; therefore, there are unique advantages to develop vanadium (V) containing hot rolled ribbed steel bars (HRB). Even for the fine grained steel bar (HRBF) produced by controlled rolling and controlled cooling, a little addition of vanadium can substantially improve its combined properties. The anti-seismic steel bars (HRB400E, HRB500E) used as major bearing material in structures require high strength and good ductility (overall elongation ratio under maximum stress and tensile to yield ratio) . Therefore, vanadium containing steel bars are most appropriate in this respect.

4.5 Modified measures in the design code

In the latest revised “Code for Design of Concrete Structures” GB50010-2010, requirements for steel bar properties and their optimization and selection criteria are proposed.

First of all, the 500 MPa grade high strength steel bar is added, and the 235 MPa grade low strength plain steel bar is eliminated and replaced by 300 MPa grade steel bar. At the same time, the 335 MPa grade steel bar is to be combined into 300 Mpa grade ribbed steel bar. The strength grades of 300, 400, 500 MPa have been established, which are consistent with international practices.

For pre-stressed steel bars, besides 1960 MPa grade high strength steel strands, the large diameter (18-50 mm) pre-stressed threaded steel bar is added as the reinforced bar for big span and heavy load structures. The gap of 1000 MPa grade steel bar has been filled, and middle strength pre-stressed steel wire has been added as the reinforced bar for middle and small span and light load structures. And the indented steel wire with bad properties has been eliminated.

Secondly, the requirement for steel bar ductility has been stated clearly: The steel bar is graded not only by strength, but also by ductility. Overall elongation ratioδ_{gt} (uniform elongation ratio) under maximum stress is used, and the limit of tensile to yield ratio (f_t/f_y) of steel bars is proposed. These modifications are of practical significance to prevent fracture and collapse of structures under accidental action and ensure safety.

In addition, expressions of steel bars have been unified. The types of steel bars are distinguished by letters HRB, HRBF, RRB and suffix “E”. The strength grades of steel bars are expressed by the value of standard strength (MPa) 300,400, 500. And different diameter symbols Φ, Φ, Φ, Φ,

Φ^F, Φ^R, ϕ^P, ϕ^H, ϕ^S, ϕ^T … are used to express the brands of steel bars.

5 Conclusions

For several decades, the continuous and rapid economic development in China has been quantity oriented at the expense of heavy consumption of resources and energy. This growth pattern will in no doubt exhaust the heritage left by our ancestors, overdraw the resources left to our descendants, ruin ecological balance and cause environmental pollution……,so it is not sustainable. The steel and building sectors should play a leading role in energy saving, consumption reduction, emission cutting and environmental protection.

So far, heavy fund has been injected into infrastructure construction while anti-disaster performance of structures should be further improved. The only way is quality oriented sustainable economic growth. To do so, quality of building materials shall be improved in the construction sector; steel bars used in concrete structures shall be optimized and selected appropriately by improving their strength, ductility and combined properties.

Based on investigation results, this paper discusses the development trend of steel bars used in concrete structures. However, joint efforts of the steel and construction sectors are expected to take actions. The suggestions in this paper are only the author's personal findings aiming to throw light on this topic. Comments, remarks and criticism should be appreciated.

Reference

[1] Xu Youlin, The status and development of steel bars used in concrete structure in China, China Civil Engineering Journal, Vol 5, 1999.

[2] Cheng Zhijun, Xu Youlin, Wang Quanli, The Development and Application of Micro-alloyed HRB Grade Steel Bars, Architecture structures, Vol 1, 2002.

[3] Xu Youlin, Investigation of Wenchuan Earthquake Disasters and Reflection on the Structural Safety of Buildings, China Architecture and Building Press, May, 2009.

[4] Xu Youlin, The Effect of Steel Bars on the Structural Safety–the Performance of Steel Bars in Wenchuan Earthquake Disaster , Industrial buildings, Vol 11, 2009

[5] Xu Youlin, *et al*, Application Techniques of Hot Rolled Ribbed High Strength Steel Bars in Concrete Structures, China Architecture and Building Press, 2010.