Interpretation and Characterization of Seismic Performance of Rebars in Domestic and International Standards

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0 Introduction

In recent years, the catastrophic earthquakes happened in Wenchuan, Yushu, and Haiti have caused great loss of lives and properties in different countries, and even the economy of these countries was affected greatly by the earthquakes. Therefore, the seismic performance of buildings have aroused great attention worldwide. Our country is under rapid industrialization. The construction sector accounts for 51% of total steel consumption. As most of the buildings in our country are reinforced concrete structures, the consumption of rebars is about 25% of total steel consumption, and both production and consumption of rebars are growing rapidly (see Fig.1). Therefore, it is necessary to research the seismic performance of rebars by learning from proven experiences from earthquake-prone countries in their seismic resistance design and their standards for concrete structures so as to improve the seismic performance of concrete buildings in China and minimize the losses caused by earthquakes.

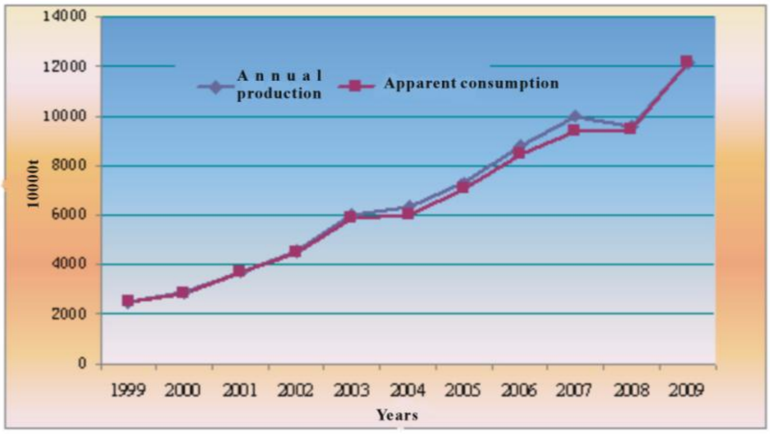

Fig.1 The production and consumption of rebars (1999-2000)

1 Interpretation of seismic performance

The seismic performance requires the building during its service life to exhibit different anti-seismic abilities corresponding to different frequencies and intensities of earthquakes. According to the general target required by the domestic and foreign earthquake fortification criteria, the building is expected to“ be undamaged after minor earthquake, maintainable after moderate earthquake, and stand up after major earthquake”. Therefore, to satisfy this target, the systemic and integral seismic resistance of the building is very important.

1.1 Seismic resistant behavior of structures is complicated

The seismic resistant and mitigation behavior of a structure is a complicated and comprehensive matter. The law of earthquake generation and transmission is a subject of geophysics. The law of ground motion caused by earthquake is a random process of earthquake dynamic behavior. The structural dynamic effect caused by ground motion is a subject of structural dynamics. The destruction and collapse of a structure is related to the mechanical properties of structural materials under dynamic actions. The uncertainties of earthquake effects, coupled with the nonlinearity of the structure make the seismic resistance behavior of structures more complicated.

1.2 Systemic seismic resistance of structures is more important

The basic characteristics of the earthquake action are: randomness, uncertainty of amount and distribution. The effects caused by an earthquake action, which are different from the loading effects, relate significantly to structural properties. Such difference exists not only in amount, but also in distribution. Generally the most disadvantageous combination can be found during the structural design, but the earthquake action is a random process. Therefore, the concept design based on integral seismic system is very important. And the concept of systemic seismic resistance is also much concerned in the seismic design in foreign countries. Strictly speaking, the current specifications are intended not for structural design, but for component design. The current structural design method is a component design based on calculation of the internal structural forces by elasticity approach, aiming to ensure each component and joint point can bear the anticipated force. However, the safety of each component does not mean the safety of the whole structure. The bearing capacity of each structural component and the bearing capacity of the whole structure are two different concepts. According to the theory of plasticity behavior, the bearing capacity of the whole structure is the minimum bearing capacity under all failure mechanisms, and this is called upper bound limit theorem.

1.3 The structure control design of earthquake damage is very essential

According to the upper bound limit theorem, it is not hard to achieve the target “be undamaged after minor earthquake, and be maintainable after moderate earthquake” in actual structure designs. But in order to achieve the target “stand up after major earthquake”, the most important thing is to control the structural damage. The structural redundancy is an important concept in seismic resistance. An important method which can increase the structural redundancy is to set redundant structural components that can respond to different failure mechanisms, and this brings the method of capacity design, in which "grades" exist between structural components and secondary or redundant units will be damaged or consumed first during an earthquake so that the whole structure can be protected under this defensive line. According to this principle, design methods such as "strong shear and weak bend" are now being used in earthquake-resistant reinforced concrete structures in Japan as well as in other earthquake-prone regions. According to the requirements of these design methods, corresponding requirements have been proposed for rebars and other important structural components.

2 Characterization of seismic performance of rebars

As mentioned above, structure seismic resistance is very important. However, a structure's seismic resistance is based on the seismic resistance of its structural components. Rebars are an important construction steel material. Therefore, the seismic performance of rebars is being researched intensively all over the world, especially in earthquake-prone regions. The research results have been brought into standards and many become characterizable and measurable indices. After a comprehensive analysis of the standards used in different countries, it can be found that there are four major indices of seismic resistance characterization: strength, ductility, tensile to yield strength ratio, and welding property.

2.1 Increase the strength and ductility of rebars

The strength usually refers to the yield strength (R_{eL}) of rebars. R_{eL} is used as the strength grade of rebars all over the world, because the yield strength is a major index in structural design, which can determine the bearing capacity of a reinforced concrete structure.

The ductility of rebars usually refers to the capacity of bearing plastic deformation as long as the structure is not broken. The ductility is usually expressed by the total elongation ratio of the rebar under the maximum force - A_{gt}, but sometimes it can also be expressed by the elongation ratio at fracture - A_5.

There is a tendency that the total elongation ratio under the maximum force, A_{gt}, is used to replace the elongation ratio at fracture, A_5. Because A_5 can only reflect the residual plastic deformation capacity at the rebar necking fractures, while the total elongation ratio under the maximum force, A_{gt}, can not only reflect the residual deformation at the region within a distance of L_0 from the necking fractures, but also reflect the elastic deformation of recovery. The calculation formula of A_{gt} is given below:

$$A_{gt} = \left[\frac{L - L_0}{L_0} + \frac{R^o{}_m}{E} \right] \times 100$$

Since the total elongation ratio under the maximum force, A_{gt}, reflects the real state of the rebar under forces, and can replace A_5

completely, the elongation ratio A_5 has been removed and only A_{gt} is specified in the standards of countries such as the UK, New Zealand, and Australia.

2.2 Tensile to yield strength ratio of rebars

The tensile to yield strength ratio of rebars refers to the ratio of actual measured ultimate tensile strength to actual measured yield strength. Larger tensile to yield strength ratio is anticipated for rebars used in seismic resistance structures. When a section has become plastic, the hinge will have enough rotation capacity to prevent the premature failure of the rebars.

The tensile to yield strength ratio of rebars is the ratio of actual measured ultimate tensile strength to actual measured yield strength. Rebars used in seismic resistance structures should not be largely different in their yielding strengths. The range of yielding strengths should be controlled in order to prevent the fracture morphology change of the structural components. For example, if the rebars used for beams are largely different in their strengths, adverse results may be caused in which the plastic hinges do not appear in the expected locations.

2.3 Ensure the welding property of rebars

During the heating process of welding, the rebar's joint point affected by the heat will undergo complete phase transmission. According to different heat inputs during the welding process, the phase structural morphologies of the rebar obtained will also be different, and the property of the rebar be changed accordingly. Therefore, to ensure that both the phase structural morphology and the mechanical property of the rebar after welding are no worse than the requirements of the base material is a basic guarantee for the seismic performance of the rebar.

3 The characterization of seismic performance in the rebar standards of our country

The current standards GB1499.1 -2008 *Hot Rolled Plain Rebars Used in Reinforced Concrete* and GB1499-2007 *Hot Rolled Ribbed Rebars Used in Reinforced Concrete* have been implemented since 2008. The revised standards have introduced advanced standards used abroad and reflected the production status and utilization requirements of 400 MPa and 500 MPa high strength rebars in the domestic market. The revised standards promote the structural adjustment and the upgrade of the rebar industry and rebar products, increase building safety, ensure the principles of seismic resistance, use both micro alloy strengthening and process strengthening, and standardize the fine grain size rebars produced through process strengthening in that future development will be restricted by resources and costs. In general, the revised standards have laid the foundation for the economic and efficient development of rebar production and utilization.

3.1 About the strength grades

The rebar strength grades specified in GB1499.1 and GB1499.2 are shown in Table 1.At present, most of the rebars used in our country are of 335 MPa grade. The consumption amount of 400 MPa grade hot rolled rebars is increasing in recent years, but the production of 400 MPa grade hot rolled rebars had only occupied 25.4% of the overall rebar production by 2008. The annual production of 500 MPa grade hot rolled rebars was only 327.7 thousand tons its use was limited to a few key projects. The 500 MPa grade hot rolled rebars have been standardized in GB 50010 *Code for Design of Concrete Structures* which has been revised recently, and there are still lots of work to be done in construction utilization.

Table 1 Rebar strength grades specified in GB1499

Brand	R_{eL}/MPa	R_m/MPa	Standard
HPB 235，HPB 300	235，300	370，420	GB1499.1
HRB 335，HRBF 335	335	455	GB1499.2
HRB 400，HRBF 400	400	540	
HRB 500，HRBF 500	500	630	

3.2 About tensile to yield strength ratio

In the standard GB1499, except for the conditions listed in Table 2, seismic resistance rebars should also satisfy the following requirements: First, the ratio of actual measured tensile strength to actual measured yield strength should be no less than 1.25. Second, the ratio of rebar yield strength to specified yield strength characteristic vale should be no more than 1.30. Such rebar can satisfy the design and utilization requirements of all kinds of structures (including first grade and second grade seismic resistance structures), and can increase building safety. According to the standards, the brand rebars used in seismic resistance structures with higher resistance requirements will be added an E after HRB or HRBF.

3.3 About the ductility of rebars

To ensure the seismic performance of rebars, the ductility indices of rebars have been adjusted in the newly revised standard GB1499.2. The comparison of the new version and the previous version of ductility indices is shown in Table 2. The elongation ratio *A* of 400 MPa and of 500 MPa grade rebars has been increased to 16%~17%, and the total elongation ratio under maximum force, *A*gt, shall be no less than 7.5%. Therefore, the overall ductility indices of rebars have been increased, especially the total elongation ratio under maximum forces, *A*gt, has been increased greatly and has basically achieved the maximum ductility requirements of international or European standards. Such rebars can be used in reinforced masonry structures high in ductility requirements.

Table 2 Comparison of the new version and the previous version of ductility indices

Standard No.	Standard version	Brand	A /%	A_{gt} /%
GB1499.2 Ribbed rebars	Current standard	HRB335，HRBF335	17	7.5
	Previous standard	HRB335	16	2.5
	Current standard	HRB400，HRBF400	16	7.5
	Previous standard	HRB400	14	2.5
	Current standard	HRB500，HRBF500	15	7.5
	Previous standard	HRB500	12	2.5

3.4 About the welding property of rebars

In the standard GB1499.2, it has been stipulated that the brand, chemical composition, and equivalent carbon content (melting analysis) should meet the requirements listed in Table 3.

Table 3 The chemical composition of rebars stipulated in the standard GB1499.2

Brand	Chemical composition (mass fraction)/% (no more than)					
	C	Si	Mn	P	S	Ceq
HRB335 HRBF335	0.25	0.80	1.60	0.045	0.045	0.52
HRB400 HRBF400						0.54
HRB500 HRBF500						0.55

The calculation formula of equivalent carbon content has also been listed in this standard. The formula is: equivalent carbon content Ceq (mass fraction) = C+Mn/6+(Cr+V+Mo)/5+(Cu+Ni)/15.

The welding property of the rebar is not only related to the equivalent carbon content of the brand, but also related to the welding process. Therefore, in order to ensure the welding property of the rebar, not only the upper limit value of equivalent carbon content is stipulated (see Table 3), the welding process and related acceptance regulations are also specified in JGJ18-2001 *Procedures and Acceptance Regulations for Rebar Welding* (under revision).

4 Characterization of rebar seismic performance in major foreign standards

At present, Japan, the United States, Europe, UK, Australia/New Zealand all have their standards for hot rolled ribbed rebars.

a) ISO 6935-2:2007 for steel used in reinforced concrete (Part 2: Ribbed Rebars) is a mixed standard including 10 grades for weldless steel and 11 grades for welding steel.

b) The Japanese JIS G 3112:2004 standard for steel used in reinforced concrete refers to international standards, but stipulates the steel grades according to national utilization requirements, which differs from the international ones a little in some specific indices.

c) The European standard BS EN 1O080:2005 is basically the same as BS 4449:2005+A2:2009, but strength grades are not stipulated in BS EN 1O080. Considering the completeness of a standard system, the European standard is quite scientific, hence, its certification system and inspection schemes are adopted by many other countries.

d) The American Society for Testing and Material (ASTM) has two rebar standards: *ASTM A 615/A 615M-2009 Ribbed and Plain Round Carbon Rebars Used in Reinforced Concrete*, and *ASTM A706/A 706M-2009 Ribbed and Plain Round Low Alloy Rebars*. The technical requirements of these two standards are quite different. In ASTM A 615/A 615M-08a, there are three steel grades - 280, 420, and 520, but no specified welding property or tensile to yield strength ratio, the delivery state shall be hot rolled, which indicates that the rebars can be produced through remained heat treatment process. While in ASTM A706/A 706M-06a, there is only one steel grade - 420, the welding property is specified, and the upper limit and lower limit of yield strength are stipulated. It is a standard for high quality rebars.

e) In Australia/New Zealand AS/NZS 4671:2001 standard for rebars used in reinforced concrete, there are five different steel grades - 250N, 300E, 500L, 500N, and 500E. The standard stipulates that L represents low grade; N, normal grade; and E, seismic resistance grade.

In summary, the technical progress of rebars production and new requirements of the architecture industry are both being reflected by standards of different countries all over the world, especially the indices which can affect the seismic performance of buildings have been extensively modified in the new versions of the standards. These requirements and modifications can be summarized from the following five aspects.

4.1 Clearer requirements for seismic resistance rebars

In Australia/New Zealand standard, the quality requirements of seismic resistance rebars are presented for the first time. As listed in the standard, E grade is the seismic resistance grade. Rebars should not only meet the basic requirements, but also meet the regulations given in Table 4. BS 4449:2005+A2:2009 standard stipulates the B500C (see Table 5) seismic resistance rebars.

Table 4 Property requirements of seismic resistancerebars in AS/NZS 4671:2001 standard

Strength grade	Yielding to tensile strength ratio	Total elongation ratio under maximum force/%
300E	1.15～1.50	15
500E	1.15～1.40	10

4.2 Simplified requirements for basic property

In recent years, basic properties of rebars in many foreign standards have been simplified into three typical and essential requirements: yielding strength - R_{eL}, the ratio of tensile strength to yielding strength - R_m/R_e, and total elongation ratio under maximum force - A_{gt}. For example, the regulations of the basic properties of rebar in the UK standard BS 4449 and European standard BS EN 1O080: are listed in Table 5. It can be found that the indices necessary to be inspected are very simple but very typical, capable of representing different quality requirements.

Table 5 Requirements of rebar basic properties in BS 4449 and BS EN 1O080 standards

Brand	Yielding strength $R_{m,}$ /MPa	Raito of tensile to yielding strength, R_m/R_e	Total elongation ratio under maximum force, A_{gt}
B500A	500	1.05	2.5
B500B	500	1.08	5.0
B500C	500	$1.1.5 \le R_m/R_e < 1.35$	7.5

4.3 High strength

The strength grades or brands are different in the standards of different countries. However, the strength grades can generally be divided into three groups: 300MPa (low), 400MPa (middle), and Furthermore, according to the codition of different countries, the rebar brands can be divided into weldable and unweldable, earthquake resistant and earthquake vulnerable. The actual consumption amount of 335MPa grade rebars in our country is about 75% of the overall consumption amount, indicating that most of the rebars used in our country are of low strength grade. However, the mainstream rebars used in the US and Japan are of 400MPa grade, i.e. middle strength grade. And the mainstream rebars used in Europe, UK, Australia and New Zealand are of 500MPa grade, i.e. high strength grade. Especially in the UK and European standards, the tendency of strength increase is quite clear. In the previous UK standard, the strength grade was 460MPa; and in the previous European standard, 450MPa. However, after the integration of different European standards, the UK standard, in which the strength grade is 500MPa, has been adopted by the European Community, which means that the practical rebar strength has increased. The comparison of rebar grades used in different countries is shown in Table 6.

Table 6 Comparison of rebar grades used in different countries

GB1499.2	ISO 6935	AS/NZS 4671	BS EN 10080	ASTM A706/A706M	ASTM A615/A615M	BS 4449	JIS G3112
	-	250N	Strength grades that have not been mentioned in the standard	-	-	-	SR235
	B300A-R B300B-R B300C-R B300D-R B300DWR	300E		-	280	-	SR295 SD295A SD295B
HRB335 HRBF335	B350DWR	-		-	-	-	SD345
HRB400 HRBF400	B400A-R B400B-R B400C-R B400AWR B400BWR B400CWR B400DWR B420DWR	-		420	420	-	SD390
HRB500 HRBF500	B500A-R B500B-R B500C-R B500AWR B500BWR B500CWR B500DWR	500L 500N 500E		-	520	B500A B500B B500C	SD490

4.4 More detailed quality requirements for each strength grade

The UK and European standards have divided B500 into three quality grades - A, B, and C; similarly, the Australian/New Zealand standard has also divided grade 500 into three quality grades - L, N, and E. The major difference between these three grades lies in the total elongation ratio under maximum force and tensile to yield strength ratio. The elongation ratio and tensile to yield strength ratio of a rebar are related to the chemical composition of the steel, especially related to the addition of micro-alloy elements as well as the production process of the rebar. Although the production process of a rebar has not been specified in the UK and Australian/New Zealand standards, the elongation ratio and tensile to yield strength ratio are both typical indices that can reflect the rolling process of a rebar. From the quality grade A, B, C (or L, N, E) of the strength grade B500, it can be deduced that rebars of B500A grade can be produced through cold rolled process; of B500B grade, remained heat treatment process; and of B500C grade, must be produced through hot rolled and micro-alloy element addition process. Therefore, the indices contained in the standards can not only reflect the cost factor of rolling, but also reflect the quality factor of the quality grade. For example, 500C (E) grade rebars are of higher quality and can meet seismic resistance requirements. Therefore, the standards are systemic and have brought convenience to the design and management of construction sites.

4.5 Unspecified production process

The production processes of rebars specified in the standards of different countries can generally be divided into three groups: 1) hot rolling without post treating, 2) hot rolling, controlled cooling and remained heat tempering, and 3) cold working. In the previous international standard and the UK standard, different property requirements were stipulated for different production processes. However, in recent years, there is a tendency that the production process of rebars becomes unspecified, i.e. the production process can be decided by the manufacturer, see Table 7 for details.

Table 7 Regulations in different standards on rebar production process

Standard No.	Production process
GB1499.2-2007	Hot rolling, controlled rolling with fine grain size, remained heat treatment.
ISO 6935-2:2007（E）	The production process should be decided by the manufacturer.
AS/NZS4671：2001	The production process should be decided by the manufacturer, and if necessary, the production method should be explained (including hot rolling, cold rolling).
BS EN 10080-2005	The production process should be decided by the manufacturer, and if necessary, the decided process should be reported to the purchaser (including hot rolling, cold rolling).
ASTM A615/A615M-08a	Hot rolling.
ASTM A706/A706M-06a	Hot rolling.
BS 4449:2005	The production process should be decided by the manufacturer, and if necessary, the decided process should be reported to the purchaser (including hot rolling, cold rolling).
JIS G3112-2004	Hot rolling.

From the utilization aspect, major indices that should be evaluated of a rebar include the mechanical property, process property, and welding property, which are, in other words, the utilization property of a rebar. Therefore, it is possible that the production process of the rebar is unspecified in the standards. However, it does not mean that there is no requirement for the rebar production process. The production process is not specified in the standard but can be deducted from the requirements of properties.

After analyzing the effects from the production process on rebar properties through provisions and regulations expressed in both domestic and foreign standards, it can be found that the contents of these two conceptions are different. In the European standard system, it was considered that cold rolling or hot rolling only affects the mechanical properties and fatigue properties including the strength, elongation ratio, and especially the yielding to tensile strength ratio. The yielding to tensile strength ratio is the most proper method to restrict indirectly the rebar production process, because the yielding to tensile strength ratio of rebars processed by cold rolling is high; of rebars processed by hot rolling with remained heat treatment, somewhere between that of the cold rolled rebar and that of the hot rolled rebar; and of rebars processed by hot rolled, low. For example, in the BS4499 standard, the B500 MPa grade is divided into B500A, 500B, 500C, and the major difference between these three grades is the yielding to tensile strength ratio.

5 Some suggestions to promote the application of seismic resistance rebars

According to the statistics of earthquake disasters, 95% of the life loss is caused by the collapse of buildings which are poor in seismic performance. Our country faces serious earthquake threats, in that half of our provincial cities are located in areas possible attacked by earthquakes up to 6 magnitudes, and fortifications are necessary. The fortification of buildings is an important measure to prevent earthquake disasters, to increase the resistance ability to earthquakes, and to reduce the earthquake caused losses. Therefore, the fortification of buildings and of structural components should be an important task for researchers. The following suggestions are presented in this paper:

5.1 Optimizing the design system of building structures

The concepts and principles of seismic resistance design used nationally or internationally (such as “strong column and weak beam”, “shear wall”) should be used in building design practices. Some mature design requirements can be programmed into design software to facilitate the design.

5.2 Optimizing the standard system of rebars

The standards used abroad, in which one strength grade is divided into different quality grades representing different production processes indirectly and showing different quality levels directly, can be used as a reference for our national standards. For example, rebars of grade B500C are the seismic resistance rebars in the UK standard, which should be produced from hot rolling and micro-alloy elements addition process. But this presents higher requirements for the design and construction management. On one hand, the design should be detailed, which means that rebars of different quality grades should be used for different earthquake fortification regions and for different force bearing states. On the other hand, higher management level is necessary for the construction site.

5.3 Promoting higher strength rebars

Iron and Steel Industry Restructuring and Revitalization Plan, which is released by the State Council last year, definitely stipulates that rebars of 335 MPa or lower strengths should retire, that rebars of 400 MPa or higher strengths should be promoted in use so as to accelerate the upgrade of construction steel and to ensure building safety, life safety, and property safety. The consumption of 400 MPa grade rebars should aim at 80% or more of the whole consumption in three years, and the application of 500 MPa or higher grade rebars should also be promoted. To reach this target, the definition and division of rebar grades should be optimized by learning from strength grades used in international standards. The GB1499 strength grades may be redivided, cancelling the 335 MPa grade gradually, and resetting the strength grades as 300 MPa, 400 MPa, and 500 MPa. In order to promote the application of high strength rebars, rebars of the grade 400 MPa should become the mainstream, and the difference between grades should be enlarged.

5.4 Promoting functional rebars

With the market development and technical progress, some new tendencies have appeared in the demand and production of wire materials and of bar materials used in domestic constructions. For example, technical progress has brought the problem of environment protection, which presents higher requirements on construction materials. The anti-corrosion property has become a major research task for rebars in many industrialized countries, and various anti-corrosion long-life rebars have also attracted increasing applications. The research and development of high-strength anti-corrosion rebars is also progressing in relevant institutes and enterprises in our country under the support of Ministry of Science and Technology. At the same time, production lines for epoxy coated rebars have been imported by some Chinese enterprises, and the epoxy coated rebars have been put in the market. To accelerate the market application of such rebars, we have proposed corresponding plans. In order to lay a good foundation for diverse brands and structural adjustment, standard development should be in line with that of the market, and technical preparations should be made.

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