Comparative Investigation of Seismic Resistant Behaviors between Vanadium Micro-Alloyed and Post-Rolling Tempcored Rebars

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Abstract: The relationship between the seismic behavior of rebars and the seismic resistant ability of the building structures was discussed. According to the failure modes of rebars under the earthquake loadings, the seismic performance of rebar is a system of indicators focused on the high strain and low cycle fatigue resistance, which include the sensitivity of strain-aging; brittleness at low temperature, weldability and coupling of strength with ductility. The test results of seismic behaviors show that both the V microalloyed and tempcored rebars can meet the requirements of GB1499.2-2007. However, from the perspective of seismic performance system focused on the high strain and low cycle fatigue resistance, V-microalloyed rebar is much better than the tempcored rebar, especially in terms of sensitivity of strain-aging, DBTT and cyclic toughness.

Key words: rebar, seismic resistant behaviors, V-microalloying, tempcore

1 The relationship between the seismic resistant behaviors of rebars and earthquakes prevention and hazard reduction

After "5.12" Wenchuan Earthquake, the research work of earthquake defense and hazard reduction has aroused widespread concern from all parts of community and great attention from government departments at all levels. We believe that the earthquake defense and hazard reduction deserves all-round efforts and measures, one of which is to improve the seismic resistant behaviors of rebars.

China is an earthquake-prone country. According to the seismic intensity zoning map released by China Earthquake Administration in 1990, 41% of the land area in China and more than half of the cities are catalogued within the basic earthquake intensity of 7 degrees or above, 79% of the land area is catalogued within the basic earthquake intensity of 6 degrees or above. Land area of China accounts for 1/14 (7%) of the world total. However, actual earthquakes above 6 degrees in the 20th century in China accounts for 1 / 3 of the world total; In terms of damages caused by earthquakes, the death toll from earthquakes totals 1.2 million globally and China’s death toll from quakes is 600 000, accounting for 50% of the total.

For a disastrous earthquake four conditions must be met at the same time: (1) frequent and big earthquakes; (2) large population density in the seismically active zone; (3) no forecasting or inaccurate forecasting; (4) poor seismic resistant ability of buildings against earthquakes. The first two conditions depend on the nature and history beyond intervention of mankind. At present, the forecasting of earthquakes is still at the lower level. Because most people stay mostly inside the buildings, thus the mortalities of people in the earthquake are mainly caused by the collapse of buildings. Therefore, the fundamental method to reduce earthquake hazards is to take measures to improve the seismic resistant ability of buildings.

Factors contributing to the seismic resistant ability of buildings include building structures and materials. The present building structures mainly consist of raw-soil structure building; masonry structure building (commonly known as brick-concrete structure); rebar-concrete structure building and steel structure building, with the latter exhibiting stronger seismic resistant ability than the former. The raw-soil structured houses still exist in some rural areas and are vulnerable to earthquakes. Masonry structure (commonly known as brick and concrete structures) featuring cost-saving materials, easy construction, management and maintenance is popular in China. However, it suffers weak strength and poor seismic resistant ability. The rebar-concrete structure has been an important form of high-rise construction system due to its advantages in structural performance and construction technology. The structure has been increasingly valued by the engineering sector for its high stability and bearing ability, simple node structure, convenient connections, good bending properties and good fire resistance. It has become a major type of modern urban construction.

From the perspective of material science, a reinforcement-concrete building is a composite structure of concrete and rebar. The main body of the building supports brittle materials like concrete and brick masonry which can only withstand pressure. When an earthquake with forced displacement occurs, the rebar-concrete structure withstands the high-strain alternating load. The rebars inside the structure bears all pulling force, just like a skeleton maintaining the integrity of the structure. As long as the rebar does not fail, there will be no catastrophic collapse of buildings so that people in the building may have a chance to escape for survival. Field investigation results of Wenchuan Earthquake shows that the pulling-apart of the rebar leads to collapses of many structures due to poor seismic performance of rebars. There are also many structures which deformed without collapsing and stood through the disaster, thus avoiding more casualties. The reason is directly related with good seismic resistant performance of rebars. Therefore improvement of seismic behavior of rebars is of great significance for improving the seismic ability of the whole building.

2 Failure mode of rebars under earthquake loadings

The proposition of seismic resistant behavior of rebars is based on the failure modes under earthquakes loadings. An earthquake is an abrupt process of energy release. During the earthquake the load supported by buildings features transientness, alternateness and randomness. The records of earthquakes in Shibaura County and East off, Izu Peninsula of Tokyo, Japan and the Fourier Spectrum recorded at three observation points show that the maximum amplitude of earthquakes were 2Hz or so, similar to the records of Sichuan Songpan Earthquake. During Tangshan Earthquake in 1976 and Wenchuan Earthquake in 2008, the vibration frequency was 2Hz or so and the duration was within 2 minutes. For example the Elcentro Earthquake in the United States last for 10 seconds, the Tangshan Earthquake last for 23 seconds, Songpan Earthquake last for 3 seconds, the Kobe Earthquake last for 20 seconds, Shibaura Earthquake in Tokyo, Japan last for 30-40 seconds. During the earthquake, the earth shakes longitudinally for several seconds first and then shakes transversely. The major damaging factor to buildings is the transverse wave. The seismic wave spectrum (Acceleration-Time Curve seen in Figure 1) recorded in the U.S. Elcentro Earthquake shows that the earthquake loading is a random alternating load. When we carried out a field survey of Tangshan earthquake ruins, we saw a four-story library building in Hebei Mining and Metallurgy College where the ground floor completely collapsed under the action of cyclic strain of high speed and high transverse wave. The 4-story building fell into 3-story vertically (see Figure 2). Based on these facts and the failure analysis of the sample rebar taken from Tangshan relic site, it can be determined that the failure mode of the structure under the earthquake loading is mainly high-strain and low-cycle fatigue failure.

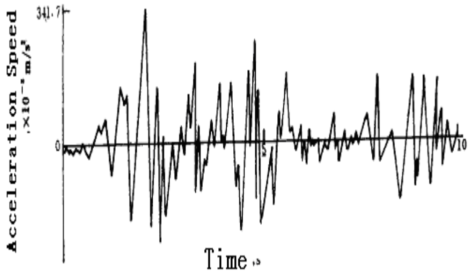


Figure 1 Seismic Spectrum of U.S. Elcentro Earthquake(1940)

Figure 2 Post-Quake Library of Hebei Institute of Mining and Metallurgy

3 The seismic performance system of rebars

According to the failure modes of the rebars under the earthquake loading, our years of research show that the seismic resistant property of rebars is a performance system focused on the high-strain and low-cycle fatigue properties. It covers the following five areas:

3.1 High-strain, low-cycle fatigue life and cyclic toughness

The high-strain and low-cycle fatigue life and cyclic toughness are considered as the basis for the seismic resistant property.

High-strain and low-cycle fatigue resistance, especially the fatigue resistance when the fatigue life $N_f \leq 100\sim 200$ weeks, is critical to improvement of seismic performance of rebars. The "Cyclic Toughness" is used in order to measure the high strain and low cycle fatigue resistance of rebars. The so-called cyclic toughness refers to $\sigma_a \times \triangle\varepsilon_t$ (σ_a is the corresponding magnitude of the strain and $\triangle\varepsilon_t$ is the range of total strain when the fatigue life N=100 weeks). It means the amount of the energy absorbed by rebars during earthquake.

"However, you persuade me that treating seismic resistant properties of structural steels as a problem of high strain fatigue was valid. So, you have my support. I also agree with you second point that it is necessary to improve the ductility and toughness of the structural steels with regard to the aspects you listed because high strain/low cycle fatigue properties are closely related to those other properties.The proposition of taking the seismic resistant performance of rebars as an issue of high-strain and low-cycle fatigue properties has been recognized by the international academic community, such as Professor C. Laird of University of Pennsylvania who is a renowned international scholar for metal material fatigue. He once wrote us to support our points: "However, you persuaded me that treating seismic resistant properties of structural steels as a problem of high strain fatigue was valid. So, you have my support. I also agree with your second point that it is necessary to improve the ductility and toughness of the structural steels with regard to the aspect you listed because high strain/low cycle fatigue properties are closely related to those other properties". In the seismic design the use of static load strength as the main basis is inconsistent with the failure modes of the rebars during earthquake.

3.2 Sensitivity of strain aging

At present rebars used in China are mostly C-Mn-Si series. Such steel has a high sensitivity of strain aging. During construction, rebars will inevitably be subject to local plastic deformation, such as cold bending, straightening, etc. Now it is required that the widely used prestressing rebars be subject to overall plastic deformation during construction. The plastically deformed rebars will be susceptible to the effect of strain aging during the subsequent service period and result in reduction in plasticity and toughness and increase in strength and brittleness, as seen in Fig 3. It is well established that sensitivity of strain aging under room temperature may arise from free nitrogen atoms in the steel. The free nitrogen atoms are concentrated around the dislocation in the steel for pinning the dislocation. At the time of plastic deformation, the dislocation is free from pinning by the nitrogen atom which will re-pin the dislocation and block the dislocation movement during aging. New Zealand witnessed a number of accidents from brittle failure caused by strain aging. Thus it should be noted that rebars with high sensitivity of strain aging can not be used for the building structure within the earthquake fortification area. The sensitivity of strain aging of rebars is denoted by rising ratio ΔU of tensile strength and dropping ratio ΔE of elongation ratio after strain aging. For the rebars sensitive to the strain aging, the elongation ratio can be reduced by 10-40% and the impact toughness can be reduced by 40-60%, which is more likely to cause brittle failure. Thus high-strain and low-cycle fatigue of rebars is deteriorated, which will give rise to brittle failure of rebars during the earthquake, causing collapse of buildings. In addition, rebars after strain aging will be under strengthened condition, which will result in cyclic softening during high strain cyclic deformation, weakening its ability to absorb the seismic energy.

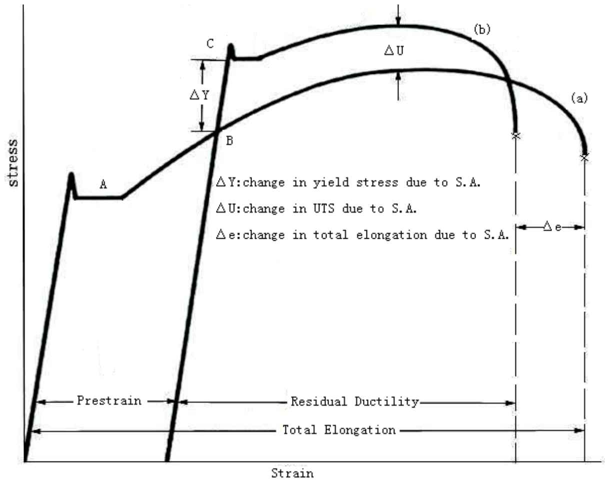


Figure 3 The Schematic Diagram of Rebars of Strain Aging Effect

Rebars in the building structure are irreplaceable. Therefore it is required that rebars used for the new projects of the seismic defense area should exhibit low sensitivity of strain aging, otherwise potential hazards will remain.

3.3 The cold brittleness and ductile-brittle transition temperature (DBTT)

The earthquake fortification areas are widely distributed in China, including some regions and cities with cold winters such as Beijing, Shenyang, Changchun, Baotou and Urumqi. The minimum temperature in these areas may reach -30 ℃ ~ -40 ℃. The ductility of rebars changes with temperature. When the ambient temperature decreases, the ductility of rebars decreases; when the temperature drops below a certain temperature, the rebars will change from ductile state under room temperature to brittle state under the low temperature. If an earthquake occurs, the building may fail due to cold brittleness of rebars. Quite a few catastrophic accidents due to cold brittleness of steel have been documented home and abroad. The Kobe Earthquake occurred on January 17, 1995 when the low temperature resulted in brittle failure of rebar-concrete structured column body. In addition, our test results show that rebars with lower cold brittleness exhibit better sustainable overloading capability under the action of alternating earthquake loading, which is conducive to improvement of the seismic resistant performance. The cold brittleness of rebars is detonated by DBTT (Ductile-Brittle Transition Temperature). When a series of impact experiments are conducted, the temperature corresponding to impact energy A_{KV} = 27J can be considered as the ductile-brittle transition temperature of the rebar.

3.4 Welding performance

The welding performance is an important property indicator of rebars. After welding, the microstructure and properties of the weld and heat affected zone will change and become a weak point in the rebars. At the time of an earthquake catastrophic fracture may initiate from the welding joint. During Tangshan Earthquake, a power plant broke down because several welds cracked. The welded joint is composed of a fusion zone and a heat affected zone. The fusion zone features noticeable inhomogeneity in chemical composition, resulting in inhomogeneity in microstructure which consists bainite, martensite and bainite + martensite. Thus the welded joint is the weakest link. Under the action of high-strain and low-cycle fatigue loading, most of fracturing occurs in the fusion zone. A weldability test of class Ⅲrebars found that the fracturing occurred at the tensile fracture surface in the heat affected zone, suggesting an evident brittle failure. The welding behaviors of rebars depend mainly on the carbon content and carbon equivalent Ceq, weld and H_{max}, the maximum hardness of heat affected zone. To obtain the high seismic resistant property, ductile failure must be identified from the tensile test after welding, with the fracture occurring at the base metal, exhibiting the same strength and plasticity levels with the base metal.

3.5 Balance between strength and plasticity

The high-strain and low-cycle fatigue properties of rebars are related to their plasticity. The traditional theory of Coffin-Manson holds that the high-strain and low-cycle fatigue resistance depends mainly on the plasticity of the materials. But extensive test results confirm that the material strength also plays an important role in the low cycle, especially $N_f \leq 100\sim$ 200 fatigue resistance. Therefore, the rebars with high plasticity and too low strength or high strength and too low plasticity are not conducive to improvement of seismic performance. However rebars with higher plasticity could act as a "plastic hinge" in an earthquake, so that buildings may crack but not fail. Meanwhile, with the development of high-rise buildings, rebars are expected to exhibit high strength. Therefore we should take the whole picture into consideration and allow good balance between strength and plasticity. It is necessary to stipulate in China's national standard GB1499-1998 that the yield strength of gradeⅢ rebars be above 400MPa and tensile strength be above 570MPa. However, its requirement for plasticity is too low, as elongation is lowered from 16% of grade Ⅱsteel to 14 %, which is detrimental to ensure good high-strain and low-cycle fatigue performance.

With reference to the above system of the seismic resistant behaviors of rebars, the seismic resistant behaviors of HRB400 rebars produced through vanadium micro-alloying and post-rolling tempcored process were tested, and comparative analysis was made aiming to provide basis for selecting rebars by the designer.

4 Testing materials and testing methods

4.1 Testing material

The testing material is a hot-rolled ribbed rebars with strength of 400MPa and specifications of φ20mm, chemical composition shown in Table 1. No 1 is V-Fe micro-alloyed rebar and No. 2 tempcored rebar.

Tab.1 Chemical composition of tested materials %

No	Types	C	Si	Mn	P	S	V	N/ppm	O/ppm	V/N
1	vanadium microalloyed	0.19	0.56	1.33	0.024	0.024	0.059	84	50	7.0
2	Tempcored	0.23	0.59	1.36	0.029	0.024		52	120	—

The basic parameters of rolling process of vanadium microalloyed rebars include:

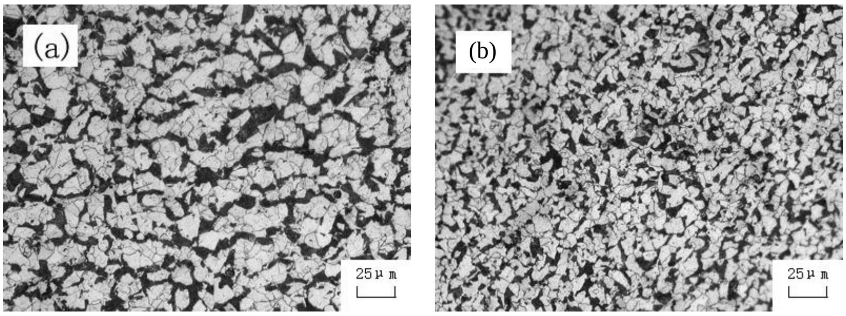
Billet heating temperature: 1120 ℃ ± 20 ℃; isothermal temperature: 1070 ℃ ± 20 ℃; tapping temperature: 1000 ℃ ± 20 ℃.

Rough rolling temperature: 950 ℃ ± 20 ℃; Finish rolling temperature: 860 ℃ ± 20 ℃; rolling followed by air cooling.

The rolling parameters of tempcored rebars include:

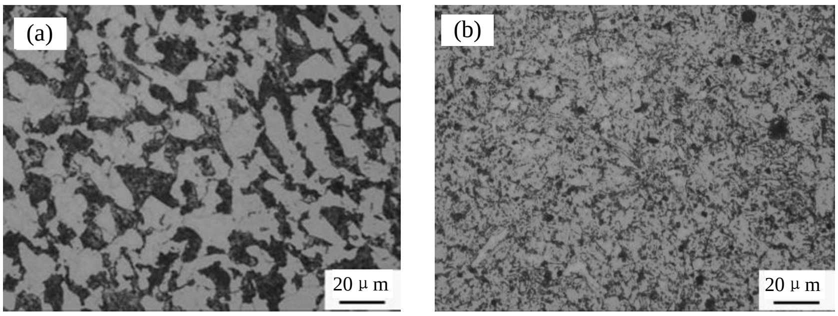
Rolling temperature: 1050 ℃, Temprimar; the cold bed temperature: 740 ℃ ~ 760 ℃; dual rolling, rolling speed: 13m / s.

Microstructures of the two rebars are shown in Figure 4 and Figure 5. On the edges of tempcored rebars, we can see the tempered structure with thickness of 1 ~ 1.5mm formed by temprimaring.



(a) core ; (b) edge

Figure 4 Microstructure of Vanadium Micro-Alloyed Rebars



(a) core ; (b) edge

Figure 5 Microstructure of Tempcored Rebars

4.2 Testing Methods

The tensile and strain aging test was carried out according to the national standards, the specimen being the unprocessed rebar samples. The method of artificial aging is used for strain aging. After 10% of pre-strain was generated on the rebars, the aging last for 3 hours at 100 ℃. The characterization method of strain aging sensitivity is:

$$\Delta U = \frac{(\sigma_b)_{\text{after aging}} - (\sigma_b)_{\text{before aging}}}{(\sigma_b)_{\text{before aging}}} \times 100\% \qquad (1)$$

$$\Delta E = -\frac{(\delta_5)_{\text{after aging}} - (\delta_5)_{\text{before aging}}}{(\delta_5)_{\text{before aging}}} \times 100\% \qquad (2)$$

ΔE and ΔU represent the reducing rate of ductility and increasing rate of strength resulting from strain aging.

The rebar samples were subject to flash butt welding test according to JGJ18-2003 (rebar welding and acceptance specification). The welder model of UN100 was used with the rated capacity of 100kVA, the primary voltage of 380V, series number of 8. During welding, length control, flashing allowance, upset allowance, transformer stack number met the requirement of specifications.

The test rebar was processed into a standard V-notch specimen for conducting a series of impact tests and determining the ductile-brittle transition temperature DBTT of tested rebars. In the test ethanol and liquid nitrogen were used for cooling until the set temperature was reached. Then temperature insulation was kept for 20 minutes or so to make internal and external temperature even. According to the related standard, the difference between the cooling temperature and set temperature (super-cooling) was 2～4 ℃. According to the results of impact tests, an impact curve was drawn. DBTT (J27) is obtained from the impact curve using the energy method (the corresponding temperature when impact energy A_{KV} = 27J).

The rebar sample was processed into the standard fatigue specimen shown in Figure 6. The high-strain and low-cycle fatigue test was carried out on Instron Model 1342 servo-hydraulic testing machine. During the test an axial extensometer of 12.5mm was used to keep $\triangle \varepsilon_t$, the total strain range constant, within the range of 2%, 3%, 4% and 5% respectively. Through an analog-digital converter, computers were used to automatically collect test data (stress response) with the sampling frequency of 100 points per week. The tests were conducted at room temperature. The cycling waves are sine waves with the loading frequency of 0.1 ～ 0.4Hz. Given the dispersive nature of the data, the test points of same parameters are ≥ 3.

5 Test results and discussion

5.1 Tensile properties

The results of tensile test of the tested steels are shown in Table 2. From Table 2, both the vanadium micro-alloyed and tempcored rebars with conventional properties and seismic resistant behaviors are consistent with provisions of GB1499.2-2007. The maximum uniform elongation *A*gt of vanadium micro-alloyed steel is greater than that of tempcored rebars, but the yield strength ratio of Cuby R_m / R_{el} is slightly lower than that of tempcored rebars.

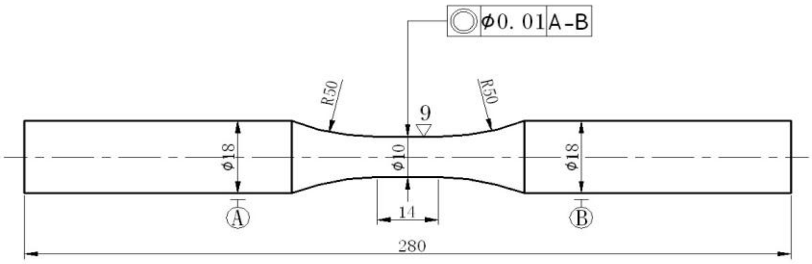


Figure 6 the Schematic Diagram of High-Strain and Low-Cycle Fatigue of the Specimen

Table 2 Tensile properties of tested rebars

No	Types	Conventional Properties			Seismic resistant Properties		
		R_{el}/MPa	R_m/MPa	A/%	A_{gt}/%	R_m /R_{el}	$R_{el\ (actual)}$/ $R_{el(Standard)}$
1	vanadium micro-alloyed	475	597	28.9	15.7	1.26	1.19
2	Tempcored	453	607	28.8	12.8	1.34	1.13
	GB1499.2-2007	≥400	≥540	≥16	≥9	≥1.25	≤1.30

5.2 Strain aging sensitivity

After 10% pre-strain and strain aging at 100 ℃ for three hours, the tensile properties of rebars and the strain aging sensitivity calculated in accordance with (1) and (2) are shown in Table 3. It can be seen from Table 3 that the strain aging sensitivity of vanadium micro-alloyed rebars is significantly lower than that of the tempcored rebars. Especially the lowered ductility rate of the vanadium micro-alloyed rebars is only 1.4%, while that of tempcored rebars is 12.8%. It is mainly due to the addition of vanadium, the micro-alloying element which absorbs free space N element and C element in the steel, prevents the pinning of the gapping elements around the dislocation lines and cleans the substrate. It can be seen from Table 1 that the ratio of V and N is 7.0 in the vanadium micro-alloyed rebars, while the tempcored rebar contains no V and does not inhibit the strain aging effect. The lower sensitivity of strain aging is significant for maintaining high ductility of rebars after being used for some time and improving seismic resistance of rebars.

Table 3 Tensile properties after strain aging and sensitivity of strain aging

No.	Types	Pre-strain aging		After strain aging		Sensitivity of strain aging	
		R_m/MPa	A/%	R_m/MPa	A/%	ΔE/%	ΔU/%
1	Vanadium microalloyed	597	28.9	613	28.5	1.4	2.7
2	Tempcored	607	28.8	645	25.1	12.8	6.2

5.3 Welding behaviors

The tensile properties of flash butt welding of the two types of rebars are shown in table 4. By comparing Table 2 and Table 4, the strength and ductility of the vanadium micro-alloyed rebars after welding is basically the same with that of pre-welding; the yield strength and ductility of the tempcored rebars is slightly lower than that of the pre-welding by a small margin. Overall, welding has little effect on the tensile properties of rebars. It can be seen from the nature and location of fracture that all tested rebars are of ductile fracture, and are broken in the base metal. It means that weld and heat affected zone do not become a softening zone.

Table 4 Welding properties of the rebar

No.	Type	R_{el}/MPa	R_m/MPa	A /%	R_m/ R_{el}	location of the fracture	Property of fracture
1-1	Vanadium micro-alloyed	474	597	29.6	1.26	Base metal	Toughness
1-2	Tempcored	447	609	27.3	1.36	Base metal	Toughness

5.4 Ductile-brittle transition temperature

The impact test results of the two types of rebars at the low temperature and normal temperature and the ductile-brittle transition temperature are seen in Fig 5, 6 and 7.

Table 5 Results of low-temperature impact test of vanadium micro-alloyed rebars

No.	Type	Impact Energy A_{KV}/J				J27/℃
		-40℃	-20℃	0℃	27℃	
1	vanadium micro-alloyed	35	51	109	164	<-40

Table 6 Results of low-temperature impact test of tempcored rebars

No.	Types	Impact energy A_{KV}/J				J27/℃
		-50℃	-30℃	-10℃	10℃	
2	Tempcored	20	33	57	77	-36

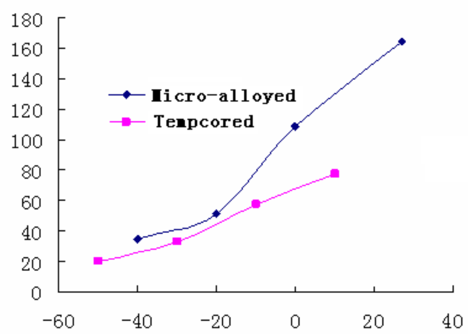


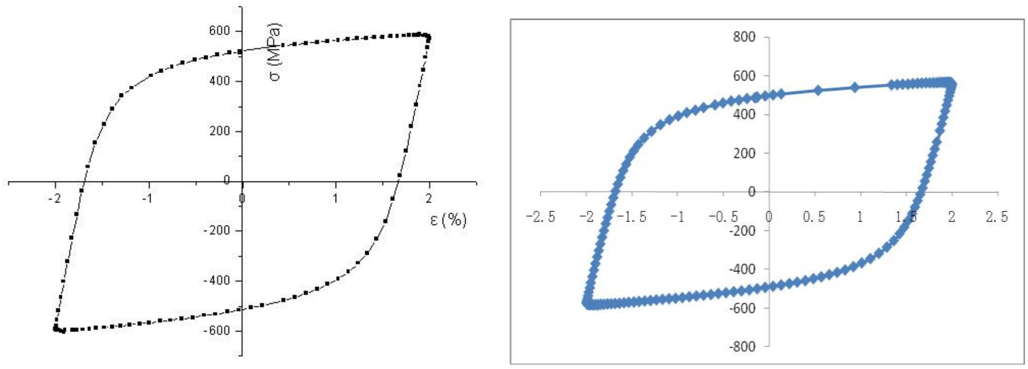
Figure 7 Comparison of Low-Temperature Impact Testing Result of the Two Rebars

It can be seen from Figure 7, the impact toughness of micro-alloyed rebars at room temperature and low temperature is superior to that of tempcored rebars, in particular the impact toughness at room temperature. The ductile-brittle transition temperatures of the two kinds of rebars are <-40 ℃ and -36 ℃ respectively. It is related to relatively low C content (see Table 1) and relatively small grain size of the micro-alloyed rebars.

5.5 High-strain and low-cycle fatigue properties

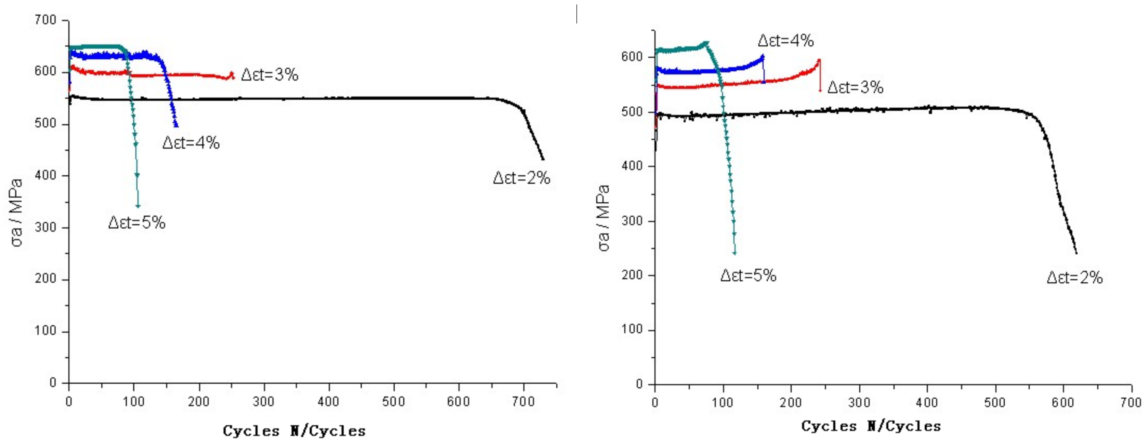
5.5.1 The stress-strain hysteresis loop and loop response characteristics

The stress-strain hysteresis loop of the two types of rebars in the strain control mode ($\Delta\varepsilon_t$ = 4%) is shown in Figure 8. The closed and smooth curve indicates the good control process of strain. The stress response curve obtained from stress-strain hysteresis loops (the relationship curve of stress amplitude and cycles) is seen in Fig 9. It can be seen from Figure 9 that the two types of rebars share the similar stress cycle response characteristics. With the stress amplitude remaining basically unchanged under the constant stress, the two types of steels are cyclically stable materials.



(a) Vanadium micro-alloyed rebars (b) Tempcored rebars

Figure 8 Stress - strain hysteresis loop ($\triangle\varepsilon_t$ = 4%)



（a）V-microalloyed rebars （b）Tempcored rebars

Fig 9 Curve of cycle response characteristics

5.5.2 Cyclic stress-strain relationship

According to the measured elastic strain amplitude ε_{ea}, the plastic strain amplitude ε_{pa} and stress amplitude σ_a (See Table 7) from the half-life stress-strain hysteresis loop, the numerical fitting of the cycle stress-strain relationship can be conducted through the Hollomon formula. The result of fitting can be seen in Table 8. The cycle strain hardening coefficient and the cycle strain index of the vanadium micro-alloyed rebars are higher than those of tempcored rebars which show that the cyclic strain hardening ability of the vanadium micro-alloyed rebars is stronger than that of tempcored rebars.

5.5.3 Strain-life relationship

According to the data of high-strain and low-cycle fatigue life of specimens in Table 7, the fitting is conducted according to Coffin-Manson formula:

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p \quad (3)$$

Where $\Delta\varepsilon_e = B(2N_f)^{-b}$ $\Delta\varepsilon_p = C(2N_f)^{-c}$ （4）

to obtain the Coffin-Manson formula:

$$\Delta\varepsilon_t = B(2N_f)^{-b} + C(2N_f)^{-c} \quad (5)$$

(5) The parameters B, b, C, c in (5) are the fatigue strength coefficient, fatigue strength index, fatigue ductility coefficient, and fatigue plasticity index respectively. Fitting results are shown in Table 9.

Table 7 Data of High-Strain and Low-Cycle Fatigue

No.	ε_a	ε_{ea}	ε_{pa}	$\Delta\varepsilon_t$	$\Delta\varepsilon_e$	$\Delta\varepsilon_p$	σ_a/MPa	$2N_f$(Cycle)
1	0.010	0.00310	0.00690	0.020	0.00620	0.01380	549.5	1438
	0.015	0.00336	0.01164	0.030	0.00672	0.02328	593.5	506
	0.020	0.00360	0.01640	0.040	0.00720	0.03280	643.0	324
	0.025	0.00399	0.02101	0.050	0.00797	0.04203	652.5	270
2	0.01	0.00271	0.00729	0.02	0.00542	0.01458	501.5	1473
	0.015	0.003	0.012	0.03	0.006	0.024	544.3	490
	0.02	0.00323	0.01677	0.04	0.00646	0.03354	569.5	286
	0.025	0.00347	0.02153	0.05	0.00694	0.04306	600.9	209

Table 8 Cyclic Stress-Strain Relations

No.	Types	σ_a—ε_{pa} Relationship	σ_a—ε_a Relationship
1	Vanadium micro-alloyed	$\sigma_a=1300.17\varepsilon_{pa}^{0.1742}$	$\sigma_a=1452.11\varepsilon_a^{0.2117}$
2	Tempcored	$\sigma_a=1117.56\varepsilon_{pa}^{0.16302}$	$\sigma_a=1220.23\varepsilon_a^{0.19303}$

Table 9 Strain-Life Relationship

No.	Types	Fitting Result through Coffin—Manson formula
1	Vanadium micro-alloyed	$\Delta\varepsilon_t=1.3277(2N_f)^{-0.6337}+0.0158(2N_f)^{-0.1311}$
2	Tempercored	$\Delta\varepsilon_t=0.01297(2N_f)^{-0.12108}+0.7371(2N_f)^{-0.54223}$

5.5.4 Cyclic toughness

N_f = 100 is substituted into Coffin-Manson formula obtained from the fitting in Table 9 to figure out the total strain range Δεt value. Based on the relationship between the total strain range and the total strain amplitude （$\varepsilon_a=1/2\Delta\varepsilon_t$）, ε_a is substituted into Hollomon cyclic stress-strain relationship in formula 8 to calculate the corresponding σ_a and then calculate the $\Delta\varepsilon_t\cdot\sigma_a$, , the cycle toughness of rebars. The cyclic toughness of the two rebars is shown in Table 10.

Table 10 Cyclic toughness

No.	Types	$\Delta\varepsilon_t$	σ_a /MPa	Cycle toughness /J.cm^{-3}	Relative Cycle toughness
1	vanadium microalloyed	0.0541	676.28	36.60	1.27
2	Temprcored	0.0485	595.17	28.87	1

Cyclic toughness is a major indicator of the seismic resistant property of rebars. As can be seen from Table 10, the cycle toughness value of vanadium microalloyed rebars is 1.27 times that of tempcored rebars, a 27% increase on the basis of cyclic toughness of tempcored rebars. With the addition of vanadium in microalloyed rebars, the carbonitride is finely precipitated in fine granules (Figure 10) from the ferrite. It enables the uniform distribution of cyclic plastic deformation and delays the fatigue crack; on one hand it hinders the spread of fatigue cracks through the boundary grain, on the other hand it lowers the segregation of harmful elements on the grain boundary. These factors contribute to improvement of the high-strain and low-cycle fatigue properties and cycle toughness of rebars.

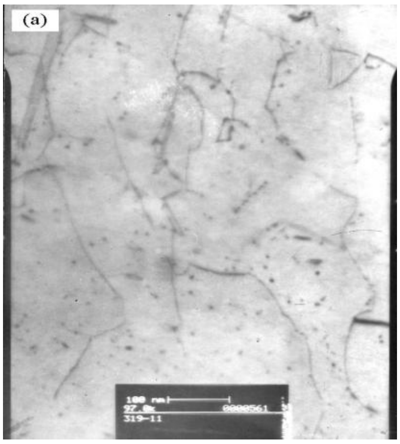


Fig 10 The second phase particles precipitated from ferrites of vanadium micro-alloyed rebars (TEM picture)

6 Conclusion

(1)The development of high seismic performance of rebars in China is of great significance to improve seismic resistant capacity of rebar-concrete buildings and reduce personnel and property loss due to earthquakes.

(2)The failure mode of rebars under earthquake loading is high-strain and low-cycle fatigue. The seismic resistant performance of rebars is an indicator system focused on the high-strain and low-cycle fatigue performance, including strain aging sensitivity, low temperature brittleness, weldability and the balance between strength and plasticity.

(3)The vanadium micro-alloyed rebars and after-heat treatment of rebars used in the test meet the performance requirement for the seismic rebar specified in GB1499.2-2007. The uniform elongation of vanadium micro-alloyed rebars is higher than that of tempcored rebars, but the tensile strength to yield strength ratio of vanadium micro-alloyed rebars is lower than that of tempcored rebars.

(4)From the point of the seismic resistant performance indicator system focused on the high-strain and low-cycle fatigue properties, the seismic resistant performance of the tempcored rebars used in the test is worse than that of vanadium micro-alloyed rebars, particularly there are great differences in terms of strain aging sensitivity, cycle toughness and ductile-brittle transition temperature.

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