Niobium Bearing Structural Steels
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DEVELOPMENT AND APPLICATION OF STEELS FOR BRIDGES AND BUILDINGS IN CHINA

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Abstract

This paper summarizes the current status in development and application of steels used for bridge construction in China. It outlines the three stages of development experienced in China: (1) from 1949-1990, where development was slow and characterized by the production of 16Mnq series (YS 345MPa). Such steels suffered from lack of refinement, controlled rolling processing as well as the quality of steel metallurgy, often leading to poor low temperature toughness properties; (2) from 1990-2000, with improved steelmaking, rolling technologies and techniques, the quality of bridge steels greatly improved together by microalloying with elements such as Nb being widely applied; (3) 2000-onwards, the focus has been on steels that permit the development of high performance bridges that deliver good loading, are resistant to shaking, exhibit corrosion resistance qualities, easy to fabricate etc. Such steels have shown improvement in base properties and exhibit good toughness, weldability and corrosion resistance. The paper concludes by discussing the future direction and development of bridge steels in China.

Development and trends of steel for bridge steels

In 1870, arch trusses of bridge crossings across the Mississippi River near Saint Louis in America were constructed from low alloy steel which the content of Cr at 1.5~2.0% [1]. Joints of the steel structure are mainly riveted and the design criteria are based mainly upon the tensile strength. With the wide application of welding in some fabrications, the design criteria are mainly based upon the yield strength. Thus, the weldability and impact toughness of steels are beginning to emphasize a reduction in the carbon content and carbon equivalent which has resulted in the development of steels with low carbon and microalloy levels. Micro-alloy elements, such as V, Ti and Nb play an important role. These elements, along with Al, are grain refining elements and used in some special steels. These elements have already used as the micro-alloying elements to develop some high strength and low alloy steel in specific cases. Now the steel for bridge are developing towards the trend of multi-element and compound alloying from single element alloying.

Due to the weakness of low temperature toughness and weldability about traditional high strength steel for bridge, the experts on material at home and abroad offer the conception of High Performance Steels. High Performance Steels improve some properties than the traditional steel. Besides higher strength, High Performance Steels have higher ductility, better fracture toughness, better weldability, better cold formability, and better corrosion resistance. As one of the high performance steels, high strength weathering steels for bridge, such as HPS-70W in ASTM A709, SMA570W in Japan, are developed to be far ahead. HPS-70W has been widely applied to the bridge in America. The serial of SMA570W has also been used in the steel structural bridge, steel structural building. What's more, it is standardized under the JIS. Basically, there are three technical routes about high strength weathering steel for bridges. Firstly, it is adopted the production process of quench and temper, such as 70W and 100W in the ASTM A709-95. This kind of steel has strict requirements on weldability and must preheated before welding resulting in higher cost. Secondly, the steel is produced through thermomechanical processing at 0.07-0.10%C level, such as HPS70W, eliminating the need for quench and temper. Thirdly, the basis of the microstructure of ultra low carbon bainite is to make the high strength weathering steel for bridges, such the ultra low carbon bainite steel in the American patent (US6315946) which is an improved type of SMA570W in the JIS specification.

A very long development stage exists for bridges in China from the 1950s to today. From the Wuhan Yangtze River Bridge and Jiujiang Yangtze River Bridge to the Wuhu Yangtze River Bridge, the main span of the bridge has lengthened from 128m to 312m and its structure connections have gradually moved from tying and welding to integral joint. The best illustration of this change is the construction of the Wuhu Yangtze River Bridge. It symbolizes that Chinese bridge construction and design has achieved international standards.

Before the 1990s, steel used for Chinese bridges has been at the lower level of traditional high strength low alloy steel, such as 16Mnq, 15MnVq and 15MnVNq. All of these steels have poor cryogenic toughness and poor weldability at thick cross sections. For example, in the railway bridges, the heaviest thickness of steel plate is only 32mm. Moreover, the 15MnVNq which contains vanadium causes the low temperature toughness to be unstable and its weldability to be poor. The 15MnVNq steel is applied only in the Jiujiang Yangtze River Bridge. Subsequently, none of the bridge construction utilized the 15MnVNq steel in China. In the middle of 1990s, when the Wuhu Yangtze River Bridge was constructed, since there were no optimal bridge steels that could be applied in this famous project bridge, the department of bridge design decided to import steel from overseas. In this situation, China Zhongtie Major Bridge Engineering Group and Wuhan Iron and Steel Corp. successfully produced the 14MnNbq steel in joint development, which was the special steel applied to this large span bridge. The 15MnVNq steel is alloyed with V while the 14MnNbq steel is alloyed with the Nb element. The Nb steel is reduced in C content and melted with ultra pure metallurgy practices. These factors guarantee that the 14MnNbq steel will exhibit excellent low temperature impact toughness (-40□ A_{KV}≥120J) and improved weldability for steels with yield strengths greater than or equal to 370MPa. The effect of thicker cross sections for 14MnNbq steel is effectively solved as well. Therefore, 14MnNbq steel can be commercially produced at thicknesses of 32~50mm. After the construction of Wuhu Yangtze River Bridge, 14MnNbq steel meets the comprehensive requirements for railway bridge construction and it is the first choice in building large span railway bridges today in China. Meanwhile, alloying with Nb element has received approval and is being applied on a large scale in the research and production of bridge steels in China.

With the leapfrog development of Chinese railway bridges and the constant improvement of railway bridge span and bearing capacity, it is inevitable for bridge steel thicknesses exceeding 50mm at higher strengths will be further promoted. Additional research on new types of high strength bridge steels which bear excellent weldability and low temperature toughness is necessary. Thus, WISCO developed the series of high strength bridge steels with the ultra low carbon bainite microstructure that is WNQ570 steel and WNQ690 steel. The former is successfully applied to Nanjing Dashengguan Yangtze River and the cantilever beam in an offshore drilling platform and the latter is successfully used in the Floating Crane made at Shanghai Zhenhua Port Machinery Co. LTD.

Generally, it is apparent that there is an obvious similarity in the development of bridge steels in China and abroad. First, it develops from a microstructure of ferrite and pearlite in which there is a great difference in the composition and microstructure. Then, the development of a microstructure of bainite and ferrite in which there is a little difference in the composition and microstructure. Now, the development of an acicular ferrite transforming at intermediate temperatures in which there is a good uniformity of composition and microstructure.

Development and trends for building steels

Steel structure architectural design considerations involve the advantages of light deadweight, high strength, large extension, good anti-seismic capability, rapid construction speed, small structural member section, high headroom and long span, easy to reconstruct and well cost effective economic target. The steel structure must also exhibit an environmental protection type, be reused and be easily recycled compared with concrete structures. Today, steel structures are widely used on architectural designs in developed countries.

The structural steel standard of ASTM A992 in America implemented in 1998, describes the 350MPa grade steel of yield strength must have excellent weldability and strict control over the tensile properties. Within this standard, the emphasis is on the minimum and maximum yield strength and yield ratio (YR) in America. It also limits the maximum carbon equivalent (Ceq) to ensure the excellent weldability [2]. In 1990, after Manjil-Roundbar Earthquake, it also implements the new specification about anti-Seismic building on design of steel structure in Eran [3]. Meanwhile, Japan proceeds to develop a series of steels with low YR type properties for buildings, such as HT490, HT590, and HT780 [4]. All of these steel grades exhibit a small range of yield strength fluctuation. NKK took the lead in the development of a 60 kg grade steel for buildings with a YR less than 0.80[5]. At present, construction steels for buildings with tensile strengths of 490MPa, 590MPa and 780MPa grade have been developed and are widely applied in civil engineering applications globally.

Structural Steel Standards

The main product standards of structural steel for building in developed countries are as follows:

(1) America: ASTM A283-93 Low and Medium Strength Carbon Steel, which includes the serial of A283; ASTM A572-93 High Strength Low-Alloy Nb-V Steel for Welded Structure, which includes the serial of A572.

(2) Japan: KS D 3515-1992 & JIS G 3106-1992 [SM] Steel for Welded Structure, which includes the serials of SM400 and SM490; KS D 3503-1993 & JIS G 3101-1987 Steel for General Structural Purposes, which includes the serial of SS300, SS400 and SS490; JIS G 3136-1994 [SN] Steel for Shipbuilding Structure, which includes the serials of SN400 and SN490.

(3) England: BS 4360-1986 Steel for Welded Structure, which includes the serials of 40, 50 and 55.

(4) German: DIN 17100-1986 Steel for General Structural Purposes, which includes the serials of St33, St37, St44, and St52.

With the development of steel structures for buildings in China, the industry standard YB 4104-2000 “Steel plate for high-rise building” was formulated in 2000. It was adopted from the Japanese standard JIS G 3136-1994 and included the serials of Q235GJ and Q345GJ. National standard GB/T 19879-2005 Steel Plates for Building Structure was implemented at the end of 2005. This standard is combined with the standard “High Strength Low Alloy Structural Steel” (GB/T 1591-1994) and Japanese standard JIS G3136-1994, and steels are extended from serials of Q235GJ and Q345GJ to Q235GJ, Q345GJ, Q390GJ, Q420GJ and Q460GJ. Both standards feature further limiting the content of Sulfur and Phosphorus compared with standard GB/T 1591-1994, requiring the upper limit to yield strength, relaxing the requirement of yield ratio compared with JIS G 3136-1994, and limit carbon equivalent to protect the weldability. In general, this standard does not embody advanced compared with foreign standards at all. Moreover, both standards above do not involve the requirement of high heat input welding, and also no consideration of fire resistance and weather resistance. In the standard JIS G 3136-1994, the maximum welding line energy which the steel SN490B can be borne is only 37kJ/cm [6]. Presently, the highest strength steel is Q460 (tensile strength of 550-720MPa) in standard GB/T 19879-2005. The steels which are widely applied are Q235 (tensile strength of 375-500MPa) and Q345 (tensile strength 470-630MPa) in China. The high strength steel plates for building structures have not yet been developed into a complete serial. Also, additional special performance steels and sizes have not matched. Currently, the primary development trends for steel in building structures are as follows: high strength, anti-seismic (low yield ratio), fire resistance, weather resistance, Z-direction property, high heat input energy and welding. Steels for building structures are developing towards high strength, high performance, and large scale as shown in Figure 1 [6, 7].

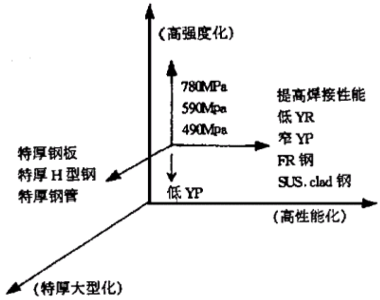

Figure 1. Developing trends of steel for building structure

Steel for bridge and building structures in WISCO

In order to meet the requirements of the market for high performance steel in the bridge and building structure, WISCO developed independently new steels for bridge and building structures recently, and applied these grades to major engineering projects in China and abroad.

Safety reliability requirements for high strength large scale structural bridge steels demand lightweight, excellent toughness, good weldability and long life. Both the designers and steel producers focus on these steel plate mechanical property attributes to meet these stringent safety requirements. Bridge designers and manufacturers urgently desire that WISCO can produce these high performance bridge steels through its advanced metallurgical equipment and process conditions to meet more demanding steel structure design requirements.

In order to meet the changing market demands, WISCO independently developed five serials of s more than 20 high performance steel for bridge applications, These serials include steel for railway bridges, highway bridge, sea-crossing bridges, large span bridge guardrail, and high strength steel with good weathering resistance for bridges.

In 1996, supported by China Zhongtie Major Bridge Engineering Group, WISCO developed 14MnNbq, which was successfully applied on the bridge over Jing-Hang Canal and passed the technical appraisal sponsored by the Ministry in the same year. WISCO supplied the steel for the Wuhan Yangtze River Bridge despite strong global competition at the end of 1997. The steel 14MnNbq successfully overcomes the thickness effect satisfactorily applying the railway bridge steel in thickness up to 50mm. Moreover, the steel has excellent low temperature toughness and weldability, and is also the first choice in building the large span railway bridges in China. After construction of Wuhan Yangtze River Bridge, WISCO won the supplying goods rights of Wuhan Yangtze River 3rd Bridge, Nanjing Yangtze River 2nd Bridge. Meanwhile, WISCO developed serials of control rolling type steel of WQ490D, WQ490E and provided steel plates to

Changdong Huanghe River Bridge, Yichang Yangtze River Bridge, and Junshan Yangzte River Bridge, which amounted to 140,000 tons of plate steel.

As the member of participation in the National Project 973, WISCO is developing the first serials of high strength weathering bridge steels in China. The serials of steel will have tensile strengths of 600-900MPa grade, in which 600MPa grade and 700MPa grades are already in mass production. Other serials of steel are ultra low carbon bainite (ULCB) as the design theme, with microstructure refinement and homogeneous microstructure, which results in high strength, good toughness and excellent weldability. After several industrial experiments their actual product level reached the international advanced level of foreign steel producers. These serials of steel are low cost, high performance, and environment-friendly. In China, they represent the development trend of bridge steels for the near future.

The main features about the serials of high strength weathering for bridge steel with in WISCO are as follows:

(1) During developing of high strength weathering bridge steels, ultra low carbon acicular ferrite microstructure, strict ladle metallurgy cleaning treatment, and TMCP are used, so the steels are high strength, excellent cryogenic toughness, good weathering, and perfect weldability.

(2) Exhibit low cold cracking sensitivity and welded joints having excellent mechanical properties (at -40°C impact energy greater than 110J at welded joint in submerged arc welding, manual welding and gas arc welding.

(3) WNQ570 and WNQ690 show good corrosion resistance and are superior to 09CuPCrNi grade.

Steel for Building Structure

In order to adapt to the rapid development of steel for building structures, WISCO has recently developed six series of steel, that would be 18 steels for building structure, which is the serial of fire-resistant and weathering structure construction steel, the serial of high toughness structure construction steel, the serial of anti-seismic steel for building structure, the serial of fire-resistant structure construction steel, the serial of weathering structure construction steel and ultra low yield strength steel for building structure. The tensile strength ranges from 490MPa grade to 590MPa grade. WGJ510C2, fire resistant and weathering structure construction steel, has passed the technical appraisal sponsored by the Ministry in 2001. WGJ490B and WGJ490C, two high toughness and low yield ratio construction steels were passed with the technical appraisal sponsored by the Ministry in 2004. WGJ510B and WGJ510C, two high toughness and low yield ratio structure construction steels were passed with the technical appraisal sponsored by WISCO in 2006.

WGJ510C2, a fire resistant and weathering construction steel exhibits excellent performance. Firstly, it has a good fire-resistant which the yield strength at 600°C is not less than two-thirds of the yield strength at room temperature. Secondly, it has good weathering resistance exhibiting corrosion resistance 2 to 8 times that of Q345. Thirdly, it has high Z-direction properties with more than 35% reduction of area. WGJ510C2 can bear high input energy welding at 50-100kJ/cm. WGJ490B, WGJ490C, WGJ510C and WGJ510D, the grades of high toughness and low yield ratio steels for building structures, exhibit high toughness of 47J at 0°C--40°C, low yield ratio with anti-seismic (ReL/Rm<0.80 can be applied in the area with a frequent occurrence of earthquakes) and good weldability.

The main features about the serials of high performance steel with fire-resistant and weathering for structure construction in WISCO are as follows:

(1) Based upon new optimal multi-compositional design, fire resistive steels are produced with a yield strength at 600°C maintaining not less than 2/3 of its yield strength at room temperature and exhibiting excellent weathering characteristic with a corrosion resistance 2 to 8 times better than Q345.

(2) Through the use of microalloy technology practices, optimum microalloy additions are made at optimum N and O level. This results in the formation of a dispersive distribution of second phase particle of a high melting point. These particles retain their strength and toughness in the heat affected zone during high heat input energy welding.

(3) Rigorous control of the content of S, P, gas and inclusions results in good internal quality and soundness and plates with good anti-lamellar tearing resistance leading to high Z-direction properties.

The main features about the serials of high performance steel with high toughness and low yield ratio and anti-seismic for structure construction in WISCO are as follows:

(1) Adapted the special process of controlled rolling and controlled cooling in the two phase region, obtaining a microstructure with a reasonable ratio and distribution of the soft phase (ferrite) and the hard phase (acicular ferrite and pearlite), which contribute to the optimal matching of strength and toughness. This balance can guarantee the steel plates have a low yield ratio (≤0.80) and excellent anti-seismic performance.

(2) Controlling rigorously the content of S, P, gas and inclusions, which results in high internal cleanliness and good internal quality, guarantee the steel plates have good anti-lamellar tearing, then cope effectively with the difficulty of low Z-direction properties.

(3) Steel plates have optimal matching about strength and toughness, with high strength, high toughness, low yield ratio and high Z-direction properties.

In general, both the high performance steels for bridge and building structure in WISCO exhibit high performance. The performance indices of steel plates are all higher than the other similar steel plates produced at home and abroad. In some cases, performance may be higher.

Application achievements about steel for bridge and building structure in WISCO

WISCO has produced the high performance steels for bridges amounting to 600,000 tons meeting the enterprise standard, industry standard and national standard. The steel plates are successfully applied to the Nanjing Dashengguan Yangtze River Bridge with Jinghu High Speed Railway (Figure 2), Hangzhou Bay Sea-Crossing Bridge (Figure 3), Wuhu Yangtze River Bridge (Figure 4) and the floating crane at 4000 tons (Figure 5). WISCO has obtained significant enterprise and societal economic benefits that has resulted in enormous contributions to the key projects. In Table 1 lists the application achievements for high performance bridge steels by WISCO.

Table 1. The application achievement about high performance steel for bridges in WISCO

No.	Steel grade	Bridge	Quantities of Steel (tons)	Time of Completion or under Construction(year)
1	WQ530E(14MnNbq) Steel for railway and highway bridge	Wuhu Yangtze River Bridge	46000	1999 ~ 2001
		Changdong Yellow River 2nd Bridge	4200	1998
		Bridge in Myanmar	2100	1998
		Qinshen high speed railway bridge	8700	2000
		Songhuajiang River Bridge	2000	2001
		Changshou Yangtze River Bridge	8000	2002
		Xingcheng Canal bridge	2000	2005
		Nanjing Dashengguan Yangtze River Bridge	23800	2007
		Subtotal	**96800**	
2	WQ490D(Q345qD) Steel for railway and highway bridge	Wuhan Yangtze River 3rd Bridge	12000	1999
		Luokou Bridge	1200	1998
		Yichang Yangtze River Bridge	6000	1999

		Junshan Yangtze River Bridge	7000	2000
		Haihe Bridge	3000	2003
		Nanjing Dashengguan Yangtze River Bridge	8250	2007
		Subtotal	**37450**	
3	WQ510D Steel for highway bridge	Yangluo Yangtze River Bridge	20000	2005
		Subtotal	**20000**	
4	WQ490E（Q345qE） Steel for highway bridge	Nanjing Yangtze River 2nd Bridge	22000	1999～2000
		Runyang Yangtze River Bridge	4500	2002
		Subtotal	**26500**	
5	WNQ570 High strength Steel with weathering for bridge	Nanjing Dashengguan Yangtze River Bridge桥	13000	2007
		Offshore platform	1000	2004
		Subtotal	**14000**	
6	WNQ690 High strength Steel with weathering for bridge	Floating crane with 4000 tons	800	2007
		Subtotal	**800**	
7	WGZ345C Steel pipeline for sea-crossing bridge	Hangzhou Bay Sea-Crossing Bridge	370000	2003
		Subtotal	**370000**	
8	Q390C-HL Bridge guardrail	Hangzhou Bay Sea-Crossing Bridge	12000	2007
		Subtotal	**12000**	
	Sum		**577550**	

Figure 2. Nanjing Dashengguan Yangtze River Bridge

Figure 3. Hangzhou Bay Sea-Crossing Bridge

Figure 4. Wuhu Yangtze River Bridge

Figure 5. Floating Crane with 4000 tons

Steel for building structure

Presently, WISCO has produced high performance steels for building structures amounting to 300,000 tons by enterprise standard, industry standard and national standard. The steel plates are successfully applied to the many key project constructions. Table 2 lists the specific application achievement for high performance building structures supplied by WISCO.

Table 2. Application achievements about high performance steel for building structure

No.	Engineering	Steel	Quantities(tons)	Time(year)
1	China Mingshen Bank Building in Wuhan	Q345B/C-J	24000	2001-2002
2	Zhongguancun Financial Center Tower	Q345B/C-J	9000	2003
3	Beijing Television Center	Q345B/C-J	45000	2004
4	Beijing Yintai Building	Q355NHD-J	3000	2004-2005
5	Capital International new Airport in Beijing	Q345C/D-J	12000	2005
6	Power Plant in Indonesia	Q345B/C-J	9900	2004
7	Hejing Building in Guangzhouu	Q345B/C-J	4000	2004

8	National Stadium in China	Q345C/D-J	30000	2005
9	Building CCTV	Q345B/C/D-J Q390D-J	35000	2005-2006
10	PetrolChina Company limited	Q345C-J	3400	2005
11	Guangzhou TV Tower	Q345C-J Q390C-J	34000	2006
12	Zhujiang East Tower	Q345D-J Q390D-J	22000	2007
13	Beijing financial resources Building	Q345C-J	11000	2007
14	Lhasa Railway Station	Q345B-J	12000	2005
15	Beijing Railway South Station	Q345C/D-J	35000	2006-2007
16	3rd term of Beijing National Trade Center	Q345C/D-J	12000	2006-2007
17	Wugang Keji Building	WGJ510C2	2800	2005
18	Shanghai disabled sport and art center	WGJ510C2	200	2001
19	National Grand Theatre in Beijing	WGJ510C2	220	2002
	Sum		304520	

Figure 6. National Stadium in China

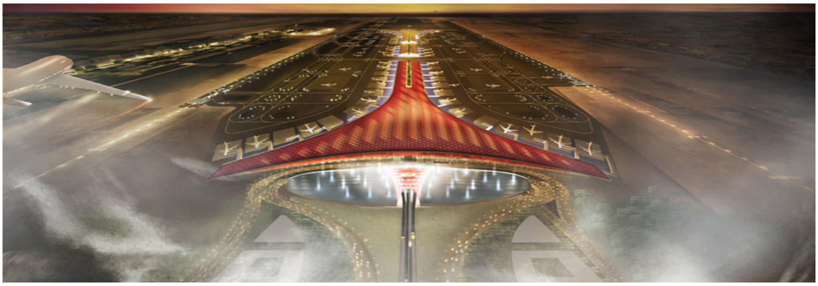

Figure 7. Capital international new airport in Beijing

Figure 8. CCTV Tower

Figure 9. Duangzhou TV Tower

Conclusions

The high speed development of the national economy has caused the bridge and construction industry to expand rapidly. Consequently, new steel grades have been developed and steel quality has continuously improved. WISCO successfully developed and applied these high performance steels for bridge and building structure applications. Positive contributions were made in large scale and high parameter bridge steel plates and high-rise and high span building structural steel plates. Their excellent properties and metallurgical quality were highly evaluated by designers and manufacturers and customers, successfully meeting their criterion. The independent development of these high performance steels for bridge applications is a successful and important step for WISCO. Applications in mass customization have positioned WISCO in the leader position for the production of bridge steels in China.

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