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DESIGN AND CONSTRUCTION OF SIMPLE BEAM BRIDGES FOR HIGH-SPEED RAILS IN CHINA: STANDARDIZATION AND INDUSTRIALIZATION

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Abstract. High-speed rail provides a safe, efficient, and economic transportation system for regions with high population density such as eastern China. To accommodate the rapid development of high-speed rails in China, the bridges with standard spans have been identified as the main infrastructure type. This article provides a state-of-the-art review on the design and construction of the standard simply-supported beam (simple beam) bridges for high-speed rails in China. The structural components discussed include the main girder, deck, and substructure. The live load models, deformation limiting values, and construction methods for the bridges are also discussed. Additionally, the experimental tests were conducted to verify the static and dynamic performances of the structure. The main objective of this paper is to provide the latest design and construction experience of Chinese standard simple beam bridges in high-speed rail and show how a quick and quality engineering has been achieved by utilizing these standardized bridges.

Keywords: construction, design, high-speed rail, simple beam bridge (SBB), standardization.

1. Introduction

High-speed rail (HSR) plays an important role in daily activity of people, economy, and public transportation for a country with high population density such as China. Over the past few decades, a total of 20 countries have developed the HSR network, mostly in Europe and East Asia. According to the International Union of Railways (UIC), HSR is defined as the railway system whose operation speed exceeds 200 km/h. Tokyo-Osaka Shinkansen built in Japan in 1964 is the first HSR in the world, whose maximum operating speed was 210 km/h. Then, France and Germany opened the TGV southeast HSR and Hanoverian-Wurzburg HSR with the operating speed of 250 km/h in 1983 and 1991, respectively. Today the HSRs in Europe have expanded into a regional service network. The completion and operation of Qinghuangdao to Shenyang Passenger Dedicated Line (PDL) in 2003 indicated that Chinese railways began to enter the high-speed construction (Smith, Zhou 2014). As described by Yan (Yan *et al.* 2015), China is currently the leading country on HSR construction. Until September 2016, the total mileage of HSRs in China has exceeded 20 000 km, which is more than the rest of the world's HSR tracks combined. The construction of HSRs is still ongoing and China is committed to connect all provincial capital cities as well as the cities with population of more than half million by 2020 to establish a railway network of nation (Zheng 2008). By then, the travel time between two cities of 2000 km distance will be reduced to be within 12 hours.

Bridges have been commonly used in HSR construction. The proportions of bridges with respect to the total rail length for the major HSR lines in China and other countries are shown in Fig. 1. Compared with other countries, bridges account for a high percentage of a HSR line in China (Liu *et al.* 2010). For example, the bridge proportions of Beijing-Tianjin HSR and Beijing-Shanghai HSR are over 88% and 80%, respectively (Sun 2008). Besides, it should be noted that 95% of these bridges were built as standard simply-supported beam (simple beam) bridges (SBBs) with short spans (e.g., 20 m, 24 m, 32 m, 40 m, etc.). The 32 m standard concrete box girder was the main structural type among them, accounting for more than 90% of the total number of bridges (Liu *et al.* 2015). The medium and long span bridges such as continuous beams, continuous rigid frames, steel truss arches (Dai *et al.* 2016; Liu, Dai 2011; Zheng *et al.* 2011), and cable-stayed bridges (Dai *et al.* 2014) were chosen only when crossing over an inevitable physical barrier (e.g., river and existing highway or HSR line) (Hu *et al.* 2014).

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Standard SBBs were largely adopted in the HSRs in China because of the following features: (1) Standardization in the design and construction of beams accelerate the whole construction process of a HSR to a large extent; (2) Bridges provide a stable and smooth line for high-speed trains and are advantageous in terms of foundation settlement control compared with the subgrade structure; (3) Bridges occupy relatively less land and avoid the interruption of an existing transportation line, particularly in places where there are other structures surrounding the rail line (Jin 2014; Zhou, Ai 2014). Moreover, as the main infrastructure component of a HSR, first, the standard SBBs must have enough vertical, transverse, longitudinal, and torsional stiffness to strictly control the displacement under the live load (Cao, Chen 2012). Second, durability and ease for inspection and maintenance should be considered during the design stage (An *et al.* 2010; Papaelias *et al.* 2008). Third, the bridge structure is better to match the environment with elegant appearance and smaller noise (Zhang *et al.* 2012). Lastly, the specifications and types of standard SBBs are to be simplified as much as possible for the purposes of convenient construction and quality control (Givoni 2006; Raghunathan *et al.* 2002).

This paper presents an updated review on the design and construction of the standard SBBs used in the HSRs in China. First, the main girder, deck, and substructure of SBBs are discussed in detail. The HSR live load model adopted in China is presented and compared to other live load models used in Europe and Japan. Then, the deformation limiting values of SBBs, as specified in the Chinese HSR code and Eurocode are discussed. Second, the construction method for the SBBS including the longer ones is described. Third, the verification tests on the performance of SBBs are presented. This article aims to provide the latest design and construction experience of Chinese HSR's SBBs and to demonstrate that the common use of standard SBBs has become a main feature of Chinese HSR construction.

2. Design of simple beam bridge systems

2.1. Main girder type

Box girders represent the main structure type of HSR bridges in most countries. Continuous beam bridges were mainly adopted in France and Korea; while simple beam bridges (SBBs) and continuous beam bridges (CBBs) were equally used in Germany and Italy. For the newly built HSR bridges in France and Germany, CBBs seem to be more dominant. However, SBBs have been more commonly used in China. The reasons for such differences are twofold: (1) The European economy and technology are more developed; and (2) European HSR lines are shorter and the bridges proportions are smaller (Sun 2011).

Detailed dimensions of the various SBBs used in China are shown in Table 1. The 24 m beam has two separate depths to ensure the harmonious appearance when connected with different lengths of beam. Based on a large number of theoretical and experimental studies and considering the construction capability, the 32 m standard prestressed concrete box beam bridge (Fig. 2) was eventually

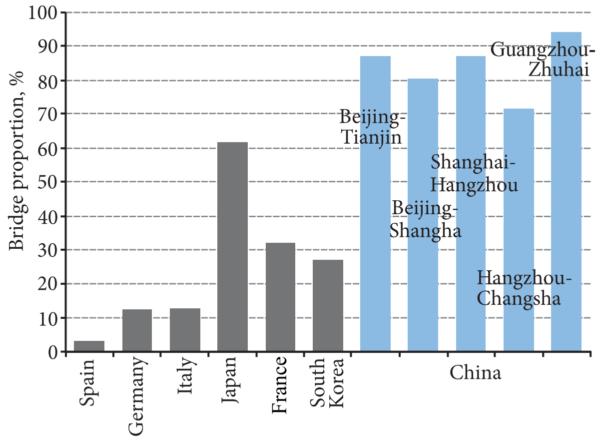


Fig. 1. Percentages of bridges in HSRs

Table 1. Detailed dimensions of HSR simple beams, in m

Span	Full length	Beam depth	Width of top flange	Width of bottom flange	Thickness of top flange	Thickness of bottom flange	Thickness of web	Construction method
20	20.6	2.45	13.4/12	5.80	0.30	0.28	0.45	Precast
24	24.6	2.45/3.05	13.4/12	5.80	0.30	0.28	0.45	Precast
32	32.6	3.05	13.4/12	5.50	0.30	0.28	0.45	Precast
40	40.6	3.05	13.4	5.74	0.30	0.30	0.50	Cast-in-place
56	57.1	5.30	13.4	6.70	0.35	0.30	0.50	Segmental precast
64	66.3	5.00	13.4	6.8	0.30	0.50	0.40	Segmental precast

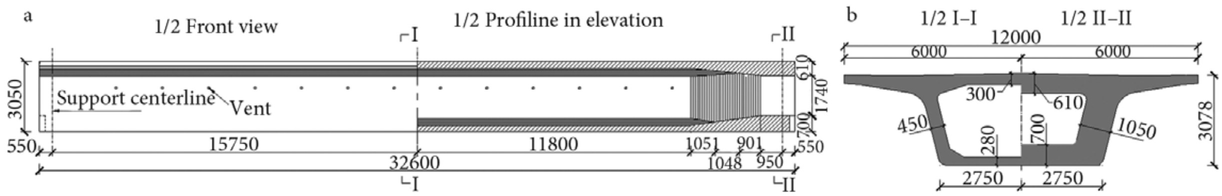


Fig. 2. 32 m standard simple beam, in mm: a – elevation view; b – cross-section

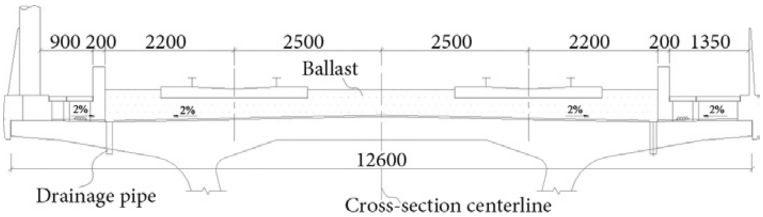
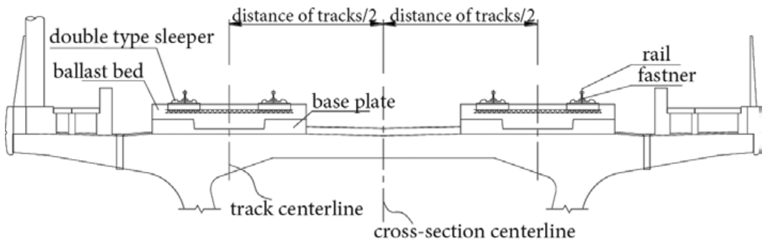
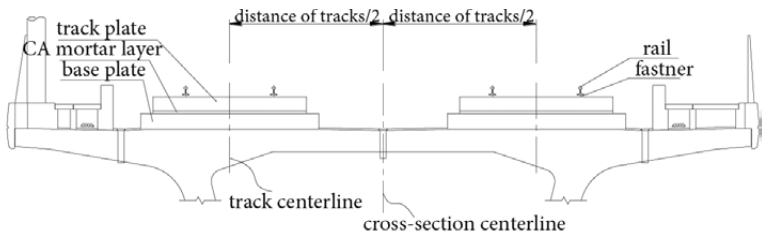
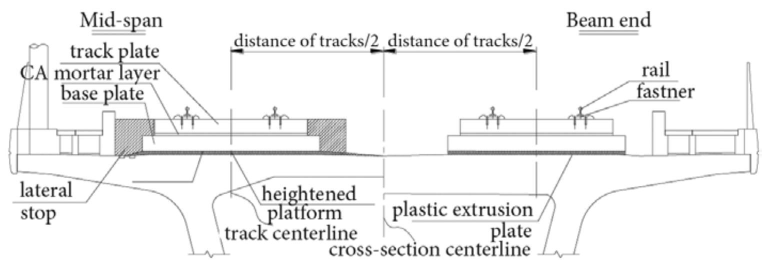
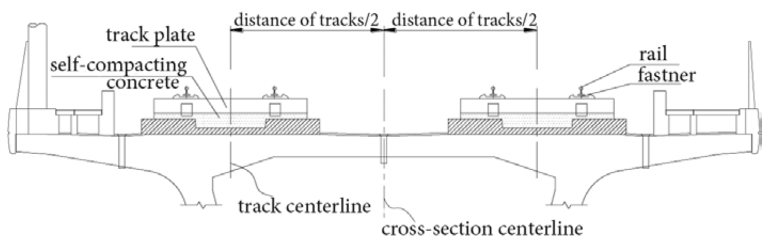
adopted as the main structural type for the HSR bridges in China. As shown in Fig. 2, the circular lines at the turning positions of the box section and inclined web have been used for aesthetics and the streamline effect. As mentioned in the above, such beams account for more than 90% of all HSR bridges in China (Hu *et al.* 2013). The 20 m, 24 m, and 40 m SBBs were used to accommodate the span and geological conditions. Longer SBBs were also used in Chinese HSR bridges, e.g., the Pulandian Bridge (18×56 m) in Harbin-Qiqihar HSR and the Baimahe Bridge (15×64 m) in Wenzhou-Fuzhou HSR. For long-span simple beams, concrete box girders were precast segmentally and then assembled in place (Yang 2014), in which the detailed dimensions are indicated in Table 1.

The width of cross-section was 13.4 m on several 350 km/h pilot lines completed prior to 2008 (e.g., Beijing-Tianjin, Zhengzhou-Xian, and Wuhan-Guangzhou HSRs) and later reduced to 12.0 m (e.g., Shanghai-Hangzhou and Beijing-Shijiazhuang HSRs) by eliminating the maintenance lane on each side of the section (Li *et al.* 2007). This width reduction has since become a policy for all cross-section types in China, resulting in cost savings in on construction materials. In order to utilize the existing construction equipment and formwork, all girder dimensions but the width are kept unchanged.

2.2. Deck system and substructure

Table 2 shows the track structure types for the HSRs in China. The ballastless track bed is normally used for the

Table 2. Track structure types for the HSRs in China

Type and main application	Cross-Section diagram	Technical features
Ballast track bed (Freight-passenger joint lines)		Simple construction; Frequent maintenance
CRTS I double sleeper track (Wuhan-Guangzhou HSR; Lanzhou-Urumqi HSR)		Continuous track bed; Convenient construction; Low mechanization level; Low cost
CRTS I slab track (Shanghai-Ningbo HSR)		Unit structure; Low longitudinal temperature force; Good maintainability
CRTS II slab track (Beijing-Tianjin HSR; Beijing-Shanghai HSR)		Complicated structure; High temperature force; Low Track-bridge interaction; High cost
CRTS III track (Wuhan intercity rail)		Good damping performance for rail; Firm connection of track slab and support layer

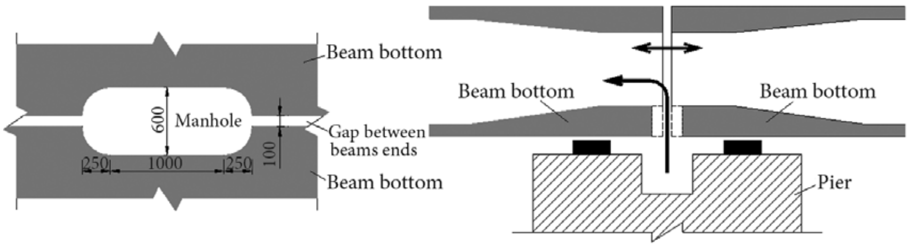


Fig. 3. Manhole in the two adjoining beams at a beam end, in mm

HSRs with a train speed exceeding 300 km/h and sometimes used for joint freight-passenger lines with the average speed of 250 km/h. While the ballast track bed is predominantly used in joint freight-passenger lines. The ballastless HSR track structures in China have been grouped into four China Railway Track Systems (CRTS) (Dai, Su 2016): CRTS I double sleeper track, CRTS I slab track, CRTS II slab track, and CRTS III track. The first three track structures are created based on German or Japan track technology; the fourth one is an independent innovation utilizing the advantages of sleeper track and slab track and is considered as the future main ballastless track type for the HSRs in China.

The deck assembly includes the track structure, waterproof and drainage system (e.g., sealing layer, drainage pipe, and expansion joint), maintenance lanes, cover plate, handrail, noise barrier, retaining wall or bump wall, and overhead line column. The ballast deck typically adopts an open drainage system, while the ballastless deck uses a combined system with open drainage on the edge of top flange and an under-deck closed drainage system to transport the runoff. With the waterproof system, the sewage will flow indirectly on the beam surfaces. For the ballast deck, the distance between the retaining wall's inner face and the railway centre line is 2.2 m for accommodating the large maintenance equipment.

Similar to the SBBs, a standard design for piers and abutments needs to be established also. To ensure that the pier has enough rigidity and considering the suitability and economy of structures, solid piers with round ended cross-section are adopted when the pier height is under 20 m; while hollow piers with rectangular cross-section are suitable for piers taller than 20m (Zhen 2007; Zhu *et al.* 2010). Light-weight piers are not allowed for a HSR in China (*TB 10002.1-2005 Fundamental Code for Design on Railway Bridge and Culvert*; *Code for Design of High Speed Railway).*

Pier caps are eliminated. Instead, a fillister with the depth of 0.5–1.0 m is set up. The maintenance personnels are able to enter the beam easily through the fillister and the manhole located at the bottom floor of the beam. As shown in Fig. 3, a hole is reserved at the beam end and the holes between the two adjoining beams form a manhole with the size of 1500 mm × 600 mm. The position for each of these holes matches with the aforementioned fillister on the pier. Note that the height of manhole inside the end cross beam is more than 1600 mm. When inspecting and maintaining, the workers enter the beam from each pier and walk along the beam without hindrance. More importantly, this design detail does unaffect the arrangement of

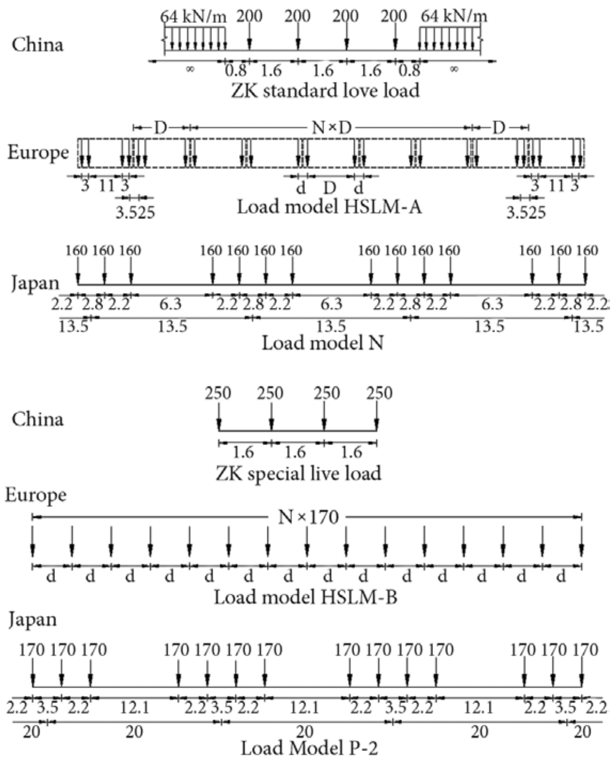


Fig. 4. Main HSR live load models in the world, in kN·m

the prestressing tendons inside the beam, nor weaken the beam strength at the beam end. In addition, the position and space of placing the jacks are reserved for future replacement of the beam supports more conveniently.

2.3. Live load model

As an important design parameter of the bridge, the live load model affects the bearing capacity and construction cost directly. Thus, the design live load model should meet the requirement of transportation capacity and the development of train vehicles (Yang *et al.* 2008). Japan used types "N" and "P" live load models which are very close to the actual load distribution of trains. According to the *Eurocode EN1991-2 Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges*, five railway load models are given to define the rail traffic actions in Europe. Among them, Load model 71 represents normal rail traffic on mainline railways and Load model HSLM represents the loading from passenger trains at speeds exceeding 200 km/h. In China, the so-called "ZK" live load model is adopted for HSRs, which includes a standard live load (= 80% of the Load model 71) and a special live load (Dai *et al.* 2012; Xin *et al.* 2006; *TB 10621-2014*). These live load models are shown in Fig. 4 and have been compared further. Structural performances for the SBBs (20 m, 24 m and 32 m) including reaction forces, bending moments, deflections, and angular rotations at the end of the decks were evaluated and compared under the action of different live load models, as shown in Fig. 5.

As observed from Fig. 5, the load effect of the ZK load is far greater than that of the other two live load models

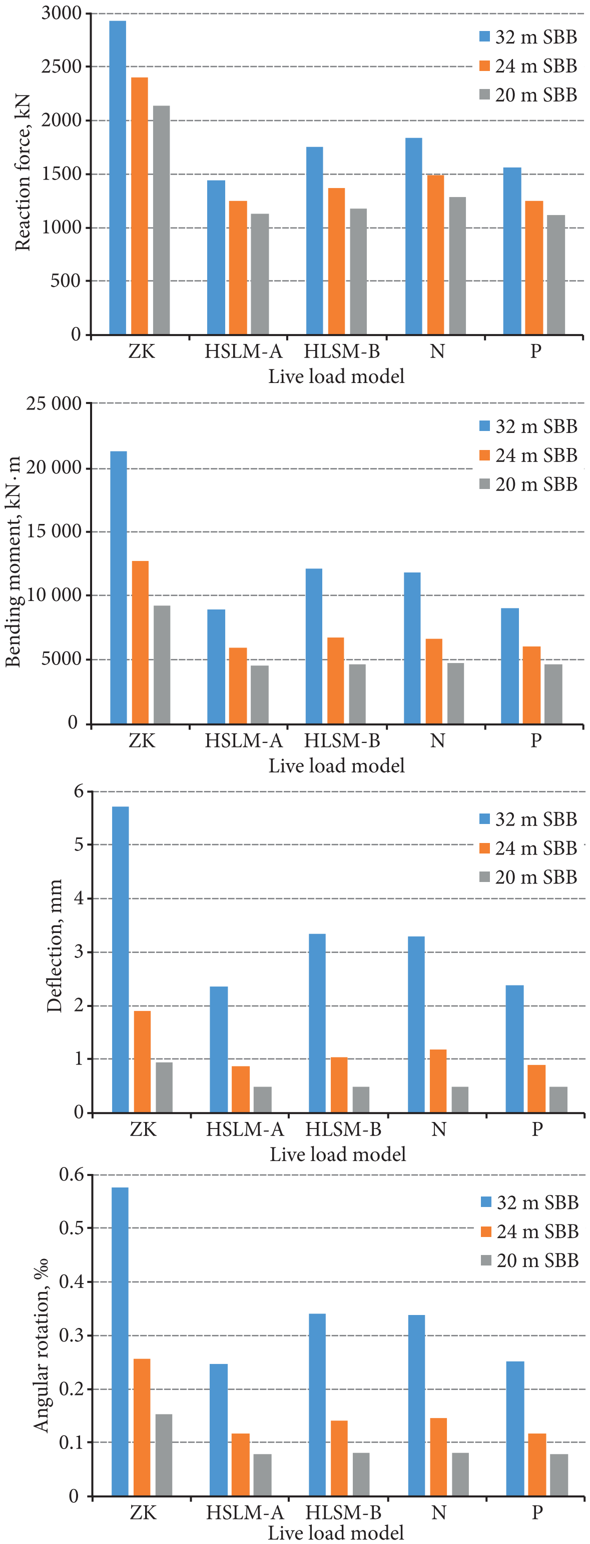


Fig. 5. Performance of SBBs with different live load models

used in Europe and Japan, while the effect of HSLM and Japan load model is relatively close to each. For example, the mid-span deflection caused by the ZK load is 41.5% greater than that by the HSLM-B load and 42.5% greater than that by the "N" type load for the 32 m SBB. In addition, the deflection/span ratios of the SBBs with ZK load are 1/21164 (20 m SBB), 1/12658 (24 m SBB), and 1/5591 (32 m SBB), respectively. It is worth to note that they are far less than the limiting value. Thus, the SBBs possess a relatively large stiffness to withstand larger live loads.

2.4. Deformation limiting values

Strict vertical and transverse deflection limits and enough structural stiffness are all required in the design of a SBB to ensure the track stability and smoothness of a HSR (Tian *et al.* 2015; Xu 2011). Table 3 compares the deformation limiting values between the Chinese HSR code *TB 1062–2014* and the Eurocodes *EN 1991-2*; *EN 1990-Eurocode: Basis of Structural Design – Annex A2: Application for Bridges (Normative)*. It should be noted in Table 3 the Chinese code requires a simple beam with three or more spans to be loaded with two tracks, while the Eurocodes assume a single loaded track condition which induces about 60% of deformations corresponding to the two loaded track condition.

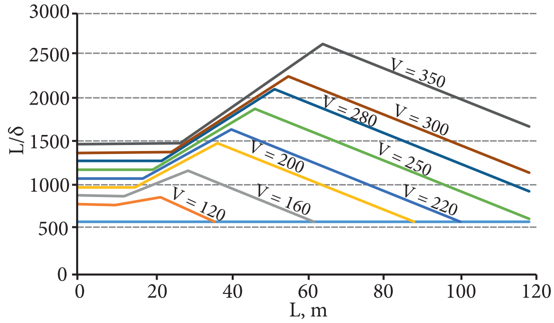
The transverse deflection of the deck should be limited to ensure that the following two requirements are satisfied in either design code. First, the maximum transverse angular variations in the Chinese HSR code and the Eurocodes are 1‰ and 1.5‰ (speed range $V > 200$ km/h), respectively. Second, the radius of horizontal curvature should be less than 14 000 m (single deck bridge) and 17 500 m (multi-deck bridge) as specified in the Eurocodes. While in the Chinese HSR code, this requirement is replaced with that the beam transverse deflection should be less than or equal to *L/4000* (L being the bridge span).

Limitations on the longitudinal displacements at the ends of decks specified in the Eurocodes are given in Table 3. However, there is is unsatisfying requirements in the Chinese code. The maximum twist of a track gauge of 1.435 m measured over a length of 3 m should be less than 1.5 mm. This requirement is the same in both codes. As to the angular rotations at the end of the adjacent decks, they are given directly in the Chinese code. These limiting values should be multiplied by 0.5 at the end of a deck and the adjacent abutment. But in the Eurocodes, the angular rotations are limited by limiting the corresponding vertical displacement, as indicated in Table 3. The two codes apparently adopt different indexes to evaluate the levels of comfort. Sperling ride index was assessed according to the effect of mechanical vibrations in China. While the Passenger comfort depends on the vertical acceleration b_v inside the coach according to the Eurocodes.

3. Construction of simple beam bridges system

Cast-in-place (CIP), mobile erection machine for beams, and precast erection are the main methods for constructing the SBBs. Table 4 shows the comparison of these methods in terms of construction period and economy. The

Table 3. Main deformation limiting values in the Chinese HSR code and the Eurocodes

Contents	Chinese HSR design code			Eurocode	
Vertical deformation of the deck	Speed	L < 40	40 < L < 80		
	250 km/h	< L/1400	< L/1400		
	300 km/h	< L/1500	< L/1600		
	350 km/h	< L/1600	< L/1900		
Transverse deformation of the deck	Maximum beam end angular variation		1.0‰	Maximum angular variation	1.5‰
	Transverse deflection		< L/4000	Minimum radius of curvature	14 000 m (17 500 m)
Longitudinal displacement of the deck	No limits			Relative longitudinal displacement between the end of a deck and the adjacent abutment or between two consecutive decks δ_B (mm)	≤5[a] (≤30[b])
				Longitudinal displacement of the upper surface of the deck at the end of a deck due to deformation of the deck δ_H (mm)	≤8[c] (≤10[d])
Deck twist	1.5 mm / 3 m			1.5 mm / 3 m	
Angular rotations at the end of the decks	Ballast track	≤4.0‰		Vertical displacement of the upper surface of a deck relative to the adjacent construction (abutment or another deck) due to variable actions shall fall behind 2 mm and 3 mm	
	Non ballast track	≤3.0‰ (cantilever beyond support ≤0.55 m) ≤2.0‰ (0.55 m < cantilever beyond support ≤ 0.75 m)			
Comfort criteria	Sperling ride index	<2.5 (very good)		Vertical acceleration	1.0 (very good)
		2.5~2.75 (good)			1.3 (good)
		2.75~3.0 (acceptable)			2.0 (acceptable)

Notes: [a] – it is for continuous welded rails without rail expansion devices or with a rail expansion device at one end of the deck; [b] – it is for rail expansion devices at both ends of the deck where the ballast is continuous at the ends of the deck; [c] – it is adopted when the combined behaviour of structure and track is taken into account; [d] – it is adopted when the combined behaviour of structure and track is neglected.

Table 4. Comparison of construction methods

Contents	Cast-in-place	Mobile erection machine for beam	Precast erection
Construction period	1.5 beams monthly	2 beams monthly	60 beams monthly
Budgetary cost (RMB)	780 000 / beam	870 000 / beam	720 000 / beam
Quality control	Difficult	Difficult	Reliable

bridge is constructed once the substructure has been finished when adopting the CIP construction method. However, this method requires more temporary equipment and construction time. The CIP method is suitable for the places where relative less bridges are required. As to the construction method of mobile erection machine for beams, the two steel girders attached with the formworks are installed on both sides of the pier first, then the concrete is cast on the steel girders according to the design. This method saves the space required to precast and store the beams since the manufacture and erection of beams are finished at the same place. However, its construction period is still too long and poor in terms of the completion of concrete shrinkage or creep. The precast erection construction method is regarded as the most optimal construction method. It ensures the manufacturing quality and improves the construction progress and efficiency due to the industrialized production. Thus, the beams are typically precast in local factories (located at 28–40 km along a rail line) and then are set in the position using erection machines. Only in the place where the bridge connects with a tunnel or the traffic is congested, the first or the second construction method will become an option.

During the storage of beams, if the position of bearings is unlevelled, the tensile stress will appear on the edges of floors at the beam end. Moreover, the reactions at a support are unbalanced as a result of the unevenness of the bearings at beam ends. Thus, this uneven amount should be kept under 3 mm according to the related studies. Otherwise, cracks will result from the expected large beam end rotation. The position of bearings during the erection should also be levelled and more strictly the thickness difference between the two adjacent bearings at a beam end must be less than 2 mm.

For the long-span SBBs, segmental fabrication and field erection are very common. Taking the 56 m SBB as an example, it has been divided into 11 segments and precast in factory and then transported to the mobile falsework.

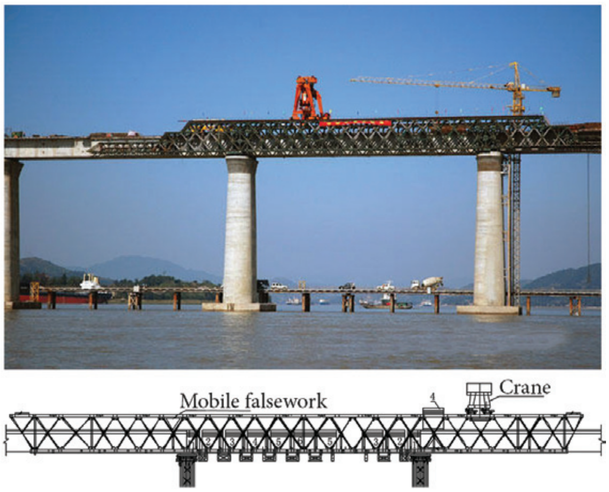


Fig. 6. Typical construction method for long-span SBBs

These segments are lifted to the design position by a crane and connected together by pouring concrete between them, as shown in Fig. 6.

4. Verification test

A static load test was performed to examine the structural design and construction quality and to test the beam's strength of beams and crack resistance. The static bending test results for a typical 32 m SBB are presented and discussed in this section. Generally, three cyclic loads equalling to the design load, 1.55 times the design load (cracking load), and 2.0 times the design load were applied and ten equivalent loading points with the same load magnitude along the web centre lines were considered in the test.

Under the design load, the deflection at the mid-span of the beam is 6.54 mm, resulting in the deflection to span ratio of 1/4817 which is under the permitted maximum limit of 1/1600. During the second cyclic loading process, when the load grade K_f (= application load/design load) increases to 1.2, the beam is still in the elastic state; when K_f is equal to 1.45, the strain of the beam bottom plate at the mid-span increases obviously; and visible cracks appear when K_f increases to 1.55. The corresponding cracking load of the beam, P, is 1722.8 kN (K_f = 1.422), which is 2.3% larger than the design value. During the third cyclic loading process, the beam cracks again when P reaches 1246 kN (K_f = 1.11). Fig. 7 shows the well-distributed cracking pattern when the beam is loaded to 2.0 times the design load. However, the beam concrete is uncrushed and the prestressed strands are unbroekn either. The beam is harmless as the cracks will be closed after the unloading. In summary, the test results show that the structure has enough safety margin and satisfies the HSR operation requirements.

The limiting natural frequency of bridge is used to avoid the possible resonance phenomenon between the bridge and a high-speed train. It is affected by the structure

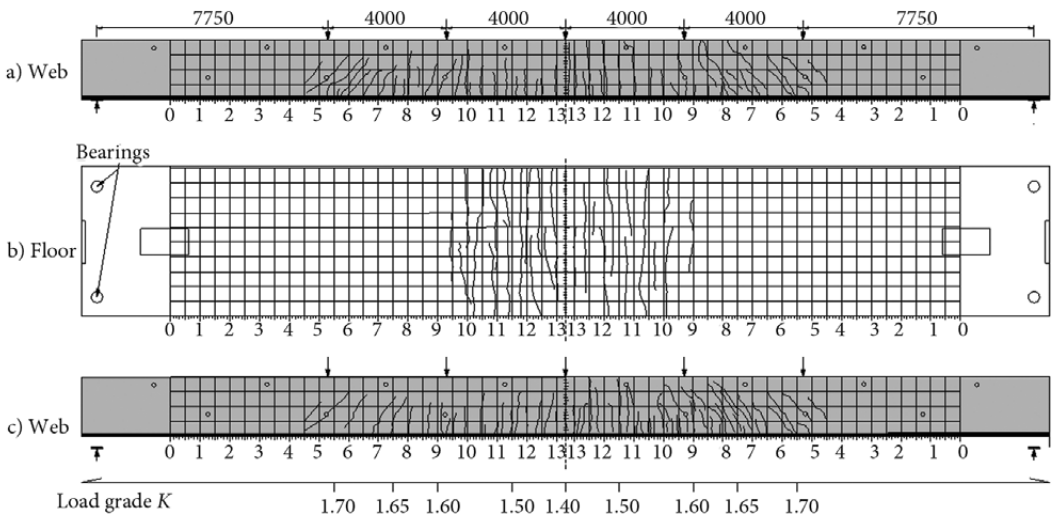


Fig. 7. Experimentally observed cracking patterns from the static load test for 32 m standard beam

stiffness, span, and the mass distribution. Among the limiting design values, the natural frequency is the controlling design index for the standard simple beams. But, the actual frequency obtained from a test differs from the design value (Dong *et al.* 2008; Liu *et al.* 2013). Figure 8 shows that the test natural frequency of 32 m SBB is above 6 Hz and is 17–34% larger than the design value (4.67 Hz). This is mainly caused by the higher elastic modulus of concrete as is in the actual condition (Cai *et al.* 2015). The design elastic modulus of concrete is 3.55×10^3 N/mm^2, but the tested value in Beijing-Shanghai HSR is 4.75×10^3 N/mm^2 (increased 33.5% compared with the design value). Another reason is that the combined behaviour of bridge and track is skipped when calculating the natural frequency of SBB during the design process.

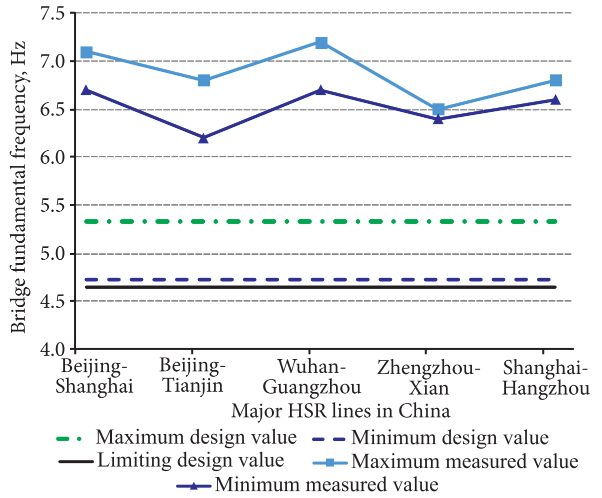


Fig. 8. Test and design natural frequencies of 32 m SBB

5. Conclusions

1. In order to accommodate the rapid high-speed rail construction and control the engineering quality in China, standard simply-supported (simple beam) bridges are hence commonly adopted in the HSR infrastructure system. This paper describes and discusses the latest experiences on the design and construction techniques for the simple beam bridges used in the high-speed rails in China. A series of concrete box girders with standard spans including 20 m, 24 m, 32 m, and 40 m are used to construct the simple beam bridges system. Though a number of studies, the 32 m simple beam is considered most common and feasible except the special or unusual circumstances.

2. With the improvement in construction technique and equipment, longer spans of 56 m or 64 m simple beam bridges are adopted to meet the geographical and environmental requirements.

3. Compared with European countries and Japan, the load effect induced from the ZK live load model included in the Chinese high-speed rail code is apparently more significant. Relevant study and research show that the simple beam bridges have enough vertical stiffness and acceptable dynamic response. It is hopeful that this paper provides insights and references to other countries for future high-speed rail construction utilizing the simple beam bridges.

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