

# Research on expansion joint for high-speed railway long-span bridges in China

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## Abstract

**Purpose** – The bridge expansion joint (BEJ) is a key device for accommodating spatial displacement at the beam end, and for providing vertical support for running trains passing over the gap between the main bridge and the approach bridge. For long-span railway bridges, it must also be coordinated with rail expansion joint (REJ), which is necessary to accommodate the expansion and contraction of, and reducing longitudinal stress in, the rails. The main aim of this study is to present analysis of recent developments in the research and application of BEJs in high-speed railway (HSR) long-span bridges in China, and to propose a performance-based integral design method for BEJs used with REJs, from both theoretical and engineering perspectives.

**Design/methodology/approach** – The study first presents a summary on the application and maintenance of BEJs in HSR long-span bridges in China representing an overview of their state of development. Results of a survey of typical BEJ faults were analyzed, and field testing was conducted on a railway cable-stayed bridge in order to obtain information on the major mechanical characteristics of its BEJ under train load. Based on the above, a performance-based integral design method for BEJs with maximum expansion range 1600 mm ( $\pm 800$  mm), was proposed, covering all stages from overall conceptual design to consideration of detailed structural design issues. The performance of the novel BEJ design thus derived was then verified via theoretical analysis under different scenarios, full-scale model testing, and field testing and commissioning.

**Findings** – Two major types of BEJs, deck-type and through-type, are used in HSR long-span bridges in China. Typical BEJ faults were found to mainly include skewness of steel sleepers at the bridge gap, abnormally large longitudinal frictional resistance, and flexural deformation of the scissor mechanisms. These faults influence BEJ functioning, and thus adversely affect track quality and train running performance at the beam end. Due to their simple and integral structure, deck-type BEJs with expansion range 1200 mm ( $\pm 600$  mm) or less have been favored as a solution offering improved operational conditions, and have emerged as a standard design. However, when the expansion range exceeds the above-mentioned value, special design work becomes necessary. Therefore, based on engineering practice, a performance-based integral design method for BEJs used with REJs was proposed, taking into account four major categories of performance requirements, i.e., mechanical characteristics, train running quality, durability and insulation performance. Overall BEJ design must mainly consider component strength and the overall stiffness of BEJ; the latter factor in particular has a decisive influence on train running performance at the beam end. Detailed BEJ structural design must stress minimization of the frictional resistance of its sliding surface. The static and dynamic performance of the newly-designed BEJ with expansion range 1600 mm have been confirmed to be satisfactory, via numerical simulation, full-scale model testing, and field testing and commissioning.

**Originality/value** – This research provides a broad overview of the status of BEJs with large expansion range in HSR long-span bridges in China, along with novel insights into their design.

**Keywords** High-speed railway (HSR), Long-span bridge, Bridge expansion joint (BEJ), Integral design, Rail expansion joint (REJ), Overall stiffness, Longitudinal frictional resistance

**Paper type** Research paper

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## 1. Introduction

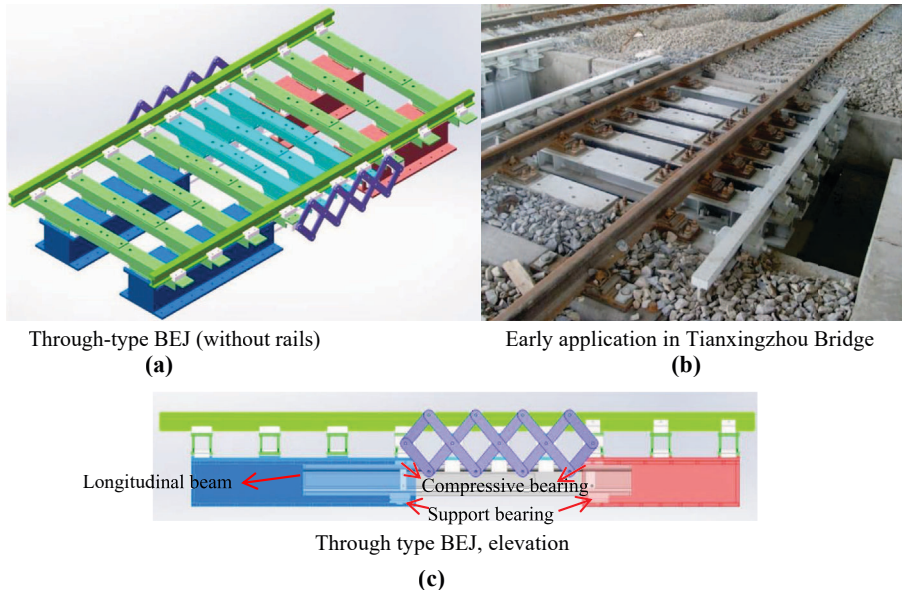
The bridge expansion joints (BEJs), a key device installed at bridge beam ends in order to accommodate movement due to factors including temperature effects, traffic loads and wind loads (Guo, Liu, Zhang, & Pan, 2014), typically features a complex structure and multiple components (Song, Lin, Xu, & Tan, 2020). In contrast with the BEJs used in road bridges (Robert, Carl, & Mark, 2001), those used in high-speed railway (HSR) long-span bridges face more critical requirements due to the demands imposed by track geometry and train running safety needs (Guo, Jiang, Gao, & Liu, 2020). Over the 15 or so years since the advent of the “golden age of development” of HSR long-span bridges in China in 2009 (He *et al.*, 2017), research on the mechanical behavior, design and maintenance of BEJs and their application has become a hot topic. Experience with the maintenance of BEJs in HSR long-span bridges in recent years has led to their status attracting much more attention than other devices, such as bearings, dampers, etc. Variation in vertical stiffness at the beam end leads to clearly higher track quality indexes (TQI) there relative to other bridge regions, necessitating frequent maintenance work in the beam end region. Furthermore, rapid temperature changes and excessive longitudinal resistance at the BEJ may cause large longitudinal stresses in the rails near the beam end, even to the extent of cracking adjacent concrete sleepers or causing instability in the connecting steel plate on sleeper ends, and limiting train speeds until laborious repair work can be performed. In short, due to the complexity of the beam end environment, the maintenance of BEJs in HSR long-span bridges in proper working condition has been found to present major challenges.

### 1.1 Overview of design research on BEJs for HSR long-span bridge

The complexity of problems related to BEJs has motivated both Chinese and international scholars to undertake significant research on these devices. Outside China, aspects of BEJs including their mechanical properties, dynamic performance under running vehicles, application of new functional materials, etc. have been subject to research which has provided measures and insights contributing to improvements in their design. McCarthy, Wright, Padgett, DesRoches, and Bradford (2014) presented an analytical model of a common modular BEJ, including critical components such as friction elements, equidistant devices, support bars and center beams, validated via full-scale experimental testing. This can serve as a predictive model for the longitudinal motion of such bridge joints. Robert, Mark, and Carl (2002) presented the development of performance requirements for modular bridge joint systems, along with test methods and test equipment for their prequalification and acceptance ensuring that systems comply with these requirements, also identifying critical issues relating to ensuring that these requirements guarantee suitable service, pertaining to life design, fabrication, installation and construction inspection. Steenbergen (2004) presented a theoretical study of the dynamic behavior of expansion lamella joints in bridge decks under traffic loading, showing that the dynamic amplification factor (DAF) could exceed 2.0, far higher than commonly assumed design values. Coelho, Vervuurt, Peelen, and Leendertz (2013) performed different rolling tests using a three-axle vehicle on modular expansion joint installed at the Martinus Nijhoff Bridge. These revealed that the status of sliding bearings had clear effects on the dynamic behavior of the modular expansion joint, with the DAF ranging from 1.4 to 6, a level likely to cause premature fatigue failure. Ancich, Chirgwin, and Brown (2006) presented results of experimental modal analysis on a hybrid modular expansion joint installed in the Anzac Bridge. Here a DAF of up to 4.6 was estimated for fully laden test vehicles, with coupled center beam resonance forming the basis of this dynamic behavior. Padgett and DesRoches (2013) stressed the importance of seismic performance criteria for BEJs during long-term service, advocating for the application of shape memory alloy with re-centering ability. Although the research above mainly concerned the design of BEJs for highway bridges, important guidance can be drawn from it, in areas including detailed analysis of BEJs and their dynamic properties, and fatigue performance testing.

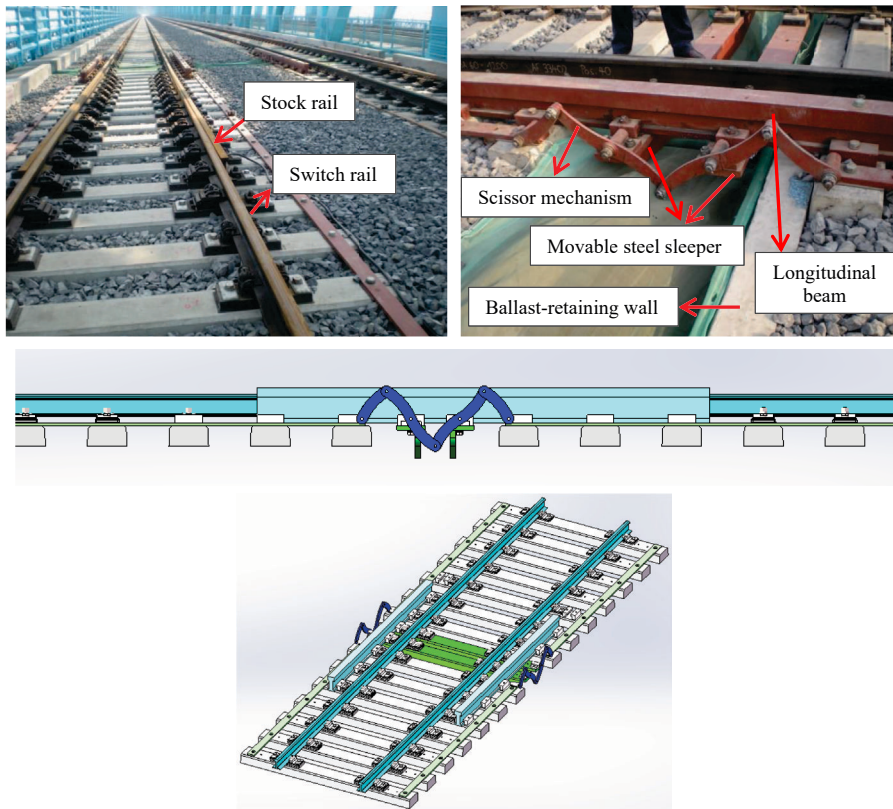
In the engineering application of railway bridge BEJs used with REJs during construction of Honshu–Shikoku bridge project in 1970s, Japanese researchers proposed an innovative class of expansion joint, namely the through-type expansion joint, and conducted numerous large-scale model tests considering various rotational angles in order to evaluate their performance (Masuura, 2008). The results of this research, which were then applied in several suspension bridges and cable-stayed bridges, including the Minami Bisan-Seto Bridge, provide an important reference for BEJs with large expansion range up to 1,500 mm. In Germany, transition plates across HSR bridge joints are commonly used in arch bridges (Zhang, 2016). These are composed of transitional plate girders, bearings, guide rods, etc. REJs with movable stock rails designed integral to deck-type BEJs for long-span bridges, were also developed in Germany. Modular deck-type expansion joints provide long extension lengths, generally ranging from 600 to 1,200 mm (Jungwirth & Scholz, 2012). The various types of BEJs for long-span railway bridges have their own respective characteristics, and train speeds must be also considered during design.

Zhuang (2008) presented the “TSSF type” through-type BEJ, designed for Wuhan Tianxingzhou Yangtze River Bridge with an expansion range of 1,000 mm ( $\pm 500$  mm). Shown in Figure 1, its main components include a longitudinal beam, movable steel sleeper, box for movement of the longitudinal beam, compressive bearing, support bearing and scissor mechanism. The longitudinal beam transfers the dynamic train load to the support bearing, while the compressive bearing exerts a degree of pre-compressive force in order to prevent the support bearing jumping under dynamic loading. The function of scissor mechanisms is to ensure even spacing between the movable steel sleepers during expansion and contraction. One side of the longitudinal beam is fixed, with the other sliding freely in the box, permitting movement. This device was adopted in the bridge, which opened to traffic in 2009 with a maximum train speed of 250 km/h, in coordination with symmetrical REJs of an old type with two stock rails at both ends. However, the two types of device were unable to fully satisfy the strict requirements of collaborative operation, and, after over ten years, some faults developed. Due to the importance of BEJs integrated with REJs, continuous research on these devices been conducted at the Nanjing Dashengguan Yangtze River Bridge (shown in Figure 2),



Source(s): Drawing: Ying Pan

Figure 1. Through-type BEJ and early application in Tianxingzhou bridge



Source(s): Drawing: Ying Pan

Figure 2. Deck-type BEJ and application in Dashengguan bridge

Tongling Yangtze River Bridge, Husutong Yangtze River Bridge, Wufengshan Yangtze River Bridge and Wuhu Third Yangtze River Bridge, etc. (Zang, Zhuang, Zhang, & Gao, 2012; Jungwirth & Scholz, 2012; Gao, Zang, & Xiong, 2015; Zhang, 2020; Guo *et al.*, 2020; Su, 2022; Yang, Gao, Meng, & Ke, 2021; Wang, 2024). This research mainly covered integrated BEJ–REJ design, the dynamic performance of train-track-bridge-expansion joints, beam end rail irregularity, evaluation criteria, etc. After intensive design research and application, China State Railway Group Co. Ltd (2021) issued a product standard for deck-type BEJs with expansion range less than or equal to 1,200 mm ( $\pm 600$ mm) for use on China Railway. This novel standard set a new trend for BEJs in China’s HSR long-span bridges, and has proven satisfactory during testing, commissioning and operation.

### 1.2 Displacement characteristics at the beam end

Many studies related to BEJs covering areas other than design and performance validation have been conducted. Quan, Wang, and Chen (2010) studied the influence of the lateral expansion of steel truss girder beam-ends on track geometry. Results indicated that variation in track geometry was mainly dependent on the distance between the steel truss girders’ lateral fixed bearing and the rail central line (i.e. temperature span in transverse direction of the beam), and that maximum lateral rail displacement of less than 2 mm, and a rate of change of

track alignment of less than 1‰, could be achieved if this distance could be controlled to within 6.7 m. These findings revealed the significance of constraint system design in providing good conditions for BEJs. [Wei \(2013\)](#) pointed out that, at a train speed of 300 km/h, the rate of wheel load reduction was positively related to the vertical rotation angle at the beam end. Faults in vertical elevation or transverse displacement at the beam end cause geometrical irregularities. [Li, Xiang, Wan, and Ren \(2012\)](#) noted that the expansion joint had important effect on train running performance. Compared to expansion joint deflection or installation error, the influence of the vertical rotation angle at the beam end on vehicle responses was more marked. [Guo, Su, Zhao, Liu, and Le \(2019\)](#) analyzed the displacement characteristics at the beam end of an HSR suspension bridge under the influence of a combination of factors, including uneven settlement of the foundation, temperature and train live load. Results showed that the maximum vertical rotation angle was 1.96‰ rad (less than 2‰ rad), and the maximum transverse bending angle was 1.9‰ rad under temperature load. With a maximum elastic deformation of 5 mm of the lateral wind-resistant bearing at the beam end, and with the auxiliary pier allowed decrease of the transverse bending angle under wind loads. [David, Roberto, Marina, Nerea, and Stanislav \(2021\)](#) pointed out that, based on experimental studies, at least 30% of the maximum allowed expansion range of existing REJs was not being utilized, and thus longer railway bridges could be developed using existing REJs with the current maximum range of 1,200 mm. [Liu et al. \(2021\)](#) suggested that proper modes for the combination of design loads and relevant coefficients should be considered, since the typical actual beam end expansion range was much less than the design value. [Wan and Li \(2020\)](#) performed calculations of the longitudinal displacement of a railway suspension bridge showing that vertical loading could cause clear longitudinal displacement at the beam end, with a speed of movement of up to 69.3 mm/s under ZKH load for mixed passenger and freight railway with train velocity 200 km/h. The installation of viscous dampers with a low damping exponent (less than 0.2) as a longitudinal support was proposed, in order to decrease this movement speed and enhance BEJ durability.

### 1.3 Bridge-track interaction with BEJs and REJs

Although track–bridge interaction has long been a topic of study, this interaction on HSR long-span bridges has not yet been fully elucidated. Due to the existence of BEJs and REJs at the beam end, the various fastener types on the main bridge, and the displacement or deformation of the bridge, for long-span bridges, this interaction is very complex. [Liu \(2014\)](#) investigated various REJ layout schemes for a long-span steel truss arch bridge with a temperature span of over 340 m, estimating that REJs set at both ends could improve the mechanical status of the track on the bridge, relieving track stresses, including expansion, bending and braking forces, at both ends. [Cai et al. \(2020\)](#) proposed an optimized REJ layout for cable-stayed railway bridges featuring unidirectional REJs at both bridge ends, with the REJ switch rail on the main beam, the stock rail on the approach bridge crossing over the beam expansion joint, and small resistance fasteners laid along the side of stock rail in order to reduce the longitudinal force on the fixed pier near the main beam. [Yan, Gan, Zhang, and Zeng \(2021\)](#) pointed out that, for kilometer-scale railway suspension bridge, bending forces become dominant compared to expansion forces, creating rapid longitudinal relative displacement of 9.7 mm at both ends of the loading region of a moving train, posing a risk to the stability of the ballasted track. [Cai, Liu, Gao, Su, and Yang \(2023\)](#) suggested paying increased attention to rail longitudinal forces on the main span caused by bending loads, also pointing out that relative displacement between the REJ stock rail and the main beam can cause poor stability of the track bed and fasteners, unless minimal longitudinal resistance can be guaranteed, ensuring that the stock rail can slide smoothly on the sleepers. The research findings above have deepened the understanding of bridge–track interaction on HSR long-span bridges, and the importance of BEJ–REJ coordination at the beam end.

#### 1.4 Survey of measurement or monitoring results for BEJs and REJs

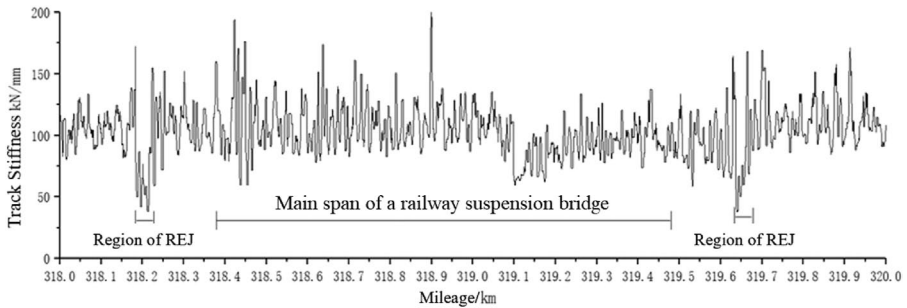
Measurement or monitoring results for BEJs or REJs in HSR long-span bridges can yield important information concerning their performance, serving as references for maintenance during their operation. The dynamic responses of BEJs have been measured during pre-opening testing and commissioning of some HSR lines in China, and additional specialized testing, covering factors such as track stiffness and ballasted bed condition, has also been carried out recently on HSR long-span bridges. Furthermore, long-term health monitoring systems have been installed on some long-span railway bridges, allowing continuous collection of data on their beam end displacement characteristics. Meng, Yao, Liu, and Wang (2015) tested the dynamic responses of vehicle, track and bridge on site during the passage of comprehensive inspection trains over Dashengguan Yangtze River Bridge. The test data revealed that axle box acceleration peaked as high as  $1,174.3 \text{ m/s}^2$  in the northern REJ region, slightly higher than the  $1,102.5 \text{ m/s}^2$  peak recorded in the southern region. In the REJ regions, measured vertical force on the rails exceeded that on the ballasted track on the main bridge; this was also the case for rate of wheel load reduction, vertical rail track displacement and vibration acceleration, all of which ranged from 20 to 80% higher. The vertical acceleration of the bridge in the middle of beam end was  $0.22\text{--}0.25 \text{ m/s}^2$ , higher than in other positions, reflecting excitation by the running train combined with the stiffness change of the bridge-track-BEJ system at the beam end. However, the vibration of the bridge attenuated quickly after the train departed the beam end, a finding shared with many other instances of HSR testing and commissioning. In their investigations of a steel truss rail-cum-road cable-stayed bridge, Wang and Ding (2019) identified large transverse temperature gradients between the bottom truss members in two side trusses, which they determined to possess a dominant influence on the horizontal rotation angle (HRA). The quasi-static component of the measured HRA caused by the temperature field was the dominant component, with a maximum value was  $0.19\text{‰}$  rad, accounting for 87.15% of the total measured HRA, far greater than the dynamic components.

Various measures designed to monitor stiffness change in HSR long-span bridges have been adopted. Xiao *et al.* (2021) proposed mobile track stiffness detection via track loading vehicles on railway suspension bridges. Figure 3 shows a track loading vehicle in China. Figure 4 shows the bridge track stiffness measurements, which indicate areas of significantly reduced (around  $50 \text{ kN/mm}$ ) track stiffness in the REJ/BEJ region, less than half of the  $110 \text{ kN/mm}$  average on the main span.



Source(s): Authors' own work

Figure 3. Chinese track loading vehicle



Source(s): Authors' own work

Figure 4. Track stiffness of railway suspension bridge

Xu *et al.* (2023) proposed the ballast dynamic stiffness (BDS) method for detecting the support condition of ballast beds under sleepers, which has the advantage of being fast and non-destructive, and applied this for ballast dynamic modulus (BDM) inspection of an HSR railway cable-stayed bridge, including its REJ and BEJ regions, alongside a whole-bridge ballast bed thickness estimation method. The latter employed an intelligent radar inspection car for data collection and processing using convolutional neural networks (CNNs). Using these methods, measurements of ballast conditions on the bridge under test during the heat of summer and cold of winter were obtained. These results revealed lower average BDM values of  $0.14 \text{ N/mm}^3$  in the summer and  $0.16 \text{ N/mm}^3$  in winter at both REJ ends, compared to values of  $0.253$  and  $0.224 \text{ N/mm}^3$  at the bridge mid-span in summer and winter, respectively. This was indicative of better track vertical support conditions in the mid span in comparison with the REJ regions.

Tan, Lin, and Mei (2021) combined analysis of monitoring data, test data and daily maintenance data in their examination of change rules for the REJs of the Tongling Yangtze River Bridge, with a bridge temperature span of 649 m, on the Hefei–Fuzhou HSR. In total, this bridge features four unidirectional REJs with deck-type BEJs laid at both ends under two railway lines. Results revealed expansion-displacement of rails of 447.4 mm ( $\pm 223.7$  mm) over one year. The displacement of the stock rail itself due to temperature change was  $\pm 38.4$  mm, along with  $\pm 185.3$  mm displacement of the main beam end. With rail temperature varying between  $-5.7$  and  $43.8$  °C over one year, estimated rail expansion on the long-span bridge of roughly 130 m was expected, making the rails a key area of day-to-day maintenance, along with the beam end BEJs and REJs. Since stock rail expansion was restricted to a large extent by longitudinal resistance offered by the ballast bed, optimal ballasted track tamping intervals of once a month in autumn and winter, and twice a month in spring and summer, were determined, based on rail expansion statistics of 62.0, 87.0, 82.5 and 59.3 mm for the four quarters, respectively. Chen, Liu, Zhou, Liu, and Fu (2021) estimated a temperature-displacement model using a least squares support vector machine (LSSVM) for a rail-cum-road cable-stayed bridge with main span 630 m, with the aim of predicting damage to its expansion joints. Based on health monitoring data for 2017 and 2018, expansion joint displacement was positively correlated with effective temperature, and a threshold for detecting damage in these joints was established based on statistical analysis of the residuals, which were approximately normally distributed. This was shown to be effective in indicating expansion joint faults.

## 2. Investigation into BEJs in HSR long-span bridges and lessons from practice

This section summarizes detailed investigation into BEJs in HSR long-span bridges in China. First, the typical faults affecting BEJs and REJs were collected, and related causal factors analyzed, based on maintenance experience and mechanical inference. This systematic work

provided a conceptual basis for optimization BEJ design. Testing on BEJs was then conducted on several bridges in order to explore their mechanical behavior, and lessons derived from these results along with practical experience of BEJs in application.

### 2.1 Fault collection and analysis for BEJs and REJs on HSR long-span bridges

In order to obtain a detailed understanding of the operational status of BEJs and REJs on HSR long-span bridges, investigations were conducted on several representative in-service bridges. Typical faults were summarized and categorized for the two types of BEJs, through-type and deck-type, as shown in [Tables 1 and 2](#). Some faults common to these two types of BEJs included uneven spacing and skew of movable steel sleepers (MSS), obvious track irregularity near the REJ and relatively rapid degradation of the REJ. Other faults, which differed in terms of performance degradation, mainly related to the scissor mechanisms or fasteners. Major causal factors for faults included rail resistance changes between different contact surfaces, and unevenness or abrupt changes in vertical stiffness.





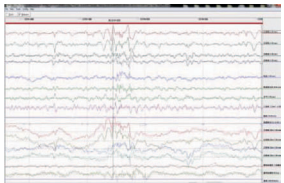
### 2.2 Testing of long-span railway bridge BEJs used with REJs under operational conditions

A series of field tests was carried out on BEJs used with REJs to investigate the performance of their key components and overall mechanical behavior. A long-span steel truss cable-stayed railway bridge was selected, with main span of 580 m and design expansion range of 1,200 mm. This bridge design adopted a semi-floating restrictive system, i.e. longitudinally-fixed bearings arranged at the 4th pylon, with six displacement-restrictive viscous dampers installed at the 3rd pylon, as shown in [Figure 5 \(a\)](#), and longitudinally-mobile bearings on the side piers and auxiliary piers providing vertical support. BEJs with two movable steel sleepers were installed at the girder gap to reduce longitudinal stress in the rails, as shown in [Figure 5 \(b\)](#), REJs with 1,200 mm design expansion range, were also installed on each railway line.

During the field testing, stresses in steel components such as longitudinal beams, movable steel sleepers and scissor mechanisms were measured under a test train running at various speeds, with results as shown in [Figure 5 \(c\)](#). Beam end longitudinal displacement was also recorded by using displacement gauges, with six gauges installed to measure the displacement of movable steel sleepers and at the beam end adjacent to the main bridge and approach bridge. Meanwhile, the derailment coefficient, rate of wheel load reduction, and wheelset lateral force were also measured using ground inspection units, as shown in [Figure 5 \(d\)](#).


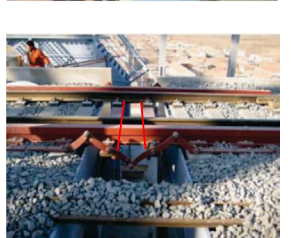
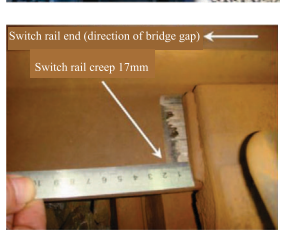
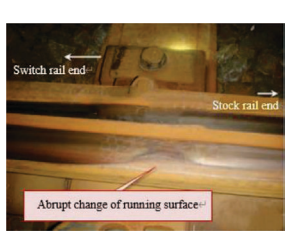
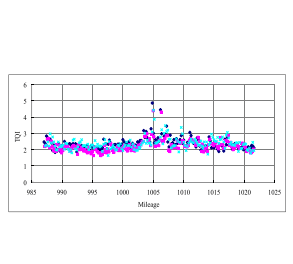
Results for the stresses measured in various BEJ components under the comprehensive inspection train, at measurement points shown in [Figure 6 \(a\) and \(b\)](#) are given in [Table 3](#). Some conclusions can be drawn from these. *First*, the stress levels in longitudinal beams, movable steel sleepers and scissor mechanisms under the vertical train loads at various running speeds were generally low, demonstrating that structural strength was not a decisive factor. *Second*, the stresses in the longitudinal beams were slightly higher than those in the movable steel sleepers and scissor mechanisms, and different stresses were recorded in the mid-spans of two adjacent longitudinal beams. Stress at measurement point No. 1 was higher by a factor of 1.2–1.6 than that at No. 2. *Third*, the stresses in the two scissor mechanisms shown in [Figure 5\(c\)](#) were compressive, unlike those in the longitudinal beams and movable steel sleepers, and the stress at measurement point No. 1 was about three times higher than at measurement point No. 2, for train speeds in the 120–160 km/h range. *Fourth*, the stress at mid-span in the movable steel sleepers was higher than at the transitional cross section, as shown in [Table 3](#). Stress ratios of 1.32 and 1.40 were recorded, respectively, for the same movable steel sleeper on the approach bridge side and the main bridge side. *Fifth*, through comparison of the values under high speed with quasi-static values for a train speed of 5 km/h, clear dynamic effects on the BEJs at the beam end are apparent. For longitudinal beams and movable steel sleepers, the dynamic amplification factor (DAF) was 1.81–2.31 and 1.68–2.37, but further increase were not observed for train speeds from 120 to 160 km/h. A relatively conservative DAF value of 2.5 could be chosen for these components during design of a BEJ for train running speeds in this range. The DAF value for

**Table 1.** Typical faults of through-type BEJs and associated REJs

Fault image	Fault description	Major probable cause
	<p>Scissor mechanisms' crack or fracture, resulted in malfunction in their control of steel sleeper movement.</p>	<ol style="list-style-type: none"> <li>1. Improper design of Scissor mechanisms' joint at bolted connection with steel sleeper, including weakened cross section or unsuitable shape.</li> <li>2. Positioning of Scissor mechanisms beneath sleepers, making access and maintenance difficult.</li> <li>3. Unreasonable design of elastic bar fastening systems, creating uneven or large resistance during expansion and contraction.</li> </ol>
	<p>Uneven spacing and skew of movable steel sleepers, a phenomenon common to most BEJs.</p>	<ol style="list-style-type: none"> <li>1. Large, uneven resistance between fasteners and sleepers after long-term operation, due to performance degradation of elastic bar fastening systems.</li> <li>2. Uneven resistance of ballast bed on main bridge and on approach bridge near bridge beam end.</li> <li>3. Lack of consideration of design integration of BEJ and REJ.</li> </ol>
	<p>Failure of elastic bar fasteners used on rail track at the bridge beam end, reducing resistance on rails.</p>	<ol style="list-style-type: none"> <li>1. Improper selection of elastic bar fasteners.</li> <li>2. Fatigue cracking caused by stress concentration under high frequency train vibration, or abnormal track system vibration due to serious rail corrugation.</li> </ol>
	<ol style="list-style-type: none"> <li>1. Detachment of welding seam at junction of expansion box with bridge deck; rust along welding seam.</li> <li>2. Deviation between central line of BEJ and track central line.</li> </ol>	<ol style="list-style-type: none"> <li>1. Substandard onsite welding of expansion box to bridge deck.</li> <li>2. Failure to strictly monitor and guarantee BEJ construction quality.</li> </ol>
	<p>Obvious track irregularity near REJ; relatively rapid degradation of REJ.</p>	<ol style="list-style-type: none"> <li>1. Uneven fastener and ballast bed resistance; stiffness change under track during the dynamic expansion of rails.</li> <li>2. Difficulty maintaining long-term stability of track for symmetrical REJs.</li> <li>3. Incorrect fastener installation.</li> <li>4. Bad curve section at REJ location.</li> <li>5. Lack of proper guidance on REJ maintenance.</li> </ol>

**Source(s):** Authors' own work

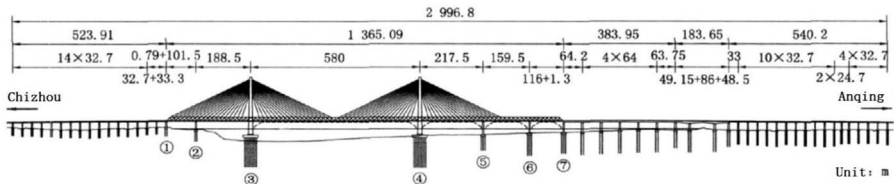
**Table 2.** Typical faults of deck-type BEJs and related REJs

Fault image	Fault description	Major probably cause
	<p>Flexural deformation of Scissor mechanisms causing increase in scissor resistance and non-uniform spacing of steel sleepers during expansion.</p>	<ol style="list-style-type: none"> <li>1. Insufficient lateral stiffness of Scissor mechanisms, resulting in deformation due to displacement &amp;/ deformation of main girder under temperature effects and wind loading.</li> <li>2. Mismatched ballast bed and fastener resistance on left and right sides of rails, causing torsional deformation of BEJ.</li> </ol>
	<ol style="list-style-type: none"> <li>1. Unevenly spaced and skewed movable steel sleepers.</li> <li>2. Escape of fastener system rubber pads.</li> </ol>	<ol style="list-style-type: none"> <li>1. Uneven resistance of ballast bed on main bridge and approach bridge near bridge beam end.</li> <li>2. Uneven resistance of REJ and BEJ fasteners.</li> <li>3. Reduced fastener pressure due to repeated expansion and contraction, permitting escape of rubber pads.</li> </ol>
	<p>Large accumulative creep in switch rail (which should theoretically be fixed for unidirectional REJs)</p>	<ol style="list-style-type: none"> <li>1. Occurs under influence of long rail welded at end of approach bridge switch rail, due to rail temperature variation and insufficient fastener pressure undetected during regular checks.</li> </ol>
	<p>Abnormal running surface on track above stock rail and switch rail.</p>	<ol style="list-style-type: none"> <li>1. Abrupt change of rail top running surface during dynamic expansion of stock rail, due to stock rail top surface elevation slightly in excess of that of switch rail.</li> <li>2. Inconsistent left and right switch rail top surface elevation on REJ altering point of contact between train wheels and track.</li> <li>3. Equipment defects occurring during fabrication and transportation.</li> </ol>
	<p>Obvious track irregularity near REJ; relatively rapid REJ degradation.</p>	<ol style="list-style-type: none"> <li>1. Stiffness change due to unsupported sleepers or decreased ballast bed compactness caused by the dynamic REJ expansion/ contraction.</li> <li>2. Symmetrical REJs' difficulty maintaining long-term stability of track.</li> <li>3. Incorrectly installed fasteners.</li> <li>4. REJs located in curve sections.</li> <li>5. Poor maintenance of BEJs and REJs.</li> </ol>

**Source(s):** Authors' own work

scissor mechanisms 1 was obviously larger, ranging from 5.3 to 9.5 under different train speeds, hence a reinforced design for the scissor mechanisms was proposed.

Results for the beam end longitudinal displacement during passage of the comprehensive inspection train showed that the contribution of the train load to longitudinal displacement



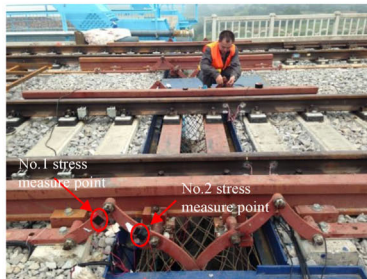
Layout of the railway cable-stayed bridge

(a)



Bridge structure end view and REJs at beam end

(b)



Installation of measurement points on BEJs

(c)



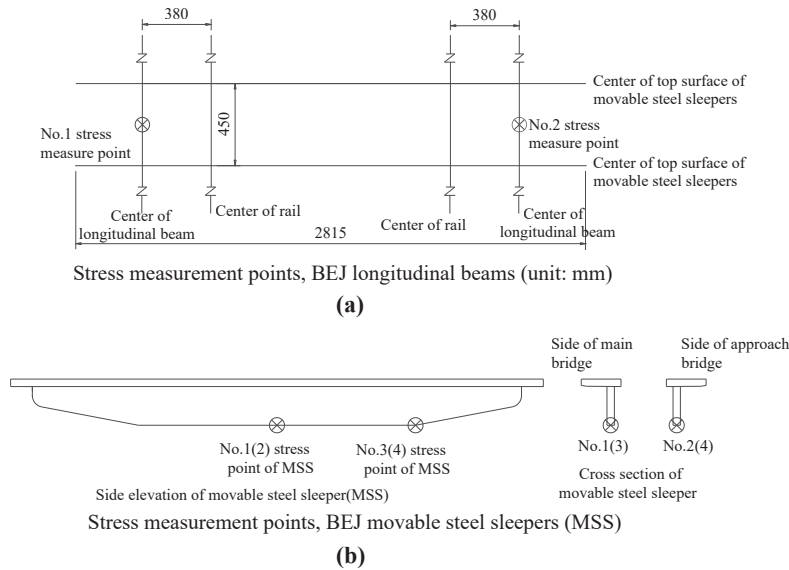
Ground inspection unit installed on track

(d)

Source(s): Authors' own work

Figure 5. Field testing of BEJs and high-speed train running performance at beam end

could be neglected, with maximal longitudinal displacement at the gap between the two steel sleepers of only 1.4 mm under a train speed of 120 km/h. Such a phenomenon was reasonable since the linkage between the 4th pylon and main girder was longitudinally-fixed, with bearing friction under high pressure also playing an important role. Additional monitoring results from a HSR suspension bridge also suggest that the longitudinal displacement caused by running trains can be smaller than estimates derived via simulation; when the running train passed over this bridge, the maximum measured displacement of the beam end bearing was only 3 mm (Xiao *et al.*, 2021), compared to an estimate of 42 mm, taking into account the most unfavorable effect of a single-track ZK design live load (0.8 UIC), representing the static train load of HSR in China. Various influences, including train-track-bridge interaction and bearing friction, have potential to render beam end displacement characteristics very complicated, and this topic is worthy of further investigation through both intensive theoretical study and field testing. These results also suggest that the effects of bearing friction, dampers, etc. should be



Source(s): Authors' own work

Figure 6. Location of stress measurement points on key BEJ components

Table 3. Stresses in steel components of deck-type BEJs under comprehensive inspection train at various speeds

No.	Train speed/km/h	Scissor mechanisms 1 (MPa)	Scissor mechanisms 2 (MPa)	Longitudinal beam1 (MPa)	Longitudinal beam2 (MPa)
1	5	-0.52	-0.71	3.58	2.31
2	120	-2.77	-0.91	6.88	5.88
3	140	-4.53	-1.29	5.83	5.02
4	160	-4.94	-1.40	6.70	5.11

No.	Train speed/km/h	MSS1 (MPa)	MSS2 (MPa)	MSS3 (MPa)	MSS4 (MPa)
5	5	2.77	2.73	1.71	1.74
6	120	5.42	5.11	4.17	4.56
7	140	4.74	4.78	3.64	3.92
8	160	3.77	5.28	2.71	3.87

Source(s): Author's own work

properly considered during the calculation of longitudinal beam end displacement, and that proper design values should be adopted.

To monitor train running performance, ground inspection units were installed near the bridge gap before the bridge was opened to traffic. This system was capable of recording the weight exerted on the rails by the wheels of running trains, and of monitoring safety indexes including rate of wheel load reduction and derailment coefficient. The results for a single axle in one test are shown in Table 4. These reveal that the total wheel weight ranged from 11.8 to

**Table 4.** Train running performance parameters recorded by ground inspection unit at beam end

Train speed (km/h)	Train body no.	Left wheel weight (kg)	Right wheel weight (kg)	Total wheel weight (ton)	Wheel load reduction rate		Derailment coefficient	
					Left wheel	Right wheel	Left wheel	Right wheel
162	1	6,894	5,710	12.6	0.216	0.128	0.05	0.066
167	2	6,555	6,473	13.0	0.087	0.008	0.059	0.078
167	3	6,085	5,736	11.8	0.168	0.162	0.064	0.081
169	4	6,371	7,112	13.5	0.074	0.034	0.062	0.093
169	5	6,441	6,280	12.7	0.152	0.16	0.065	0.081
170	6	7,177	6,681	13.9	0.05	0.023	0.067	0.078
167	7	6,535	5,871	12.4	0.041	0.034	0.071	0.08
167	8	6,358	5,777	12.1	0.145	0.147	0.069	0.071

**Note(s):** Results refer to a single axle; each test used four axles in total

**Source(s):** Author's own work

13.9 tons, lower than the design train live load. The wheel load reduction rate and the derailment coefficient generally remained below 0.2 and 0.1, respectively, at a train speed of 162–170 km/h. These values are far lower than the threshold values of 0.6 and 0.8, demonstrating the bridge's satisfaction of train safety requirements.

In addition to the ground inspection data, numerous field test results on train running performance at the beam end have been obtained during the testing and commissioning of HSR long-span bridges prior to their opening to traffic. Results derived via inspection using a comprehensive inspection train during bridge maintenance can also provide information on the beam end performance of BEJs, while special experimental or health monitoring systems including measurement points on BEJs can also provide intensive monitoring of their characteristics.

### *2.3 Lessons learned concerning BEJs used with REJs under operational conditions on HSR long-span bridges*

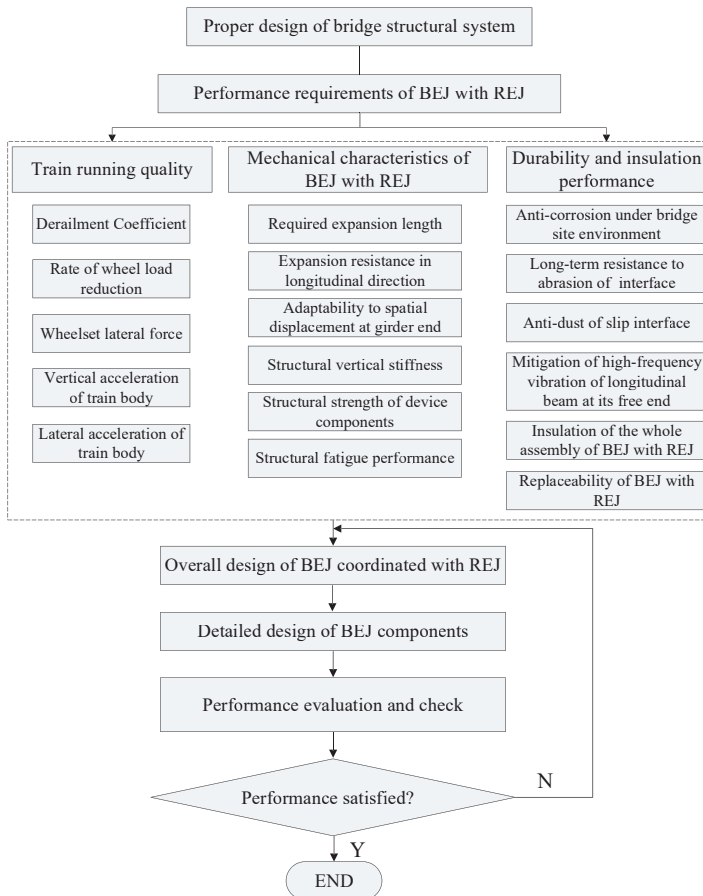
Practice and experience concerning BEJs used with REJs on HSR long-span bridges in China has been accumulating for over ten years. These devices have undergone development, and knowledge concerning their design and maintenance has deepened. Lessons can now be drawn from this practical experience, some of which is worthy of adoption in the form of basic design and maintenance guideline. First, stiffness-oriented design of BEJs should be emphasized. Since the component stress under the train load is rather low, accommodation of stiffness in the beam end region becomes the crucial issue. This mainly refers to uniformity of rail top stiffness in the transitional region of the main bridge, the bridge gap supported by BEJ, and on the approach bridge, which was a comprehensive stiffness index. Second, low resistance in the longitudinal direction during expansion and contraction should be considered a major performance objective of BEJs used with REJs. The two aspects above are the core performance targets, which should be taken into account, during the performance-based integral design of BEJs used with REJs.

## **3. Performance-based integral design of BEJs and REJs**

### *3.1 Introduction to performance-based integral design of BEJs and REJs*

Performance-based design is a state-of-the-art structural design philosophy which has been widely studied in recent years. Since the BEJ and REJ are both beam end structures critical to the accommodation of bridge and rail track displacement and deformation, for these, the main

performance requirements include train running quality, expansion range, longitudinal expansion resistance, structural strength and vertical stiffness, fatigue performance of key components, and adaptability to some degree of spatial displacement at the beam end. For the BEJ assembly as a whole, there are also insulation performance requirements, since this needs to be coordinated with the REJ. Performance-based integral design of the BEJ and REJ was therefore performed in order to fulfill the above-mentioned requirements, which are vital to ensuring train running safety, along with the proper functioning and durability of these devices. Figure 7 shows a performance-based integral design flowchart for BEJs and REJs. Before this is carried out, the bridge structural system must be checked and evaluated, since a proper structural system is required to provide satisfactory conditions for the BEJs and REJs. Specifically, the vertical and transverse angles of rotation at the beam end should be restricted to low levels (National Railway Administration of the People’s Republic of China, 2015), with vertical bearings under the mid beam end for wide girders, and wind-resistant bearings installed between pylons or piers and the girders. Restrictive countermeasures to decrease bridge expansion range, such as elastic cables between pylons and girders, or cable stayed-suspension system, can also be adopted. During performance-based design, performance



Source(s): Authors’ own work

Figure 7. Flowchart for performance-based integral BEJ and REJ design

indices must first be clarified, and threshold values for each parameter confirmed. These performance indices and their corresponding values are listed in Tables 5–7. Table 5 gives

**Table 5.** Indices of train running quality at beam ends with BEJs and REJs

Train running quality	Threshold value	Train running quality	Threshold value
Derailment coefficient Q/P	0.8	Train body vertical acceleration $a_z/m/s^2$ (In-service train load + road traffic load + temperature + lateral wind)	1.5
Wheel load reduction rate P/P	0.6	Train body lateral acceleration $a_y/m/s^2$ ((In-service train load + road traffic load + temperature + lateral wind)	1.2
Wheelset lateral force Q/kN	$10 + P_0/3$	Sperling index W	Excellent Good $W \leq 2.5$ $2.50 < W \leq 2.75$
Train body vertical acceleration $a_z/m/s^2$ (In-service train load + temperature)	1.3		$2.75 < W \leq 3.00$
Train body lateral acceleration $a_y/m/s^2$ (In-service train load + temperature)	1.0		

**Note(s):**  $P_0$  refers to static axle load  
**Source(s):** Author’s own work

**Table 6.** Spatial displacement thresholds for beam ends with BEJs and REJs

Mechanical characteristics of BEJ used with REJ	Performance requirements
Threshold for spatial displacement at beam end	Vertical angle at beam end/% $\circ$ rad $\leq 2.0$ Transverse angle at beam end/% $\circ$ rad $\leq 1.0$ –1.5 Vertical deflection of crossbeam at beam end/mm $\leq 2$
Required expansion length/mm	Design value of bridge
Expansion resistance in longitudinal direction/kN	Longitudinal resistance of sliding fastening of each node $\leq 2$ Number of movable steel sleeper(s) $N = 1 \leq 15$ Number of movable steel sleeper(s) $N = 2 \leq 30$ Number of movable steel sleeper(s) $N = 3 \leq 45$
Structural vertical stiffness/mm	Vertical displacement of bottom surface of movable steel sleeper below center of railway line under 230kN maximum vertical load $\leq 1.5$ Vertical displacement difference between top surface of longitudinal beam in mid-span and top surface of longitudinal beam above center of supporting sleeper adjacent to movable steel sleeper under 230kN vertical load $\leq 0.8$
Structural strength of components of BEJ/MPa	Meet design code*requirements
Structural fatigue performance of components	No component damage or permanent deformation

**Note(s):** Design code refers to “Code for Design on Steel Structure of Railway Bridge (TB 10091–2017)”, National Railway Administration of the People’s Republic of China  
**Source(s):** Author’s own work

**Table 7.** Durability and insulation performance of BEJ with REJ

Durability and insulation performance of BEJ with REJ		Performance requirements
Anti-corrosion of all metal parts of BEJ, except stainless steel		After 120-h neutral salt spray test, protection level of parts treated with rust prevention shall not be lower than 5 After rust prevention treatment metal parts, shall conform to dimensional accuracy and performance requirements Rust resistance requirements for installations in special corrosive environments shall be determined by negotiation between supplier and purchaser
BEJ Insulation	Resistance value of the whole assembly in dry state after fatigue test over $3 \times 10^6$ loading cycles	> 10M

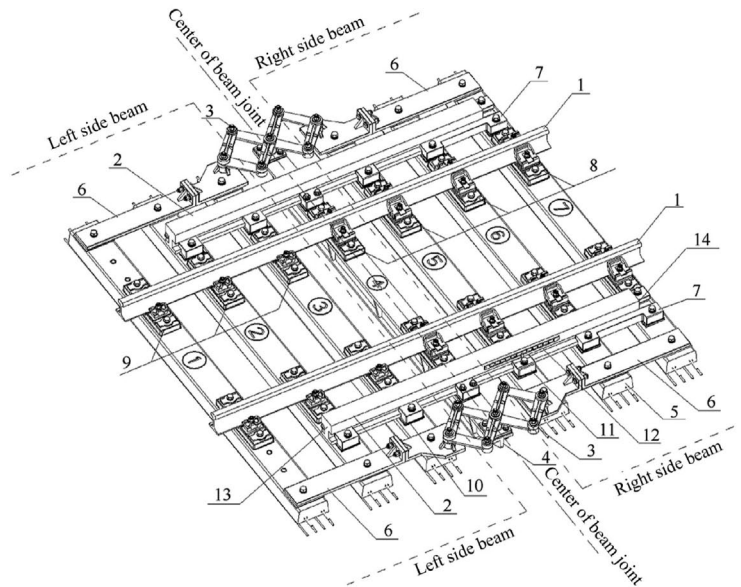
**Source(s):** Author's own work

indices of train running quality at beam ends with BEJs and REJs. [Table 6](#) provides threshold values for spatial displacement at the beam end, along with major performance requirements for BEJs. [Table 7](#) contains mainly requirements for BEJ durability and insulation performance.

### 3.2 Overall and detailed design of BEJs used with REJs

After confirmation of performance requirements and threshold values, BEJ design at the overall and detailed levels should be performed, in a process which may include iterative structural optimization of the BEJ in order to ensure that its performance requirements are fully satisfied. Overall design of the BEJ mainly comprises the arrangement of major structural components, i.e. longitudinal beam(s), movable steel sleeper(s), scissor mechanisms and fasteners. The number of movable sleepers must be selected to accommodate the expansion and contraction range under the combined effects of design loads, while the number and structural size of the longitudinal beams must also satisfy the requirements for vertical stiffness, as shown in [Table 6](#). Also, the height of the longitudinal beam shall also not exceed the top surface of the adjacent rail by more than 25 mm; this is the construction clearance required in China's HSR system. This restriction is also decisive in the design of scissor mechanisms; for this reason a horizontal structure is usually suggested. Fasteners are also key components of the BEJ. During integral design of BEJs used with REJs, sliding fasteners must be adopted for the movable steel sleeper and its fastenings on all sleepers towards the REJ's switch rail end, and matched constant resistance fastenings must be used in other ranges. [Figure 8](#) presents an overall deck-type BEJ 3D design scheme, for design expansion range 600 mm ( $\pm 300$  mm). This uses two longitudinal beams parallel to the rails, one movable steel sleeper perpendicular to the longitudinal beam, and two pairs of scissor mechanisms at both ends of movable steel sleepers. For a larger BEJ expansion range, e.g. 1,200 mm, two movable steel sleepers will be necessary, and the number of longitudinal beams will also increase, with one more beam between and parallel to the rails and above the sleepers. The scissor mechanisms connect the track structures of the main bridge and the approach bridge using the movable steel sleepers, and maintain even spacing between the steel sleepers.

The overall BEJ arrangement shown in [Figure 8](#) provides a simple, direct and effective design. When the train passes the beam joint, the BEJ helps to transmit the train load acting on the movable sleeper to neighboring sleepers in the beam joint, and down into the track bed via the longitudinal beam. And when the temperature changes, the BEJ can accommodate the resulting displacement through the coordination of the movable steel sleeper with that of the longitudinal beam, via the use of the scissor mechanisms and sliding fastenings.



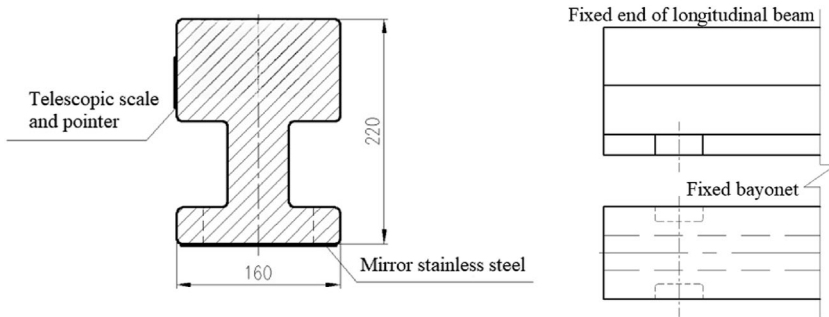
1 Rail	6 Connecting plate on sleeper ends	11 Sliding iron buckle (steel fastener of longitudinal beam)
2 Longitudinal beam	7 Anti-bounce device at movable end of longitudinal beam	12 Telescopic scale and pointer
3 Scissor mechanisms	8 Sliding fastener	13 Fixed end of longitudinal beam
4 Movable steel sleeper	9 Constant resistance fastener	14 Movable end of longitudinal beam
5 Supporting sleeper	10 Pressing iron buckle (fixed compressive steel fastener)	

**Note(s):** On the ballastless track, concrete sleepers with reinforced trusses are used; on the ballasted track concrete sleepers are used

**Source(s):** Authors' own work

**Figure 8.** Overall design scheme for deck-type BEJ with expansion range 600 mm

Besides overall design, structural detail design of the key structural parts of the BEJ is also very important. This must include the longitudinal beam, movable steel sleeper, scissor mechanisms, anti-bounce device at the movable end of the longitudinal beam, fastening system, etc. The longitudinal beam, 2,800 mm long in this design, is one of the most important components of the deck-type BEJ. At one end, this is fixed to a sleeper, while the other end can slide longitudinally relative to the sleepers beneath it, bearing the load of the train acting on the movable steel sleeper and transmitting this to those on either side of the beam joint and thus down into the track bed. It must also offer low longitudinal resistance, with sliding steel fasteners allowing smooth longitudinal movement of the movable steel sleeper. Furthermore, its design lifespan should be not less than that of a concrete sleeper. To realize the above functions, an I-shape cross section is suggested, providing contact surfaces on both sides for steel fasteners. Based on the vertical stiffness requirements, it must possess a moment of inertia of  $12,554 \text{ cm}^4$ , around 1.3 times of those used in some similar foreign BEJs. To minimize the longitudinal friction between the steel sleeper and the movable end of the longitudinal beam, mirror stainless steel must be welded at the bottom of the beam, providing a sliding surface. At the fixed end of the longitudinal beam, a bayonet fitting attaches it via pressure to a steel fastener. Details of the structural design of the longitudinal beam are shown in [Figure 9](#).

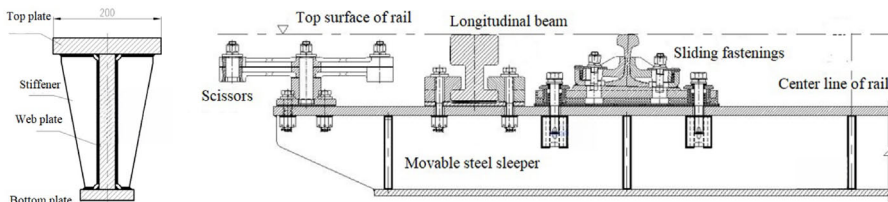


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Figure 9. Detailed design of longitudinal beam for deck-type BEJ (Unit: mm)

The movable steel sleeper must be capable of providing continuous support for rails attached to it using sliding fastenings, while also moving longitudinally along the longitudinal beam as the width of the beam joint changes. Its design lifespan should be the same as that of the longitudinal beam. This design also adopts a symmetrical I-shaped cross section for this component, consisting of a top plate, web plate, bottom plate and stiffeners as shown in Figure 10. With a length of 3,800 mm, its moment of inertia is 17,267 mm<sup>4</sup>, 2.2 times of those used in some similar foreign BEJs.

Scissor mechanisms ensure that the movable steel sleeper slides evenly along the longitudinal beam by pulling or pushing it via connecting nodes when the width of the beam joint changes. This design uses a diamond structure as shown in Figure 11. Its components include long and short limbs, axle pins and axle pin sockets, nuts, washers and cotter pins



Source(s): Authors' own work

Figure 10. Details of design and arrangement of movable steel sleeper for deck-type BEJ (unit: mm)



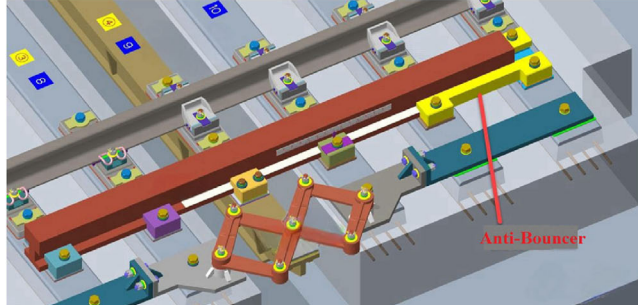
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Figure 11. Detailed design of scissor mechanisms for deck-type BEJ

horizontally arranged to ensure that its nodes remain approximately even with those on the sliding steel fasteners on the movable steel sleeper. This type of structure has advantages in terms of pushing and pulling strength, lower maintenance and superior reliability and stability. To improve the bending strength of this scissor mechanism, each limb is stiffened and each node is reinforced. Meanwhile, anti-rotation slot is used for high strength bolts, with a threaded steel jacket. Design details such as these ensure that the resistance of this mechanism is as low as possible, and make it more convenient to assemble and maintain. According to calculations on the long and short limbs, its sectional moment of inertia along the horizontal axis, representing vertical flexural capacity, is  $13.8 \text{ cm}^4$ , while that along the vertical axis, representing the longitudinal flexural capacity, is  $234 \text{ cm}^4$ .

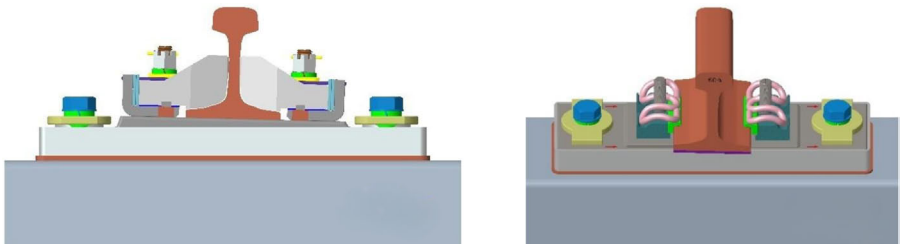
The anti-bounce devices at the movable ends of the longitudinal beams have three major functions: providing a groove to contain the ends of the longitudinal beams, limiting vertical and transverse displacement of the ends of the longitudinal beams and preventing those beams pushing on adjacent sleepers during expansion and contraction of the joint. An anti-bounce device is shown in Figure 12. This innovative design detail, which has proven effective in application, and appears to be unique to Chinese BEJ designs.

Fasteners for running rails used in this BEJ design include sliding fastenings and clip fastenings. To adapt them for HSR maintenance, vulcanized rubber-coated steel plate is used in these fastening systems. The vertical stiffness of the rubber-coated steel plate must exceed  $50 \pm 5 \text{ kN/mm}$  for ballast track, and  $25 \pm 5 \text{ kN/mm}$  for ballastless track. The longitudinal resistance of the sliding fastenings must not exceed  $2 \text{ kN/node}$ , while at least  $20 \text{ kN/node}$  is required for the clip fastenings. The fasteners should allow longitudinal level adjustment from  $-4$  to  $+20 \text{ mm}$ . The sliding fastenings and clip fastenings should permit lateral (left or right) adjustment of  $\pm 16$  and  $\pm 10 \text{ mm}$ , respectively. These fasteners are shown in Figure 13.



Source(s): Authors' own work

Figure 12. Detailed design of anti-bounce device for deck-type BEJ



Source(s): Authors' own work

Figure 13. Sliding fastenings (left) and type-485 clip fastenings (right)

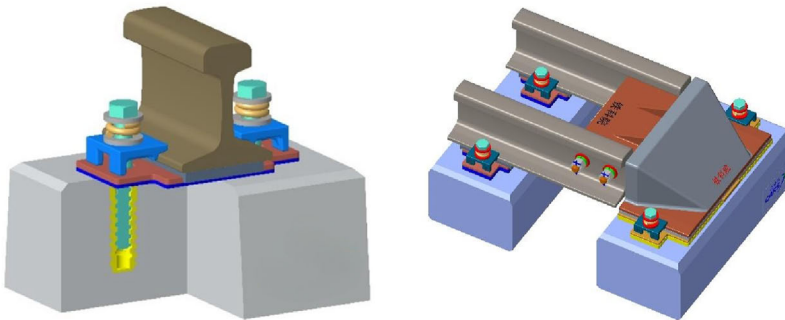
In addition to running rails, auxiliary rails can be installed on the ballast track sections of this deck-type BEJ to improve the vertical stability of the track system in the region of the REJ and BEJ, and reduce the negative effect on track regularity of any voided sleepers. These auxiliary rails can be installed in the middle of sleepers and/or on both sides of the center of the rail. Auxiliary rail fasteners must be tightened and insulated, with longitudinal resistance not less than 8 kN/node, and to enhance the integrity of the auxiliary rails, shuttle heads should be installed at both of their ends, as shown in Figure 14.

The concrete sleeper matched with deck-type BEJ is almost the same as that used in REJs, i.e. with a cross section similar to the switch sleepers used in passenger-dedicated railway lines. However, due to the arrangement of the longitudinal beam, scissor mechanisms, running rail, auxiliary rail and fasteners on the sleeper, its length is 3,700 mm, i.e. longer than that used in the REJ. It features pre-embedded nylon sleeves for fasteners of running rail, pressing iron buckle of longitudinal beam and end-of-sleeper connecting plate, as shown in Figure 15.

The design described above has been incorporated into Chinese standards (Q/CR 836–2021), and has been used in several HSR long-span bridges in China, including girder-type bridges, arch bridges and cable-stayed bridges, with expansion range from 600 to 1,200 mm and a design train speed of over 200 km/h.

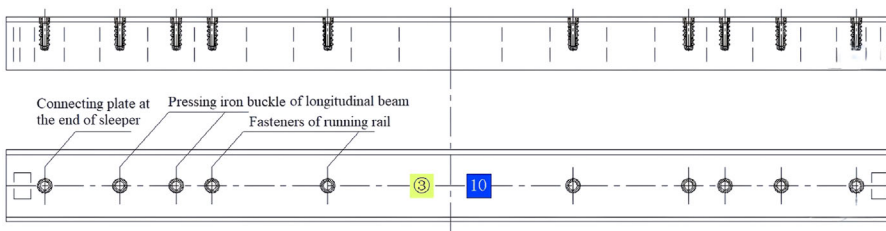
### 3.3 Verification of mechanical behavior of newly-designed BEJs used with REJs

Verification of the mechanical behavior of newly-designed BEJ must be performed, covering both static and dynamic performance indices related to mechanical behavior. The main static indices which must be verified, include expansion length and resistance, structural vertical stiffness, and structural strength and fatigue performance of BEJ components. Table 6



Source(s): Authors' own work

Figure 14. Auxiliary rail fastening system and shuttle head



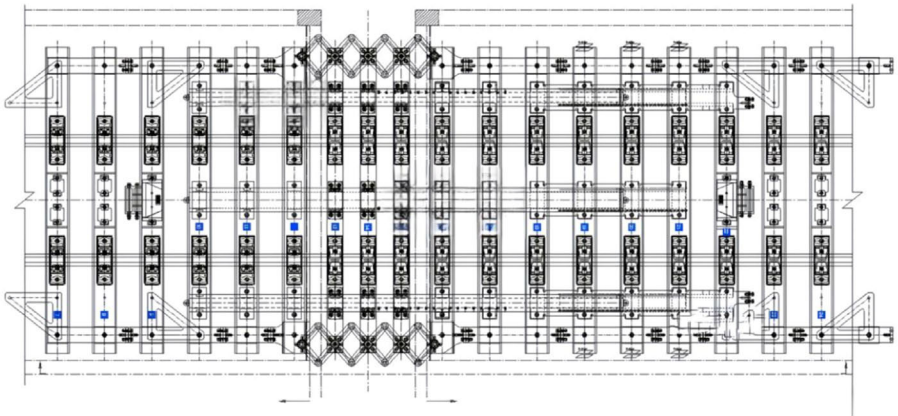
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Figure 15. Concrete sleeper matched with deck-type BEJ for ballast track

provides a full listing. Dynamic indices, mainly referring to train running quality at the beam end with BEJ, are shown in Table 5.

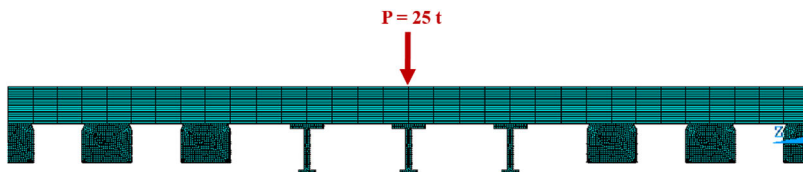
Figure 16 shows a newly-designed BEJ with expansion range 1,600 mm undergoing static and dynamic performance verification. Its design concept and general layout match those of the one in Figure 8. Three movable steel sleepers, rather than one, have been positioned in the joint to accommodate the increased expansion length, and the number of limbs used in the scissor mechanisms has also been increased accordingly. Three longitudinal beams are arranged parallel to the rails, with one longitudinal beam in the middle and two to either side outside them. The aim of this arrangement is to improve vertical stiffness of the expansion joint. Furthermore, triangular plates are installed on either side of the adjacent concrete sleepers to ensure the integrity of the railway track.

Static analysis was carried out for this BEJ considering the case of vertical train loading, with the primary aim of checking the components' vertical stiffness and levels of structural stress. A finite element model was built using ANSYS® engineering simulation software, allowing a maximum expansion length of 800 mm, as shown in Figure 17. In this model, the steel sleeper, longitudinal beam and rail were simulated using element BEAM188 in order to permit full consideration of the bending and shear effects. The longitudinal beam connecting components and fasteners were simulated using the spring-damping element COMBIN14. The boundary condition was taken to be "simply supported". Since the maximum width of the joint was required to be less than 2,500 mm, a single concentrated modeled load of 25 tons was exerted on the mid position of the joint, representing axle load effect on rolling stock and neighborhood wheelbase effect of truck according to the code for train load diagrams in China.



Source(s): Authors' own work

Figure 16. Plan view of deck-type BEJ with expansion range 1,600 mm for ballast track

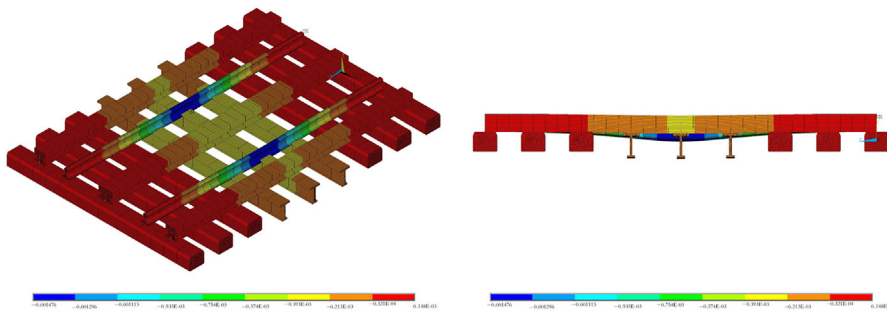


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Figure 17. BEJ in case of vertical train load

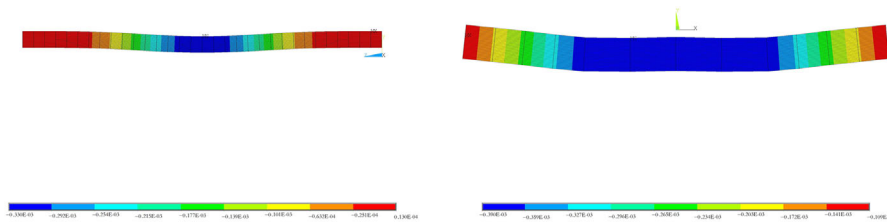
Figure 18, presents modeling of the overall deflection under vertical load with maximum expansion range. This gave a maximum rail deflection value of 1.476 mm, with deflections of the longitudinal beam and movable steel sleeper of 0.33 and 0.39 mm, respectively, as shown in Figure 19. Meanwhile, the maximum Von Mises stress in the longitudinal beam was 12.1 MPa, slightly higher than that in the movable steel sleeper (11.0 MPa), as shown in Figure 20.

Hence, the maximum deflection of the movable steel sleeper was less than 1.5 mm, and compliant with the structural vertical stiffness indices given in Table 6. Similarly, the difference in vertical displacement, under vertical load, between the top surface of the longitudinal beam at the mid-span (0.33 mm) and the top surface of the longitudinal beam above the center of the supporting sleeper adjacent to the movable steel sleeper (0.03 mm), was significantly less than the performance index value of 0.8 mm. This showed that the vertical stiffness of this BEJ with expansion range 1,600 mm was satisfactory from a static perspective. Results from the



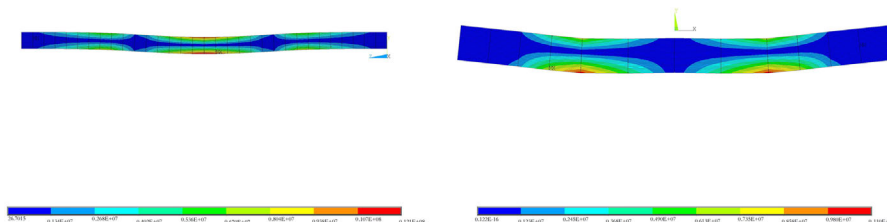
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Figure 18. Overall deflection with maximum expansion length under vertical load



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Figure 19. Deflection of longitudinal beam and movable steel sleeper with maximum expansion length



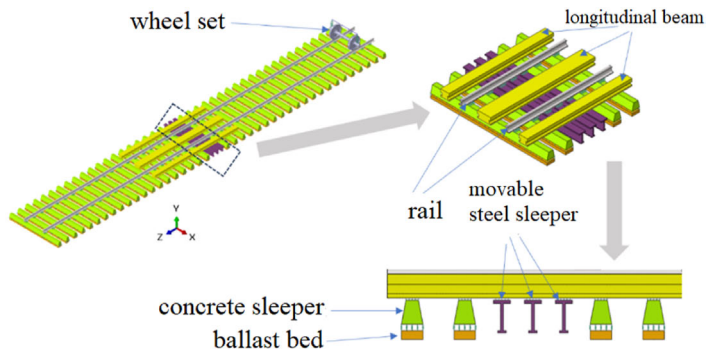
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Figure 20. Von Mises stress of longitudinal beam and movable steel sleeper with maximum expansion length

structural stress modeling were also far below the allowed levels, and it was also concluded that the design provides an adequate safety margin in terms of structural strength.

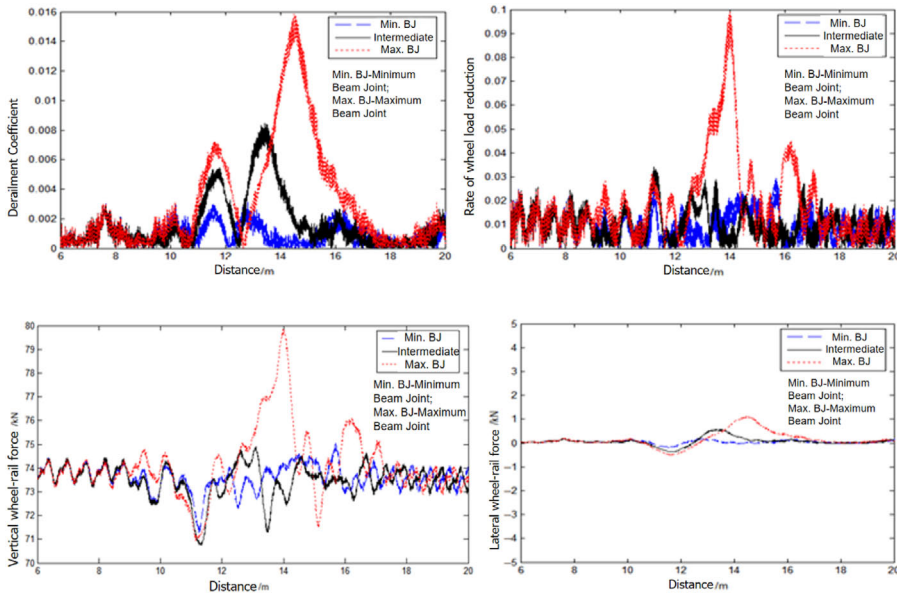
In addition to evaluation of static BEJ performance in terms of stiffness and strength, dynamic performance evaluation is also important during the design stage. Several indices of the BEJ's impact on train running quality, listed in Table 5, must be evaluated through train-track-bridge interaction analysis. Static and dynamic numerical analyses were used to ensure that the performance requirements could be satisfied, and that no modifications to the structure or dimensions of BEJ's major components were required. To check the dynamic response of a running train in the BEJ region, a train-track-BEJ model simulating the deformation of the bridge was constructed, as shown in Figure 21, for a total rail length of 26 m, including 41 concrete sleepers and three movable steel sleepers. The wheel set was started from its initial position at the origin of the Cartesian coordinate system, and moved in the positive direction of the z axis. The BEJ started at  $z = 11.2$  m, with an expansion range of  $-800$  to  $800$  mm. Spring-damping elements were used to simulate the support provided by ballast-concrete sleepers, steel sleeper-rails, concrete sleeper-rails, etc. and a maximum train speed of 250 km/h was simulated.

Major indices of train running quality, shown in Figure 22, were calculated from the simulation, including the derailment coefficient, wheel load reduction rate, and vertical and lateral wheel-rail force. Three cases were considered during the simulations, which considered the beam joint at minimum length ( $-800$  mm expansion length), intermediate length ( $0$  mm expansion length), and maximum length ( $+800$  mm expansion length). The results indicated that the maximum beam joint length case was the least favorable to the running train, as the four indices mentioned above registered the largest dynamic response. They also revealed several peak values during the passage of the train, with the first peak value appearing near the starting point of the BEJ. However, the calculated indices were well within acceptable ranges, with a maximum derailment coefficient of 0.016 (threshold value: 0.8), and maximum wheel load reduction rate of 0.1 (threshold value: 0.6). Maximum vertical wheel-rail force reached 79.8 kN near the BEJ with the maximum beam joint length, while lateral wheel-rail force reached only 1.1 kN. It is worth comparing these simulated results with real-world results from the inspection of a railway suspension bridge. These showed a maximum derailment coefficient of about 0.07 near the beam end under train speed of 250 km/h, along with a wheel load reduction rate of 0.11 at the beam end, and vertical wheel-rail force of 82.9 kN near the BEJ. The values measured during this inspection are thus quite similar to those derived from simulation, suggest that the simulated values are reasonable, and thus likely representative of the dynamic properties of the train-track system in the BEJ region.



Source(s): Authors' own work

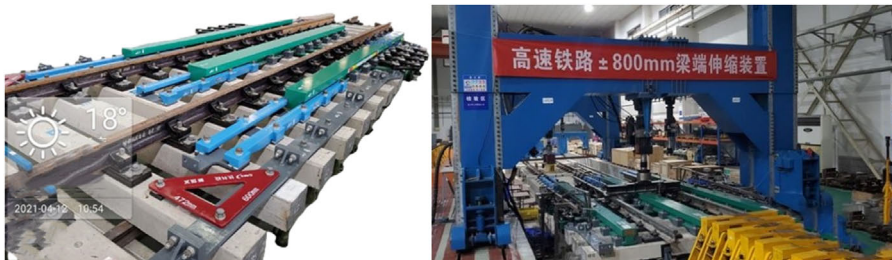
Figure 21. Train-track-BEJ model



Source(s): Authors' own work

Figure 22. Results of numerical simulation of train-track-BEJ model dynamic response

Other performance requirements for BEJs, such as resistance to expansion in the longitudinal direction, structural fatigue and insulation, are also critical to their design. However, these cannot be evaluated by numerical simulation, making physical model testing necessary. Hence, a full-scale model BEJ was manufactured, and testing was conducted at the State Key Laboratory of High-Speed Railway Track System of China Academy of Railway Sciences, Co., Ltd (see Figure 23). First, testing on the BEJ's expansion resistance was conducted under conditions of various rotational angles and their combinations. This produced maximum BEJ expansion resistance of 14.8 kN under conditions of vertical rotation of 2‰ rad and transverse rotation of 1‰ rad, clearly far less than the threshold value of 45 kN. Thus, the expansion resistance test results were satisfactory. Fatigue testing via cyclic vertical loading was performed under conditions of maximum expansion length (+800 mm), with a maximum load of 230 kN, minimum load of 46 kN, at 4 Hz frequency, over three million loading cycles in



Source(s): Authors' own work

Figure 23. Prototype of BEJ with expansion length  $\pm 800$  mm; full-scale model testing

total. After the cyclic loading, all of the BEJ components remained in good condition, without residual deformation. During the fatigue testing, maximum stress and displacement values for the major components were measured; these are listed in Table 8. This test revealed that the BEJ components were undergoing maximum stresses which were rather low compared to the yield strength of steel, and that the movable steel sleeper had undergone maximum displacement of less than 1.5 mm.

During the fatigue testing, tests of the insulation between the rail and each of the sleepers were carried out after every million cycles, i.e. three times in total. The results for the insulation resistance values were all greater than 500 M $\Omega$ , easily satisfying the requirement (more than 10 M $\Omega$ ).

The verification results summarized above indicated that this newly-designed deck-type BEJ with expansion range 1,600 mm fulfilled all performance requirements. A BEJ of this design was first installed on a long-span railway cable-stayed bridge which was opened to traffic at the end of 2021. Figure 24 shows this BEJ installed at the beam end. Given the bridge's design speed of 250 km/h, the highest speed used during inspection testing was 275 km/h. Figure 25 depicts the results from testing and commissioning. Longitudinal level and the alignment both remained within 4 mm, the grade I threshold value, according to Railway Standard TB/T 3355-2023 (National Railway Administration of the People's Republic of China, 2023). The track gauge measured during inspection was between +4 mm and -2 mm, also compliant with TB/T 3355-2023's grade I threshold value. These results indicated essentially smooth track geometry of the BEJ and REJ at the beam end, conclusively demonstrating their proper design.

**Table 8.** Maximum stress and displacement recorded during BEJ fatigue test

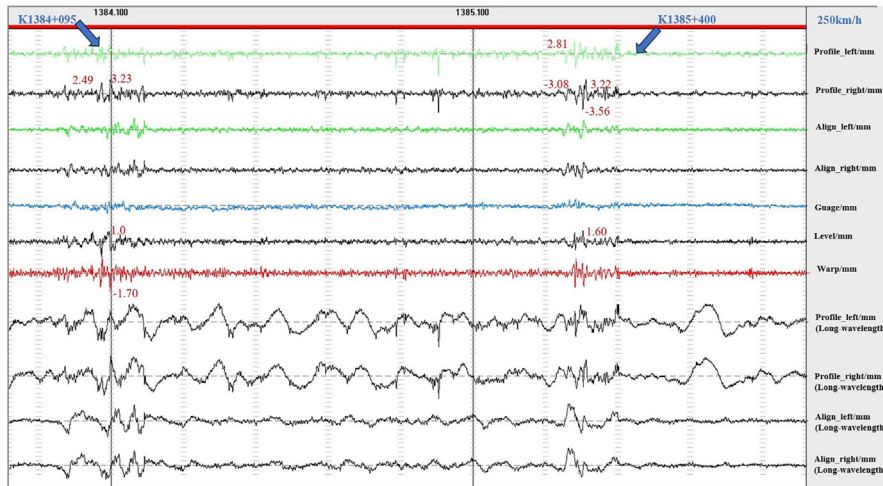
Type	Components or position	Maximum value	Note
Stress/MPa	Pressing iron buckle	5.3	Less than yield strength 785 MPa
	Longitudinal beam	21.4	Less than yield strength 355 MPa
	Rail	53.2	Less than yield strength 351 MPa
	Steel Sleeper	17.8	Less than yield strength 355 MPa
Displacement/mm	Mid-span longitudinal beam	1.04	–
	BEJ's movable steel sleeper	1.46	Less than 1.5 mm
	Rail top at mid span	1.83	–

**Source(s):** Author's own work



**Source(s):** Authors' own work

**Figure 24.** BEJ and REJ with expansion range 1,600 mm in application



Source(s): Authors' own work

Figure 25. Results of bridge track geometry inspection during testing and commissioning

#### 4. Conclusion

In recent years, expansion joints for HSR long-span bridges have undergone significant development at all levels, from theoretical perspectives to engineering application. For this study, a survey of the faults typically affecting BEJs and REJs was performed, and analysis of their probable causes conducted. In-field testing was also been carried out on the deck-type BEJs of a railway cable-stayed bridge in China, in order to obtain a general understanding of their response characteristics. Based on information obtained through these investigations, a performance-based integral BEJ design methodology was formulated, and the novel detailed deck-type BEJ design resulting from it introduced. Lessons that can be drawn from this process include the following points:

- (1) Beam end expansion joints are a fault-prone area of HSR long-span bridges. Fault investigation and inspection has made it clear that the operational status and performance of BEJs are influenced significantly by vertical stiffness variation at the beam end, longitudinal resistance and the detailed design of their key components. Performance requirements and threshold values for BEJs with REJ have thus been developed based on current design codes and experience, and verified via numerical simulation, model testing and in-field testing.
- (2) These performance requirements fall into four categories: mechanical characteristics, train running quality, durability and insulation performance. During the overall and detailed design of the novel BEJ, the structural strength of its components was determined to be adequate, with adequate safety margins and careful consideration was given to its structural stiffness and longitudinal expansion resistance. For BEJs with expansion range 1,600 mm, an arrangement with three longitudinal beams was found to sufficiently improve vertical stiffness. Under conditions of maximum + 800 mm expansion length and vertical design train load of 25 tons, rails running on a BEJ of this type underwent maximum deflection of 1.476 mm, with only 0.33 mm deflection of the longitudinal beams. This level of stiffness satisfied both the static and dynamic performance requirements of the unit. Sufficiently low longitudinal resistance is achieved through the adoption of sliding fasteners on the movable side, along with a

mirror stainless steel sliding surface with a low friction coefficient on the longitudinal beams. Results of full-scale model testing revealed that the maximum expansion resistance of the BEJ with REJ was only 14.8 kN under conditions of vertical rotation of 2‰ rad and transverse rotation angle 1‰ rad, clearly considerably less than the threshold value of 45 kN, when three moveable steel sleepers were installed.

- (3) The newly-designed deck-type BEJ with maximum expansion range 1,600 mm has been proven to satisfy the requirements of daily operation at the beam end in China. However, for expansion range in excess of 1,600 mm, e.g. 2,000 mm or more, this deck-type BEJ design may encounter challenges since the required number of movable steel sleepers would increase to more than three, increasing its frictional surface and thus certainly increasing its expansion resistance. Furthermore, while a large expansion length will require much higher vertical stiffness than the current design provides, track clearance considerations constrain the maximum height of the longitudinal beam, and the number of beams cannot be increased. Further novel BEJ structural systems for use with REJs, such as improved versions of through-type BEJs or other completely new expansion structure designs, should therefore be subjected to intensive study.

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