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Review article

Recent development of design and construction of medium and long span high-speed railway bridges in China

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ABSTRACT

Medium- and long-span bridges of the high-speed rail (HSR) projects play a significant role when crossing certain obstacles, such as rivers, existing highways, etc. This paper provides a state-of-the-art review on the design practice of these special spans in the HSR projects of China. Given standard spans are usually smaller than 100 m, special spans can be divided into two categories by the length of main span: medium length (100–200 m) and large length (200–500 m). For medium length, three structural forms are discussed as feasible design options, including steel arch, rigid frame and hybrid arch-girder. In addition, recently completed long-span bridges are reviewed to feature several innovative structural forms on the HSR of China, including steel truss arches and cable-stayed bridges with truss girder. Finally, the key technical features of long-span HSR bridges are summarized, and a discussion of the feasibility of longer spans is also included.

Contents

1. Introduction

High-speed rail (HSR) offers a fast and robust travel option that enhances the quality of life and supports economic growth. Japan was the first country to build a passenger dedicated line for high speed travel, also known as Shinkansen. The first Shinkansen opened Tokyo-Osaka segment for the Tokyo Olympics in 1964. HSR in Europe first developed in several countries and now expanded into a regional service network. Over the past few decades, a total of 13 countries have developed the HSR network, mainly in Europe and East Asia. International examples from those countries have proved that high speed trains are capable of reaching speeds over 250 km/h on high speed passenger dedicated line which significantly reduce the travel hours. Detailed historical

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reviews of the development of HSR in those countries can be found in papers by Taniguchi [1], Bouley [2], the European Commission [3], Gourvish [4], Zuber [5], and Harrison et al. [6].

HSR in China is composed of upgraded existing lines with an average design speed of 250 km/h and new lines with an average design speed of 350 km/h, including 9356 km of new built lines and 3209 km of upgraded lines. By 2020, the total length in China will reach more than 20,000 km with a complete grid network that will connect all provincial capital cities as well as large cities with population more than five million. For a typical HSR line in China, most spans are composed of standardized simply-supported beam (with span of 24 m, 32 m and 40 m) when spanning lower than 40 m and a few standardized continuous beam bridges (main span from 48 m to 100 m). For example, 95% bridges in the Beijing–Shanghai segment are standard span (90% simply-supported beam along with 5% continuous beam) and only 5% are special spans. Even though medium and long span bridges only cover a small portion of a HSR line, it plays a key role in the completion of the entire line, crossing over physical barrier such as existing highway, HSR lines and rivers, etc.

The selection of a rational and cost-effective structural form is the main assignment in bridge design. Structural forms for long-span railway bridges have evolved during the past two centuries, primarily featuring with longer span and more diverse forms. On the heel of the birth of the steam railways, iron truss bridges were widely constructed to support these earliest railway trains. In the late 19th century, three milestone railway bridges were successively built to support the larger live load of trains, including the Eads Bridge (1874, 158 m), the Brooklyn Bridge (1883, 486.3 m), and the Firth of Forth Rail Bridge (1889, 521 m). These bridges represented the advanced building techniques used on an arch bridge, a suspension bridge and a cantilever truss. The development of those well-recognized spans relied on the use of steel rather than iron which reduced the dead load weight. As railroads expanded throughout the world in the early 20th century, engineers raced to design bridges that were stronger and longer, without adding too much weight. A number of longer spans were developed, such as the Hell Gate Bridge in New York (1916), and the Sydney Harbor Bridge (1932). In the 1970s, Japan began the construction of the Honshū-Shikoku Bridge Project, connecting Honshū and Shikoku islands. The link between Okayama and Kagawa is the only one with railroad connections. A total of six long-span bridges were built to support both the highway and the railway, including a continuous truss bridge, two cable stayed bridges, and three suspension bridges. Currently, China is the leading country in the large number of regular rail upgrades and new HSR constructions.

The development of railway bridges in China began with the completion of the Qiantang River Bridge in 1937. Two milestone steel truss bridges were built subsequently across the Yangtze River in Wuhan (1957) and in Nanjing (1968). Since then, the steel truss bridge was used as the main structural form for the railway bridges in China until the first cable-stayed bridge with a main span of 312 m was completed in Wuhu over the Yangtze River in 2000. Then, a series of cable-stayed bridges were planned and constructed [7]. Similar to the design of standard spans for HSR, the design of special spans also require a strict service limit due to the need for smoothness of the track and the stability of the high speed train. For a certain span range and site condition, several options of structural form are available [8,9]. Special spans in HSR of China can be divided into two categories by the length of the main span: medium length (100–200 m) and large length (200–500 m). Several cable-stayed bridges with a longer main span more than 500 m are also included in the long spans. No suspension bridges are currently used in the HSR of China. The suspension bridge is too flexible to maintain low deflection on main girder and tracks such that it is not easy to meet the service limits of HSR. Further studies on the use of HSR suspension bridge in China is still in progress.

The objective of this paper is to present an up-to-date review of the emerging design and construction techniques on medium and long spans on the HSR of China, including the key design philosophies, the main structural dimensions and the construction methods. For medium length bridges, three forms are discussed, including steel arch, rigid frame and hybrid arch-girder. For large length bridges, the discussion focuses on steel truss arches and truss cable-stayed bridges. This paper summarizes the structural options for special spans for future HSR constructions.

2. Deflection control

HSR requires high deflection limits to ensure track smoothness. No matter what structural forms selected for the special spans, the control of the deflection on the main girder is still a key design issue because the average design speed of trains on those spans is more than 250 km/h [10]. The threshold limits on bridges with a ballastless track bed are higher than bridges with ballast track bed, because it is difficult to adjust the smoothness on the ballastless deck. Thus, all the long-span HSR bridges in China used ballast track. However, no detailed requirements are applied to long-span bridges, since the design and analysis of those bridges are usually carried out case by case, which at least should satisfy those minimum limits of small span HSR bridges. Four key aspects on the deflection control on small span are as follows: (1) Vertical deflection of the beam, smaller than 2.0 mm; (2) the rotation at the beam end, smaller than 0.4%; (3) long-term deflections (for example, creep effects), smaller than L/1000 (L in m and result in mm); (4) longitudinal deflection of the substructure. All those requirements must be met in order to ensure the smoothness of the track and the safety of the trains.

Track stability and smoothness of the HSR is highly dependent on the control of the vertical and lateral deflection of the main girder. Design specifications by the former Ministry of Railways (MOR) of China have certain requirements on short-term and long-term deflection on short length continuous beams [11]: the vertical deflection must be smaller than 1.1 L/1000 (L is the main span); lateral deflection must be smaller than L/4000; and beam end rotation must be smaller than 0.2% in a ballast track bed and 0.1% in a ballastless track bed. However, no such requirements in the design specifications have been proposed for special spans, including the medium length continuous beam, the arch bridge and the cable-stayed bridge. Deflection limits on similar bridges from international examples were studied and compared to develop a recommended range for the long-span designs [12].

Due to higher serviceability limits compared to conventional railway bridge design, other technical issues associated with dynamic response of HSR bridges have been studied by many previous studies, such as seismic performance [13–17], track–structure interaction [18–20], creep effect [21,22], thermal effect [23], etc. In the development of HSR bridge in China, those special issues (such as thermal expansion, seismic design, wind effect and creep effect) have been considered and additional analysis may be required for multiple loading cases that may cause large deflection. (1) A single span over 100 m long requires measures to control the thermal expansion and contraction of the rail, because the continuous welded tracks could become distorted in hot weather and cause the derailment of a train. Clips and anchors were widely used in the HSR on multiple span bridges [24]. Zhu [25] compared the multiple combinations of expansion devices on a cable-stayed bridge. It were found that the optimal way to control the thermal