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Short Communication

Experimental analysis of railway bridge under high-speed trains

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1. Introduction

To meet the needs of passenger transportation, more and more high-speed railway lines are being constructed in the world. Under the load of high-speed trains, the bridges are subjected to high impacts. Therefore, in many of the countries, the dynamic behavior of high-speed railway bridges has been systemically studied in the development of high-speed railways [1–7].

In China, the 404-km-long Qin(huangdao)–Shen(yang) Special Passenger Railway, with the design train speed of 200 km/h and an 83-km-long high-speed experimental section of more than 300 km/h, has been completed and put into operation. The 1300-km-long high-speed railway between Beijing and Shanghai is now also under planning and design.

During the design of the Qin–Shen Railway, the Ministry of Railways of China organized the Academy of Railway Sciences and several universities to study the dynamic characteristics of high-speed railway bridges through theoretical analysis, numerical simulations and field experiments. In November 2002, a field experiment was carried out on the bridges, tracks and roadbeds in the experimental section of the Qin–Shen Railway. In the experiment, the China-made high-speed train called China-Star was used, and the highest train speed reached 321.5 km/h. Many useful results were achieved from the experimental data [8]. In this paper, the experimental results of a bridge under China-Star high-speed train are presented.

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2. Experiment on Gouhe River Bridge

2.1. Introduction to the bridge

The experiment was carried out on the Gouhe River Bridge, which consists of successive 28 24-m-span double-track prestressed concrete bridges, see Fig. 1.

The PC bridges are simply supported girders with box sections, which are the main type of spans of the bridges for the Qin–Shen Special Passenger Railway [8]. The design span and the total length of the PC box girder are 24.0 and 24.6 m, respectively. The cross section of the girder is shown in Fig. 2. Four pot neoprene bearings are adopted to support each girder. The substructures of the bridge are plate piers with rounded end sections and heights of 8–10 m.

2.2. Experimental arrangement

The purpose of this experiment was to obtain the dynamic responses of the bridge, such as the deflections, displacements, accelerations and strains, and the running safety and stability parameters for the train vehicles such as the derail factors, offload factors, wheel/rail forces and car-body accelerations.

The field experiment was carried out in November 2002. The load was the China-Star high-speed train, see Fig. 1.

The sensor locations were arranged at four sections of the 22nd and the 23rd spans, as indicated in Fig. 3. These sensor locations are divided into two groups: section I–II and section I′–II′, and they had the same arrangements. The sensor locations in section I–II are described as follows.

In this group, each sensor location was given a unique number: *A* denotes acceleration measurement, *D* deflection and/or displacement measurement, *S* strain measurement and *R* rail

Fig. 1. Field test of Gouhe River Bridge under China-Star high-speed train.

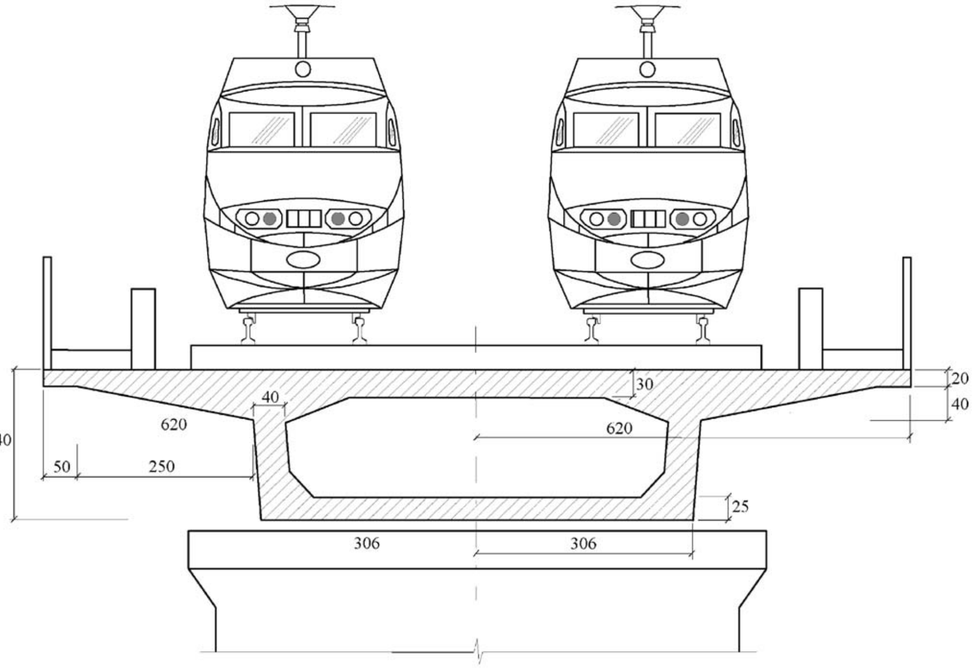

Fig. 2. Cross section of the 24-m-span PC box girder.

force measurement. The measurement directions are indicated by x, u or v (x—longitudinal, u—lateral, v—vertical), respectively.

For the 22nd girder and the 22nd pier in this group, a total of 6 vertical deflections, 2 vertical and 3 lateral accelerations, 5 lateral and 6 longitudinal strains, 4 lateral displacements, and 2 vertical and 2 longitudinal rail forces were measured.

At the mid-span section of the girder, four strain gauges (S_{1x}, S_{2xu}, S_{4x}) were glued on the bottom side of the PC box, at the center and at the locations under the railway tracks, to investigate strain changes during train passages. At the same locations, the vertical deflections (D_{1v}, D_{2v}, D_{3v}, D_{4v}) and lateral displacements (D_{2u}) of the girder were measured with LVDT and vibration pickups S891-4. At the girder deck, the lateral and vertical accelerations (A_{9uv}, A_{10v}) were measured with accelerometers HTB5511. The acceleration data of the bridge were processed with low pass filtering at 40 Hz.

To study the rigid body movement and relative movement of the girder with respect to the piers, the relative displacements at the pot neoprene bearings were measured (D_{14uv} and D_{15uv}) as well as the lateral displacements and absolute accelerations at the pier tops (D_{13u} and A_{13u}).

The rail forces were measured with the strain gauges glued on the rails (R_{11uv} and R_{12uv}) on the bridge girder. Furthermore, the vertical and lateral rail forces were obtained from these strains, according to the transform factors between the strains and the forces, which were calibrated both before and after the experiment.

Measurement amplifiers and acquisition hardware systems MEGADAC5000 and IOTECH WB-512 were all installed in the work shed beneath one of the bridge girders.

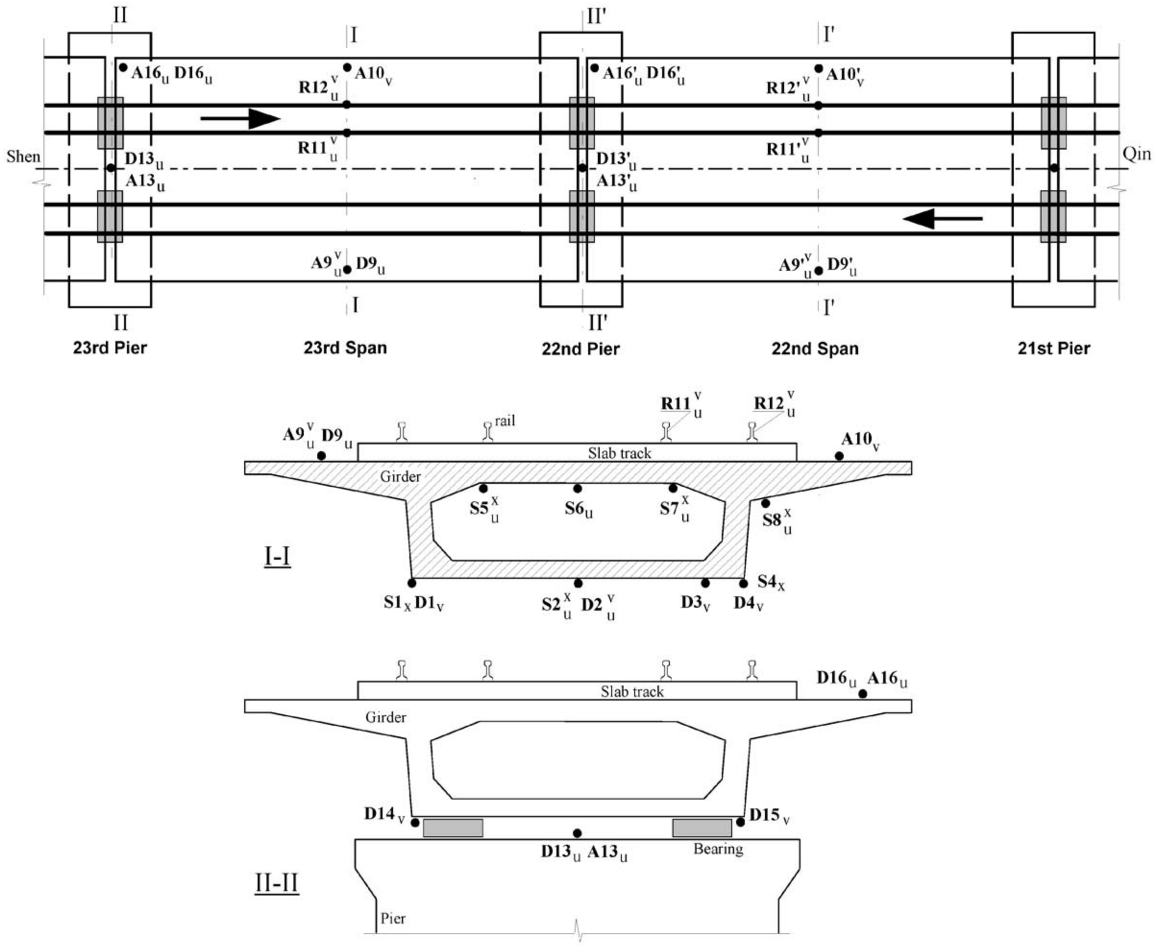

Fig. 3. Sensor locations in the experiment.

In the 7 days experiment, 64 train passages were measured at sampling frequency 5000 Hz, 240 k samples (49 s).

In the experiment, the car body accelerations, and the parameters for running stability of vehicles of the China-Star train were simultaneously measured with the instruments equipped on the train.

2.3. Train properties

The China-Star train is composed of a locomotive followed by 9 passenger cars and a locomotive with 22 bogies and 44 wheel-sets in total. The average static axle loads for the locomotives and passenger cars are 195 and 142.5 kN, respectively. The design train speed for China-Star is 270 km/h, and the maximum experimental speed reached 321.5 km/h. Fig. 4 shows the dimensions of the first three vehicles of the China-Star train.

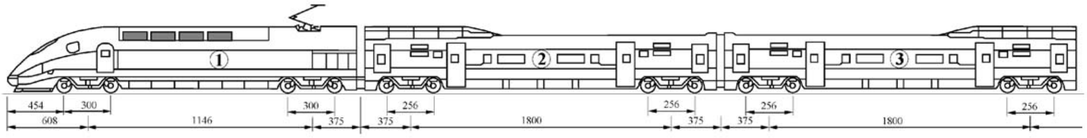

Fig. 4. Composition of the China-Star high-speed train.

2.4. Track properties

The ballastless concrete slab is adopted as the track on the bridge. The rail pads have a static stiffness of 60 kN/mm in the load interval between 15 and 90 kN. Their dynamic stiffness is about 150 kN/mm for frequencies lower than 5 Hz. The rails are CT60 profiles: $A = 7.708 \times 10^{-3}\,\mathrm{m}^2$, $m = 60.64\,\mathrm{kg/m}$, $I = 3.217 \times 10^{-5}\,\mathrm{m}^4$.

The rail geometry and irregularities were measured before the experiment. The measurement report shows that, in the range of wavelengths from 1.0 to 80.0 cm, the rail quality of the Qin–Shen Special Passenger Railway can be classified as good.

3. Experimental results

3.1. Natural vibration properties of girders

The natural vibration properties of the girders have been analyzed from the experimental data. The data were decimated with a factor 100 (low pass filtering at 200 Hz) and limited to free vibration after train passage, to result in frequencies and damping ratios of Table 1.

3.2. Dynamic responses of bridge

In the experiment, a total of 64 measurements have been recorded and analyzed. The speed of the China-Star train running through the bridge was in the range 160–307 km/h. In the following analysis, the measured responses of the bridge are referred to the longitudinal central line of the double track girder. Since the 22nd and the 23rd span are of the same structure, the measured results of the two spans are plotted in the same distribution figures. Some of the results are given below.

(1) *Vertical deflection*: The vertical deflection measured by the LVDT at the center of the span of the girder under the China-Star train is shown in Fig. 5(a). The 22 bogie passages are clearly detectable in the deflection history curve, from which the train speed can be estimated at 260 km/h.

The maximum vertical deflections of the girder under each passage of the train are plotted in Fig. 5(b). The figure shows that the deflection of the girder increases with the train speed. The maximum deflection at the central line of the girder under China-Star train is 0.87 mm, which is about 1/27,600 of the span. The static deflection of the girder under China-Star train was measured as 0.718 mm; thus the maximum impact factor can be estimated as 0.87/0.718 = 1.211.

Table 1
Natural vibration properties of the girder

Parameters	Eigenfrequency		Damping ratio (%)
	Vertical (Hz)	Lateral (Hz)	
22nd span	7.65	24.43	2.61
23rd span	7.70	24.22	2.57

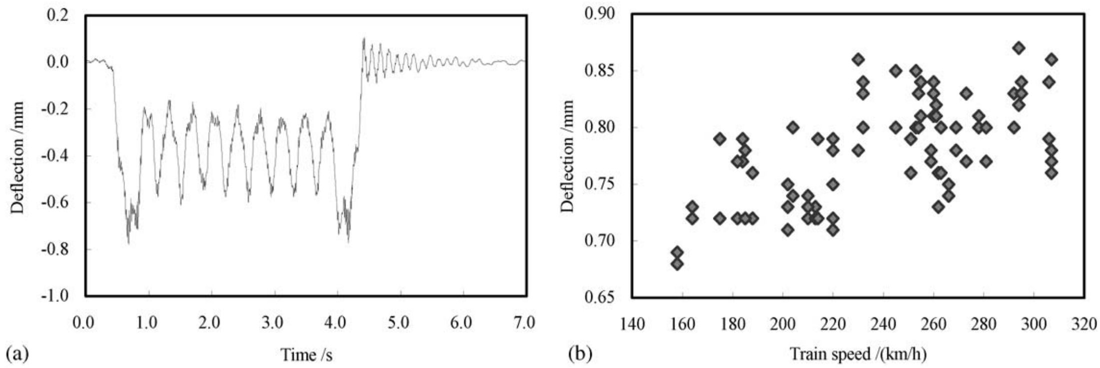

Fig. 5. Deflection of the girder at mid-span: (a) history curve, (b) distribution versus train speed.

(2) *Lateral displacement*: The lateral displacement at the mid-span of the girder and its distribution versus train speed are shown in Figs. 6(a) and (b), respectively. Those at the pier-tops are shown in Figs. 7(a) and (b), respectively.

The maximum lateral displacement of the girder under China-Star train is 0.33 mm at the train speed of 230 km/h, which is about 1/72,000 of the span. The maximum lateral displacement of the pier-top is 0.12 mm at the train speed of 307 km/h.

(3) *Vertical acceleration*: The typical vertical acceleration curve of the girder at mid-span is shown in Fig. 8(a). The distribution of the maximum vertical accelerations versus train speed is plotted in Fig. 8(b).

The vertical accelerations of the girder mainly increase with the train speed, with the maximum being 1.90 m/s^2 at the train speed of 307 km/h. This result is somewhat dependent on the sampling frequency of the acquisition and the applied filtering afterwards. This remark applies to all acceleration measurements.

(4) *Lateral acceleration*: The typical lateral acceleration curve of the girder at mid-span is shown in Fig. 9(a). The maximum lateral accelerations of each train passage measured by the accelerometers on the girder at the mid-span are plotted in Fig. 9(b).

The lateral accelerations of the girder also increase with the train speed. The maximum lateral acceleration is 1.40 m/s^2, appearing at the train speed of 307 km/h.

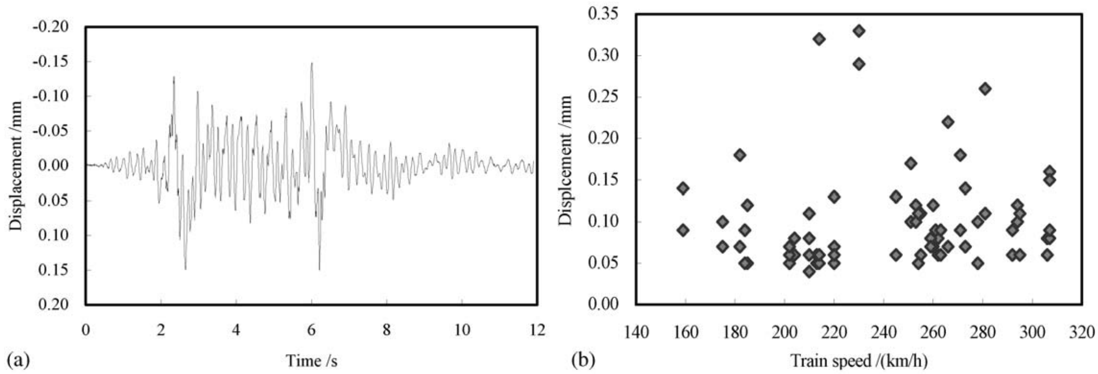

Fig. 6. Lateral displacement of girder at mid-span: (a) history curve, (b) distribution versus train speed.

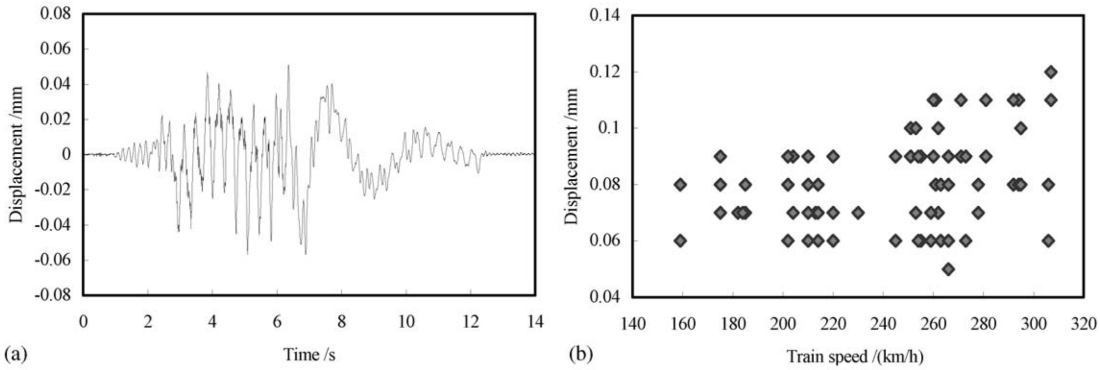

Fig. 7. Lateral displacement of pier-top: (a) history curve, (b) distribution versus train speed.

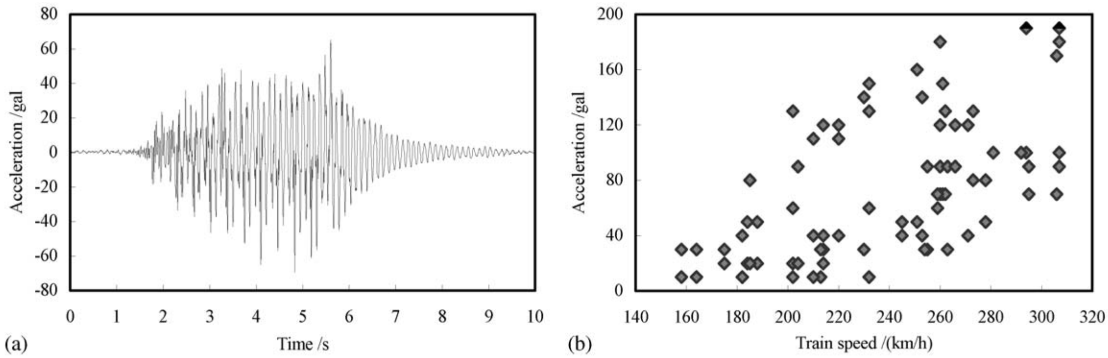

Fig. 8. Vertical accelerations of the girder at mid-span: (a) history curve, (b) distribution versus train speed.

(5) *Strain of girder concrete*: The typical curve of strain gauge signal (S_{2x}) of the bottom concrete of the girder at mid-span is shown in Fig. 10(a). The distribution of the maximum strains versus train speed is plotted in Fig. 10(b).

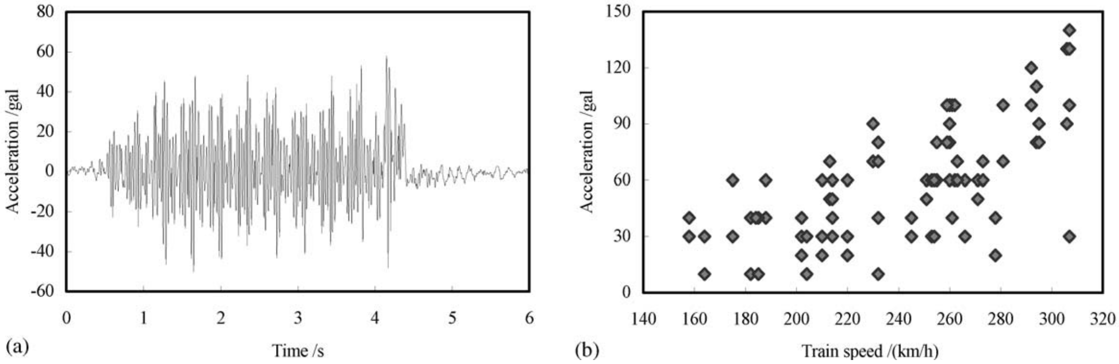

Fig. 9. Lateral accelerations of the girder: (a) history curve, (b) distribution versus train speed.

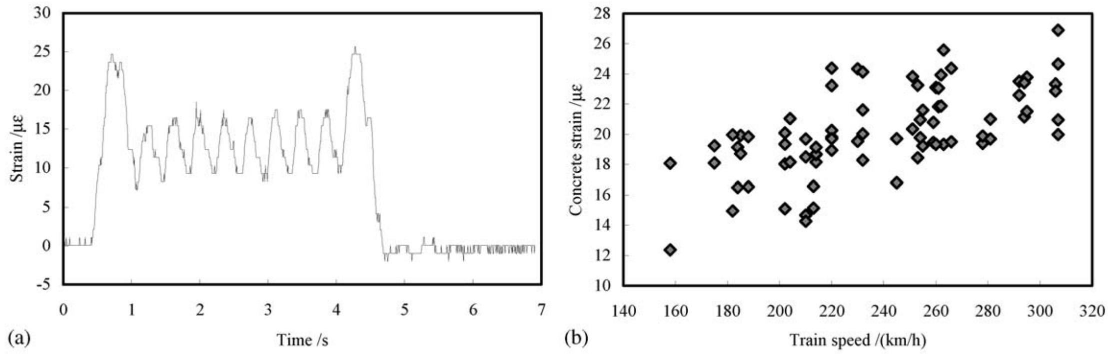

Fig. 10. Concrete strain of the girder: (a) history curve, (b) distribution versus train speed.

The strain of the girder concrete mainly increases with the train speed, with the maximum being $26.89\mu\varepsilon$ at the train speed of 307 km/h. Multiplying this strain value with the concrete elastic modulus of 35,000 MPa, the maximum stress of the bottom concrete of the girder can be calculated as 0.941 MPa.

The maximum responses of the bridge and the corresponding allowances are summarized in Table 2.

3.3. Parameters for running safety and stability of vehicles

The typical rail force curves are shown in Fig. 11. The impact forces induced by the 44 wheels can be clearly observed in the rail force curves. From the curves and according to the inter-distances between the wheels, the train speed can again be estimated as 260 km/h.

The derail factor Q/P, offload factor $\Delta P/P$ and lateral wheel/rail forces are the parameters for running safety of vehicles, which can be calculated with the measured vertical and lateral rail forces. Distributions of these parameters of the China-Star train versus train speed are shown in Figs. 12–14. The main trends are that they all increase with the train speed.

Table 2
Maximum responses of the bridge

Bridge response	Measurement	Allowance
Girder		
Vertical deflection (mm)	0.87	1.6
Lateral amplitude (mm)	0.33	0.92
Acceleration (m/s^2)		
Vertical	1.91	3.5
Lateral	1.40	1.5
Pier		
Lateral amplitude (mm)	0.19	0.30

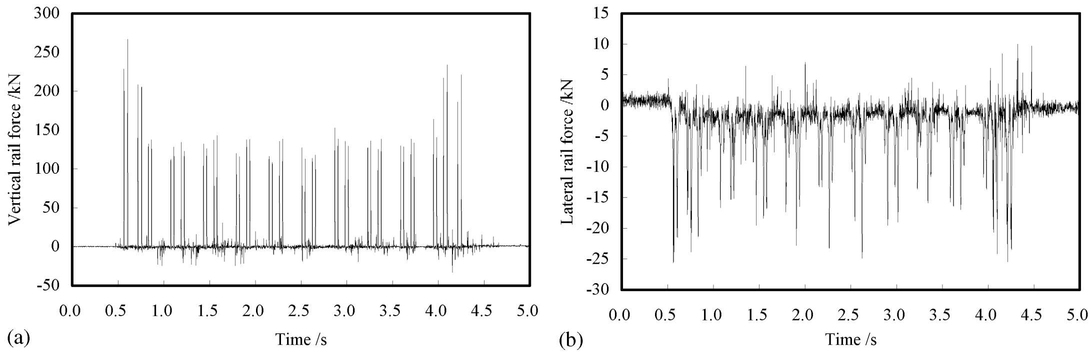

Fig. 11. Measured rail forces on the girder: (a) vertical, (b) lateral.

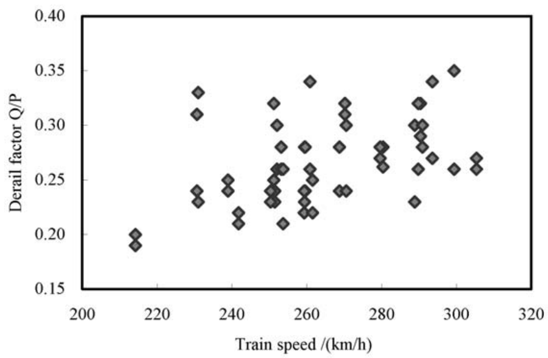

Fig. 12. Vehicle derail factor versus train speed.

The distributions of vehicle car body accelerations versus train speed are shown in Fig. 15, where Lo represents locomotive and Pa stands for passenger cars.

The maximum responses of locomotives and passenger cars and the corresponding allowances are summarized in Table 3.

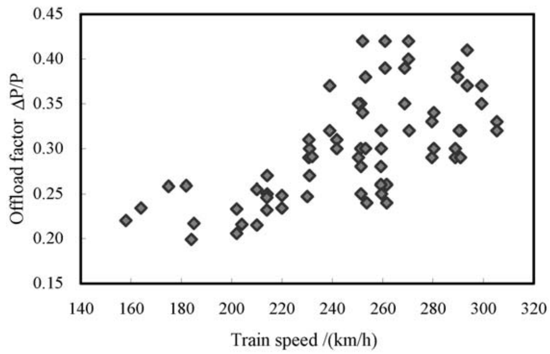

Fig. 13. Vehicle offload factor versus train speed.

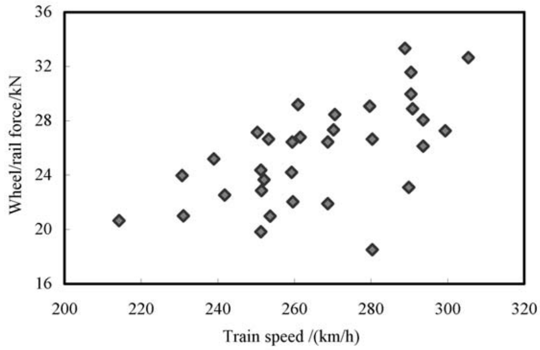

Fig. 14. Wheel/rail forces versus train speed.

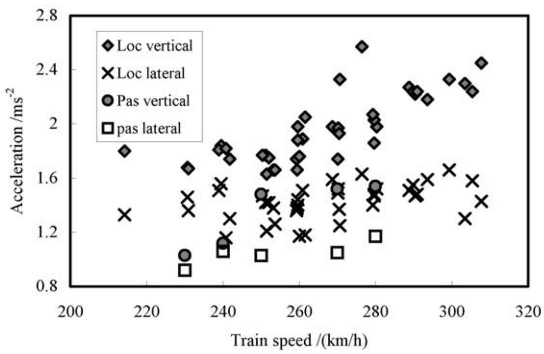

Fig. 15. Vehicle body accelerations versus train speed.

4. Conclusions

The following conclusion can be drawn up from this experiment:

(1) The 24 m PC box girder bridge on the Qin–Shen Special Passenger Railway has perfect dynamic properties. Under the China-Star high-speed train at the speed of 160–307 km/h, the

Table 3
Maximum responses of vehicles

Vehicle response	Measurement	Allowance
Locomotive		
Derail factor Q/P	0.31	0.8
Offload factor $\Delta P/P$	0.42	0.6
Lateral wheel/rail force (kN)	33.35	62.7
Car-body acceleration (m/s^2)		
Vertical	2.57	2.25
Lateral	1.66	1.75
Passenger car		
Derail factor Q/P	0.289	0.8
Offload factor $\Delta P/P$	0.383	0.6
Lateral wheel/rail force (kN)	29.5	44.6
Car-body acceleration (m/s^2)		
Vertical	1.54	2.25
Lateral	1.17	1.75

deflections of the girder, the lateral and vertical accelerations of the girder, and the lateral amplitudes of the girder and the pier are in accordance with the currently recognized safety and serviceability standards of bridges.

(2) The China-made China-Star train vehicles have good running property at high speed. The dynamic properties of the locomotives and the passenger cars, such as the derail factors, offload factors, wheel/rail forces and car body accelerations, are all in accordance with the currently recognized running safety and comfort standards of railway vehicles. The only exception is the vertical car body acceleration of locomotives that exceed the allowance of 2.25 m/s2, when the train speed is higher than its design speed of 270 km/h.

Acknowledgements

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