Study on the Health Monitoring Index of Long-span High Speed Railway Bridge Based on Service Condition

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Abstract: The technical standard system of high speed railway (HSR) infrastructure ought to cover the full life cycle of the infrastructure, including the standards of design, acceptance and operation. For long-span bridges, environmental factors like wind, temperature, creep, settlement which have a marked influence on structural performance should be taken into consideration in design and operation. Various loads are in adverse situation in the stage of design, and it is required that structures should meet strength demand in combined action, while deformation limits are prescribed in accordance with various loads, and the stiffness requirements of the structure are not put forward. Therefore, the design standards cannot be adopted directly in the operation stage of the structure. The paper carries out a comparative study on the adaptation of radius of curvature, wave length amplitude and chord length to the deformation control of long-span bridges, and proposes the analysis process of health monitoring index limit by taking a deck arch bridge as example, which can be used in static deformation control in operation stage for different bridge types and spans.

Key words: high speed railway (HSR); long-span bridge; health monitoring; static deformation limit; train-bridge coupling

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Introduction

As part of the high speed railway infrastructure, a bridge supports the track structure with high smoothness, stability and durability. The design concept of a bridge has been evolving from the traditional static stiffness to dynamic stiffness, where the operational safety, riding comfort and the bridge's dynamic performance have become the control factors. Accordingly, the purpose of its health management is to control the track geometry and maintain the operational performance rather than simply to maintain its support capacity.

The technical standard system of high speed railway (HSR) infrastructure ought to cover the full life cycle of the infrastructure, including the standards of design, acceptance and operation. For long-span bridges, environmental factors like wind, temperature, creep, settlement which have a marked influence on structural performance should be taken into consideration in design and operation. Various loads are in adverse situation at the stage of design, and it is required that structure should meet strength demand in combined action, while deformation limit is prescribed in accordance with various loads, and the stiffness requirements of the structure under the combined action of various loads during actual operation has not been put forward. Though the bridge bears multiple loads or actions during its long term service life, the effects of different loads or actions may be rather different due to different spans, different bridge types or even different geological conditions. Therefore, the deformation limits in the design standards should not be adopted by simple superposition during the operation stage. Moreover, the acceptance standards are developed to evaluate the construction quality of the structures, and thus are not suitable for the operational stage.

To reduce the construction cost of long span complex bridges, the top-level design with the life cycle concept shall be adopted. The design in the normal sense should only be one step of the life cycle design, which specifies the overall principles. The top-level design should make it clear that the design stage is not to tackle all the challenges of the full life cycle. For instance, those short-term loads or actions like live loads, wind, earthquake, or those periodic actions like temperature, sunshine, which should be born by the structure itself, must be fully considered during the design stage. Consequently, the deformation caused by these loads or actions shall not be left to the operational stage, so as to avoid excessive maintenance work. But for other actions, such as settlement, creep and the deterioration of the materials, which may lead to only monotonically increasing deformation, can be well handled with engineering measures in the operational stage, rather than be born by the structure itself. In this case, the design and construction shall only focus on limited challenges of the whole life cycle, and thus only cost only part of the expenses.

To do so, a health monitoring system based on service condition shall be established, so that corresponding engineering measures can be taken to solve specific problems as soon as the deformation reaches or exceeds the limit. The health monitoring system shall adopt limit standards or thresholds as a minimum, so that it can reflect the ability of the structure to maintain operational performance. Also, adequate inspection facilities and engineering measures are necessary to make sure the infrastructure is observable, accessible, maintainable and replaceable.

Taking a high speed arch bridge with the main span of 445 m as an example, this paper studies the contraction creep limit under the combined action of temperature and live load. The limit is then adopted for the static deformation control during the operational stage. By adjusting the height of the bearing, the requirements of running high speed train safely is met.

1 About the Studied Bridge

The studied bridge is a 721.25 m long-span deck type reinforced concrete arch bridge on a high speed line. The main span is a 445.00 m deck type reinforced concrete arch, and the approach span and over-arch spans are 1×32 m prestressed concrete simply-supported box beam + 2×65 m+8×42 m+2×65 m prestressed concrete rigid frame continuous beam + 2×37 m prestressed concrete continuous beam (see Fig. 1). The curve of the deck deformation caused by lower temperature and residual contraction creep within the T-frame on both sides and the main span is shown in Fig 2.

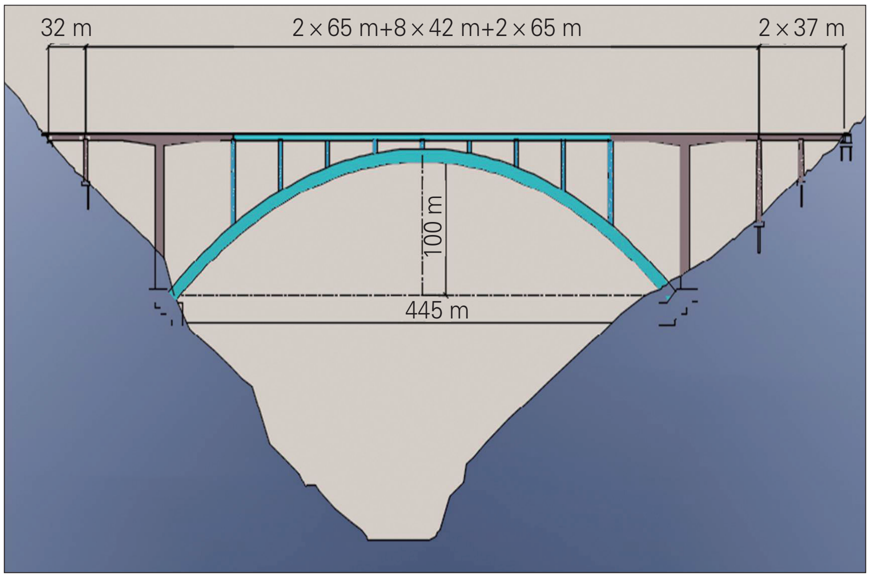
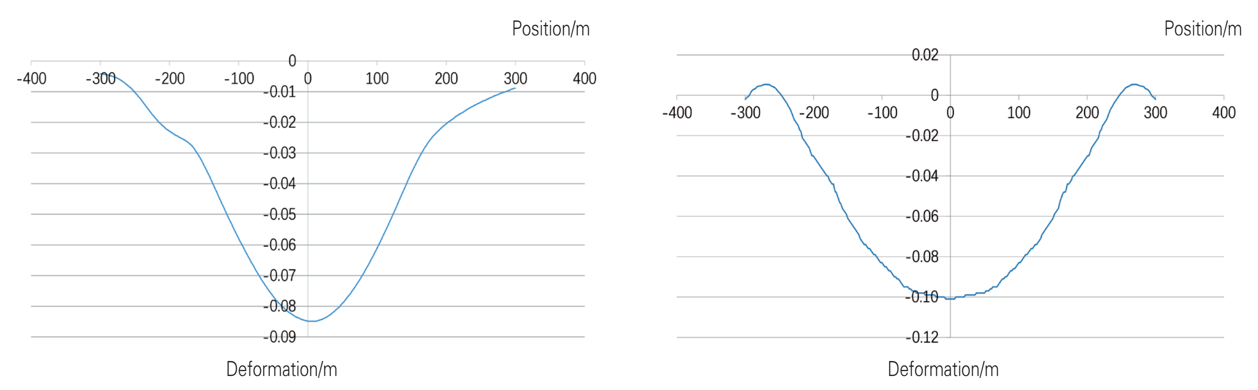


Fig. 1 Structure of the deck type arch bridge on a high speed line



(a) Deck deformation curve under 15°C of lower temperature (b) Deck deformaction curve casued by residual contraction creep

Fig.2 Curve of the deck deformation caused by lower temperature and residual contraction creep within the T—frame on both sides and the main span

2 Parameter Selection for the Static Deformation Control of Long-span Bridge

The deck formation of the long-span bridge caused by the combined action of temperature, contraction creep and other factors shows as long wave irregularity. The irregularities caused by different factors are correlated in the influence on the riding quality of the train operation. The limitation on a certain parameter does not effectively improve the train's running status on the bridge or maintain the track geometry. Therefore, in terms of the mechanism, the deformation shall be controlled by its total amount. As soon as the limit on the total amount of deformation is defined, the control standard of contraction creep can be calculated. Then the predictions on adjustment amount and the time of adjustment of the bearing are made accordingly and these adjustments shall be considered and made available in the design stage.

2.1 Status quo at home and abroad of long-wave track irregularity management

In Japan, long-wave irregularity is managed in terms of a 40 m chord corresponding to its amplitude. The proposed control value of section irregularity of a high speed line is 40 m and the amplitude of the chord shall not exceed 6 mm. While for long-span bridge, the proposed control value of irregularity is 40 m and the chord amplitude shall not exceed 7 mm. Japanese researchers compared the test results with the 40 m chord amplitude control results and found that the maximum value of train dynamic index and 40 m chord are highly consistent. (see Fig. 3). The relevant documents also mentioned that if the train operation speed increases, the control amplitude can be reduced correspondingly.

In France, 33 m chord and the corresponding amplitude is taken as the safety control index for high speed railway. In the US, for lines over Level 6 operating at the speed of 177~322 km/h, two level measuring standards at 18.9 m and 37.9 m are adopted.

In China, track dynamic irregularity management is divided into four levels as Regular Maintenance, Comfort Degree, Temporary Repair and Speed Restriction. For the lines of 200~250 km/h, the standard wave length at longitudinal level and alignment is 1.5~42.0 m and 1.5~70.0 m, while that for lines of 250(not included)~350 km/h is 1.5~42.0 m and 1.5~120.0 m. The static track chord measuring control standard mainly refers to the new line construction track geometry static acceptance standard for ballastless high speed lines in

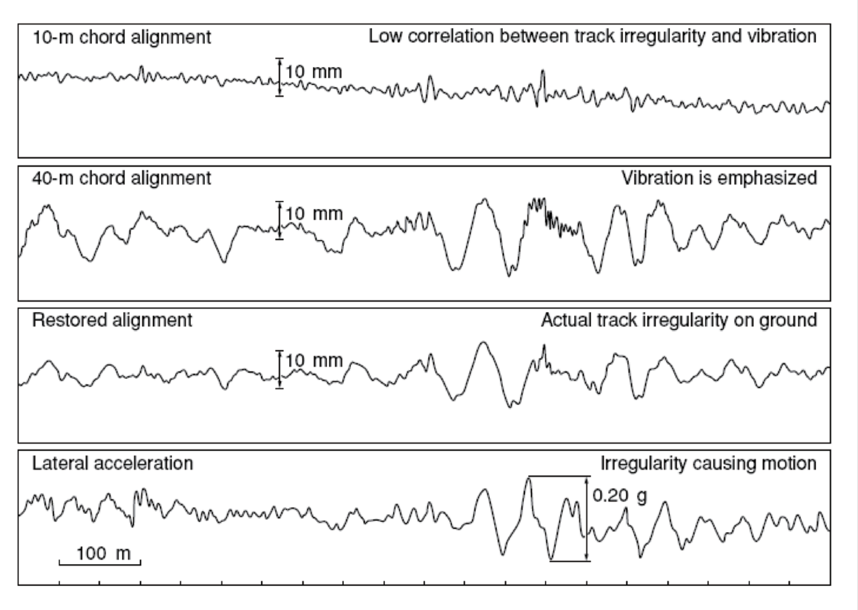


Fig.3 Relationship between 10 m/40 m amplitude and train response

Germany, as well as the engineering practices of Beijing—Tianjin Intercity Line and Beijing—Shanghai High Speed Line. Due to the different distance between fasteners of different types of slab track in China, 48α or 480α is adopted, in which α represents the fastener distance of different types of slab track. See Table 1 and Table 2 for the track geometry dynamic and static tolerance management.

From the above comparison, we learnt that the track dynamic management standard in China is based on the amplitude of a certain range of wave length, while the static long chord measuring standard in China and Germany adopts the chord offset evaluation method with 5, 150 m chord distance checking of fixed 30, 300 m chord. In Japan, France, the US, Russia, the evaluation is carried out based on the midpoint chord distance of fixed chord distance.

2.2 Parameter selection of static deformation control for long-span bridge

China's *Code for High Speed Railway Design* stipulates the minimum vertical curve radius, which is based on the vertical acceleration of the vehicle $[a]=0.4\ \text{m/s}^2$ (not considering the influence of track irregularity, train damping or stiffness), which is:

$$R_{\min}=\frac{v^2\ \text{km/h}}{3.6^2[a]}$$

When $[a]=0.4\ \text{m/s}^2$, the calculated equivalent curvature radius is as shown in Table 3. That is, when the minimum curvature radius of the deck deformation curve is within the limits of Table 3, the safety and comfort performance of the train can meet the requirements under the premise of regular track maintenance and line construction.

The influence of the deck deformation curve on the car body vibration of long span bridges such as cable-stayed bridge, continuous rigid frame and suspension bridge is similar to the vertical curve. There were also successful

Table 1 250~350 km/h high speed track dynamic quality tolerance values

Item	200 ~ 250 km/h				250（Not included）~ 350 km/h			
	Regular maintenance	Comfort degree	Temporary repair	Speed restriction 160	Regular maintenance	Comfort degree	Temporary repair	Speed restriction 200
Longitudinal level（1.5 ~ 42.0 m）	5	8	11	14	4	6	8	10
Alignment（1.5 ~ 42.0 m）	5	7	8	10	4	5	6	7
Longitudinal level（1.5 ~ 70.0 m or 1.5 ~ 120.0 m）	6	10	15		7	9	12	15
Alignment（1.5 ~ 70.0 m or 1.5 ~ 120.0 m）	6	8	12		6	8	10	12

Table 2 Long chord measuring acceptance tolerance values (acceptance standard for newly built ballastless line)

Item	Baseline length /m	Distance between measuring points /m	Tolerance /mm
Longitudinal level	480*a*	240*a*	≤10
	48*a*	8*a*	≤2
Alignment	480*a*	240*a*	≤10
	48*a*	8*a*	≤2

Table 3 Relationship between curvature radius and acceleration

Train speed v/（km·h^{-1}）	Calculation of minimum vertical curve radius/m	Recommendation in the Code/m	Actual acceleration corresponding to the recommendation value /（m·s^{-2}）
$v<250$	12,056	15,000	0.32
$250\le v<300$	17,361	20,000	0.35
$300\le v\le 350$	23,630	25,000	0.38

examples of deformation control using curvature radius in the past design practices. However, for the calculation of the upper deck arch bridge in this study, it is found that the minimum curvature radius is at the top of the arch, R=2,863 m, when considering only the lower and higher temperature difference; The minimum curvature radius is at the joint of T frame and the continuous beam above the arch, R=1,270 m, when considering only the 0.45-time residual contraction creep. When overlapping the lower temperature difference curve and the 0.50-time residual contraction creep curve, the minimum curvature radius is only 855 m, which are all far from the curvature radius requirement of 25,000 m. The reason is that the static deformation curve of a long span deck arch bridge includes not only the long wave component generated by the span of the arch bridge, but also the medium wave component generated by the arch structure, and it is difficult to achieve the static deformation of the bridge deck with the curvature radius constraint. Therefore, the curvature radius should not be adopted as the control factor of the static deformation curve of long span bridges.

Wavelength amplitude management has been used as a dynamic management standard for track irregularity quality in China. But the longest wavelength is 120 m. For long-span bridges when the span exceeds 120 m, this standard is not adoptable anymore. Consequently, the wavelength amplitude shall not be used as the control index for static deformation curve of long-span bridges.

According to the above research on the control limits of long wave irregularity in foreign countries, the chord measurement method can be used as a control index of static irregularity. The chord measurement method is based on a certain length of line as the baseline and the chord distance from the midpoint of the baseline to the rail surface as the measurement value. The result of track irregularity is $v=u_2-(u_1+u_3)/2$. The mechanism of track irregularity measurement by chord method is shown in Fig. 4.

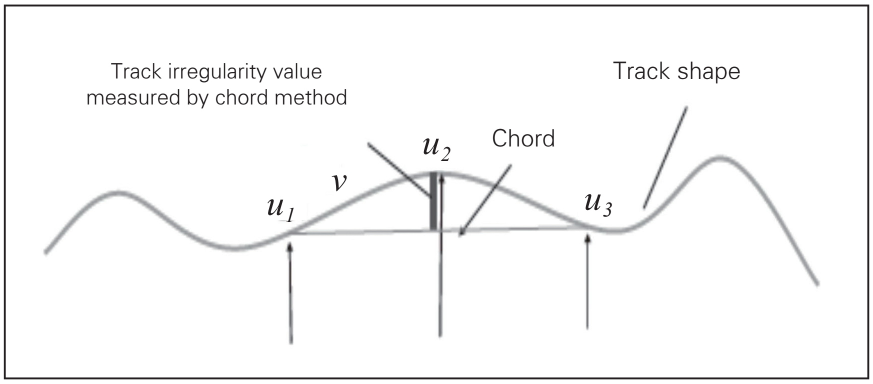


Fig.4 Mechanism of track irregularity measurement by chord method

Chord measurement method can cover the full wavelength range from short wave to long wave, but it cannot reflect certain individual wavelengths. Taking the chord length of 40 m as an example, the wavelength of 2.0, 2.5, 5.0, 10.0 and 20.0 m cannot be controlled by chord measurement no matter how much the amplitude is. But for the long-span bridge in this study, the chord measurement method can reflect the influence of bridge deck deformation.

According to the study results of Japanese scholars' Shigeaki Ono and Takehiko Ukai on track irregularity management standards, under the existing 40 m chord control standard, the vibration acceleration of the E2 train running at 275 km/h is higher than that of the FASTECH train running at 360 km/h, and the 40 m chord value of 6mm is rather equivalent to the 60 m chord value of 7 mm in terms of train response. Considering that there is no periodicity in the deformation of long-span bridges, and the dynamic performance of high speed trains is better than that of medium speed trains, therefore, it is proposed that further analysis will be carried out taking 40 m chord 7 mm limit value as the overall limit of deck static irregularity to the Sannai—Maruyama bridge on the extension line of the Northeast Shinkansen line in Japan.

3 Static Deformation Limit for Long-span Bridge

Referring to the operational practice of high speed railways in Japan, this study takes 40 m chord value 7 mm as the total limit of the static irregularity of the deck track. The static irregularity of the deck track includes the random irregularity of the track structure under regular maintenance condition and the deck deformation, while the deck deformation includes the influence by both temperature and contraction creep, so they need to be analyzed separately.

3.1 Chord measurement results of irregularity on earth section

Taking the Beijing—Shanghai high speed railway as the engineering background and taking 500 m as one section, the track irregularity on the ground-level sections is measured by the 40 m chord method. The maximum value results are shown in Table 4.

Table 4 shows that the maximum irregularity value of K1013—K1015.5 section appears in the first 500 m section. But in fact, the maximum value appears at the starting time of the track inspection and the cusp of irregularity appears, and thus this value has no reference meaning.

The average value of the above 4 working conditions by chord measurement method is 3.280 mm. The final maximum value of chord measurement method of track irregularity on ground section is selected as 3.500 mm, which can represent the maximum value of random track irregularity under regular maintenance condition.

In conclusion, when the total limit of chord measurement is 7 mm, the limit of bridge deformation by chord measurement method is 3.5 mm.

Table 4 Maximum value of track irregularity by chord measurement on earth sections mm

Section	K887—K880	K1013—K1015.5	K925—K927	K951—K953
500 m section 1	2.625	9.227	5.885	2.822
500 m section 2	1.757	3.365	1.538	3.018
500 m section 3	2.518	6.185	4.043	3.380
500 m section 4	3.112	4.035	2.815	2.398
500 m section 5	2.435	4.215		
500 m section 6	2.900			

3.2 Deck deformation limit of a long-span arch bridge determined by chord measurement method

The static deformation control of bridge aims at residual contraction creep and temperature is not the target for static deformation control due to its periodicity. The bridge deformation curve caused by temperature and residual contraction creep is analyzed with the chord method. Then the temperature caused deformation+$k\times$ residual contraction creep are calculated. The value of k is 0~1.00, and the temperature rise and fall is 15 ℃ according to design data. The results are shown in Table 5.

Table 5 shows that to meet the limit of 3.0~3.5mm of deck deformation curve, the creep deformation value should be multiplied by the coefficient of 0.40.

Table 5 Calculation results of chord measurement method mm

k	Higher temperature+Creep	Lower temperature+Creep	Creep
0.00	2.314	2.314	3.374
0.05	2.287	2.352	
0.10	2.267	2.423	
0.20	2.392	2.647	
0.30	2.582	2.967	
0.40	2.782	3.296	
0.50	2.983	3.629	
0.60	3.188	3.965	
0.70	3.392	4.301	
0.80	3.597	4.637	
0.90	3.801	4.973	
1.00	4.006	5.309	

3.3 Train-bridge coupling analysis and verification of deck static deformation limit

To verify the limit value of the deck deformation curve obtained by chord measurement method, CRH380BL EMU (8-car consist) is used to measure the track irregularity of the Wuhan—Guangzhou high speed railway. The combined curve of temperature and residual contraction creep is used as the initial irregularity value of the deck to carry out train-bridge coupling vibration analysis, in which the coefficient of residual contraction is 0.4~1.0, and the train response results are shown in Table 6. In contrast, the train response without considering irregularity or initial deck deformation is also presented.

According to the *Code for High Speed Railway Design* in China, the vertical acceleration of the car body on the bridge should not exceed 1.3 m/s^2. Under the influence of environmental factors, the vertical comfort degree should meet the criteria. According to the working condition 8 of Table 6, it is required that the residual contraction creep is 0.6 times of the total creep value after track laying, that is, the maximum creep deformation does not exceed 60 mm. Fig. 5 shows the deck deformation curve under this working condition.

Based on the above analysis, it is suggested that the limit of bridge deck deformation caused by environmental factors shall be controlled at 4 mm/40 m under the condition of 350 km/h for long-span arch bridge. For the deck arch bridge in this study, the corresponding upward residual creep value is 60 mm.

4 Conclusion

(1) For high speed railway long-span bridges, the deformation limits in the design standards shall not be adopted by simple superposition during the operation stage. The health monitoring system based on service condition shall be established, so that corresponding engineering measures can be taken to solve specific problems as soon as the deformation reaches or exceeds the limit.

(2) In order to control the track irregularity caused by deck deformation, the adaptability of the wavelength amplitude, curvature radius and chord measurement method is compared and analyzed. When the span of the bridge is long, the wavelength of the deck deformation curve is often

Table 6 Train response results combining temperature deformation and contraction creep

Working condtion	Included/not included in irregularity	Deck initial deformation	Speed / $(\mathrm{km\cdot h^{-1}})$	Car acceleration/ $(\mathrm{m\cdot s^{-2}})$		Vertical conform	
				Motor	Trailer	Motor	Trailer
1	Included	None	350	1.040	1.126	2.599	2.546
2	Not included	None	350	0.487	0.472	1.995	2.085
3	Not included	Lower temperature15 ℃+ Contraction creep	350	1.307	1.428	3.019	2.958
4	Not included	Higher temperature15 ℃+ Contraction creep	350	1.226	1.263	2.774	2.739
5	Included	Lower temperature15 ℃+ Contraction creep	350	1.573	1.731	3.114	2.979
6	Included	Lower temperature15 ℃+ 0.80×Contraction creep	350	1.408	1.536	3.007	2.910
7	Included	Lower temperature15 ℃+ 0.70×Contraction creep	350	1.292	1.374	2.710	2.843
8	Included	Lower temperature15 ℃+ 0.60×Contraction creep	350	1.209	1.276	2.802	2.858
9	Included	Lower temperature15 ℃+ 0.50×Contraction creep	350	1.152	1.179	2.696	2.659
10	Included	Lower temperature15 ℃+ 0.40×Contraction creep	350	1.123	1.081	2.628	2.722
11	Included	Higher temperature15 ℃+ Contraction creep	350	1.507	1.602	2.812	2.972
12	Included	Higher temperature15 ℃+ 0.80×Contraction creep	350	1.341	1.407	2.792	2.872
13	Included	Higher temperature15 ℃+ 0.70×Contraction creep	350	1.292	1.374	2.710	2.843
14	Included	Higher temperature15 ℃+ 0.60×Contraction creep	350	1.209	1.276	2.802	2.858
15	Included	Higher temperature15 ℃+ 0.50×Contraction creep	350	1.152	1.179	2.696	2.659
16	Included	Higher temperature15 ℃+ 0.40×Contraction creep	350	1.123	1.081	2.628	2.722

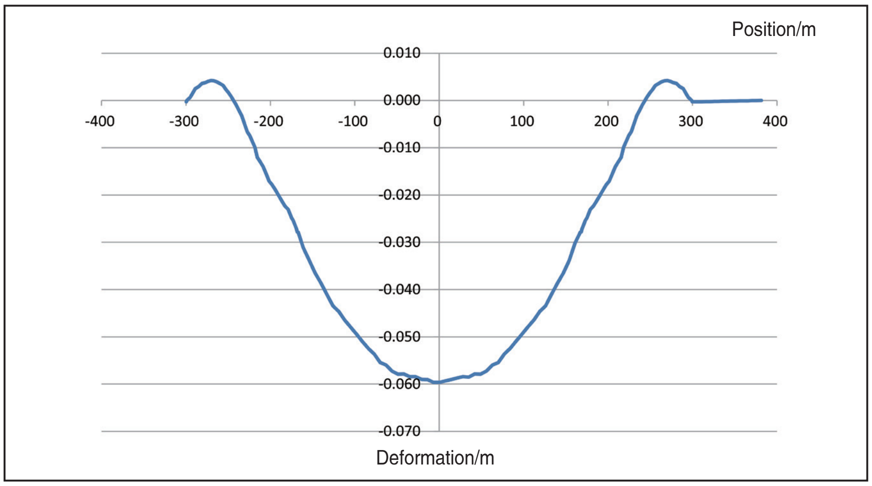


Fig.5 Maximum deck defromation curve meeting train running performance of a deck arch bridge on a certain high speed line

beyond the scope of the track quality dynamic management standard, and thus the curvature radius is not suitable for the deck deformation control of the deck arch bridge, and the chord measurement method is finally recommended as the control index of deck static irregularity.

(3) Referring to the operational practice of the high speed railway in Japan, this study takes 40 m chord value 7 mm as the total limit of the static irregularity of the deck track. After eliminating the random irregularity of the track structure, it is suggested that the limit of bridge deck deformation caused by environmental factors shall

be controlled at 4 mm/40 m under the condition of 350 km/h for long-span arch bridges.

(4) To reduce heavy maintenance and repair work, the deck deformation caused by periodic effects such as temperature and sunshine shall not be considered as the subject of static deformation control. The bridge deck deformation caused by periodic effect needs to be borne by the structure. In the design, the deck deformation caused by settlement, contraction creep and other environmental factors should be taken into account as a static control target. The control standard of contraction creep or settlement can be calculated based on the total limit value of 4 mm/40 m deck static deformation. Then the predictions on adjustment amount and the time of adjustment of the bearing can be made accordingly and these adjustments shall be considered and made available in the design stage.

(5) To control the long-term static deformation of bridges, it is necessary to establish a health monitoring system based on service condition, and in the design and construction process, the possible interfaces for engineering measures and monitoring measures shall be reserved for the operation stage.

References

[1] Eurocode 1: Actions on Structures Part 1.4: General Actions: Annex E[S]. 1999.

[2] TY〔2012〕No.83, *Regulations of Ballastless Track Maintenance of High-speed Railways* [S]. Beijing: China Railway Publishing House, 2012.

[3] FRYBA L. Dynamic interaction of vehicles with tracks and roads [J]. *Vehicle System Dynamics*, 1987(16): 129-138.

[4] CHU K H, GARG V K. Railway-bridge impact: simplified train and bridge model [J]. *Journal of the Structural Division*, 1979(9): 105.

[5] ADAMS G G, BOGY D B. Steady Solutions for Moving Loads on Elastic Beams with One-Sided Constrains [J]. *Journal of Applied Mechanics, Transactions of ASME*, 1974(4): 800-804.

[6] ZHANG N, XIA H, DE ROECK G. Spectrum and Sensitivity Analysis of Vehicle-Bridge Interaction System [C]. Taipei: Proceedings of ISEV, 2007.

[7] Pan Jiaying, Gao Mangmang. *Dynamic Analysis on Railway Train-Track-Bridge System* [M]. Beijing: China Railway Publishing House, 2008.

[8] Gao Mangmang. Study on HS Train-Track-Bridge Coupled Vibration and Vehicle Running Performance [D]. Beijing: China Academy of Railway Sciences, 2001.

[9] KALKER J J. Survey of wheel-rail rolling contact theory [J]. *Vehicle System Dynamics*, 1979, 8(4): 317-358.

[10] Ye Yangsheng, Wei Feng, Hu Suoting, et al. Study on Construction Technologies of Precast Simply-supported Box Beam on High-speed Railway with 40m Span [J]. *China Railway*, 2016(10): 5-10.

[11] TB 10621—2014, *Code for Design of High Speed Railway* [S]. Beijing: China Railway Publishing House, 2014.

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