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Condition assessment for high-speed railway bridges based on vibration response caused by vehicles

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ABSTRACT

This paper analyzes the reasons of stiffness degradation for high speed bridge and put forward a specific and effective method for the condition assessment of bridge. Based on the bridge health monitoring system, this paper does comparisons and analysiswith the strain response data to identify the stiffness degradation. Firstly, according to the daily monitoring strain data, the location of stiffness degradation and the corresponding position-number of sensors can be confirmed. But whether the result is accurate or not has a certain relationship with the data, so it should be noted the selection of data. Then, after knowing the location, this paper elects the index β_i to identify the degree of stiffness degradation. Through analyzing the relationship between β_{ir} and the simulating degradation degree α, it can be concluded that for a same simply supported beam bridge, no matter where its stiffness degradation happens, the degradation curve all follows a certain rule. By obtaining the location and degree of the bridge, the process of condition assessment is finished. The method used in this paper to locate and identify the stiffness degradation is simply and effective.

1. INTRODUCTION

With the rapid development of high speed railway, bridge begins to play an important role in the high speed –track-bridge system. Its health is in closely connection with the safe and comfort operating. When the high speed railway bridge structure is in the process of long-term service, it will be affected by the wind, earthquake, temperature, humidity, train vehicles, chloride ion erosion, carbide and other environmental loads. In the normal operation of bridge, although these environmental loads cannot significantly damage the strength of structure, for long-term behavior of the bridge, especially for high speed train operation safety it has a critical influence. Under the action of corrosion environment and vehicle loads, the internal structure will appear damage and accumulate gradually by the invasion of the corrosive medium, and led to the decrease of the bearing capacity of structure and reliable declined. At the same time, the degradation of material will lead to the decrease of steel material area, the decline of mechanical property, the bond-slip between concrete and steel and even corrosive cracking of the steel within the bridge structure. This can cause stiffness degradation sharply and structure down-warping, which have extremely bad effects on the traffic safety of high speed railway. For the structure of high speed railway prestressed concrete bridge, it can be seen that stiffness degradation of structure results in the decrease of driving safety which is the control factor for high speed railway bridge structure failure. Studying the bridge structure performance degradation model, assessing reasonable and predicting the performance degradation of high speed railway bridge structure is the important basic research work for guaranteeing the safe operation of high speed railway train.

Considering many reasons may lead to the stiffness degradation, it needs to monitor the bridge in real time for checking the stiffness degradation and making condition assessment. Combining bridge health monitoring system and stiffness degradation identification method, this paper wants to form a set of bridge condition assessment method to evaluate the state of bridge. The bridge health monitoring system compared with the traditional monitoring methods had the advantage of instantaneity, automation, integration and networking. By using of these advantages of bridge health monitoring system, this paper hoped to get the real-time response when detecting the bridge. By means of processing and analyzing the response data, it could pick out the relevant index for condition assessment. In comparison of the indexes in health or degradation could evaluate the bridge. The condition assessment of bridges based on the health monitoring system was shown in Fig.1.

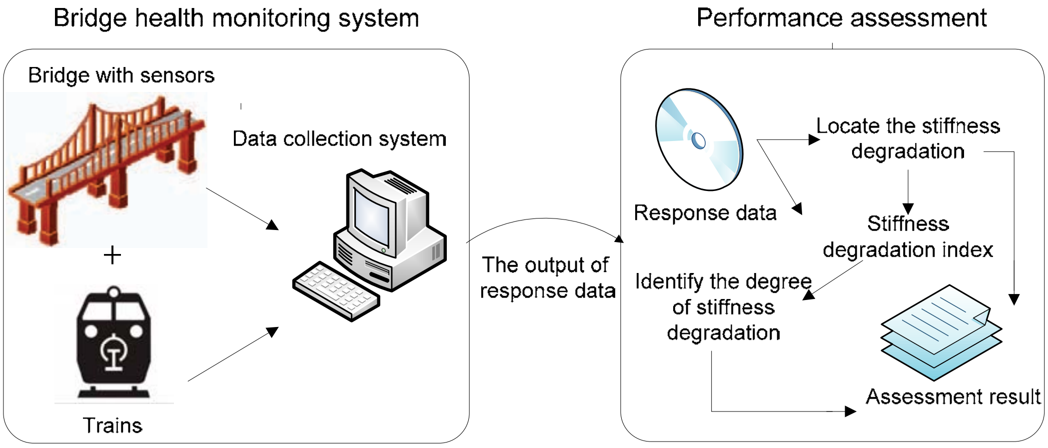

Fig.1 Condition assessment for bridges based on the health monitoring system

2. CONDITION ASSENSSMENT METHOD

In the process of the high speed train going by the bridge, the train-track-bridge coupling system will generate the corresponding response. Through analyzing the features of response data of bridge, the stiffness degradation information of bridge can be obtained. As the curve showed in Fig.2, it is the response data of the bottom on a simple-supported beam bridge. In the figure, it can be clearly seen: (1) the high speed train began to drive on the bridge at t=6.5s, and the bridge started to generate forced vibration; (2) t=6.5s to 9s, the train was on the train, and the amplitude of response data caused by vehicle was obvious; (3) after t=9s, the train leave the bridge, and the bridge began to do free damping vibration. However, according to the structural dynamics and any other theory, no matter what the shape of the beam vibration curve is, the mechanical and dynamic properties the curve reflected can show the change characteristics of the stiffness of the structure.

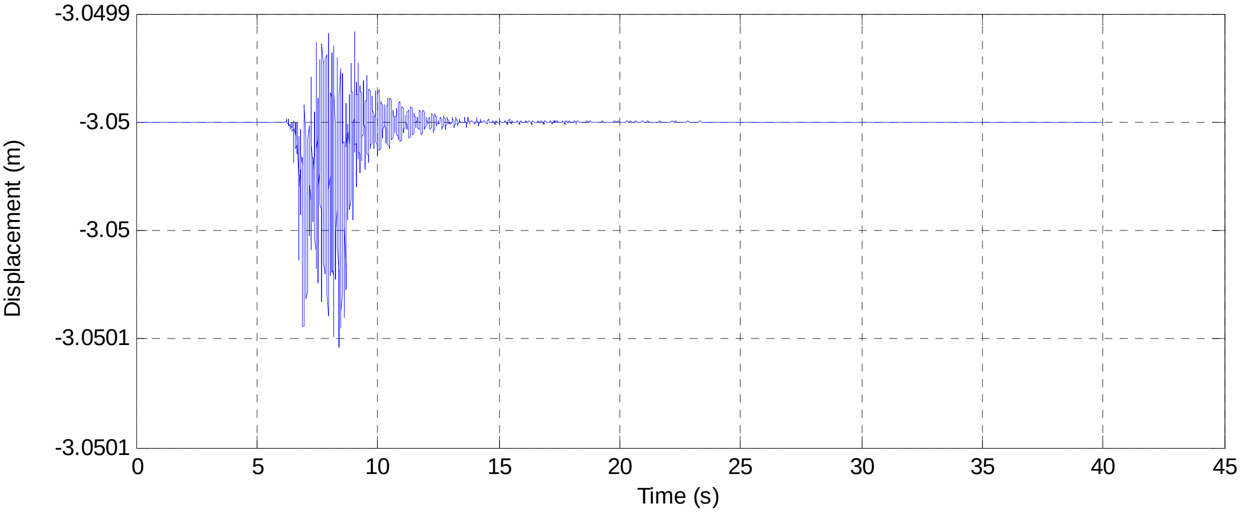

Fig.2 The response data of somewhereon a simple-supported beam bridge

The purpose of this paper is to use the features of vibration response data to analyze the stiffness degradation situation of the bridge when a train goes by. The analysis method in this paper do not need to use the complicated mechanics analysis model of bridge, only need to arrange a certain number of sensors on the beam and analyzing the response data which is collected by those sensors, and by doing all those, the location and degree of the stiffness degradation can be identified.

2.1 Locate stiffness degradation

In general, the structure health monitoring system could measure the acceleration, displacement, temperature, strain response and any other response data. In the various response data mentioned above, the strain response could mostly reflect the stiffness change of the structure. This paper selected the strain response data to identify the stiffness degradation of the bridge.

In this paper, by checking the strain data of daily accumulation by health monitoring system could observe the change of strain of the measure points on the whole span. Knowing the change of strain could identify the stiffness degradation locations.

Assumed that $\{\psi_u\}$ and $\{\psi_d\}$ were respectively the strain response of the health bridge and the bridge after stiffness degradation. At the j point of the structure, it adopted the absolute value of both the two kinds of responses did subtraction as the basic, and used the value to identify the locations of stiffness degradation, the absolute value was like that: $\Delta\psi(j)=|\psi_u(j)-\psi_d(j)|$. At the locations of stiffness degradation, its $\Delta\psi$ was obviously bigger than other $\Delta\psi$. Checking the $\Delta\psi$ of all the sensors could identify the locations of stiffness degradation. The more number of sensors were arranged, the more accurate the locations were identified. Because the stiffness degradation was a gradual process, putting together the strain response of when the same axle of the train passed the same location on the bridge, the stiffness degradation characteristics was more evident.

This method was very simple, but considering the influence of the external environment factors to the strain response data, it needed to pay attention to note some premises:

(1) Need a lot of daily monitoring data of bridges for analysis;
(2) Better to analyze under similar external environment temperature.

2.2 Identify the degree of stiffness degradation

Through locating stiffness degradation in section 2.1, the corresponding sensor number *i* could be accurately obtained. After knowing which sensor may occured stiffness degradation, the steps for identifying the degree were multiple.

This paper would use the theory of strain modal analysis for analyzing the response data, to get the strain modal curve of the bridge span. The value corresponding to the strain modal curve was strain modal vector $\varphi = \left[\varphi_{1r}, \varphi_{2r}, ..., \varphi_{ir}, ..., \varphi_{nr}\right]$. Picking out a reference value φ_b from the strain modal vector for normalized calculation:

$$\left\{\phi_{1r,}\phi_{2r,}, ..., \phi_{ir,} ...\phi_{nr,}\right\} = \left\{\frac{\varphi_{1r}}{\varphi_{br}}, \frac{\varphi_{2r}}{\varphi_{br}}, ..., \frac{\varphi_{ir}}{\varphi_{br}}, ..., \frac{\varphi_{nr}}{\varphi_{br}}\right\}$$

Where r was represented the modal order; n was represented the total number of sensors; I was the sensor number.

After normalized calculation, this paper took a stiffness degradation index β_{ir} to identify degree.

$$\beta_{ir} = \frac{\phi_{ir}^{*} - \phi_{ir}}{\phi_{ir}} * 100\%$$

ϕ_{ir}^{*} was the modal value of the stiffness degradation bridge.

The size of β_{ir} and the degree of stiffness degradation had certain relations, this paper would account for the relations in the following case study.

3. NUMERICAL CASE STUDIES

3.1 The simulation of the train-track-bridge interaction model

This paper established the train-track-bridge model. Through simulating the dynamic interaction of train-track-bridge, it could obtain the response data of bridge.

3.1.1 The mechanical model of high speed train and track

This paper selected the domestic commonly used high speed train type CRH2 to simulate (CRH is short for China Railway High-speed). CRH2 emu (electrical multiple unit) is the four axis locomotive vehicle model, vehicle is a system composed of car body, bogies, wheel sets and any other basic components linked by primary suspension , secondary suspension, vertical damper, longitudinal traction link, torsion spring and other elements. In order to simplify the calculation and save the computation time, in the locomotive vehicle dynamics research, these components are usually regarded as rigid body. Among the basic components, there are elastic or rigid constraints, to limit the relative movement of them.

The design weights and complement weight tale of every section of the CRH2 emu is shown in Table.1 and Table.2, its specific parameters can be seen in Table.3.

Table.1The design weighs of every section in CRH2 emu

Car number	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***Total weight /t***
Car type	T1	M1	M2	T2	T1	M2	M1	T2	
Service weight /t	42.8	48	46.5	42	44.1	48	46.8	41.5	359.7
Complement weight /t	47.2	56	53.3	50	48.5	56	50.9	46.6	408.5
Average axle weight /t	11.8	14	13.3	12.5	12.1	14	12.7	11.7	102.1

Table.2The complement weight of every section in CRH2 emu

Car number	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***Total***
Complement	51	100	85	100	55	100	51	64	610
Complement weight /t	47.2	56	53.3	50	48.5	56	50.9	46.6	408.5t
The percentage of complement weight to total weight	11.9%	14.2%	13.5%	12.7%	12.3%	14.2%	12.9%	11.82%	

Table.3The specific parameters of CRH2 emu

Parameters /mm	***Value***	***Parameters /mm***	***Value***	***Parameters***	***Value***	***Parameters /t***	***Value***
Track gauge	1435	Car width	3380	Number of bogie	16	Wheelsetweight	20
Leading unit length	25700	Car height	3700	Total length of car body /m	201.4	Wheel diameter	860
Middle car length	25000	Fixed wheelbase	2500	Number of axles	32	Bogie weight	35
Bogie pitch	17500	Coupler height	880^{+10}_{-5}			Max axle weight	14

3.1.2 The bridge model

This paper selected Yang Zhuang Bridge as the simulated simply supported beam bridge model. This bridge was a 3-32m prestressed concrete simply supported box gird bridge in the high speed railway project from Bei Jing to Shang Hai. The section of bridge was tapered section, and its specific cross section form was shown in Fig.3.

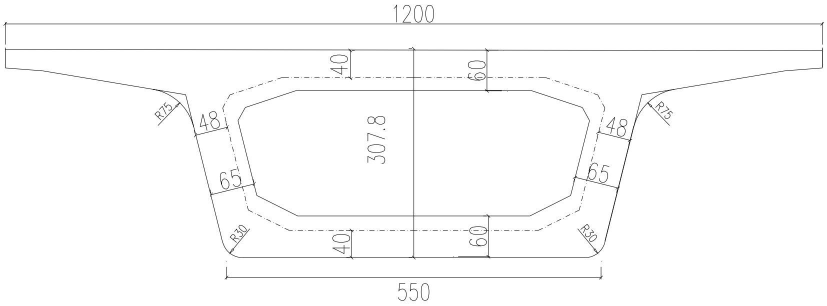

Fig.3The section of sidespan and midspan schematic plot

Note: The dotted portion in the figure was the internal cross section size of midspan

3.1.3 Simulation of the model

Firstly, after obtaining all the structure parameters, the bridge model including span, pier and abutment is build up and meshed in ANSYS, and the high speed train and track model are simulated in UM. Secondly, it needs to set the interface file of ANSYS and UM, so that to load the bridge model and its N order modal information into UM. Then, the train-track model and the bridge model should be coupled together in UM. Finally, by solving and analyzing the train-track-bridge model in VBI module, the displacement, acceleration, velocity, stress, strain and more other information can be obtained, the process is shown in Fig.4.

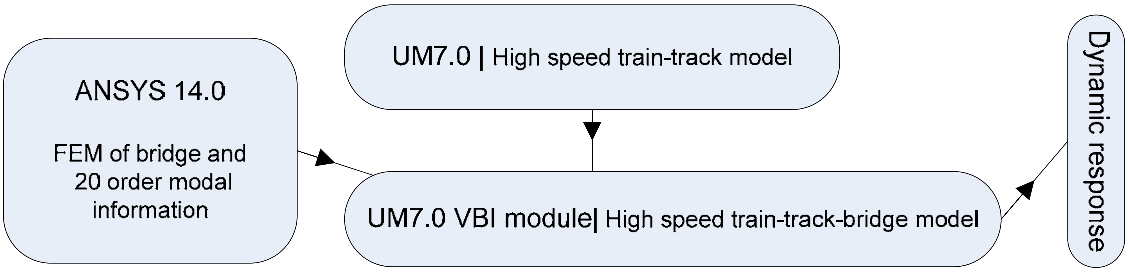

Fig.4High speed train-track-bridge simulation model established process

By the process above, the high speed train-track-bridge simulation model can be shown in Fig.5.

Fig.5 The high speed train-track-bridge simulation model

3.1.4 The arrangement of sensors on the bridge

According to the stress mechanism of the bridge span bearing bending, the most easily damaged location of box cross section was bottom. The bridge built by this paper was the solid entity model which was different from the most used beam model, and it could be simulated the stiffness degradation at any location by changing its elasticity modulus. In this paper, the location of stiffness degradation was shown in the shadow part of Fig.6. The second span in Fig.5 was selected to simulate the stiffness degradation, and its simplified model was shown in Fig.7.

The three-span simply supported beam numerical model in this paper could get the natural frequency, acceleration, displacement, strain data and so on. However, considering the economic practicality，the bridge with the length of 32m in the practical environment was impossible to arrange so many strain sensors displacement sensors. Due to the strain data could directly reflect the change characteristics of the structure stiffness, applying the theory of section 2.3 and the Fourier transform theory for frequency analysis, this paper only arranged strain sensors on bridge span, and then used the strain response and any other basic data to deduce the natural frequency, displacement and other data. The arrangement of strain sensors was shown in picture (3) of Fig.7.

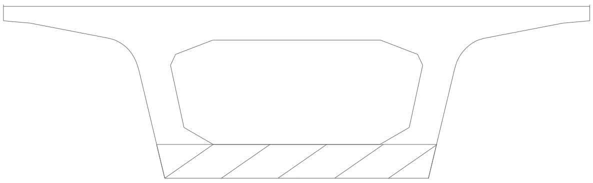

Fig.6 The location of stiffness degradation

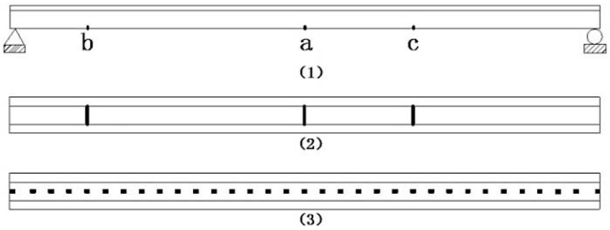

Fig.7Stiffness degradation locations of the second span

In picture (1) of Fig.7, the midspan was at section a; 4.3m was at section b; 22.3m was at section c; picture (2) was the bottom schematic diagram of bridge; picture (3) showed the locations of strain sensors.

The degree of stiffness degradation could be defined as: $\alpha = \frac{E - E^*}{E}$.

where E was the original stiffness of bridge, and E^* was the stiffness after stiffness degradation.

3.2 Locate of stiffness degradation

In order to simulate the actual circumstances of the normal operation, this paper considered four kinds of working conditions. The overall dynamic model was treated as a bridge health monitoring system. Changing the parameters of the whole system to form different working conditions, it could take condition assessment for the bridge after analyzing and comparing the measured response data. The four working conditions were shown in Tab.4.

Table.4 Working conditions

NO.	***Specific Parameter Adjustment***			
	Degradation location	*The degree of stiffness degradation*	*Speed*	*Passenger loads*
1	a	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	80m/s	Normal
2	b and c	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	80m/s	Normal
3	a	10%, 20%, 30%, 40%, 50%	80m/s	Normal
		10%, 20%, 30%, 40%, 50%	60m/s	
4	a	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	80m/s	All full or partial load

Using the strain analysis method, the locations of the stiffness degradation of the four kinds of working condition could be identified. The results were shown in the figures below.

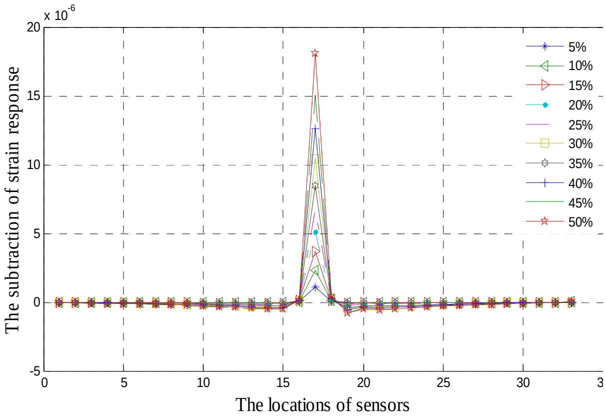

Fig.8Working condition 1

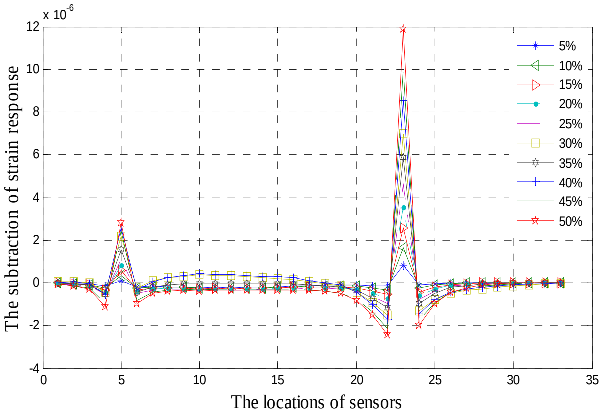

Fig.9Working condition 2

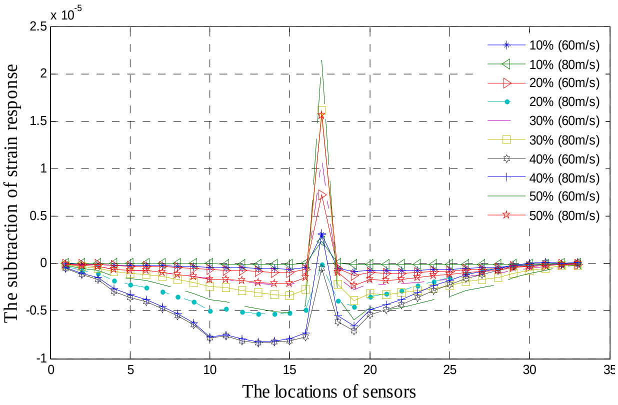

Fig.10Working condition 3

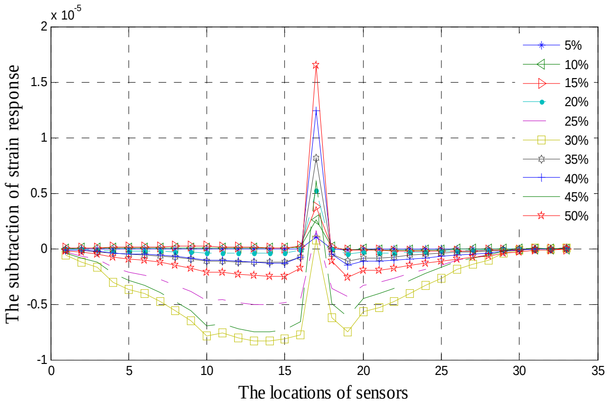

Fig.11Working condition 4

From the identified results, it could be easily seen that the subtraction of the strain at the stiffness degradation point were much bigger than other sensor points. Mixing the four kinds of working conditions together could get the more realistic results, which considered the different speeds, the different locations of stiffness degradation and the different passenger loads. The result was showed in Fig.12.

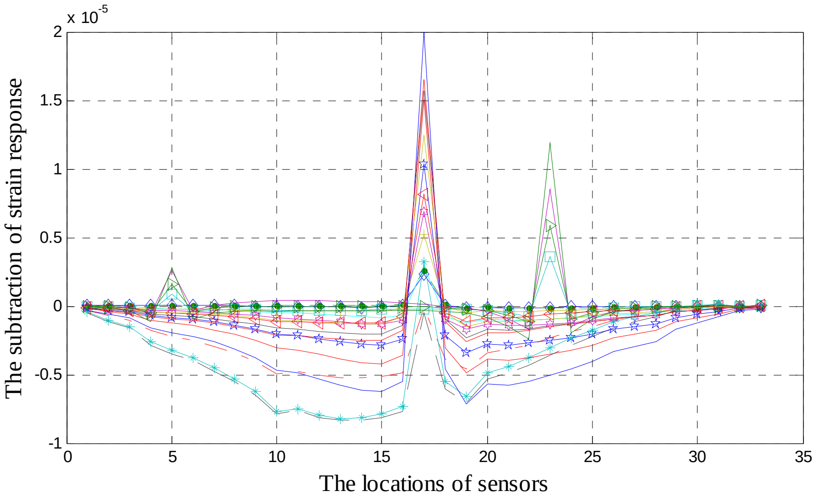

Fig.12 The result of mixing the four kinds of working conditions together

The above identified results showed that it could indeed identify the locations of the stiffness degradation using the strain analysis method. But it needed to notice that this method must be based on the long-term health monitoring of bridges. Through analyzing the accumulation of response data, the changing tendency of the bridge stiffness could be got.

3.3 Identify the degree of stiffness degradation

The above section had put forward the effective method to locate the stiffness degradation of bridge. Here using the theory of section 2.2 to identify the degree of stiffness degradation.

This paper simulated the following eight working conditions under the speed of 80m/s and the same passenger loads. The specific information of the eight working conditions was showed in Tab.5. It should benoted here that the stiffness degradation may happened at single or multiple different places.

Table.5 The eight working conditions

No.	***Working Condition***		**No.**	***Working Condition***	
	location	α		location	α
5	4.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	9	4.3m and 23.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%
6	12.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	10	12.3m and 26.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%
7	16.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	11	4.3m,12.3m and 26.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%
8	22.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%	12	8.3m,12.3m and 23.3m	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%

After simulating the above working conditions, the strain response data should be used the method described in 2.1 to locate the stiffness degradation. It needed to find out that which sensor was the closest sensor to the location of stiffness degradation. When making sure where the stiffness happened, the corresponding index β_i could be used to identify the degree of stiffness degradation. Fig.13showed the relationship between α and β and the fitting curve of the fifth working condition. In the fitting curve, α from 5% to 50% could find all the corresponding β.

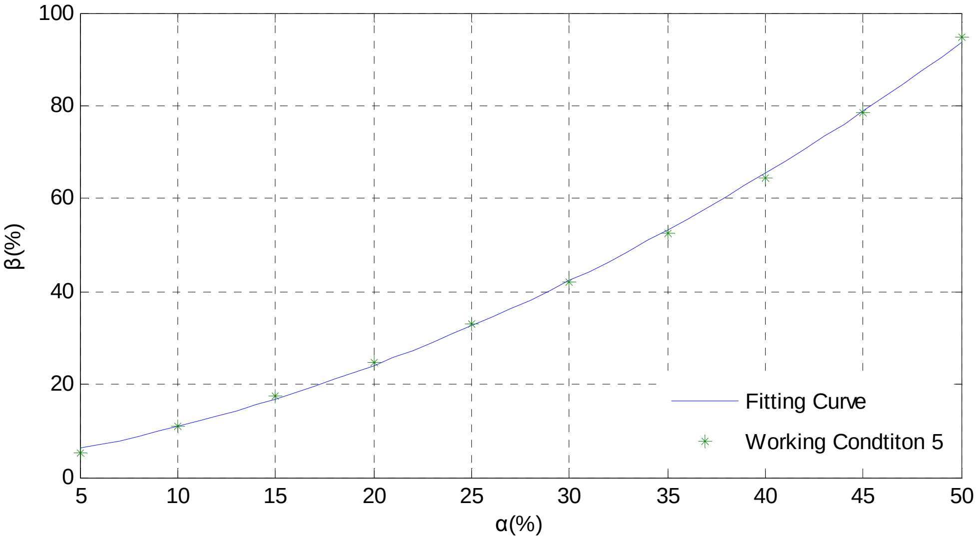

Fig.13Stiffness degradation index versus α in working condition 5

All the β_i of the eight work conditions could be calculated. Focus on the sensors where the stiffness happened. For each sensorin the case of a given α, one point representativeof the relation of α versus β canbe plottedIn Fig.14.In Fig.14, it could be easily seen that α and β had certain corresponding relationship. With curve fitting, the curve function was:

$$\beta=0.0226\alpha^2+0.5693\alpha+2.332$$

Fig.14 showed that with the increase of α, β began to present a tendency of scattered around the curve. It proved that when using this method to identify the degree in case of a smaller stiffness degradation degree, β of the location with single and multiple stiffness degradation could be identified accurately by the fitting curve. When the degree of stiffness degradation was bigger, the identified index β compared with the value calculated by the fitted curve may have a little discrepancy. However, the discrepancy was not very big and acceptable. The case proved that this method was simple and effective, but it needed to note that there were several premise:

(1) Each bridge had its unique fitted curve, different bridges should base on the response data to fitting itself curve.

(2) α-β curve was obtained by a large number of monitoring response data analysis; a small amount of response data could not get the exact curve.

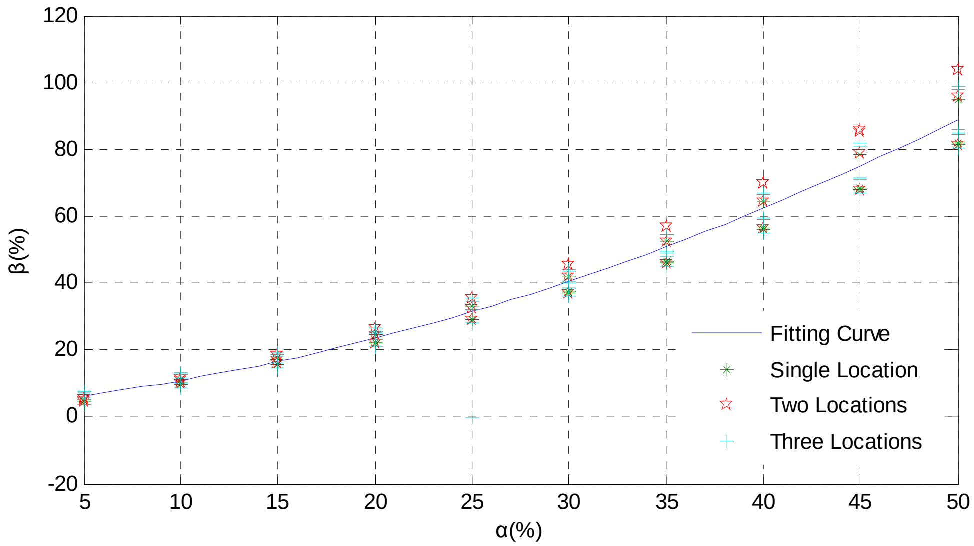

Fig.14Stiffness degradation index versus α in all working conditions

4. Conclusion

This paper developed the method of condition assessment which was mainly used to assess the stiffness degradation situation of the bridge. Based on the bridge health monitoring system, from the strain response data, this method could analyze the location and degree of stiffness degradation. This paper used the subtraction of the strain to locate stiffness degradation, and identified the degree of stiffness degradation with the index deduced by the strain modal theory. The identified results are in accordance with the simulation in advance which proved that the method has the feasibility and rationality. But the location and identification methods of this paper had a certain limit. Due to the response data were influenced by environmental factors such as ambient temperature, the change of these factors may seriously affect the identified results. It needed to choose the corresponding situation where the external environment factors were relatively similar so that can obtain a better result.

REFERENCES

Li S.Z, Wu Z.S.(2008),"A model-free method for damage locating and quantifying in a beam-like structure based on dynamic distributed strain measurements", *Computer-Aided Civil and Infrastructure Engineering*,**23**(5), 404-413.

ZhaiW.M and Xia H (2011). "Train-Track-Bridge Dynamic Interaction: Theory and Engineering Application". *Science Press*, ch.2.

Zhang S.G.(2008), "China Railways CRH2". *China Railway Publishing House*.