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Statistical analyses on multi-scale features of monitoring data from health monitoring system in long cable supported bridges

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Abstract

Strain-time histories and other data acquired from a structural health monitoring system (SHMS) installed on a bridge reflect the real-time structural response of the bridge under actual service and environmental loading. It is necessary to understand the inherent features of the data if we want to have confidence in using them to assess the health state or detect potential damage in the structure. This paper aims at exploring the inherent features of strain-time histories data from SHMS in order to find out their behavior in multiple temporal scales and to obtain reliable, clean and normalized data at the dominant scale of stresses inducing fatigue. Firstly, the strain history data from SHMS installed on Runyang Yangtze Bridges (RYB) were analyzed within three typical temporal scales to explore their different characteristics and their own cut-off frequency which span different orders of magnitude. Then, based on the description of the multi-scale features of the monitored data, a further investigation of the dominant scale controlling fatigue failures was carried out. The result shows that, the strain data corresponding to the typical temporal scales of 10^6, 10^3 and 10^0 sec are caused by temperature change, with cut-off frequency $f_{c,1}$ in the 10^{-2}Hz range, by train load, with $f_{c,2}$ in the 10^{-1}Hz range and by truck load, with $f_{c,3}$ in the 10^0Hz range. Noise shows significant coupling effect when coarse scale strain data are used for the evaluation, which may lead to significant error even it is in small level acceptable in engineering analyses.

Keywords: Multi-scale features; monitoring data; fatigue assessment; strain history; fatigue accumulation;

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1. Introduction

With the development of structural health monitoring technique in recent years, stress spectrum based on real-time strain history recorded by the health monitoring system installed on a bridge is a valid alternative to the acquisition of stress spectrum formerly based on experience and statistics. Compared with stress spectrum in accordance with criterion or statistics, fatigue stress spectrum based on real-time strain history could re-create realistic and accurate structural working conditions therefore making great strides in realizing the exact evaluation of fatigue life, and in ensuring accuracy and reliability of fatigue assessment [1,2]. How to make full use of online monitoring data recorded by health monitoring system to acquire fatigue stress characteristics and the health state of monitored bridge has become an important issue nowadays [3-5].

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Runyang Yangtse Bridge (RYB) is a long-span bridge combining the southern Runyang Yangtse Suspension Bridge (RYSB) and the northern Runyang Yangtse Cable-stayed Bridge (RYCB). The main span of RYSB maintains the first rank in China and the third in the world at present. Strain-time histories and other data acquired from the structural health monitoring system (SHMS) installed on these bridges reflect the real-time structural response under actual service and environmental loading. It is therefore necessary to well understand the inherent features of the recorded data if we want to have confidence for using them to assess the health state or detect potential damage in the structure. This paper aims at exploring the inherent features of strain-time histories data from SHMS in order to find out their behavior in multiple temporal scales and to obtain reliable, clean and normalized data at the dominant scale of stresses inducing fatigue. Statistical analyses on the vast data recorded by SHMS installed on RYSB and RYCB are also presented.

2. Inherent features of strain data from SHMS in multiple temporal scales

The sensor system in the SHMS [6] includes accelerometers (Acc), strain gauges (Str), temperature sensors (T-V,T-Of), displacement sensors (Dspl), anemometers, and GPS. In addition, induction system of vehicle speed and weight, data acquisition and processing system (Ki, i=1~11) are involved. The types and locations of the sensors in the RYSB are shown in Fig. 1. The main girder with the width of 38.7m and the height of 3.0m of RYSB is an orthotropic box-shaped girder constructed by welding many plates, beams and bars. 80 strain gauges were installed on beams and slabs of RYSB including vibratory strain gauges (Str-V), optical fiber sensors (Str-Of) and welded strain gauges (Str-R). Vibratory strain gauges and welded strain gauges are applied to record dynamic strain history of related members mostly installed in the mid-span.

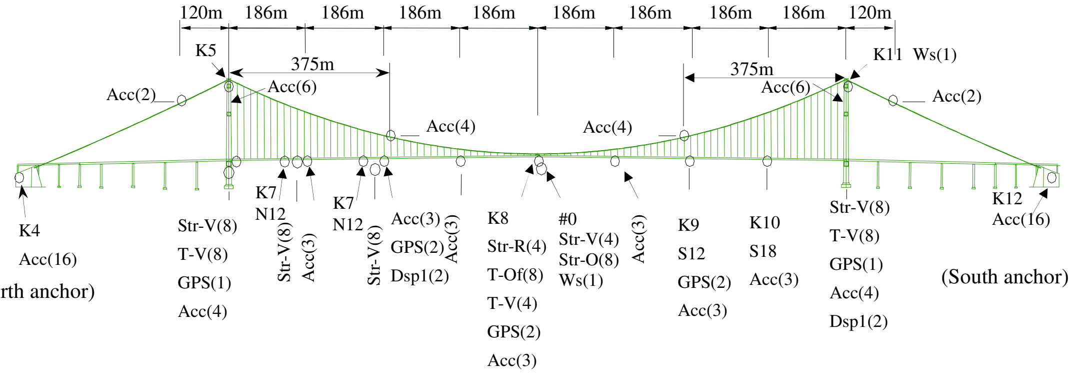

Fig. 1 Layout diagram of sensors in RYSB

Strain histories recorded by almost all strain gauges installed in the deck of RYB were analyzed one by one. Due to space limitations, it is not possible to show the results from all strain gauges and only the strain gauges "YBH4-13", a set of strain rosette installed on top deck at mid-span of RYSB, are selected to demonstrate the data analyses in multiply temporal scales of 10^6, 10^3 and 10^0 sec. The temporal scale about 10^6 means the time in week (0.6×10^6 sec), month (2.592×10^6 sec) and years (3.11×10^7 sec). However it is difficult to continuously show the curve of strain-time history for weeks and months since the data of dynamic strain are acquired in the rate of 25.2 per sec.. The strain histories in the scale of 10^6 sec recorded by "YBH4-13" are shown discontinuously in Fig. 2, in which the data in one hour of 7 days from 10 to 16 Aug. 2005 from "YBH4-13" are given. The strain behavior in the temporal scale of 10^6 shows the total response of the bridge structure under service loading including temperature and environmental variation. Further observation of the strain-time history in temporal scale of 10^3 and 10^0 sec are shown respectively in Fig. 3 for the data from "YBH4-13" on RYSB, in which the strain-time curves for one day in the temporal scale of 10^6, 20 min in the temporal scale of 10^3 and 6 sec in the temporal scale of 10^0 sec are given in figures (a), (b) and (c) respectively.

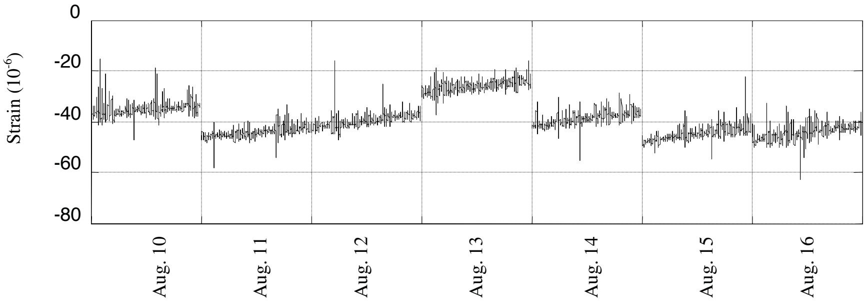

Fig. 2. Strain history from 18:00 to 19:00 on Aug. 10-16 recorded by "YBH4-13" installed on RYSB

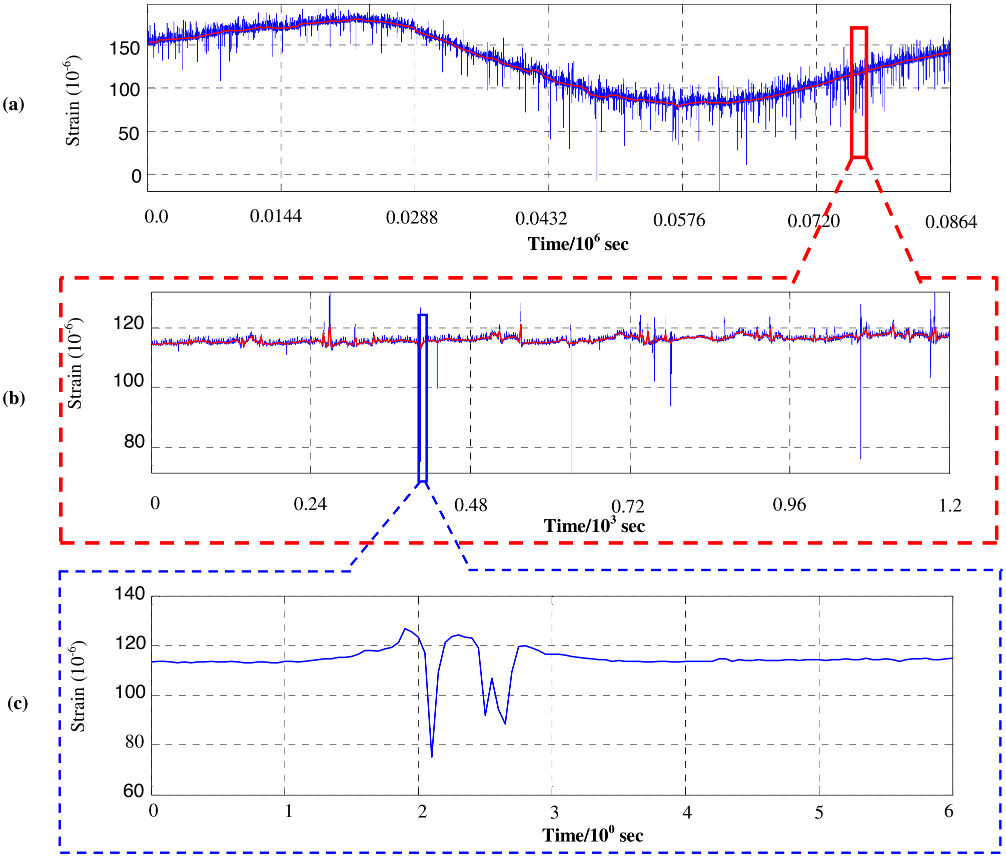

Fig. 3. The strain history recorded by "YBH4-13" installed on RYSB, displayed in the temporal scale of (a) 10^6 sec, (b) 10^3 sec and (c) 10^0 sec respectively

Strain time curves in Fig. 3 reveal that strain has different characteristics over three typical time scales, each having their own cut-off frequency of different orders of magnitude. The characteristics of the aforementioned monitoring data lead to the use of wavelet and multi-resolution analysis methodology for separation and extraction. Wavelet coefficient thresholds were developed and adopted during the strain information extraction process using the method of controlling probability (p-method) and controlling noise (n-method). The results show that wavelet methodology can separate different types of strain information effectively, and that the similarity and dissimilarity between different type of bridges and different type of strain gauges can be clearly detected after separation [7].

Wavelet methodology can also accurately discriminate among specific types of strain and allows the strain data to be compressed with an attractive ratio while keeping a satisfactory recovery capability. By using theoretical and case studies in the frequency domain, the data can therefore be extracted and separated through the signal processing methods. It can be found from the separated results that, the response due to temperature change is in the range of cut-off frequency $f_{c,1}=10^{-2}$Hz, that due to train load is in $f_{c,2}=10^{-1}$Hz and that due to truck load is in $f_{c,3}=10^{0}$Hz.

3. Statistical analyses on fatigue stress features and damage based on monitoring data from RYB

The fatigue cycle distribution, inter-coupling of the three kinds of strain and the effect of noise on fatigue evaluation were statistically analyzed.

3.1 Stress range and corresponding cyclic numbers

200-day-samples of the data from RYSB and RYCB were analyzed and rain-flow counting method was adopted to obtain the stress spectrum. Cyclic numbers of each stress range were summed up to acquire total cyclic numbers in 200 days, as shown in Fig 4 and Fig 5. It can be seen that the maximum stress range is not more than 10MPa, and cyclic numbers corresponding to stress range of each level higher than 8MPa are less than 30 for RYSB and 5 for RYCB. This indicates that cyclic numbers and fatigue damage generated by overweight-vehicles are different in RYCB and RYSB.

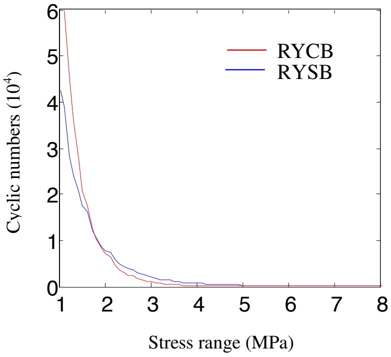

Fig. 4 Total cyclic numbers under the stress range of each level lower than 8MPa

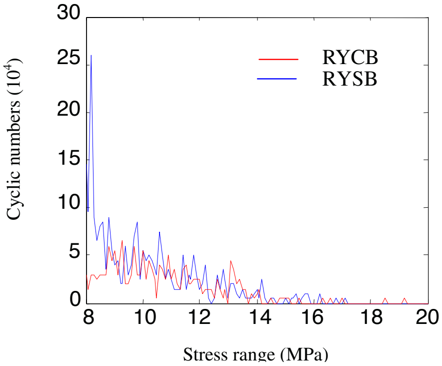

Fig. 5 Total cyclic numbers under the stress range of each level higher than 8MPa

3.2 Statistical analyses on fatigue damage increment

fatigue damage of bridges is due to multi-timescales; however, researches on data every day are unpractical due to large data processing issues. From data recorded by health monitoring system, relative damage sample of every day provide some answers. The method of performing researches on extracted samples from adequate days to deduce cumulative properties is called parameter estimation, and is one of the methodology developed in mathematical statistics [8]. According to structural drawings of box-girders of Runyang Bridges, corresponding welding construction drawings and detail classifications of fatigue resistance of different members in BS5400 [9], weld detail classification near two gauges is considered as the category of F2.

In order to evaluate adaptability of the cumulative distillation function to relative damage increment, supposition test is adopted. For the purpose of assessing the degree of accuracy in using the method for predictions, Kolmogorov-Smirnov test method is used to produce accurate evaluation of the predicted results. Cumulative probability $F(X_i)$ according to theoretical frequency is compared with actual cumulative probability $F_n(X_i)$ corresponding to each actual frequency n_i, and least upper bound of the difference of the two values for every samples, $D_n=\sup\Delta=\sup\left|F_n(X_i)-F(X_i)\right|$, is compared with the critical value of D_n. When compared to the value of the theoretical distillation function with sample cumulative frequency distillation function at the same sampling point, relative damage increments in the two bridges under investigation agree with the lognormal distribution. Fig. 6 shows the comparison between the lognormal cumulative distillation function obtained using the proposed method and empirical cumulative distillation as a function of logarithm value of original data.

Further studies on fatigue damage increment induced by temperature and vehicle respectively showed that, damage increment obtained from original strain history is twice higher than that due to noise filtered strain history in both the cable-stayed and the suspension bridge. Damage accumulation obtained by neglecting thermal deformation caused by thermal loading produces a 25% reduction of predicted damage with respect to the case when thermal effects are considered. Vehicle and varying temperature have a greater influence on RYSB than on RYCB. Under the same vehicle loads, relative damage increment in RYSB is 2.3 times higher than that in RYCB.

OVSB — the original value of damage in RYSB
OVCB — the original value of damage in RYCB
FVSB — the best fit of damage in RYSB
FVCB — the best fit of damage in RYCB

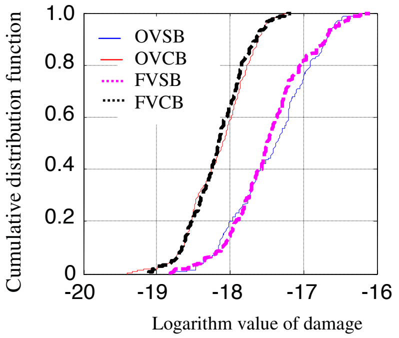

Fig. 6 Empirical cumulative distribution and theoretical normal distribution

Conclusions

✧ The strain response recorded by SHMS within three typical temporal scales has different characteristics, which have their own cut-off frequency with different orders of magnitude. By using theoretical analyses and case studies in the frequency domain, the data can therefore be extracted and separated through the specified signal processing methods.

✧ Relative cumulative damage is well represented by a lognormal distribution in both bridges. Under the same environment and vehicle loads, fatigue damage due to vehicles and varying temperature in RYSB is twice higher than that in RYCB. Furthermore, damage increments obtained considering thermal deformations goes 25% above those obtained disregarding thermal effects.

✧ The strain responses within three typical temporal scales are not coupled to each other when evaluating fatigue damage accumulation. However, noise shows significant coupling effect when coarse scale strain data are used for the evaluation.

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References

1. Li ZX, Chan THT, Ko JM. Fatigue Analysis and Life Prediction of the Bridges with Health Monitoring Data – Part I: Methodology and Strategy. *International Journal of Fatigue*, 2001, 23(1): 45-53
2. Chan THT, Li ZX, Ko JM. Fatigue Analysis and Life Prediction of the Bridges with Health Monitoring Data – Part II: Application. *International Journal of Fatigue*, 2001, 23(1): 55-64
3. Xin XZ, Su MB, Chen Shuli ,et al. Study on the Statistical Comparison Diagnostic Method for Health State Evaluation of Long-span Railway Bridges. *Journal of the China Railway Society.* 2006, 28(2): 116-121.
4. He XH, Chen ZQ, Huang FL, et al. Preliminary Studies on Safety Monitoring and State Assessment for Nanjing Yangtse River Bridge. *Journal of Vibration and Shock,* 2003, 22(1): 75-78.
5. Construction headquarters of Yangtze River Highway Bridge in Jiangsu Province. *Bidding document of structural health monitoring system of Runyang Bridge*, 2004
6. Li ZX, Chan THT, Zheng R. Statistical Analysis of Online Strain Response and Its Application in Fatigue Assessment of a Long-span Steel Bridge, *Engineering Structures*, 2003, 25(14): 1731-1741
7. Wu BJ, Multiscale analyses of structural health monitoring data for condition assessment, Dissertation for the Degree of Master of Engineering, Southeast University, Nanjing, 2008
8. Gao ZT. *Fatigue statistics*. Beijing: National Defense Industry Press, 1986.
9. BS 5400, Steel, concrete and composite bridges, Part 10. Code of practice for fatigue, 1980, 1~48