Fatigue Safety Monitoring and Fatigue Life Evaluation for Existing Concrete Bridges

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Abstract This paper firstly combines acoustic emission (AE) technique with monitoring of traffic loads and dynamic strain in healthy monitoring of concrete bridge structures. AE sensors and strain gauges were located on the web zone, deck plate and bottom plate of the box girder of Yaoxian Bridge, weigh-in-motion system (WIM system) was located in the pavement. Three monitoring systems clock was set synchronizedly, so they could monitor AE information, vehicles information and dynamic strain at the same time. Through the amplitude distribution and *b*-value analysis of AE signals, it finds the monitored bridge is in good service condition. The fatigue life of steel bars as well as strands in the box girders was calculated based on recorded data. Then, based on fatigue failure mechanism of concrete bridges, fatigue life evaluation approaches using S-N curves and fracture mechanics are presented. The evaluation results show that the fatigue life of the bridge is over 200 years, longer than the design service life. Finally, based on current study, it concludes that acoustic emission is an effective technique to evaluate existing concrete bridges.

Keywords existing concrete bridges, fatigue damage, fatigue load, acoustic emission, fatigue life

1. Introduction

Concrete bridges are widely used in China, accounting for 90 percent of all highway bridges. With the rapid development of highway transportation, traffic volume, vehicle weight and speed are constantly increasing, and overload phenomenon is difficult to eliminate, so fatigue damage caused by above problems cannot be neglected [1]. Current safety evaluation in China is mainly based on Code for Maintenance of Highway Bridges and Culverts and Specification for Inspection and Evaluation of Load-bearing Capacity of Highway Bridges. In order to evaluate the fatigue safety and remaining fatigue life of existing concrete bridges, emphasis should be laid on fatigue load monitoring, fatigue damage and fatigue life evaluation.

After World War II, some developed countries were beginning to research on fatigue fracture of concrete bridges, and corresponding design codes are gradually formed [2~5]. British scholar Tilly studied the reduction coefficient of fatigue strength of steel bars under different levels of corrosion [6], the result was used to evaluate durability and remaining life of concrete bridges; Schlafli and Bruhwiler of Swiss Federal Institute of Technology Lausanne have studied the basic method for fatigue evaluation of existing concrete bridges, and conducted fatigue safety evaluation of existing concrete bridges in Swiss [7].

With the development of non-destructive technique (NDT), real-time monitoring of the fatigue damage of existing bridges becomes possible [8]. Acoustic emission (AE) is a typical non-destructive technique, which can realize the effective monitoring of fatigue crack propagation in steel bridges. Nowadays some researches are trying to apply AE technique to concrete bridges.

This paper combines weigh-in-motion (WIM) technique, dynamic strain monitoring technique with AE technique to evaluate a typical concrete bridge with box girders. Through fatigue life evaluation based on S-N curve and fracture mechanics, in combination with AE signals analysis, fatigue safety of the concrete bridge is comprehensively evaluated.

2. Fatigue Safety Monitoring Technique and Evaluation Methods

2.1 Weigh-in-motion Technique

HI-TRAC 100 is an advanced weighing system which includes two piezoelectric sensors, one induction coil sensor and a data acquisition unit (shown in Figure 1). When vehicles pass the bridge, the induction coil set in pavement picks up different responses, and the piezoelectric sensors send the information to the acquisition unit. Then the controlling unit can calculator the specific information of the passed vehicle and record the information. The system can record comprehensive information about the vehicles moving through, such as weight, speed, direction, axle number and so on.

Figure 1. TDC WIM system

2.2 Acoustic Emission Technique

AE signal is a transient elastic stress wave generated by sudden changes in materials like deformation, cracking and transformation [8~9]. Figure 2 shows the model of AE signal production and spreading, when structure or material is in the condition of tension, compression or impact, the internal crack tip of structure will lead to a transient release of stress that can produce stress waves. When the crack propagates, the stress waves spread in all directions. Then these stress waves could be picked up by AE sensors attached on the surface of structure.

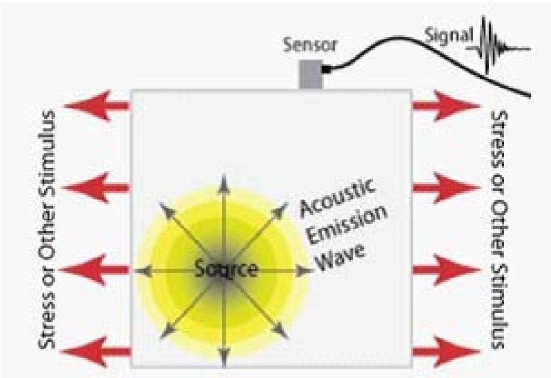


Figure 2. Model of AE production and spreading

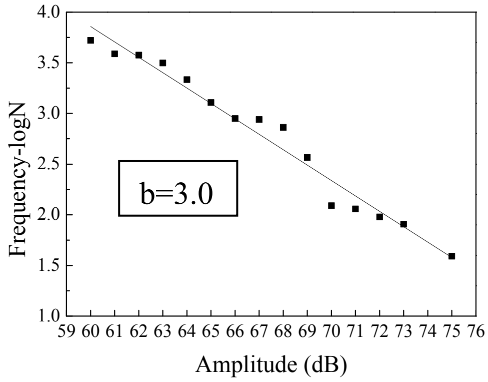


Figure 3. Example of calculation of *b*-value

Researchers began to apply AE technique to bridges monitoring in 1970s. Colombo developed *b*-value analysis method in 2003, and successfully evaluated the damage degree of reinforced concrete beam [9]. The analysis result shows that changing trend of maximum *b*-value reflects microcracks propagation; while minimum *b*-value reflects macrocracks development, which shows a good correlation with cracking process of reinforced concrete beam. Figure 3 shows *b*-value calculation method, while N stands for counts of different amplitude. Least-square fitting method is adopted to draw the line, the slope of the fitted line is -0.152, *b*-value is 3.04 according to the relationship between them.

2.3 Fatigue life evaluation method based on S-N curve and Miner law

According to Miner linear fatigue accumulative damage, fatigue damage can be calculated by Equation (1):

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i} \tag{1}$$

In each stress range level $\Delta\sigma_i$, the fatigue damage D_i was linearly proportional to n_i, where n_i is the number of cycles at σ_i, N_i stands for cycles under stress range level $\Delta\sigma_i$ and D is the total damage when fatigue failure occurs. Fatigue life Y can be calculated by Equation (2):

$$Y = \frac{D_{\mathrm{cr}}}{D_T} \times T \tag{2}$$

While D_{cr} stands for critical fatigue damage, T stands for monitoring time and D_T is fatigue damage during time T. Previous experiments show that, under random loading, D_{cr} is around 1, so the value of D_{cr} is taken as 1.

2.4 Fatigue life evaluation method based on fracture mechanics

In order to simulate the process of crack initiation, crack propagation to destruction in steel bars, assume the initial crack is semi-circle and the depth is a_0, so the crack propagation can be calculated by Paris formula (Equation 3).

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot \Delta K^{\mathrm{m}} \tag{3}$$

While C and m are material constants; $\Delta K = Y \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a}$, $\Delta\sigma$ is stress range and Y is a modified coefficient.

According to K criterion in linear elastic fracture mechanics, if $K_I \geq K_{IC}$, the steel bar tends to brittle fracture, the critical crack depth is a_{cr}; if the steel bar tends to yield dstruction along with the crack propagation, the critical crack depth is a_y. Thus the critical crack depth of fatigue failure of steel bar is a_{fr}=min (a_{cr}, a_y). Fatigue life can be calculated by Equation (4):

$$N = \int_{a_0}^{a_{fr}} dN = \int_{a_0}^{a_{fr}} \frac{1}{C \cdot \Delta K^m} da = \int_{a_0}^{a_{fr}} \frac{1}{C \cdot Y^m \cdot \Delta\sigma^m \cdot \pi^{m/2} \cdot a^{m/2}} da \tag{4}$$

3. Fatigue stress and traffic load monitoring

Accumulating fatigue damage caused by passing vehicles is needed for fatigue safety evaluation of existing concrete bridges, but there is no fatigue vehicle spectrum in China, so it is important to acquire actual traffic load or fatigue stress.

Yaoxian Bridge (shown in Figure 4) is a key bridge of provincial road 305, from Tongchuan to Jiaopin in Shaanxi, China. It is an 8-span prestressed box girder bridge with span length of 30m. Since the bridge is near a coal mine, many coal-trucks pass the bridge everyday, so the bridge is under great fatigue stress. In this paper, the writer has conducted dynamic strain monitoring for 21 days. Figure 5 shows a typical dynamic strain curve.

Figure 4. Yaoxian Bridge

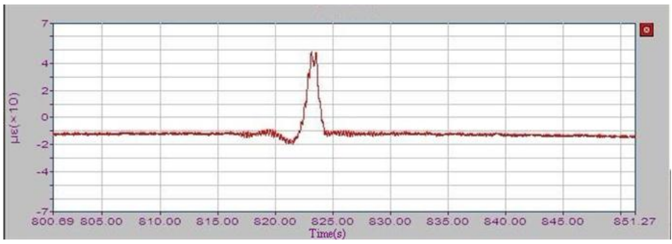
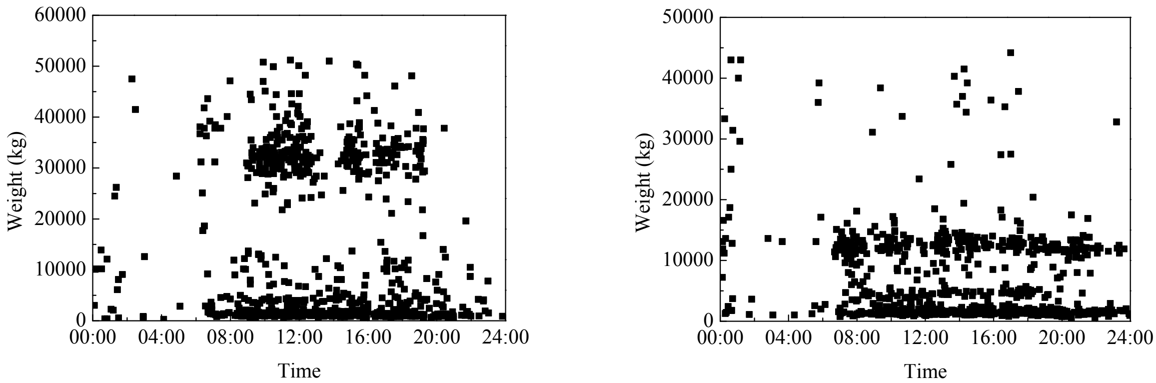


Figure 5. Example of dynamic strain curve

Through the analysis of recorded vehicles information, vehicle make-ups of every day are similar. Figure 6 is the vehicle load information of 4th September, 2011: passage time of full trucks is mainly from 9:00 to 13:00 and from 14:00 to 19:00; among all vehicles, weights of 1,12 and 33 tons are most, and there are more vehicles passing bridge in daylight than night. Full trucks of Tongchuan direction are mainly 30 tons to 40 tons, the maximum recorded weight is 55 tons; vehicle loads of Jiaoping direction are mainly around 1 tons and 12 tons.



(a) Tongchuan direction (lane 1) (b) Jiaoping direction (lane 2)

Figure 6. Vehicle load information during a day

Figure 7 shows the vehicle load distribution of Yaoxian Bridge. Total monitoring time is 35 days, the total number of passing vehicles is 57802, and the average traffic volume is 1650 during a day. Cars accounts for 46.7 percent, trucks with 2 axles accounts for 19.8 percent, trucks with 3 axles accounts for 25.2 percent, other kinds are 8.3 percent. Maximum vehicle load is lighter than design loads, and no overloaded vehicle is recorded. Total weight and axle weight of all vehicles are lighter than fatigue vehicles in Europe Code, and there are less than 500 trucks in every lane during a day, so during design service life fatigue damage caused by recorded vehicle loads is little.

4. AE monitoring and signals analysis

4.1 Site monitoring information

The AE monitoring was started in 23rd August, 2011, ended in 7th September, 2011, and the NO.2 and NO.3 box girder of the first span was chosen to be the monitoring region. In order to identify the different signal characteristics of different locations, sensor locations are on the every part of the box girder, as shown in the Figure 8: NO.7 and NO.11 sensors are on the deck plates; NO.2, 5, 9 and NO.13 sensors are on the bottom plates; other 10 sensors are on the webs.

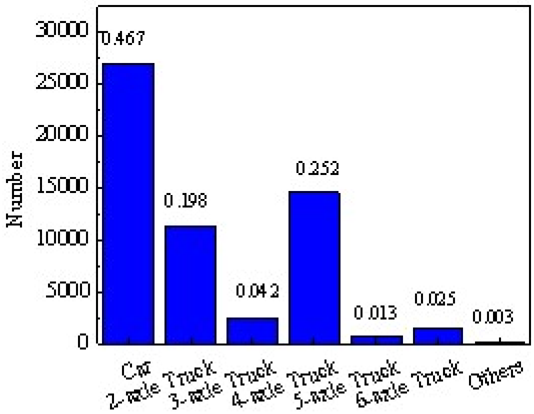


Figure 7. Vehicle load distribution

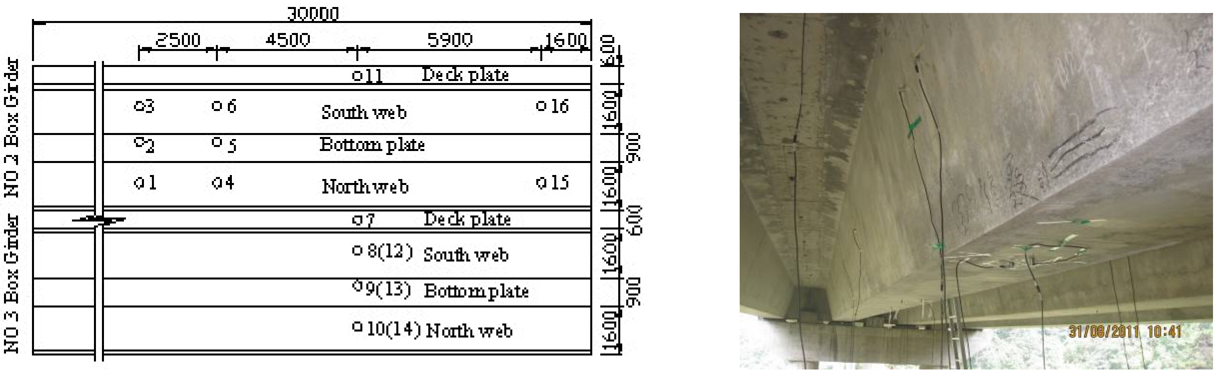
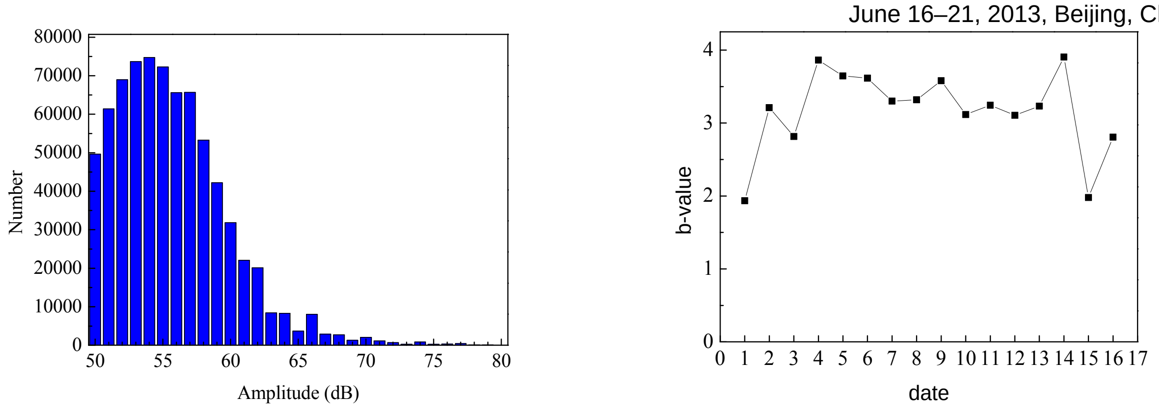


Figure 8. AE sensor locations (mm)

The acoustic emission equipment used in the bridge monitoring was made by Physical Acoustic Corporation, including an independent AE system: Micro-II, R3I and R15a sensors. R15a with 150 kHz-resonant-frequency was located at positions of NO.12, 13, 14, R3I with 30 kHz-resonant-frequency sensors are for the other monitoring positions. Based on the level of noise in the monitoring site, the threshold level was set at 50 dB.

4.2 Characteristics analysis of AE data

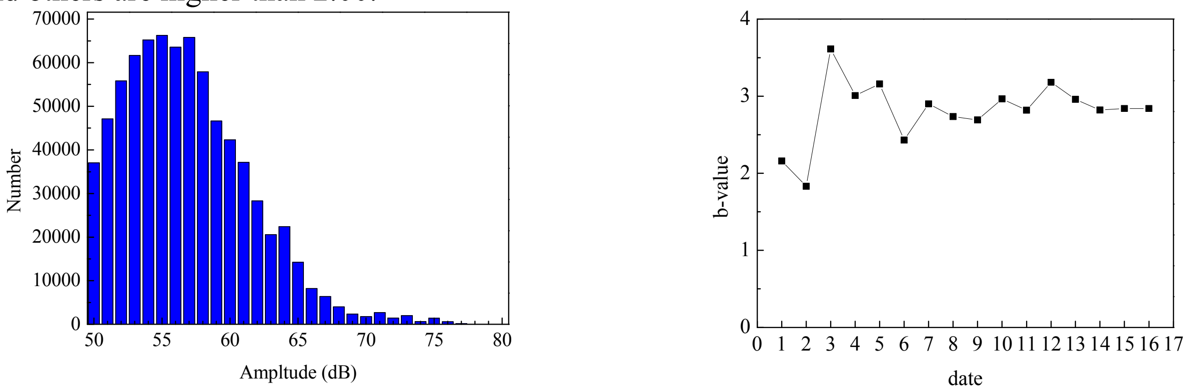
NO.2, 4, 7 sensors have recorded the most hits in 3 different locations respectively, so signals acquired by this 3 sensors were analyzed to evaluate the box girders. Figure 9 shows the analysis results of data acquired by NO.2 sensor on bottom plate: (a) is the amplitude distribution of 16 day's data, there are more than 70000 signals at 54dB, amplitudes of almost all signals are lower than 70dB; (b) is the *b*-value changing trend, the minimum *b*-value is 1.94, and the maximum is 3.90.



(a) Amplitude distribution (b) Changing trend of *b*-value

Figure 9. Data analysis of NO.2 sensor (23rd August, 2011 to 7th September, 2011)

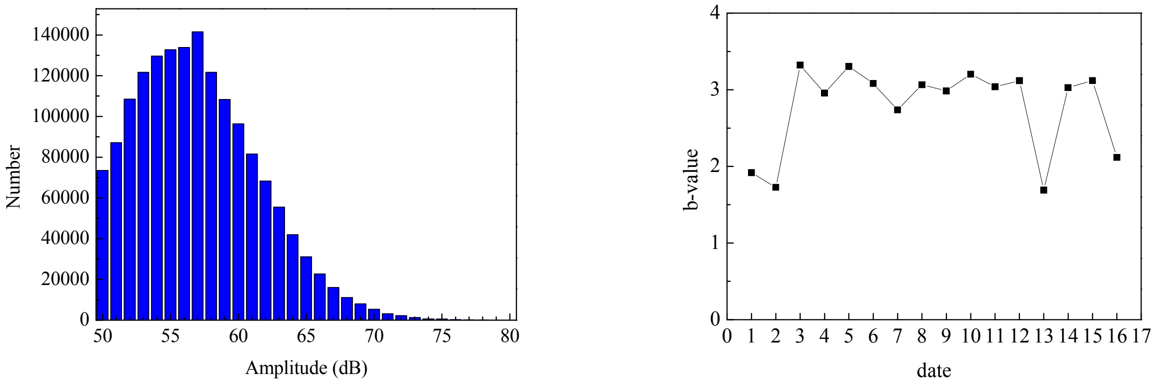
Figure 10 shows the analysis results of data acquired by NO.4 sensor on web: (a) is the amplitude distribution of 16 day's data, there are more than 6000 signals at 57dB, amplitudes of all signals are lower than 75dB; (b) is the *b*-value changing trend, the minimum *b*-value is 1.83, and others are higher than 2.00.



(a) Amplitude distribution (b) Changing trend of *b*-value

Figure 10. Data analysis of NO.4 sensor (23rd August, 2011 to 7th September, 2011)

Figure 11 shows the analysis results of data acquired by NO.7 sensor on deck plate, which acquired the most signals in all sensors: (a) is the amplitude distribution of 16 day's data, there are more than 14000 signals at 57dB, amplitudes of all signals are lower than 75dB; (b) is the *b*-value changing trend, the minimum *b*-value is 1.72 occurred in the 13rd day (4th September, 2011).



(a) Amplitude distribution (b) Changing trend of *b*-value

Figure 11. Data analysis of NO.7 sensor (23rd August, 2011 to 7th September, 2011)

From the amplitude distribution of 3 typical positions, it is easy to find sensor on deck plate acquired the most signals, and sensor on bottom plate acquired the least. Amplitudes of almost all signals are lower than 70dB, and there are most signals at 57dB, so the noise level in site is around 57dB.

According to research by Colombo, changing trend of maximum *b*-value reflects the propagation of microcracks, and changing trend of minimum *b*-value reflects the propagation of macrocracks; when *b*-value is higher than 1.7, the structure is in period of microcracks propagation[9]. Figure 9 to Figure 11 shows the *b*-value changing trend of 3 locations, all *b*-values are higher than 1.7, and no macrocrack has been detected, and so Yaoxian Bridge is in the period of microcracks, it is in good working conditions.

5. Fatigue life evaluation

5.1 Fatigue life evaluation based on S-N curve

From all S-N curves of different fatigue details in research documents and specifications in different countries, S-N curve in European Institute of steel construction (ECCS) is adopted to evaluate the fatigue life of steel bars and strands in concrete bridges.

In this specification, fatigue strength of 2 million cycles is 80.0MPa, fatigue strength of constant stress range is 59.0MPa, and threshold of fatigue strength is 32.4MPa. The slope of curves changes from -3 to -5 when cycles are more than 5 million. Since most full trucks are on lane 1, 4 typical stain monitoring positions (shown in Figure 12) below lane 1 are chosen to evaluate the fatigue life of steel bars and strands in box girders of Yaoxian Bridge. The evaluation result is shown in Table 1: fatigue life of steel bars in deck plate (measure point BST2) is 3756 years; fatigue life of strands in bottom plate is longer than 1000 years. Therefore, it can be concluded that under the present fatigue load level, fatigue failure of Yaoxian Bridge will not occur during design service life.

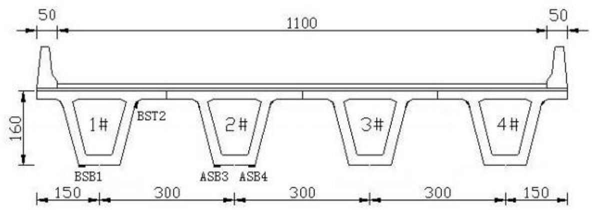


Figure 12. Strain measure points of Yaoxian Bridge.

Table 1. Fatigue life based on S-N curve

Measure point	D (10^{-6})	Y (year)
BSB1	12.16	1239
BST2	4.01	3756
ASB3	0.45	infinite
ASB4	40.31	1427

5.2 Fatigue life evaluation based on fracture mechanics

According to appearance detection, no crack was found on Yaoxian Bridge, so initial crack was assumed to evaluate the fatigue life. Fracture toughness of steel bar used in concrete bridge is $K_{IC} = 50\text{MPa}\cdot\sqrt{\text{m}}$. Fracture constants are $D = 2\times10^{-13}$ and $m = 4$ according to previous researches, threshold of crack propagation of steel bar is $\Delta K_{th} = 2.0\text{MPa}\cdot\sqrt{\text{m}}$. Fatigue life evaluation result based on fracture mechanics is shown in Table 2, under the present fatigue load level, fatigue failure of Yaoxian Bridge will not occur during design service life.

The above fatigue life evaluations are based on the present vehicle loads, with the development of transportation and other disadvantage influences, the fatigue life of concrete bridge will be far shorter.

Table 2. Fatigue life based on fracture mechanics

Measure point	Initial crack width a_0 (mm)	Maximum stress σ_{max} (MPa)	Critical crack length a_{fr} **Error! Reference source not found.**(mm)	Remaining life Y (year)
BSB1	0.1	185	7.57	245
BST2	0.1	67	10.12	1198
ASB3	0.5	47	10.49	5124
ASB4	0.1	97	9.54	578

6. Conclusions

This paper combines WIM, fatigue stress monitoring, AE with fatigue life evaluation techniques to give a comprehensively fatigue safety monitoring and fatigue life evaluation of a concrete bridge, the followings can be concluded:

(1) Using WIM and dynamic strain monitoring techniques, traffic loads monitoring for 35 days and fatigue stress monitoring for 21 days were conducted, influence of present traffic loads to concrete bridges fatigue life was studied.

(2) Fatigue safety and fatigue life evaluation model based on S-N curve and fracture mechanics is given.

(3) Through analysis of AE signals, it is found that noise level in site is around 57 dB; signals of deck is far more than of web and bottom plate of box girders, it indicates that the deck may have more fatigue damage of concrete bridges. From *b*-value analysis, Yaoxian Bridge is in period of microcracks propagation, no macrocracks was found.

(4) Fatigue life of Yaoxian Bridge based on S-N curve is 1239 years, fatigue life based on fracture mechanics is about 245 years, fatigue failure will not occur during design service life.

(5) Combination of different monitoring techniques can give comprehensive evaluation of concrete bridges.

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