Time-Dependent Fatigue Reliability Assessment of Ting Kau Bridge Based on Weigh-In-Motion Data

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ABSTRACT: An advanced probabilistic loading model is proposed in this paper to simulate the vehicles running along Ting Kau Bridge based on the weigh-in-motion system installed on the bridge. The weigh-in-motion system collects the information of vehicle speed, heading direction, lane used, axle weight, axle spacing between neighboring axles, etc. The data are employed to develop a statistical traffic load model which is able to incorporate the variation of daily traffic flow within different time intervals and the trend of the annual traffic flow as well as the statistical information. The time-dependent fatigue reliability assessment at critical locations can be carried out.

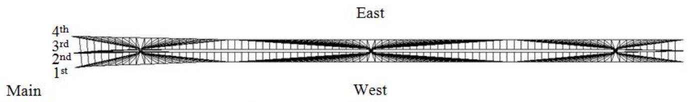
The ever-evolving developments in design and construction technologies have made spans of over 1000m possible for cable-stayed bridges. Steel is normally used in the decks either fully or partly to reduce the self-weight for those with long spans. Fatigue has been one of the most critical forms of damage for cable-stayed bridges with steel girders and assessing their remaining fatigue lives has been the primary focus in recent years. In the design and construction of cable-stayed bridges, the design life is often 100 years or more. Over the service life, the effects of environmental corrosion, material ageing, long-term load effect, fatigue, etc. will inevitably lead to accumulation of damage and possible reduction of strength. In extreme cases, catastrophic failures could happen. Fatigue of steel bridges is caused by cumulative damage under cyclic actions of various kinds of vehicle loads with different weights and physical dimensions.

In the assessment of fatigue problems, a crucial step is to determine the fatigue stress spectra. Usually, the fatigue stress spectra of bridges can be obtained through field measurements such as from structural health monitoring systems which are able to record the long-term responses for fatigue assessment and performance prediction (Elkordy *et al*. 1994). However, structural health monitoring systems are always expensive, and there are a lot of structural components on which it is difficult to install strain gauges. As a result, some other effective tools are required to obtain the fatigue stress spectra of the details that are hardly accessible (Guo and Chen 2013).

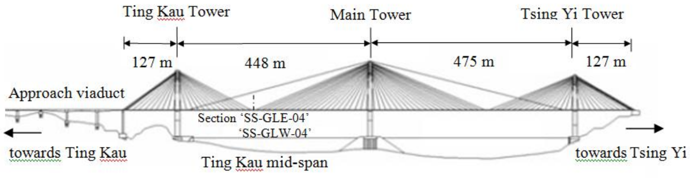
Recently, a statistical load model has been proposed by Guo and Chen (2013) so that the uncertain information of vehicle types, number of axles, axle weights, axle spacing, transverse position of vehicle, etc. can be accounted for properly. As a sequel to this statistical load model, a statistical approach of modelling the traffic load is developed based on the probabilistic traffic characteristics extracted from the measured data of weigh-in-motion (WIM) system installed on Ting Kau Bridge in Hong Kong. The traffic load model proposed in this study attempts to reflect the diurnal variations of traffic flow within different time intervals and the rate of change of the annual traffic on a bridge (Zhang *et al*. 2014). Combined with this statistical traffic load model, the stress time-histories at critical locations of the bridge are obtained, and the probability density curves of the fatigue life can be constructed for further analyses.

1. WEIGH-IN-MOTION SYSTEM

Ting Kau Bridge is a cable-stayed bridge in Hong Kong with a total length of 1,177 m completed in 1998. As shown in Figure 1, the Ting Kau main span and Tsing Yi main span are 448 m and 475 m respectively, while the two side spans are both 127m. The bridge connects Ting Kau at the north and Tsing Yi Island at the south over Rambler Channel. A statistical fatigue reliability assessment is performed to estimate the remaining service life of Ting Kau Bridge to support decisions on maintenance and rehabilitation. The dynamic WIM system installed on the bridge monitors the traffic flow and volume, and axle and gross vehicle weights. The system is capable of dynamic measurement of vehicular axle loads and speed with an intelligent vehicle classification system. As shown in Figure 2, the WIM system is located at the Tsing Yi end of Ting Kau Bridge on both carriageways. Data of WIM in 84 days each with 24 hours are filtered. After filtering, 5% of vehicles are eliminated from the database.



(a) Plan showing girder labelling



(b) Elevation

Figure 1: Schematic plan and elevation of Ting Kau Bridge.

Figure 2: Layout of weigh-in-motion dynamic weigh-bridge system.

2. STATISTICAL LOAD MODEL

The WIM data collected are divided into 6 vehicle types according to the number of vehicle axles, the first two types as shown in Figure 3 for example. To take into account the variation of daily traffic properly, the diurnal variations of highway loading are described by 4 unequal time intervals, i.e. 7:00-11:00, 11:00-17:00, 17:00-21:00 and 21:00-7:00 on the following day, to cover the morning and evening rush hours separately as well as the off-peak hours based on the hourly statistics (Zhang *et al*. 2014). Considering the random variables of each vehicle type, the probability density functions of axle weights and axle spacing in four different time intervals of each day can be obtained.

Some plots of the distribution considering the diurnal variation for different time intervals are shown in Figures 4 to 6. Furthermore, the parameters for all distributions are listed in Tables 1 and 2. μ is the location parameter (mean value), σ is the scale parameter (standard deviation) and v is a shape parameter for *t* location-scale distribution. The symbol "(1)" in the first column is used to denote those for the first time interval. It is found that most of the axle spacing of the 6 vehicle types follows the *t* location-scale distribution ('③'), while most of the axle weights follow the normal ('①') and lognormal distributions ('②').

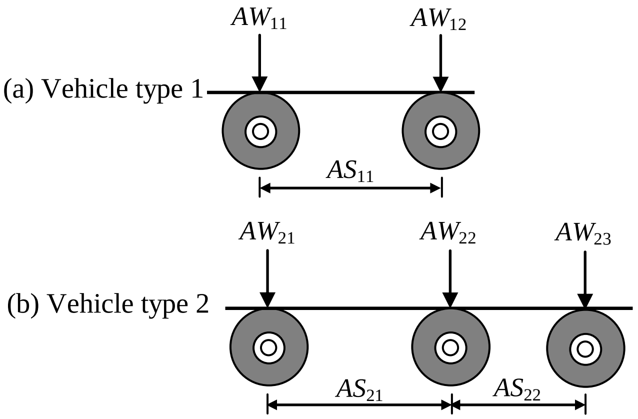


Figure 3: Vehicle type classification for Ting Kau Bridge.

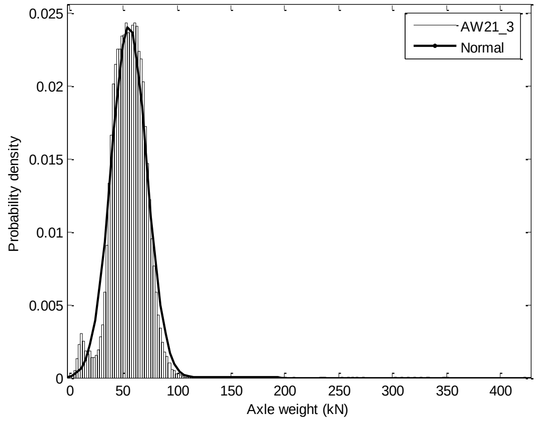


Figure 4: Distribution of axle weight for the first axle of vehicle type 2 in the 3rd time interval (17:00-21:00).

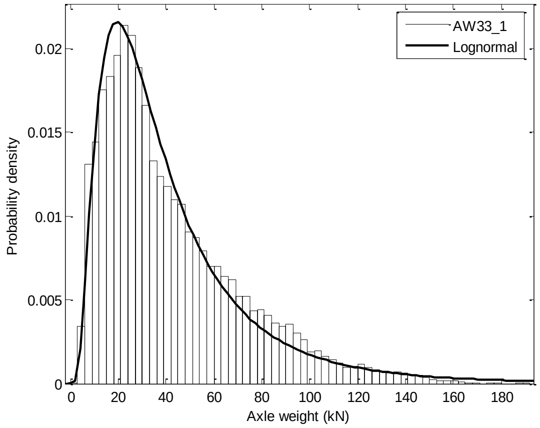


Figure 5: Distribution of axle weight for the third axle of vehicle type 3 in the 1st time interval (7:00-11:00).

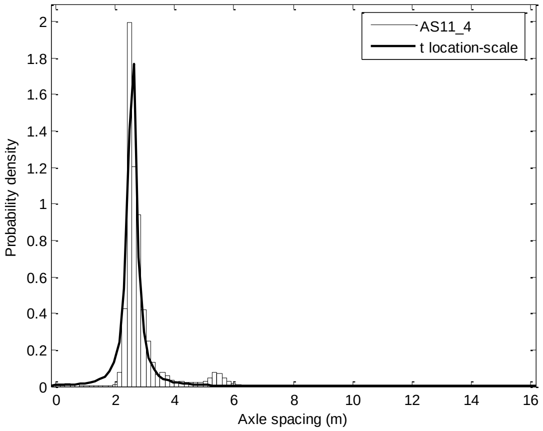


Figure 6: Distribution of axle spacing for the first axle of vehicle type 1 in the 4th time interval (21:00-7:00 next day).

Table 1: Parameters of distribution for random axle spacing of 6 vehicle types in the first time interval ('Dis' means 'Distribution').

Variable	*'Dis'*	μ	σ	ν
AS11(1)	③	*2.5676*	*0.13052*	*1.2024*
AS21(1)	③	*5.2354*	*0.30080*	*1.4579*
AS22(1)	③	*1.4355*	*0.093464*	*1.7610*
AS31(1)	①	*2.7697*	*0.88170*	-
AS32(1)	①	*5.2634*	*2.1288*	-
AS33(1)	③	*1.2316*	*0.068948*	*1.0879*
AS41(1)	③	*3.1878*	*0.20994*	*4.0925*
AS42(1)	③	*6.8215*	*0.32511*	*1.6377*
AS43(1)	③	*1.2512*	*0.070962*	*1.5072*
AS44(1)	③	*1.2568*	*0.079235*	*3.1590*
AS51(1)	③	*3.0459*	*0.20093*	*2.9606*
AS52(1)	③	*1.2747*	*0.071586*	*1.2049*
AS53(1)	③	*6.3169*	*0.29711*	*1.3438*
AS54(1)	③	*1.2527*	*0.075765*	*1.5450*
AS55(1)	③	*1.2513*	*0.074239*	*1.5141*
AS61(1)	①	*2.4479*	*0.97129*	-
AS62(1)	③	*1.2743*	*0.15662*	*0.83262*
AS63(1)	①	*0.98317*	*0.91200*	-
AS64(1)	②	*0.74483*	*0.75062*	-
AS65(1)	②	*0.21142*	*0.37379*	-
AS66(1)	③	*1.2164*	*0.13626*	*0.98418*

Table 2: Parameters of distribution for random axle weight of 6 vehicle types in the first time interval.

Variable	*'Dis'*	μ	σ	v
AW11(1)	②	*2.0982*	*0.65419*	-
AW12(1)	②	*2.0467*	*0.76570*	-
AW21(1)	①	*55.021*	*15.734*	-
AW22(1)	②	*2.0467*	*0.7657*	-
AW23(1)	①	*70.085*	*22.936*	
AW31(1)	①	*48.084*	*15.737*	-
AW32(1)	②	*3.7438*	*0.59541*	-
AW33(1)	②	*3.4977*	*0.72807*	-
AW34(1)	②	*3.6509*	*0.71893*	-
AW41(1)	①	*54.140*	*11.187*	-
AW42(1)	②	*3.9697*	*0.49263*	-
AW43(1)	②	*3.4002*	*0.60631*	-
AW44(1)	②	*3.4839*	*0.49764*	-
AW45(1)	②	*3.4304*	*0.57072*	-
AW51(1)	①	*51.546*	*13.477*	-
AW52(1)	①	*45.800*	*21.067*	-
AW53(1)	①	*47.053*	*22.043*	-
AW54(1)	②	*3.3481*	*0.62303*	-
AW55(1)	②	*3.4752*	*0.59020*	-
AW56(1)	②	*3.5000*	*0.68282*	-
AW61(1)	③	*44.965*	*6.3000*	*1.4798*
AW62(1)	①	*36.147*	*25.495*	-
AW63(1)	①	*38.853*	*25.311*	-
AW64(1)	①	*32.018*	*20.567*	-
AW65(1)	①	*31.179*	*17.650*	-
AW66(1)	①	*34.918*	*20.390*	-
AW67(1)	②	*2.8771*	*1.0300*	-

3. STATISTICAL FATIGUE LIFE ESTIMATION

When the statistical loading is applied for fatigue life estimation, the parameters of each individual vehicle and the arrangement of vehicles in each lane follow certain statistical distributions derived from the traffic data measured by the WIM system. Table 3 shows the proportion of traffic volume for different vehicle types and different lanes at different time intervals. The statistical traffic load model is employed to obtain the stress time-histories at critical locations of the bridge. Based on the simulated statistical stress time-histories, rain-flow counting is used to calculate the number of statistical cycles. The probabilistic distributions of fatigue lives can be calculated by using the statistical distribution of number of cycles. The results of fatigue life obtained using the proposed method is therefore also uncertain. Therefore Monte Carlo simulation can be used to simulate the large number of occurrences so that the variations can be revealed.

Table 3: Proportion of traffic in each lane.

	Traffic volume (%)	*Lane 1*	*Lane 2*	*Lane 3*	*Lane 4*	*Lane 5*	*Lane 6*
		Time interval 1 (07:00-11:00)					
1	*90.23*	15.50	28.57	15.74	12.96	17.90	9.33
2	*5.11*	46.21	11.37	0.36	37.72	3.82	0.52
3	*1.51*	39.05	12.31	1.44	30.04	11.86	5.30
4	*2.61*	40.50	11.45	0.27	32.37	13.53	1.88
5	*0.53*	30.26	20.06	1.06	29.11	14.79	4.73
6	*0.00881*	24.31	45.14	0.69	6.25	17.36	6.25
		Time interval 2 (11:00-17:00)					
1	*80.49*	9.26	17.07	10.92	15.02	20.99	26.75
2	*6.97*	30.35	15.74	0.67	40.79	11.41	1.04
3	*50.37*	31.82	17.33	0.68	29.11	17.53	3.53
4	*6.03*	32.70	18.04	0.44	27.37	18.85	2.61
5	*1.46*	23.80	25.87	0.45	22.54	23.27	4.06
6	*0.019*	10.80	54.94	0.31	4.01	22.53	7.41
		Time interval 3 (17:00-21:00)					
1	*79.18*	11.68	21.95	15.21	13.25	20.08	17.82
2	*6.44*	33.93	20.04	0.93	35.18	9.04	0.88
3	*5.59*	32.43	20.04	0.85	27.96	15.20	3.52
4	*6.97*	33.08	18.99	0.52	27.09	17.39	2.93
5	*1.80*	29.14	28.63	0.54	19.49	17.73	4.48
6	*0.017*	16.75	34.54	2.32	7.47	29.38	9.54
		Time interval 4 (21:00-07:00 next day)					
1	*85.79*	13.27	24.00	20.92	10.82	16.34	14.64
2	*54.67*	36.10	22.95	0.84	34.37	5.10	0.65
3	*28.36*	29.98	20.21	1.71	29.33	14.27	4.51
4	*47.60*	30.08	16.46	0.46	32.30	17.72	2.98
5	*1.13*	26.61	28.79	0.85	21.77	17.11	4.86
6	*0.017*	8.42	54.04	3.16	5.61	20.00	8.77

Once the vehicle type and the lane information are found, the next target is to generate the samples of axle weights and spacing for each vehicle. Random numbers following the normal probability density function, lognormal probability density function and *t* location distribution can be generated by the truncated Latin Hypercube sampling method, and the correlations between the axle weights and axle spacing are neglected to simplify the analysis. According to the vehicle type, the lane, axle loads and the axle spacing of the sample determined, the loads of a vehicle are generated. The influence lines of the details concerned for the specified lane are used for determining the stress time-histories under the moving axles obtained. The results associated with the influence lines obtained are multiplied by the axle weights and the results of all axles are superimposed according to the axle spacing so as to obtain the stress time-histories.

According to the stress time-histories simulated from the influence lines at various critical locations and the statistical traffic information, the traditional Monte Carlo method is used to repeat the procedures of fatigue analysis for a significant number of times so that the fatigue lives can be estimated taking into account the annual growth of traffic. A flat rate of increase is assumed for different types of vehicles.

The measurements at the linear strain gauges of 'SS-GLE-04' and 'SS-GLW-04' are studied, which are deployed to record the strains at the lower flange of the two outer girders, i.e. the 1st and the 4th main girders, as shown in Figure 1. Combining with statistical distribution of number of cycles, the statistical distributions of fatigue lives for different critical locations can be obtained. Taking into account diurnal variations, the statistical fatigue lives at locations 'SS-GLE-04' and 'SS-GLW-04' follow the normal distribution as shown in Figures 7 and 8. Using the rain-flow counting method, the fatigue lives obtained from the data on 25 Nov 2007 of 'SSGLE04' and 'SSGLW04' are 490 years and 286 years, respectively. The fatigue lives variations in 5 years at locations of 'SS-GLE-04' and 'SS-GLW-04' considering an annual growth rate of traffic of 5% are estimated as shown in Figures 9 and 10 respectively.

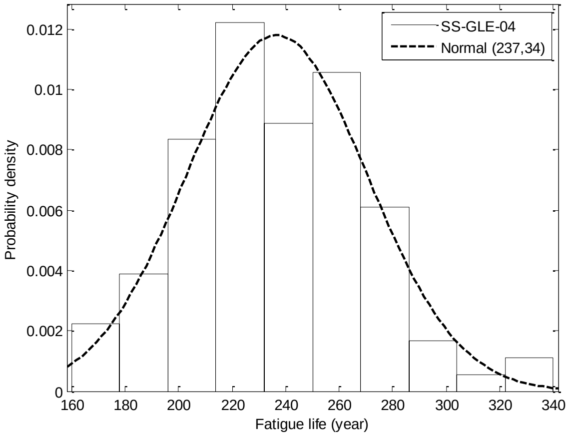


Figure 7: Probability density curve of fatigue life at location 'SS-GLE-04' considering diurnal variation.

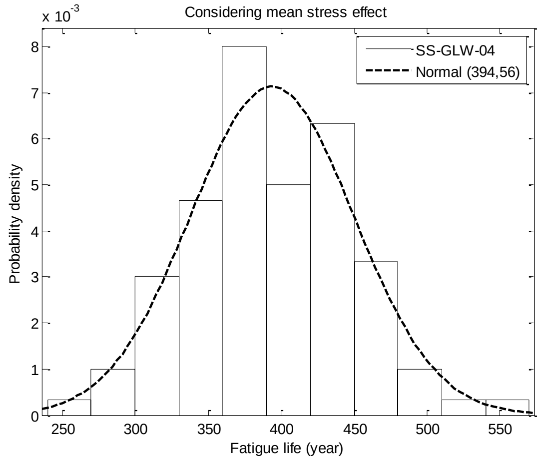


Figure 8: Probability density curve of fatigue life at location 'SS-GLW-04' considering diurnal variations.

The mean values of fatigue lives calculated using the probabilistic approach here are very close to those obtained from strain gauge measurements, which verifies the applicability of this method. Results also show that the effect of annual growth rate of traffic on fatigue life prediction cannot be ignored.

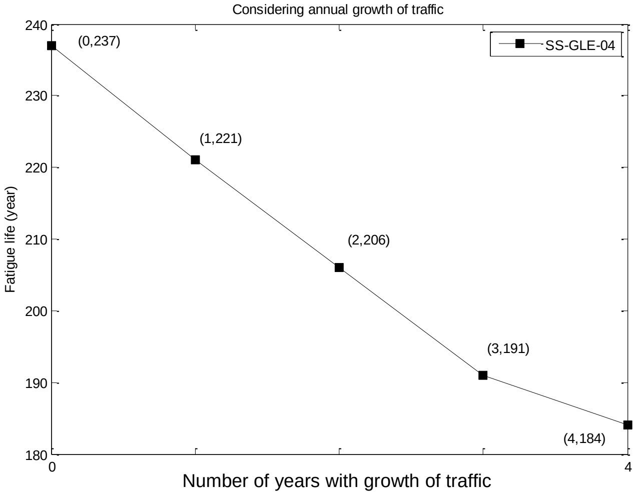


Figure 9: Fatigue life variation at location of 'SS-GLE-04' considering annual growth of traffic of 5%.

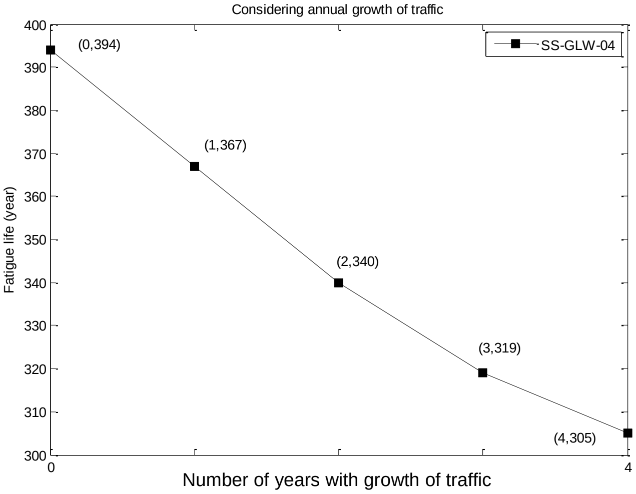


Figure 10: Fatigue life variation at location of 'SS-GLW-04' considering annual growth of traffic of 5%.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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