

# IN-SERVICE CONDITION ASSESSMENT OF LONG-SPAN BRIDGES BASED ON TRAFFIC LOAD EFFECTS USING MONITORING DATA

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## ABSTRACT

Long span bridges are widely equipped with structural health monitoring (SHM) systems. Using SHM, a wide range of real-time structural responses under ambient loading could be recorded, which provides the basis for bridge load rating and structural performance assessment. During these structural responses, displacement is an important index to represent the bridge in-service condition. In the paper, monitored girder displacements of a cable-stayed bridge are examined to assess the bridge in-service condition. The finite element model of the studied bridge is first updated based on monitored natural frequencies. Realistic influence lines of the bridge could be obtained based on the updated model, which is the baseline for assessment. Then, moving average method and window smoothing method are employed to extract the displacement induced only by traffic loading from that by wind, temperature, and environmental noise. Finally, using the extracted traffic load effects of girder displacements, the characteristic values under various remaining lives are extrapolated through constructing the limit distribution using block maxima based generalized extreme value (GEV) model fitting. Results show the predicted displacements would exceed the design level of the Chinese code after the bridge serves for another 10 years, indicating potential risk. At that time, the management of traffic loads and maintenance of bridge components should be enhanced to ensure the bridge in-service condition.

## KEYWORDS

Long span bridge, Structural health monitoring (SHM), Traffic load, Extreme extrapolation, Load effect

## INTRODUCTION

Traffic load is a main variable action during the service of bridges. Nowadays, there are many techniques to collect realistic traffic load information on bridges, such as weigh-in-motion (WIM), bridge weigh-in-motion (BWIM), and high-definition video (HDV) etc. [1-2]. In China, the transportation industry explosively grows in recent years, and vehicle overloading is very serious. Therefore, precise assessment of traffic load effects on bridges is very critical, which becomes a hot research topic [3-5].

The current research interest of traffic load effects mainly focuses on short and medium span bridges. Yuan et al. [4] collected heavy truck data to analyse the structural safety of short to medium span bridges. Ji et al. [5] used measured traffic flow to construct fatigue truck model for the assessment of steel decks in a suspension bridge. Getachew & O'Brien [6] used measured traffic data to establish load model for the assessment of short and medium span bridges in remaining lifetime. However, these measurement techniques show some deficiencies for long span

bridges: (1) the traffic data from WIM are based on sectional measurement and thus impossible to infer the vehicle load sequences over spatial bridge spans; (2) BWIM is applicable to short span bridges or culverts but difficult to clarify the loading case of multiple presence of vehicles over long length; (3) video recording could capture the dynamical behavior of individual vehicles but is hard to collect vehicle load information. Therefore, it is necessary to develop a new technical methodology for the evaluation of traffic loading effects on long-span bridges.

For the study of traffic load effects on long-span bridges, the main existing approach is to construct load sequences over long loading length through traffic microsimulation [7-8]. However, whether traffic simulation could accurately reflect realistic traffic loading is still a controversial topic. Liu et al. [9] filtered the effect of wind, temperature, and environmental noise on the cable force, and analyse the relationship between cable force and these environmental actions. Xia et al. [10] applied similar filtering algorithms to extract displacement induced by traffic loading based on monitoring GPS displacement data of a long span bridge, and extrapolated extreme traffic load effects to evaluate bridge condition.

In the paper, structural health monitoring data are utilized to assess the bridge in-service condition through the case study of a double-pylon cable-stayed bridge. First, the basic information of the studied bridge is introduced and the finite element model of the bridge is updated based on monitored dynamic properties. Then, girder displacements in several important locations are studied, and traffic load effects are maintained with the filtering of load responses induced by temperature, wind, and environmental noise. Finally, characteristic traffic load effects are extrapolated using extreme value theory, which are compared with designed values to assess the in-service condition of the bridge.

## DESCRIPTION OF THE BRIDGE

### Bridge overview

The studied case is a double-pylon cable-stayed bridge with the span arrangement of 70+160+448+160+70 m as shown in Figure 1. The bridge carries six-lane bidirectional traffic. The height of the concrete diamond pylon is 170 m. The width of the streamline flat steel box girder is 28 m. There are 56 pairs of stayed-cables with four spatial cable planes.

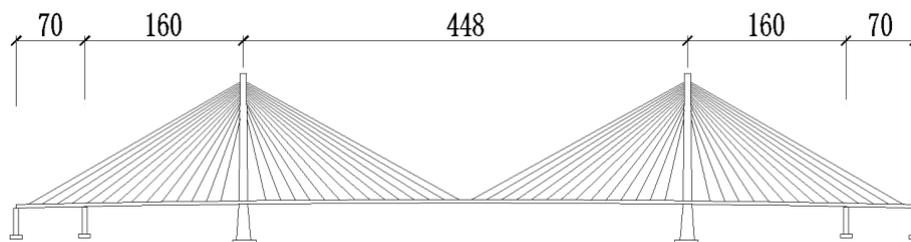


Fig. 1 – Overall layout of studied cable-stayed bridge (unit: m)

### Finite element model updating

The studied bridge has been in service for almost 20 years. Though there are no serious diseases observed during bridge operation, there are still some cracks detected in the top plate of the steel box girder, anchorage zone of the stayed-cables, and water leakage in the pavement. Therefore, the actual state of the bridge may be different from design drawings, and should be updated based on structural monitoring.

The finite element model of the studied bridge is established using ANSYS based on design drawings. As shown in Figure 2, the girder and the pylon are modelled by beam 4 and the stayed-cable is modelled by link 10. The structure uses a semi-floating system.

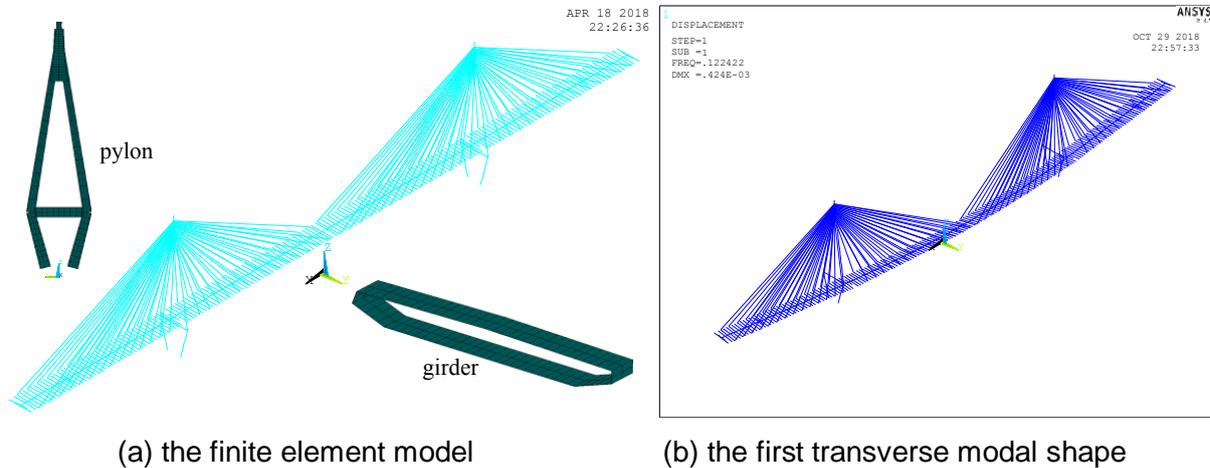


Fig. 2 – FE model and first model shape of the bridge

Based on the dynamical features from structural health monitoring, the first six-order modes of the bridge are obtained as shown in Table 1. The frequencies and modal shape of the bridge were measured using accelerometers installed on the bridge through ambient excitation. Since the realistic bridge state may be different from that of design drawings, the objective of model updating is to make the modified FE model be in consistent with monitoring results regarding these six-order mode frequencies. In the model updating, the well-known girder stiffness, concrete modulus of elasticity, structural boundary condition are taken as the updating parameters [11-12]. The updating results are shown in Table 1, and the first transverse modal shape is shown in Figure 2(b). Results indicate the analytical frequencies of modified FE model are well consistent with monitoring results with relative error basically no more than 8%. Therefore, it can be considered that the updated FE model could represent the realistic condition of the bridge. Note that small damage and crack of local component do not affect the overall performance of the bridge, and thus global vibration characteristics of the bridge are applied in the FE model updating.

Tab. 1 - FE model updating based on structural natural frequencies

Vibration order	Mode direction	Monitoring	FE model Updating	Relative error /%
1	Transverse	0.114	0.122	7.02
2	Vertical	0.234	0.253	8.12
3	Transverse	0.351	0.334	-4.84
4	Vertical	0.354	0.351	-0.85
5	Longitudinal	0.454	0.491	8.15
6	Torsional	0.482	0.503	4.36

Finally, the updated FE model is the baseline for the investigation of traffic loading effects on the bridge. According to the Chinese bridge design code [13], denoted D60, the lane load model shown in Figure 3 is used to calculate the girder displacement, where multi-lane factor, longitudinal reduction factor and impact factor are all considered. The influence lines of girder displacement in the quarter and middle positions of the central span are shown in Figure 4.

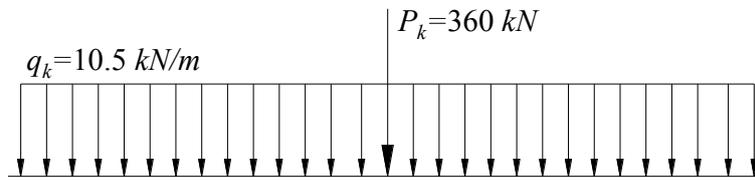


Fig. 3 – Lane load model defined in D60.

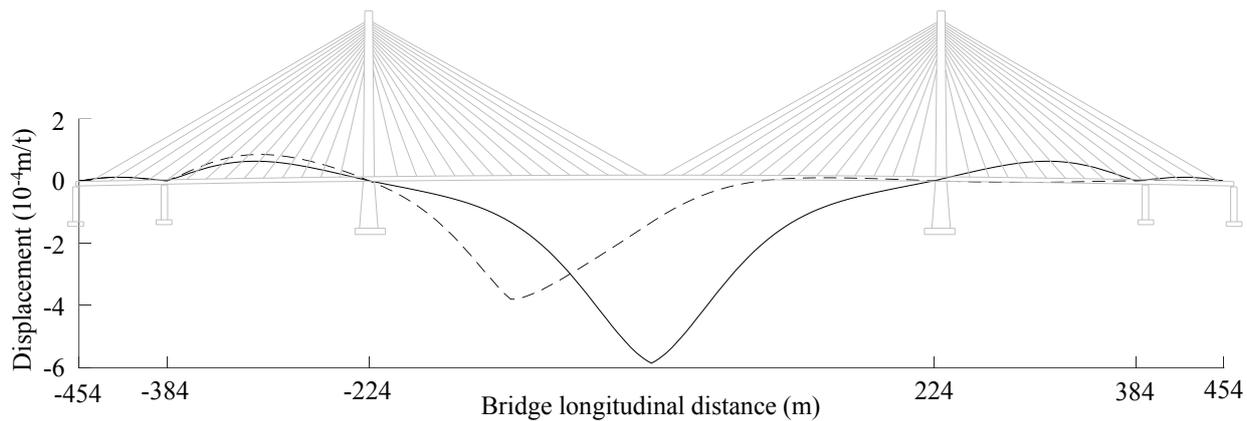


Fig. 4 – Influence lines of girder displacements of in the quarter and middle positions of the central span.

## EXTRACTION OF TRAFFIC LOAD EFFECTS

The studied bridge has installed structural health monitoring system since 2014, which includes displacement monitoring of girder and pylon, stress monitoring of steel deck, and accelerometer of girder etc. In the paper, the displacement monitoring of main girder in the quarter and middle positions of the central span is illustrated in the paper. Figure 5(a) shows time-history of one-day displacement in the middle of the central span. It is well known that monitoring data include the effects of environmental noise, wind, temperature, and traffic. Therefore, load effects induced by factors expect traffic should be filtered so that the bridge in-service condition could be estimated.

### Filtering of environmental noise

Realistic measured displacements are affected by testing equipment and environment, which means the measured data cover a large number of residuals and fluctuate within a certain range. Therefore, it is necessary to filter these residuals, and the common approach is utilizing moving average method. Using moving average algorithm could smooth out the effect of sudden fluctuations on the measurements. Furthermore, there is some environmental noise, which could be addressed through the  $3\sigma$  principle to filter the influence of environmental noise on the results of measured displacements. Figure 5(b) shows the filtered time history of one hour after employing moving average method and the  $3\sigma$  principle. Results indicate the outliers are all filtered.

### Filtering of quasi-static effect

Bridge load effects are not only induced by traffic but also wind and temperature. The effect of temperature is a quasi-static process that load effect from temperature is slowly distributed. The change process of temperature load effect could be regarded as static, which is equivalent to the self-equilibrium position of bridge without vehicle action. Load effect induced by wind includes

static and dynamical impact. Load effect under static wind changes slowly than that of traffic flow, which could also be regarded as quasi-static effect. While, the dynamic effect of wind load is largely smaller than that of vehicle load in normal condition, therefore they are ignored hereon.

The load effects induced by traffic on bridges change rapidly with time. In order to filter these quasi-static effects, the time history of displacements should be subtracted from the equilibrium positions of the bridge under wind and temperature loading. Therefore, the average value of load effects in a certain time interval could be chosen as the equilibrium position of the bridge and a time interval of 10 min is used hereon [10]. The corresponding time-history results of load effects only induced by traffic over one hour are shown in Figure 5(c), which includes the static and dynamic traffic load effects. The displacements induced by traffic loading varied generally in the range of -0.3~0.2 m.

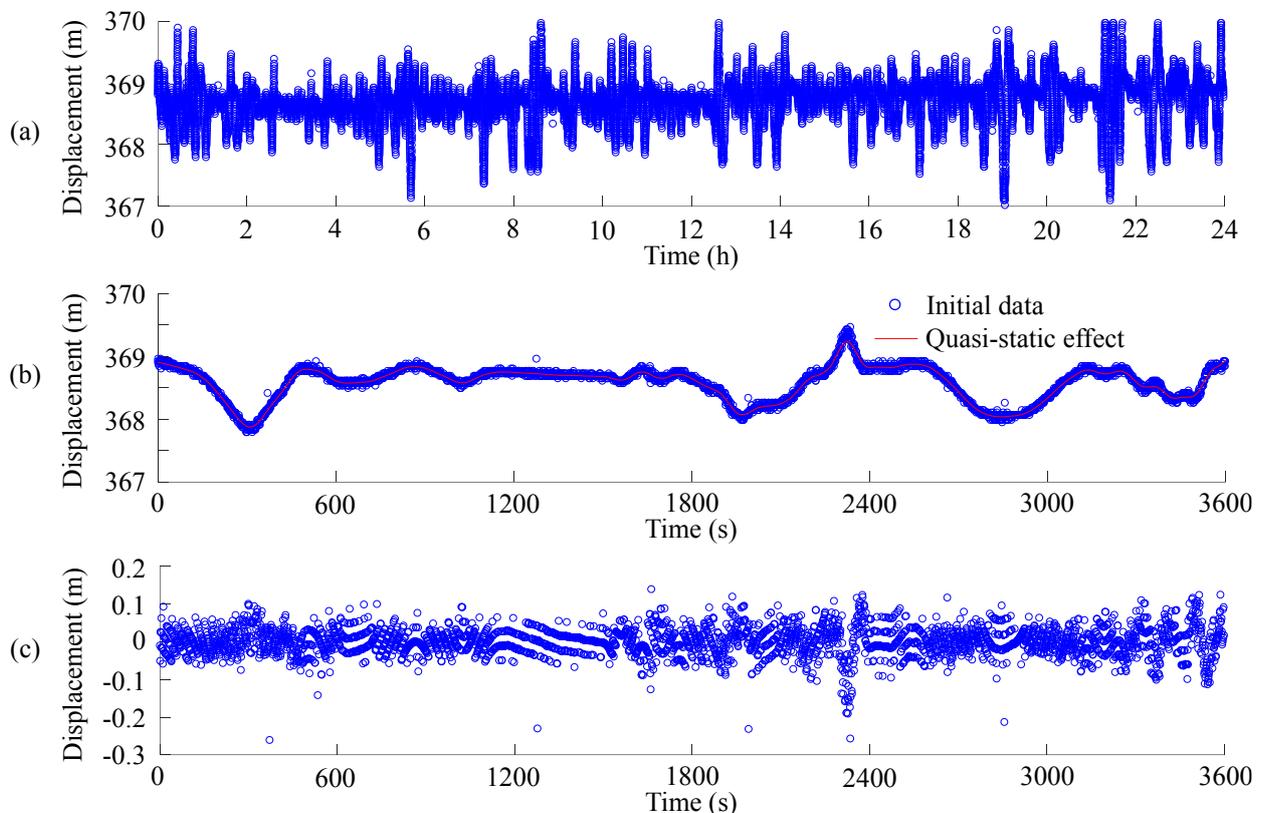


Fig. 5 – Data analysis of the time history of girder displacement: (a) initial data; (b) data filtering; (c) extracted data

## BRIDGE IN-SERVICE CONDITION ASSESSMENT

### Extrapolation of traffic load effects

Structural health monitoring system is installed from 2014, and total 16 months of monitoring data of girder displacement from 2014 to 2015 are used. Girder displacements in the quarter and middle positions of the central span are investigated to extract traffic loading effects to evaluate bridge in-service condition. Obviously, the 16-month test results are not sufficient to reflect the variable and extreme characteristics of vehicle load in long return period. Therefore, the extreme value theory is employed to predict the extreme value of bridge traffic load effect under any evaluation period based on existing monitoring data.

According to classical extreme value theory [14], the constructed samples using block maxima could be described through generalized extreme value (GEV) distribution, and the distribution model is as following

$$G(x; \xi, \sigma, \mu) = \exp \left\{ - \left( 1 + \xi \frac{x - \mu}{\sigma} \right)^{-1/\xi} \right\} \quad (1)$$

where  $\mu, \sigma, \xi$  are the location, the scale, and the shape parameters of the generalized extreme value distribution,  $\xi=0, \xi > 0$  and  $\xi < 0$  represent the type I (Gumbel), II (Frechet), and III (Weibull) GEV model.

GEV is established on the basis of the progressive extreme value model, and samples from block maxima should satisfy the following three conditions: (a) the observation could be simplified as a random variable, i.e. independent of time; (b) these random variables meet the same underlying distribution; (c) the observed variables are independent to each other. For traffic load effects on bridges, it is necessary to select a rational interval so that the requirement of independent and identical distribution could be satisfied. Generally, a day is selected as the block size for extreme value analysis. GEV is used to build the limit distribution of traffic load effects, and maximum likelihood is used to estimate parameters of GEV.

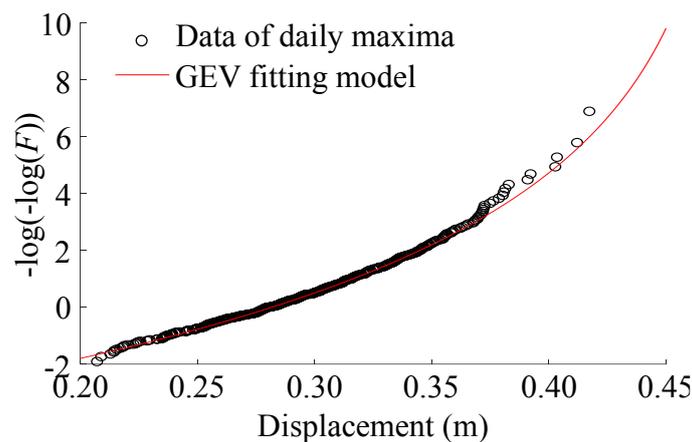


Fig. 6 – GEV fitting on daily maxima of girder displacement in the middle of the central span

Figure 6 shows GEV fitting on daily maxima of girder displacement in the middle of the central span. Totally 480 daily maxima are plotted in the probability paper. The fitting GEV model is estimated through maximum likelihood algorithm, and the shape, scale, location parameters of the GEV model are -0.1922, 0.0381 and 0.2822 respectively. It is known from Figure 6 that GEV could well describe the data. Based on the GEV distribution, characteristic value of any reference period could be easily obtained.

### In-service condition assessment

The calculated displacements through deterministic traffic load model in D60 are 457 mm and 268 mm for the quarter and middle positions of the central span.

The specified level of traffic load in the design code is 95% quantile assurance in the design life of 100 y. Therefore, the characteristic value of displacement from monitoring should be in consistent with that design level regarding remaining life. Table 2 shows the extrapolated characteristic values of traffic load effects through GEV modelling under various remaining lives with 95% quantile assurance, and they are compared with the design level to assess bridge in-service condition.

Table 2 shows the changing of girder displacements in the quarter and middle positions of the central span. With the increase of the remaining lives, characteristic traffic load effects increase but the increasing tendency tends to be gentle. This tail tendency is consistent with the results of GEV fitting in Figure 6, where the tail curves upward, indicating the change of deflection prediction in remaining lives is small. Note that the predicted characteristic displacement is highly related with the variation of traffic loads on the bridge. If traffic loads on the bridge are incorporated with high randomness, then the change of future displacement prediction will be large. Based on the results, it can be revealed the traffic loads on the bridge are less randomness.

The characteristic values of displacements induced by traffic loading within 10 y are all lower than the calculated values from the design code. While, realistic traffic load effects of the bridge beyond 10 y are greater than those of the design code. Since displacement represents bridge in-service condition, the results indicate the bridge is in good condition within 10 y. However, the displacement of the bridge may exceed the design level when the evaluation period is greater than 10 y, and the good in-service condition could not be ensured. Therefore, management of traffic loads and maintenance of bridge components should be enhanced after the bridge further been in service for ten years.

*Tab. 2 - Comparison of extrapolated traffic load effects and calculation results from design code under various remaining lives*

Remaining life	Displacement in the middle of the central span /mm		Displacement in the quarter position of the central span /mm	
	Extrapolated value	Design value	Extrapolated value	Design value
5 y	452		261	
10 y	457		267	
20 y	460	457	271	268
50 y	463		275	
80 y	464		277	

## CONCLUSION

The assessment of girder displacement under traffic loading in remaining life provides knowledge on bridge in-service condition. Based on monitoring data of displacement from the health monitoring system, the time-history of displacements induced only by traffic loading is obtained. Characteristic traffic load effects under various remaining lives are extrapolated and quantitatively analysed, to assess bridge in-service condition. The major conclusions are as follows:

- (1) Moving average method and window smoothing method could extract load effects induced by traffic based on monitored data from those produced by wind, temperature, and environmental noise. The extracted traffic load effects provide the basis for the operational analysis of vehicle load on bridges.
- (2) Based on extracted displacement induced by traffic loading, daily maxima based GEV extrapolation could be utilized to build the limit distribution of any return period.
- (3) According to the monitoring displacement of the studied bridge over 16 months, the extreme value prediction of girder displacement caused by traffic loading shows the realistic values are larger than the design level after being in service for another decade. Therefore, it is necessary

to enhance the management of traffic loads and maintenance of bridge components to ensure the bridge in-service condition.

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