Reliability Analysis and Evaluation of Existing Concrete Bridge under Vehicle Load

Zhe Gao[1, *], Qingbing Li[2], Yao Feng[3], Xiaoyan Yang[4], Chuang Chen[4]

[1]Baise University, Guangxi, China

[2]Ningbo Zhengxin Detection Technology Co., Ltd., Ningbo, Zhejiang, China

[3]Financial Investment Evaluation Center of Jinzhou Development Zone, Jinzhou, Liaoning, China

[4]Ningbo Institute of Technology, Zhejiang University, Ningbo, Zhejiang, China

[*]Corresponding author

Keywords: Bridge engineering, Load effect, Statistical analysis, Safety, Serviceability

Abstract: The influences of vehicle load and corrosive environment on existing highway bridge structures are investigated in the Chinese context. These two factors are the primary cause of the diseases of bridges, e.g. damage and aging, and hence the deterioration of their carrying capacity and functionality. The vehicle load effect on standard bridges with various spans suggested by the Chinese codes are calculated and statistically analyzed. Associated probability distribution models are then established allowing for different overload treatment policies. The reliability index of existing bridges is calculated based on the checking factors for load-bearing capacity evaluation in current Chinese codes. The result shows that the maximum distribution of vehicle load effect in design reference period obeys the lognormal distribution. The reliable indexes of the “Well-performed” existing bridges calculated with the random traffic flow in non-controlling and toll-by-weight areas are smaller than the code-stipulated target reliability index.

1. Introduction

The load-bearing capacity inadequacy due to the deterioration or damage of existing bridge structures is a worldwide issue. Among 600 000+ bridges in the U.S.A., about 10% are facing structural deficiency or deterioration and the service period of bridges in trunk highway is now mostly around 44 years. Plus, a large quantity of bridges built up around 1950s and 1960s has now reached their design service life, where reuse has been an urgent issue. According to incomplete statistics, some bridges in European countries have stepped into their maintenance period and the percentages of bridges waiting for maintenance are 39%, 37%, 26% and 30% in France, Germany, Norway and Britain. In mainland, China, 15% of the bridges in national, provincial and prefectural highway have been in service for more than 30 years while more than 60% of country highways were completed before 1980s. It is shown by the bridges of developed countries that concrete bridges, after servicing for 20 to 30 years, would encounter problems of safety and durability. At the present, the evaluation requires the predication of vehicle loads based on possible use of bridges and the determination of actual member dimensions and material performance of bridges according to the outcome of bridge inspections. Overload operation has brought enormous latent hazards for the safety and durability of bridges in recent years. Noticing these phenomena, scholars conducted researches on actual vehicle loads of bridges in service based actual traffic flow [1, 2] and probability distribution of vehicle loads in design reference period [3, 4]. However, it is not prescribed in these researches the vehicle load probability model of each lane according to the characteristics of corresponding traffic flows. And in real situations, vehicle load in each lane varies drastically.

In this paper, the commercial structural analysis software MIDAS was adopted to build up the finite element model of 56 standard bridges with different spans prescribed by Chinese General Drawing Collection for Highway Bridges to calculate vehicle load effects. And then the probability distribution of moment and shear was determined. The subsequent merging process gives the

  DOI: 10.25236/ic3ec.2020.018

probability models and associated statistical parameters of the moment ratio and shear of bridges under different overload treatment policies within design reference period. With the probability distribution and associated statistical parameters of the vehicle loads collected in 1990s and around 2011 and of the resistances of well-performed existing bridges, a reliability index for existing bridges based on current Chinese codes was put forward.

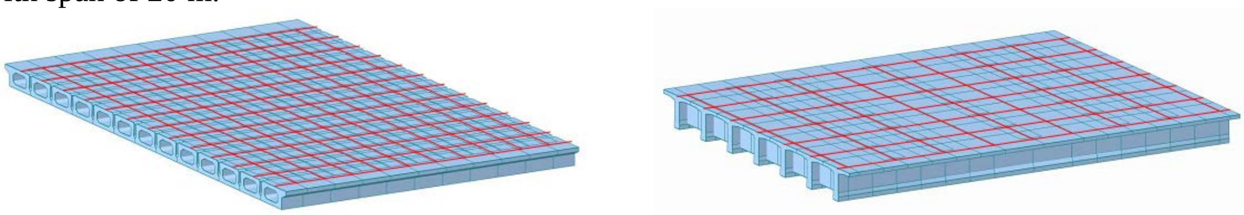
2. Vehicle Load Effect

Vehicle load effect refers to the internal forces resulted from the action of vehicle load on highway bridge structures, e.g. moment and shear. It is unrealistic to directly measure the internal forces in a bridge structures. Thus, vehicle load effects are determined with mechanical computation based on the data of actual traffic flow or virtual vehicles data generated with stochastic sampling.

2.1 Bridge Model

The simply supported pre-stressed concrete cored slab bridges and T-beam bridges specified by the Chinese General Drawing Collection for Highway Bridges were taken as example for calculating the internal forces of the key sections of highway bridges. The various lengths considered for the cored slab bridges are 10m, 13m, 16m, and 20m. The spans of T-beam bridges in this study are 20m, 25m, 30m, 35m, and 40m. Shown in Figure 1(a) is a simply supported prestressed concrete cored slab bridge with zero slope and a thickness of 1.25m. There are thirteen cored slabs in the transverse direction with their centre-to centre distance of 1.24m. The width of the bridge is 14.88m. A simply supported prestressed concrete T-beam bridge with a zero slope is illustrated in Figure 1(b). Seven T-beams with a centre-to centre distance of 2.35m in the transverse direction, the bridge is of 14.1m wide. The bridges considered were all designed three traffic lanes and its design loading class is Grade I highway.

The simulation of the bridges was carried out with the structural analysis software Midas/Civil. A longitudinal beam along the bridge was used to simulate every cored slab or T-beam. The connection between the longitudinal beams was simulated by virtual transversal short beams with zero mass. The bridge models were completed with the Isotropic Beam Element. Figure 1 also reads the sections and element division of cored slab bridge with the span of 10 m and T-beam bridges with span of 20 m.



(a) cored slab bridge (b) T-beam bridge

Figure 1 Basic Flow Chart of Simulation Motorcade for Monte-Carlo Method

2.2 Calculation of Vehicle Load Effect

It was assumed in the calculation of vehicle load effects that vehicle types on the roadway and the associated probability distribution keep steady in a certain period of time, and structural nonlinearity could be ignored for determining the load effects on bridges with small and medium spans. The traffic flow of random vehicle in each lane was generated through a Monte-Carlo simulation method. And then the load effect was obtained by the vehicle load imposed on influence line or surface of the key sections of bridges.

2.2.1 Section Probability Distribution of Vehicle Load Effect

The section probability distribution of vehicle load effect is the probability distribution of the vehicle load effect due to random vehicle flow at some instance. The sample values of vehicle load effects, i.e. moment and shear, were calculated with actual data in non-controlling, toll-by-weight and overload controlling area and then statistical analysis was implemented. The statistical histograms of vehicle load effect of some prestressed concrete bridges with different span are shown in Figure 2. It can be observed from Figure 2 that similar to vehicle loads vehicle load effects also obey multi-peak distribution [5, 6]. The probability density function of vehicle load effects can be represented as the weighted sum of lognormal probability density function and two speaks normal probability density function, namely

$$f_Q(q) = q_1 \frac{1}{\sigma_{\ln Q_1} q} \varphi\left(\frac{\ln(q) - \mu_{\ln Q_1}}{\sigma_{\ln Q_1}}\right) + q_2 \frac{1}{\sigma_{Q_2}} \varphi\left(\frac{q - \mu_{Q_2}}{\sigma_{Q_2}}\right) + q_3 \frac{1}{\sigma_{Q_3}} \varphi\left(\frac{q - \mu_{Q_3}}{\sigma_{Q_3}}\right) \tag{1}$$

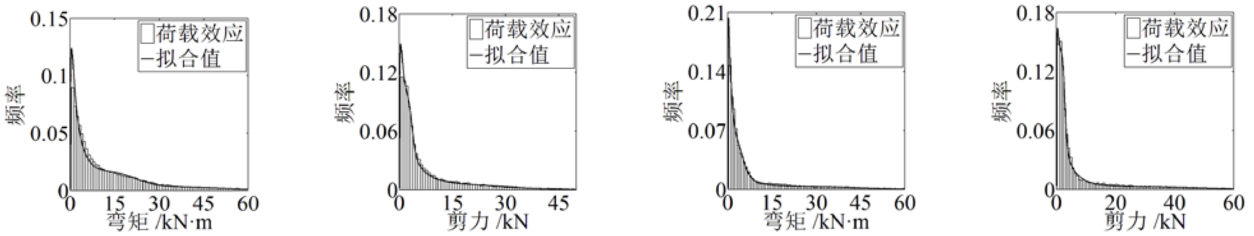
where $f_Q(q)$ is the probability density function of vehicle load effect on bridge; Q is the random variable of vehicle load effect; q_1, q_2, q_3 are proportion accounted by 1th, 2th, 3th vehicle load effect; $\mu_{\ln Q_1}$ and $\sigma_{\ln Q_1}$ are the mean and standard deviation of the logarithm of the 1th overall vehicle load effect, respectively; μ_{Q_2} and σ_{Q_2} are the mean and standard deviation of the 2th overall vehicle load effect, respectively, while μ_{Q_3} and σ_{Q_3} are the ones of the 3th overall vehicle load effect, respectively.

The probability distribution function of vehicle load effects can be described as follows

$$F_Q(q) = q_1 \Phi\left(\frac{\ln(q) - \mu_{\ln Q_1}}{\sigma_{\ln Q_1}}\right) + q_2 \Phi\left(\frac{q - \mu_{Q_2}}{\sigma_{Q_2}}\right) + q_3 \Phi\left(\frac{q - \mu_{Q_3}}{\sigma_{Q_3}}\right) \tag{2}$$

Where $\Phi(\cdot)$ is the probability distribution function of standard normal random variable.

According to sample value of vehicle load effect under random vehicle load, the maximum likelihood method is applied to estimate parameters q_1, q_2, q_3, $\mu_{\ln Q_1}$, $\sigma_{\ln Q_1}$, μ_{Q_2}, σ_{Q_2}, μ_{Q_3} and σ_{Q_3} in Equation (1).



(a) non-controlling area (b) overload controlling area

Figure 2 Vehicle load effects with L=13m for cored slab bridge

It can be observed from Figure 2 that the weighted sum of lognormal and two-peak normal probability density function can be used to represent the probability density function of the vehicle load effect on the simply supported pre-stressed concrete cored slab bridge and T-beam bridges. The statistical characteristics of vehicle load effect are well described, especially the right-tail of the vehicle load probability density curve. The longer tail reflects the influence of heavy vehicle loads.

2.2.2 Probability Distribution of Maximum Vehicle Load Effect in Design Reference Period

To determine standard values of loads on bridges or conduct reliability analysis, the probability distribution of the maximum vehicle load effect in design reference period should be adopted. The section distribution of vehicle load effect needs to be transformed to the probability distribution of maximum value in design reference period. The sample function model of vehicle load effects is transformed into equal-time-interval rectangular function.

According to Equation (2), the probability distribution function of the maximum vehicle load effects in design reference period is determined.

$$F_{QT}\left(q\right)=\left[F_{Q}\left(q\right)\right]^{T}=\left[q_{1}\Phi\left(\frac{\ln\left(q\right)-\mu_{\ln Q_{1}}}{\sigma_{\ln Q_{1}}}\right)+\sum_{i=2}^{n}q_{i}\Phi\left(\frac{q-\mu_{Q_{i}}}{\sigma_{Q_{i}}}\right)\right]^{T} \tag{3}$$

The associated probability density function is

$$f_{QT}\left(q\right)=TF_{Q}^{T-1}\left(q\right)f_{Q}\left(q\right) \tag{4}$$

Where T is the design service period of structures, in this paper T=100a.

By combining with Equation (4), the following equations were applied to calculate the mean, standard deviation and coefficient of covariance of the maximum vehicle load effects in service life.

$$\mu_{QT}=\int_{0}^{+\infty}qf_{QT}\left(q\right)dq;\sigma_{QT}=\sqrt{\int_{0}^{+\infty}\left(q-\mu_{QT}\right)^{2}f_{QT}\left(q\right)dq};\delta_{QT}=\frac{\sigma_{QT}}{\mu_{QT}} \tag{5}$$

Where μ_{QT}, σ_{QT} and δ_{QT} are the mean, standard deviation and coefficient of covariance of the maximum vehicle load effects in design reference period, respectively.

In order to make the statistical results applicable for bridges of different spans, a dimensionless parameter $k_S = S_Q / S_{QT}$. After obtaining the dimensionless parameter of the load effect ratio, the load effect ratios for different overload policies, different bridge types and different bridge spans were summarized, i.e. the potential controlling moment ratios and shear ratios for different bridge types were merged respectively. The mean and standard deviation of statistical parameters was determined with the following equation.

$$\mu_{k_{QT}}=\frac{1}{m}\sum_{i=1}^{m}\mu_{k_{QT,i}};\sigma_{k_{QT}}=\sqrt{\frac{\sum_{i=1}^{m}\left[\sigma_{k_{QT,i}}^{2}+\left(\mu_{k_{QT,i}}-\mu_{k_{QT}}\right)^{2}\right]}{m}} \tag{6}$$

Where, m is the number of load cases; $\mu_{k_{QT}}$ and $\sigma_{k_{QT}}$ are the mean and standard deviation of the load effect ratio, respectively; and $\mu_{k_{QT}}=\mu_{QT}/S_{Qk}$, $\sigma_{k_{QT}}=\sigma_{QT}/S_{Qk}$.

3. Reliability Analysis and Evaluation of Well-Performed Existing Bridges

The causes of various diseases of bridges during their service life are complex and the induced decrease in load-bearing capacity is different. In this session, the reliability of existing bridges was calculated by assuming that bridges stay “well-performed” within their service life. The combination of dead load and vehicle load is considered for calculating the reliability of bridges within design reference period, then the limit state function of bridge structures can be expressed as

$$Z=R-S_{G}-S_{QT}=0 \tag{7}$$

Where, S_G is dead load effect, obeying the normal distribution, S_{QT} is the maximum value of vehicle load effect within the design load effect of bridges, R is the resistance of prestressed concrete members, obeying the lognormal distribution.

The mean and standard deviation of S_G, S_{QT} and R can be computed with the following equations.

$$\mu_{S_G} = \mu_{k_G} S_{G_k}, \quad \sigma_{S_G} = \mu_{S_G}\delta_{S_G} = \mu_{k_G} S_{G_k}\delta_{S_G}$$
$$\mu_{S_{QT}} = \mu_{k_{QT}} S_{Q_k}, \quad \sigma_{S_{QT}} = \mu_{S_{QT}}\delta_{S_{QT}} = \mu_{k_{QT}} S_{Q_k}\delta_{S_{QT}}$$
$$\mu_R = \mu_{k_R} R_k = \mu_{k_R}\left(\gamma_G S_{G_k} + \gamma_Q S_{Q_k}\right), \quad \sigma_R = \mu_R\delta_R \tag{8}$$

It can be inferred from Equation (8) that load effects of both permanent loads and vehicle loads are directly proportional to their standard value. In such circumstance, it is not necessary to involve the specific value of load effects and structural resistances in the calculation of structural reliability index, only the ratio of the load effects of different vehicle loads and permanent loads, i.e. $\rho = S_{Q_k} / S_{G_k}$, should be considered. And the ratio ρ took 0.1, 0.25, 0.5, 1.0, 1.5 or 2.5 in reference to the actual situations. According to the limit state equation given in Equation (8) to calculate the reliability index of well-performed existing bridges. The results are shown in Table 2.

Table 1 Reliability Index of Well-Performed Existing Bridges

Traffic flow	Around 2011 1990s							
Overload policy	Non-controlling		Toll-by-weight		Overload controlling		Unclassified	
Load effect	Moment	Shear	Moment	Shear	Moment	Shear	Moment	Shear
Reliability index	3.214	3.598	3.617	4.147	4.352	4.999	5.773	6.432

It can be seen from Table 1 that the reliability index of well-performed existing bridges calculated with statistical parameters of vehicle load data measured in 1990s can satisfy the target reliability index stipulated in GB/T50283. The reliability index of existing bridges calculated with statistical parameters for vehicle loads in non-controlling and toll-by-weight area cannot meet the requirement stipulated by GB/T50283, specifically, the target reliability index for Class II structural members with ductility failure 4.2 and that for members with brittle failure 4.7.

4. Conclusion

On the basis of the vehicle load data actually measured in areas with different overload treatment policies, the vehicle load effects of standard bridges specified by Chinese General Drawing Collection for Highway Bridges were calculated. And proposed were probability distribution models and associated parameters for vehicle load effect in present traffic situations. The reliability index of existing bridges is calculated for load-bearing capacity evaluation in current Chinese codes. The following are the main conclusions:

(1) The probability distribution of vehicle load effects in design reference period conforms to the lognormal distribution.

(2) Existing bridges designed with current load standard and specifications should have a reliability level not less than the target reliability level stipulated by current codes. That is to say, the target reliability index should meet the specifications of GB/T50283, 1999.

References

[1] Z. F. Xu, Q. Wang, Y. S. Liu. Research of Vehicle Load Model for Highway Bridges in Guangdong Province Based on WIM Data. Bridge Construction, vol.42, no. 3, pp. 39-44, 2012.

[2] S. W. Sun, L. M. Sun. Statistic Model of Vehicle Loads for Highway Bridges. Journal of Tongji University (Natural Science), vol. 40, no. 2, pp. 198-204, 2012.

[3] A. S. Nowak, H. Nassif, L. Defrain. Effect of Truck Loads on Bridges. Journal of Transportation Engineering, vol. 119, no. 6, pp. 853-867, 1993.

[4] X. Y. Yang, J. X. Gong, Q. W. Zhang. Analysis of Probabilistic Model of Stay Cable Stress and Reliability under Random Vehicle Loads. Journal of Architecture and Civil Engineering, vol. 31, no. 2, pp. 90-98, 2014.

[5] G. Mei, Q. Qin, D. J. Lin. Bimodal Renewal Processes Models of Highway Vehicle Loads. Reliability Engineering & System Safety, vol. 83, no. 3, pp, 333-339, 2004.

[6] J. X. Gong, X. Y. Yang. Research on Probabilistic Model of Highway Bridge Vehicle Loads (1) --Non-controlling Area. Journal of Highway and Transportation Research and Development, vol. 27, no. 6, pp. 40-45, 2010.