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Sensitivity Parameter Analysis of Negative Moment Dynamic Load Allowance of Continuous T-Girder Bridge

Fan Yang, Ye-lu Wang, Yang Zhao

***Abstract*—**The dynamic load allowance, as an application result of the vehicle-bridge coupled vibration theory, is an important parameter for bridge design and evaluation. Based on the coupled vehicle-bridge vibration theory, the current work establishes a full girder model of a dynamic load allowance, selects a planar five-degree-of-freedom three-axis vehicle model, solves the coupled vehicle-bridge dynamic response using the APDL language in the spatial finite element program ANSYS, selects the pivot point 2 sections as the representative of the negative moment section, and analyzes the effects of parameters such as travel speed, unevenness, vehicle frequency, span diameter, span number and forced displacement of the support on the negative moment dynamic load allowance through orthogonal tests. The influence of parameters such as vehicle speed, unevenness, vehicle frequency, span diameter, span number, and forced displacement of the support on the negative moment dynamic load allowance is analyzed by orthogonal tests, and the influence law of each influencing parameter is summarized. It is found that the effects of vehicle frequency, unevenness, and speed on the negative moment dynamic load allowance are significant, among which vehicle frequency has the greatest effect on the negative moment dynamic load allowance; the effects of span number and span diameter on the negative moment dynamic load allowance are relatively small; the effects of forced displacement of the support on the negative moment dynamic load allowance are negligible.

***Keywords*—**Continuous T-girder bridge, dynamic load allowance, sensitivity analysis, vehicle-bridge coupling.

I. INTRODUCTION

WHEN a vehicle passes through a bridge at a certain speed, the effect on the bridge structure caused by the vehicle is greater than the response produced by the structure under the same conditions of static load, and this increased effect of the vertical dynamic response produced by the vehicle on the bridge structure is described by the concept of dynamic load allowance [1]. Bridge dynamic load allowances can make complex dynamic problems static, with complex force mechanisms, and have been widely concerned by scholars.

There is a study which has shown that the dynamic load allowance is influenced by many random factors together [2]. The bridge deck flatness is an important factor affecting the dynamic load allowance, which increases with decreasing unevenness level of the bridge deck [3]. The accuracy of the vehicle model is crucial to the dynamic load allowance calculation. Wang et al. [4] proposed a three-axis vehicle model. Lu et al. [5] proposed a set of 5-axis vehicle model parameters based on the design vehicle loads in the Chinese bridge code. Wu et al. [6] compared the impact effects of moving spring-mass, quarter, plane and full vehicle models and showed that the dynamic load allowances were well calculated for the plane vehicle model and the full vehicle model effects.

In the analysis of the role of vehicle weight, the study showed that the dynamic load allowance decreases with the increase of vehicle weight [7]. Compared to heavy vehicles, the small weight vehicles will produce a larger dynamic load allowance, while the effect is smaller at static load. Although the dynamic load allowance obtained is larger, the total load effect is still small, so that the dynamic load allowance obtained has no practical significance. In terms of vehicle speed, scholars have not reached a consensus on the relationship between the dynamic load allowance and vehicle speed. Some studies have found that the dynamic load allowance increases with the increase of vehicle speed [8], [9], and a study has shown that the dynamic load allowance does not increase or decrease monotonically with vehicle speed [10]. Based on this, the current work takes a prestressed concrete continuous T-girder bridge as the research object, adopts a five-degree-of-freedom three-axis planar vehicle model, uses the APDL language in the spatial finite element program ANSYS to solve the coupled vehicle-bridge dynamic response, and analyzes the influence of various parameters on the negative moment dynamic load allowance through orthogonal tests, and the effects of each, and the influence law of each parameter is summarized.

II. VEHICLE-BRIDGE COUPLING DYNAMIC LOAD ALLOWANCE ANALYSIS THEORY

A. Dynamic Load Allowance Calculation Method

Highway bridge design codes generally use the dynamic load allowance to characterize the dynamic impact effect of the vehicle on the bridge structure. The dynamic load allowance is the increase factor of the vertical dynamic effect on the bridge structure when the vehicle crosses the bridge. The dynamic load allowance of vehicle load can be expressed as (1):

$$\mu = \frac{Y_{dmax}}{Y_{jmax}} - 1 \qquad (1)$$

where Y_{jma} is the maximum static effect value measured at the

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maximum static effect on the effect time course curve measured when the vehicle crosses the bridge; Y_{dmax} is the maximum dynamic effect value measured at the maximum static effect on the effect time course curve.

B. Vehicle Model and Vibration Equation

With reference to the mainstream models used in bridge dynamic load tests, the current work adopts a five-degree-of-freedom three-axis planar vehicle model. The vehicle model is shown in Fig. 1.

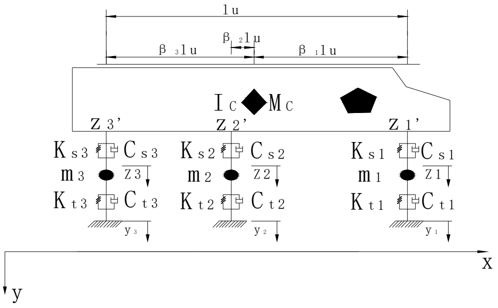

Fig. 1 Five-degree-of-freedom three-axis planar vehicle model

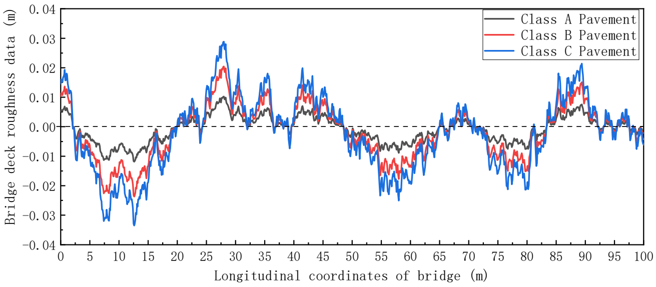

Fig. 2 Bridge deck roughness curve

In Fig. 1, the car body mass Mc has elevation and pitch rotation degrees of freedom α and vertical displacement z. The sum of frame and wheel pair masses M1, M2 and M3 have vertical displacement degrees of freedom Z1, Z2 and Z3, Ks and Cs are the first-series suspension stiffness and damping, and Kt and Ct are the second-series suspension stiffness and damping.

C. Bridge Deck Roughness

A study has shown that bridge deck unevenness is one of the main excitation sources affecting the vibration response of coupled vehicle-bridge systems [11]. Therefore, how to establish the bridge deck unevenness model becomes a key issue in the study of vehicle-bridge coupled vibration [12]. In this paper, the Fourier transform inversion method and the reference to the Chinese standard are used to generate bridge deck unevenness samples.

The numerical simulation model of bridge deck unevenness is calculated as:

$$|X_k| = \sqrt{\frac{N}{2\Delta l} G_x(n_x)} \qquad \left(k = 1,2,\ldots,\frac{N}{2}\right) \tag{2}$$

where: $|X_k|$ is the modal value of the discrete Fourier transform signal; $G_x(n_k)$ is the discrete form of the given power spectral density function; $n_k = k\Delta n, \Delta n = 1/L; \Delta n$ is the frequency interval, L is the bridge length, N is the number of sampling points, Δl is the sampling interval.

After investigation, it can be obtained that the unevenness of A, B and C grade bridge deck is the most common in China. Fig. 2 shows a set of randomly generated unevenness samples of bridge deck.

III. SENSITIVITY PARAMETER ANALYSIS OF NEGATIVE MOMENT DYNAMIC LOAD ALLOWANCE

The bridge dynamic load allowance is affected by many factors, which are inseparable from the vehicle dynamic characteristics, bridge structural dynamic characteristics, vehicle speed, bridge deck flatness, number of vehicles and driving position. In this paper, the three-span continuous girder pivot point 2 section is used as a representative of the negative moment critical section, and the influence of the negative moment dynamic load allowance of six factors, namely, travel speed, unevenness, vehicle frequency, span diameter, number of spans and forced displacement of the support, is studied by orthogonal test mathematical and statistical methods.

A. Finite Element Model

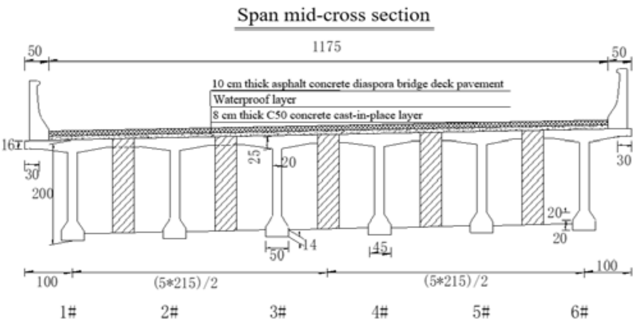

Fig. 3 Cross-sectional drawing of prestressed continuous T-girder bridge (unit: cm)

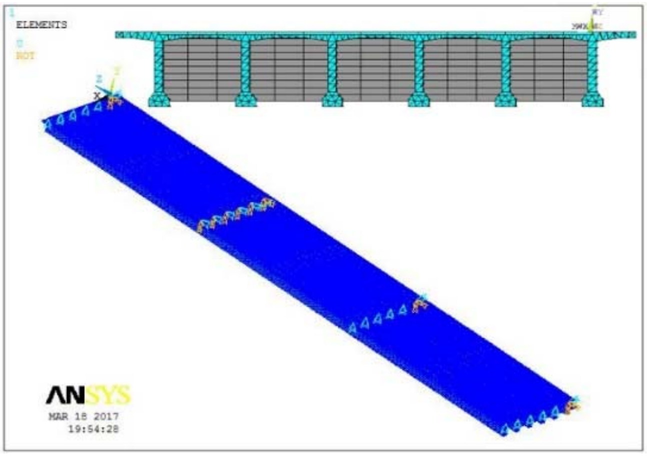

Fig. 4 Schematic diagram of three-span continuous T-girder bridge model

In the current work, a 30 m standard span continuous T-girder bridge is used as the research object, and the cross-sectional dimensions are shown in Fig. 3. The superstructure is simulated by beam unit, the crossbeam adopts equivalent stiffness, and the spatial finite element model is shown in Fig. 4, ignoring the influence of substructure. The vehicle model used in this paper is the five-degree-of-freedom three-axis planar vehicle model introduced above, and the vehicle parameters are shown in Table I [13].

TABLE I
VEHICLE MODEL PARAMETERS

Parameters	Numerical value
Weight (kg)	32000
Weight of per front, middle and rear wheel (kg)	500
Vehicle pitching moment of inertia (kg·m^2)	40000
Horizontal distance from the front axle to the center of gravity of the vehicle (m)	3.4
Horizontal distance from the center axis to the center of gravity of the vehicle (m)	1.6
Horizontal distance between the middle and rear axles (m)	1.5
Wheelbase (m)	1.8
Stiffness coefficient of front axle upper suspension system (kN·m^{-1})	1200
Stiffness coefficient of upper suspension system of middle and rear axle (kN·m^{-1})	2400
Damping coefficient of front axle upper suspension system (kN·s·m^{-1})	5
Stiffness coefficient of upper suspension system of middle and rear axle (kN·s·m^{-1})	10
Stiffness coefficient of front axle lower suspension system (kN·m^{-1})	2400
Stiffness coefficient of the lower suspension system of the middle and rear axles (kN·m^{-1})	4800
Damping coefficient of front axle lower suspension system (kN·s·m^{-1})	6
Stiffness coefficient of the lower suspension system of the middle and rear axles (kN·s·m^{-1})	12

B. Determination of Influencing Factors and Their Levels

The parameters of each influencing factor studied in this paper are as follows: (a) Travel speed: this paper selects four vehicle speeds of 30 km/h, 60 km/h, 90 km/h and 120 km/h as the values of vehicle-bridge coupling vibration system calculation parameters; (b) Road surface unevenness: according to the Chinese standard and combined with the actual situation of China's highways, three grades of A, B and C are selected; (c) Vehicle parameters: this paper takes the comprehensive index of vehicle frequency as the influence factor of dynamic load allowance, by adjusting the suspension stiffness and damping. The vehicle frequency is selected as 2.18 Hz, 2.66 Hz, 2.86 Hz and 3.37 Hz; (d) Span diameter: the conventional design spans of 30 m, 40 m and 50 m of highway continuous girder bridges are selected as the representative levels of spans, and the sectional dimensions are shown in Fig. 3 respectively; (e) Span number: in this paper, the conventional design spans of highway continuous beam bridges are 2, 3 and 4, and the influence of spans on the impact coefficient of negative bending moment is studied. The calculation frequency of each model is shown in Fig. 5; (f) Bearing forced displacement: according to the actual highway bridge pier or bearing subsidence and disease condition, this paper takes the selected key pivot point without drop, 2 cm drop and 4 cm drop as the representative level of bearing forced displacement.

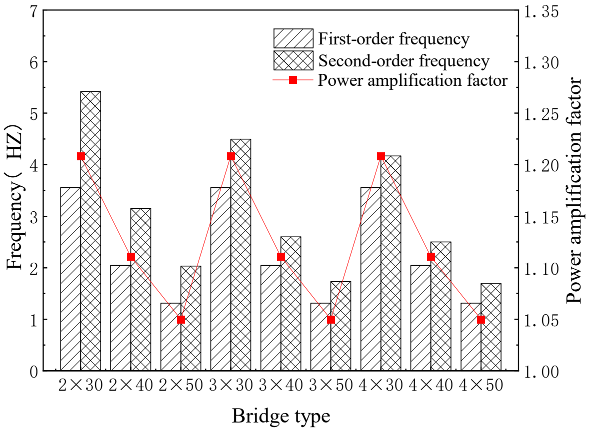

Fig. 5 Bridge type parameters

C. Orthogonal Experimental Design

In this paper, the orthogonal test was used as a parameter analysis method for the sensitivity of the negative moment dynamic load allowance, in order to study the degree of influence of each parameter on the dynamic load allowance. According to the selected factors and the corresponding level elements, the multi-factor mixed level orthogonal test design was carried out using the professional mathematical statistical software SPASS, and the designed L25 (34×42) orthogonal test table is shown in Table II.

D. Results of Sensitivity Parameter Analysis

Based on the calculation results of the negative moment dynamic load allowance of the pivot point 2 cross-section of various bridge types under various operating conditions, the analysis function of the mathematical statistical software SPASS was used to conduct orthogonal test parameter analysis. The mean effect of the calculated orthogonal test parameters is shown in Table III, and the results of the sensitivity parameter analysis are shown in Table IV.

The following conclusions can be obtained from Tables III and IV: From the vehicle frequency factor, the negative moment dynamic load allowance increases significantly with the increase of vehicle frequency, which is consistent with the results obtained from the positive moment zone. From the unevenness factor, the negative moment dynamic load allowance increases gradually with the increase of unevenness level. The unevenness impact effect is especially significant for Class C pavement. From the speed factor, the maximum value of negative moment dynamic load allowance appears at 30 km/h. With the increase of speed, the dynamic load allowance first decreases and then becomes larger, which is consistent with the conclusion that the maximum impact effect of positive moment zone appears at 30 km/h. From the span number factor, the span number and dynamic load allowance are not monotonically increasing or decreasing relationship. From the span diameter factor, with the increase of span diameter, the negative moment dynamic load allowance gradually decreases, which is consistent with the conclusion of positive moment dynamic load allowance. From the bearing forced displacement factor, the dynamic load allowance increases slightly when the forced displacement of the support increases.

TABLE II
ORTHOGONAL TEST CONDITIONS

Work conditions	Cross count	Span Diameter (m)	Speed (km/h)	Unevenness	Vehicle frequency (Hz)	Forced displacement of the support (m)
1	2	50	120	A	2.66	0
2	2	50	30	C	2.86	0
3	2	40	90	A	3.37	0
4	2	30	30	A	2.18	0
5	3	40	60	C	2.18	0
6	3	40	120	B	2.18	0
7	4	30	30	B	2.18	0
8	3	40	90	B	2.66	0
9	4	30	60	A	3.37	0
10	3	30	30	B	2.86	0
11	4	40	30	C	2.66	-0.02
12	2	40	30	B	3.37	-0.02
13	2	30	120	B	2.18	-0.02
14	3	50	60	A	2.18	-0.02
15	3	30	90	A	2.86	-0.02
16	2	40	30	A	2.18	-0.02
17	4	50	90	B	2.18	-0.02
18	3	30	30	A	2.66	-0.02
19	3	30	120	C	3.37	-0.02
20	2	40	60	B	2.86	-0.02
21	2	30	90	C	2.18	-0.04
22	2	30	60	B	2.66	-0.04
23	3	40	30	A	2.18	-0.04
24	3	50	30	B	3.37	-0.04
25	4	40	120	A	2.86	-0.04

TABLE III
MEAN VALUE EFFECT OF ORTHOGONAL TEST PARAMETERS

Factors	Speed	Unevenness	Vehicle frequency	Cross count	Span Diameter	Forced displacement of the support (m)
Level 1	1.041	0.097	0.015	0.856	1.27	0.139
Level 2	0.195	0.693	0.244	0.205	0.806	0.14
Level 3	0.396	0.784	0.265	0.312	0.44	0.145
Level 4	0.201		1.338			
Mean Square Error	3.752	3.92	6.298	2.312	2.305	0.39

TABLE IV
RESULTS OF SENSITIVITY PARAMETER ANALYSIS

Influence factor ranking	Factors	Significance level 1	Significance level 2	Significance level 3	Significance level 4
1	Vehicle frequency (Hz)	3.37	2.86	2.66	2.18
2	Unevenness	C	B	A	
3	Speed (km/h)	30	90	120	60
4	Cross count	2	4	3	
5	Span Diameter (m)	30	40	50	
6	Forced displacement of the support(m)	-0.04	-0.02	0	

IV. CONCLUSION

The current work takes the prestressed concrete continuous T-girder bridge as the research object, adopts the five-degree-of-freedom three-axis planar vehicle model, selects the pivot point 2 section as the representative of the negative moment section, analyzes the influence of parameters such as travel speed, unevenness, vehicle frequency, span diameter, span number and forced displacement of the support on the negative moment dynamic load allowance using orthogonal tests, and summarizes the influence law of each influencing parameter, and obtains the following main conclusions.

1. Overall, for the negative moment dynamic load allowance of a prestressed concrete continuous T-girder bridge, the influence of sensitivity parameters is ranked as follows: vehicle frequency > unevenness > speed > span number > span diameter > forced displacement of support.
2. The effects of vehicle frequency, unevenness and speed on negative moment dynamic load allowance are significant, among which vehicle frequency has the greatest effect on

negative moment dynamic load allowance; for pavement unevenness, negative moment dynamic load allowance increases with the increase of pavement unevenness grade; for speed, negative moment dynamic load allowance decreases first and then becomes larger with the increase of speed.

3. Span number and negative moment dynamic load allowance are not monotonically increasing or decreasing relationship, the increase or decrease of span number will not change the frequency of the structure, while the change of frequency is closely related to the negative moment dynamic load allowance, with the increase of span diameter, the fundamental frequency decreases, and the negative moment dynamic load allowance also gradually decreases; the effect of forced displacement of the support on the negative moment dynamic load allowance is negligible.

REFERENCES

[1] Zhou Yong-jun, Xue Yu-xin, et al. State-of-the-art of Theory and Applications of Bridge Dynamic Load Allowance (J). China Journal of Highway and Transport, 2021, 34(04): 31-50.
[2] Deng L, He W, Shao Y. Dynamic Impact Factors for Shear and Bending Moment of Simply Sup-ported and Continuous Concrete Girder Bridges (J). Journal of Bridge Engineering，2014, 20 (11):04015005.
[3] Deng L, Cai C S. Development of dynamic impact factor for performance evaluation of existing multi-girder concrete bridges (J). Engineering Structures, 2010, 32(1):21-31
[4] Wang TL, Huang D. Cable-Stayed Bridge Vibration due to Road Surface Roughness (J). Journal of Structural Engineering, 1992,118(5): 1354-1374.
[5] Deng Lu, He Wei, Yu Yang, et al. Research Progress in Theory and Applications of Highway Vehicle-bridge Coupling Vibration (J). China Journal of Highway and Transport, 2018, 31(7): 38-54.
[6] Wu Ming-han, Gui Shui-rong, Chen Shui-sheng. Comparison of impact factors for four models crossing T-type rigid (J). Journal of China & Foreign Highway, 2008, 28(6):130-133.
[7] Zhou Yong-jun, Zhao Yang, Zhao Yu, et al. A study on dynamic load allowance of a simply supported girder bridge based on load efficiency of a dynamic load test (J). Journal of Vibration and Shock, 2021, 40(20): 207-216.
[8] Chang D, Lee H Y. Impact Factors for Simple-span Highway Girder Bridges (J). Journal of Structural Engineering,1994, 120(3):704-715.
[9] Li H Y, Wekezerj, Kwasniewski L. Dynamic Response of a Highway Bridge Subjected to Moving Vehicles (J). Journal of Bridge Engineering, 2008, 13(5):439-448.
[10] Zhu Jin-song, XU Yu-feng. Research on the impact factor of the three-span continuous beam-arch combined bridge based on the vehicle-bridge coupled vibration (J). Journal of Railway Science and Engineering, 2019,16(4):959-967.
[11] Deng Lu, WNG Wei. Research progress om Dynamic Impact Factors of Highway Bridge (J). Journal of Dynamics and Control, 2016, 14 (04):289-300.
[12] Zhou Xiao-qing, Sun Li-jun. Relationship between International Roughness Index and Velocity of Quarter Car (J). Journal of Tongji University (Natural Science), 2005, 33(10): 47-51.
[13] Han Wan-shui, Wang Tao, Li Yong-qing, et al. Analysis System of Vehicle-bridge coupling Vibration with Grillage Method Based on Model Updating (J). China Journal of Highway and Transport, 2011, 24(05): 47-55.

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