Dynamic Effect of Simulated Running Vibration-Loads on RC Beams

Tadashi ABE*, Tetsukazu KIDA*, Toshiaki SAWANO*, Masaaki HOSHINO** and Kiyoshi KATO*

* Department of Civil Engineering, College of Industrial Technology, Nihon University, Narashino, Chiba
** Department of Transportation Engineering and Socio-Technology, College of Science and Technology, Nihon University, Funabashi, Chiba

The cracking damages frequently occur near both of bridge supports in the reinforced concrete (RC) slabs of highway bridges. This phenomenal fact may result from the load fluctuations when the heavy vehicles travel over the level differences of expansion joints. The present study used three types of RC beams in which the vibration loads having the load fluctuations with a sine wave pattern were move within the full beam span. The results have demonstrated that the vibrations with a load amplitude of ±20% or more in case of the Type A beam was given, having exceeded the impact coefficient defined in the existing Specifications. To correct this problem, an equation for evaluating the "dynamic effect coefficient" using the load amplitude as one of variables was newly proposed.

1. INTRODUCTION

One of the major factors causing the cracking damage in the reinforced concrete slabs of steel highway bridges (steel bridge RC slabs) has been thought to be dependent on load fluctuations of heavy vehicles resulting from the level differences of the expansion joints, the bumpiness of the road by speeding up and slowing down of vehicles, and so on. Particularly, when the high load fluctuations are produced after vehicles pass over the level differences of the expansion joints, it is thought likely that the cracking damage will naturally occur in the slab near both bridge supports.

In the existing specifications (Specifications for Highway Bridges I and II), the steel bridge RC slabs are designed with the effect of great fluctuations by adding the "impact coefficient," involving the design span as a variable factor, to the live load flexural moment. Accordingly, the impact coefficient defined in the existing Specification does not consider the effect of high load fluctuations produced by the level differences of expansion joints, in other words, as an impact coefficient using the load amplitude as a variable. The authors have already carried out the experimental researches as to the dynamic effect of RC beams subjected to the running vibration loads. These studies have clarified that the experimental impact coefficient easily exceeded the one prescribed in the existing Specifications when the load amplitude exceeded ±21%. Accordingly, in the present study, three types of RC beams with different widths and effective depths were used to conduct the tests on the running conditions while vibrations are produced due to the level differences of expansion joints, bumpy roads and the like; that is to say, the running test with the vibration loads and the dynamic effect on the RC beams was evaluated.

2. LOAD FLUCTUATIONS OF HEAVY VEHICLES ON ACTUAL BRIDGE

The Independent Administrative Institutions: Public Works Research Institute has conducted the significant experiments on the load fluctuations and indicated the impact force generated when the heavy vehicles travel over the level difference of expansion joints.

Figure 1 shows the peak load and the location where the left wheel on the middle axle of a three-axle dump truck traveled over a level difference in Reference 9. Figure 2 shows the results of an experiment in Reference 9 regarding the load fluctuations on the middle and rear axles produced when a three-axle dump truck with a total weight of 205.8 kN traveled over an expansion joint. These both experiments indicated that the load fluctuations of approximately ±40 ~ ±45% with respect to the axle weight were produced in the three-axle dump truck near the bridge entrance and exit. At any case, the higher load fluctuations acted on the slab after the vehicle traveled over the level difference sections.

The reference 9 denotes the results of actual measurements of the impact coefficient when a steel slab test bridge was subjected to the wheel load of large vehicle. This study reported that the calculations fitted well the actual situation when the impact coefficient resulting from the wheel load was used as the variable for the amount of level difference.
Fig. 1  Peak load and location at which load was applied.

Fig. 2  Load fluctuations of heavy vehicles.

Accordingly, in order to increase the service life of steel bridge slabs, the running tests using the load fluctuations produced by the level differences of expansion joints (in other words, vibration loads) must be conducted to certify the dynamic effect of RC members.

3. DYNAMIC EFFECT OF RC BEAMS SUBJECTED TO VIBRATION LOADS

The dynamic effect on bridge in case of the passage of heavy vehicles is evaluated by using the dynamic amplification factor (DAF) that expresses the ratio of the response when a vehicle travels while vibrating as opposed to the response when it travels without vibrating. The DAF is the one procedure for evaluating the dynamic effect of the bridge response. In design, the impact coefficient \( i = \frac{20}{(50 + L)} \), where \( L \) is the design span length, is used as a reducing function with respect to the span length.

In this test as well, the dynamic effect when a bridge is subjected to vibration loads was evaluated by determining the test impact coefficient virtue of the DAF that is derived by the deflection response.

3.1. DAF Derived from Deflection Response

Figure 3 illustrates the DAF for the deflection response at the center of span when a running vibration load is applied to a simple gird bridge.

The test impact coefficient derived from the DAF is based on the maximum static deflection derived from the deflection response value and is defined as the ratio of the difference between this value and the maximum dynamic deflection. Accordingly, the test impact coefficient \( I \) for the RC beams subjected to the running vibration loads in the present test can be given by Eq. (1):

\[
I = \frac{y_{s\text{max}} - y_{s\text{vmax}}}{y_{s\text{vmax}}}
\]

where

\( I \): Test impact coefficient, \( y_{s\text{max}} \): Maximum dynamic deflection, and \( y_{s\text{vmax}} \): Maximum static deflection.

4. PREPARATION OF TEST SPECIMENS AND MEASUREMENT METHODS

Previously, the authors evaluated the dynamic effect of running vibration loads on the RC test beams with different effective depths; so, in the present study, the dynamic effect including the effect of beam width has been verified. Then, the three types of RC beams with different effective depths and widths were used as the model test specimens consisting of six beams per each type as represented in Fig. 4.

4.1. Materials Used

The concrete for the test specimens was made with the ordinary Portland cement and the coarse aggregate of a maximum size of 20 mm. The rebar was D16 of SD 295A. Table 1 indicates the compressive strength of the concrete and the yield and tensile strengths of rebar.
4.2. Dimension of Test Specimens and Reinforcement Arrangement

The span length of test specimens was 200 cm. The development length of 40 cm was determined in consideration of D16. Thus, the total length of RC beam was 280 cm.

(1) Type A (MIA)

This type had a span length of 200 cm, a width of 30 cm and a height of 21 cm. Three rebars and two ones of D16 were set up on the tension side and the compression side in the reinforcement cage, respectively. The effective depth of the tension rebar was 17.2 cm.

(2) Type B (MIB)

The span length and the width were the same as Type A (200 cm and 30 cm, respectively) and the same reinforcement arrangement as in Type A was used (three D16 on the tension side and two D16 on the compression side). The beam height and the effective depth of the tension rebar were 25 cm and 21.2 cm, respectively.

(3) Type C (MIC)

This type had a span of 200 cm, a width of 40 cm and a beam height of 21 cm. Four D16 rebars and three D16 rebars were used on the tension side and on the compression one, respectively. The effective depth of the tension reinforcement was 17.2 cm.

Figure 5 signifies the dimensions and the reinforcement arrangement.

4.3. Measurement Locations and Measurement Method

In the running test using the vibration loads, the test impact coefficient was calculated from the dynamic amplification factor. Therefore, the five measuring points were determined at the locations of 40 cm, 70 cm, 100 cm, 130 cm and 160 cm from the left support. The deflections were measured dynamically for one round trip from the start to the end of vehicle running.

5. TESTING PROCEDURE

The same equation for the design impact coefficient for RC slabs is used when the span direction of the slab is perpendicular to the direction of vehicle movement and together when it is parallel to the direction of vehicle movement. Therefore, in the present test, the span direction of the beam and the direction of vehicle movement were made parallel to. Figure 6 expresses the diagrams of the running test using the vibration load.

5.1. Running Test Using Vibration Load

The frequency of vibration load in case of the present experiment was modeled on the vibration load after a three-axle dump truck traveled over an expansion joint as displayed in Figs. 1 and 2; so, the medium axis and the rear one of Tandem type act on it alternatively. Therefore, the fluctuations of a one-sided load with a period of 2 Hz according to the mathematical basis that the wave length per one meter of the span length can be obtained by virtue of the relationship between the frequency at the bottom of spring of the large sized truck, that is, the vibration load and the span length of bridge, and the amplitudes of ±10%, ±20% and ±30% were adopted. In calculating the DAF, the maximum value for the deflection response caused by the vibration load was applied to Eq. (1) as the maximum dynamic deflection \( (v_{dy}) \).

(1) Running method and application method of load

As illustrated in Fig. 6(a), the vibration load was placed at the support A on the test specimen and then running was initiated for one round-trip to support B and back to the support A. The individual round trip took 18 seconds (at an average running speed of 22 cm per second). The application method of load was made to increase by the load of 10 kN for each round trip, up to the load whose dynamic effect was to be evaluated. After that point, the load was increased by 5 kN for each round trip. Both load increase and running were continued until the test specimen fractured.

Figure 7 exhibits the relationship between the application of stepping loads and the running times. Figure 8 displays the loading state with a vibration load of ±20% and with a constant load.

(2) Running tests with constant loads

The maximum static deflection \( (v_{dy}) \) given in Eq. (1) is the maximum deflection response obtained from running
tests (Fig. 6(b)) using a constant load, performed in the course of running tests for the vibration loads. Thus, for the running tests using constant loads, two loading levels in the elastic range (30.0 kN and 40.0 kN for Type A and 40.0 kN and 50.0 kN for Types B and C) were set up in order to keep the residual deflection produced by running to the absolute minimum, as indicated in Fig. 7. There was the large variation in the impact coefficient in the plastic range; therefore, the evaluation was difficult and became unreasonable in practice.

6. RESULTS AND DISCUSSION

6.1. Flexural Load-Carrying Capacity and Failure Modes
Table 2 signifies the load-carrying capacity of each specimen subjected to vibration loads. Here, the load-carrying capacity corresponds to the maximum load sustained during the one round trip. The failure modes for all test specimens were the flexural fracture in the center of span while the vehicle was running.

For each type of test specimen, the load-carrying capacity in the vibration load running test with the vibration loads of ±10, ±20 and ±30% approximated to the upper limit of the load amplitude. Therefore, it was confirmed that the size of the load amplitude had no remarkable effect on the load-carrying capacity.
Dynamic Effect of Simulated Running Vibration-Loads

Fig. 9 Typical deflection-running time relation (MIA20-I).
6.2. DAF of RC Beams

Figure 9 expresses an example of the deflection vs. running time relation in case of the test specimen MIA20-1 (20% vibration load).

The maximum DAF values were observed on the return trip for both vibration loads and constant loads, because the residual deflection produced by the traveling of the vehicle was accumulated. Accordingly, in calculating the test impact coefficient, the effect of this residual deflection must be included in the analysis.

When calculating the test impact coefficient obtained from the DAF illustrated in Fig. 9 (2), the maximum deflection in case of a vibration load is applied to Eq. (1) as the maximum dynamic deflection ($y_{\text{dyn}}$), while the maximum deflection in case of a constant load is applied to this equation as the maximum static deflection ($y_{\text{stat}}$).

6.3. Test Impact Coefficient for RC Beams

Figure 10 shows the results of an analysis of the test impact coefficient I for each type of RC beam subjected to the vibration loads.

The impact coefficients for vibration loads of ±10%, ±20% and ±30% were 0.243, 0.379 and 0.496 for Type A; 0.234, 0.368 and 0.482 for Type B; and 0.224, 0.370 and 0.483 for Type C, as shown in Fig. 10. In each case, the impact coefficient was greater than the amplitude of load applied, because the flexural rigidity of the RC beam due to cracking produced by the vibration load along the entire span decreases.

6.4. Dynamic Effect Coefficient

The test impact coefficient produced when the vibration loads of ±10%, ±20% and ±30% were applied to the RC beam exceeded the amplitude of load applied for each type. Then, the impact coefficient obtained in the vibration load running test was defined as the dynamic effect coefficient $a_t$ and analyzed as a function of the load amplitude $K$. Those are signified in Fig. 11, together with their relationship as to the impact coefficient $i$ for the span of 2.0 meters defined in Specifications for Highway Bridges I.

The all dynamic effect coefficients $a_t$ closely coincided with each other regardless of the height and width of the test specimen.

Eqs. (1) and (2) described in Fig. 11 were derived from the power approximation method. The results were excellently favorable, having a correlation coefficient of $r = 1.00$.

Next, the comparison of the load amplitude displayed in Fig. 11 with the impact coefficient in Specifications for Highway Bridges I expresses that the load amplitude that exceeded the impact coefficient in Specifications for Highway Bridges I was ±20% for Type A and ±21% for the average of Types A, B and C. Thus, it was confirmed that the effective depth and width of RC beam did not give a significant effect on the dynamic effect coefficient.

(1) Standard load amplitude to which the dynamic effect coefficient is applied

Figure 12 indicates the impact coefficient $i$ (for a span of 2.0 to 4.0 meters) defined by Specifications for Highway Bridges I, calculated for the relationship between the dynamic effect coefficient $a_t$ shown in Fig. 11 and the load amplitude $K$. It can be seen from Fig. 12 that the flexural moment due to the design live load for the RC slab must be added in the range in which the dynamic effect coefficient $a_t$ exceeds the dynamic coefficient $i$ being a function of the span length. The standard load amplitude $K$ that is the boundary for the domain in such cases can be expressed by Eqs. (2) and (3) in Fig. 12.
Dynamic Effect of Simulated Running Vibration-Loads

2. Application of dynamic effect coefficient

When a load amplitude $K$ that exceeds the standard load-amplitude $K_r$ (Eq. (2)) is used, the dynamic effect coefficient $\alpha$ must be applied. Therefore, a dynamic effect coefficient $\alpha$ that includes the dynamic coefficient $i$ defined in Specifications for Highway Bridges I can be given as by Eq. (4) in case of Type A and as by Eq. (5) in case of the average value for all types.

1) Dynamic effect coefficient $\alpha$ in case of Type A:

$$K < K_r; \alpha_i = i$$
$$K = 0.52L + 21.3$$
$$i = 20 / (50 + L)$$

where,

$\alpha_i$: Dynamic effect coefficient, $K$: Load amplitude ($\%$), $K_r$: Standard load amplitude, $i$: Impact coefficient for RC beams as defined in Specifications for Highway Bridges I, $L$: Span (m)

2) Dynamic effect coefficient $\alpha$ in case of average value:

$$K < K_r; \alpha = i$$
$$K_r = 0.52L + 21.3$$
$$i = 20 / (50 + L)$$

The average value for the dynamic effect coefficients for Type A and Type B with different effective depths is $\alpha_i = 0.053K^{0.54}$. The present paper takes the effect of beam width into consideration, but it closely coincides with the reference.

From the above-mentioned, it can be seen that the impact coefficient for RC beams subjected to the running vibration loads exceeded the value in Specifications for Highway Bridges I and entered into the dangerous zone when the load amplitude exceeded ±20% during transit over the level differences of expansion joints. After all, the dynamic effect coefficient as to Eq. (3) should be adopted in the design of slabs near both bridge supports, making increase the additional flexural moment for the live load.

6.5. Application of dynamic effect coefficient to design flexural moment equation for RC slab

When a vehicle passes on the expansion joints, the running vibration loads with the peak-to-peak amplitude of approximately ±45-48% of the vehicle’s axle load are induced at both bridge girder supports (Figs. 1 and 2). The bridge
slab close to the joints suffers the dynamic effect of the large vibration loads. As an approach to solving the problem of damage to the slab, it is necessary to apply the design flexural moment equation of RC slab under the live loads, taking into account the dynamic effect coefficient derived from the present test. The moment equation \( M_{d}(1+\alpha) \) considering the dynamic effect coefficient \( \alpha \) in Eq. (4)) under the running vibration loads can be given by Eq. (6).

\[
\begin{align*}
M_{d}(1+\alpha) &= M_{c}\cdot(1+\alpha) \\
K &\leq K_{f} : \alpha = t \\
K &\leq 0.055K^{*}K_{f} \\
K_{f} &= -0.52L + 21.3 \\
i &= 20/(50+L)
\end{align*}
\]

where,

- \( M_{d}(1+\alpha) \): Design flexural moment (kN·m) of RC slab under the live loads, including the dynamic effect coefficient,
- \( M_{c} \): Design flexural moment (kN·m) of RC slab under live loads, \( \alpha \): Dynamic effect coefficient, \( K \): Load amplitude (%),
- \( K_{f} \): Standard load amplitude, \( i \): Impact coefficient for RC beams defined in Specifications for Highway Bridges I, and \( L \): Span length (m).

The application of the present equation makes it possible to design the durable RC slab by clearly determining the amplitude of loads induced by the difference in level at the expansion joints in the event of adopting the dynamic effect coefficient.

7. CONCLUSIONS

In order to prevent the cracking damage near both bridge supports due to the action of vibration-loads, the authors focused on the impact coefficient defined in the existing Specifications and carried out the running tests using the vibration loads. The following conclusions could be obtained.

1) The experimental load-carrying capacities with the vibration loads of \( \pm 10\% \), \( \pm 20\% \) and \( \pm 30\% \) closely approximated at the upper limit of the load-amplitude for each of the test beams. Accordingly, it was clarified that the vibration load had no effect on load-carrying capacity.

2) The test impact coefficients \( (i) \) approximated as to the load-amplitudes for each type. Therefore, the differences in effective depth and width of RC beam had no effect on the impact coefficient.

3) The test impact coefficient \( (i) \) exceeded the impact coefficient \( (i) \) defined in Specifications for Highway Bridges I when the load-amplitude exceeded \( \pm 20\% \).

4) In the design of RC slabs for highway bridges, the safety of design can be ensured by applying a dynamic effect coefficient considering the vibration-loads produced by transit over expansion joints.

5) To keep the dynamic effect of the running vibration loads, which are induced by the vehicle when passing the expansion joints, below the impact coefficient defined in Specifications for Highway Bridges I, it is necessary to perform the careful maintenance, such as keeping the difference in level at the joints as much as small.

REFERENCES


