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Asymmetric vibration of finger-type bridge expansion joint for design consideration

Goangseup Zi *, Xingji Zhu [1]

School of Civil, Environmental & Architectural Engineering, Korea University, 5 Ga 1, An-Am Dong, Sung-Buk Gu, Seoul 136-701, Republic of Korea

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ABSTRACT

An asymmetric vibration is proposed for the design consideration of finger-type bridge joints. It is shown, both experimentally and numerically, that the vibration of the joint-plate is not symmetric, but asymmetric; and that the end moment of finger-type bridge joints becomes maximum when the joint plate springs upward, after the load moves out from the joint, in which the tension of the anchor bolts due to this upturned vibration is much greater than the static load case with the load at the tip of the joint-plate. A simplified design formula is developed based on an energy concept, to consider this new failure mode in the design procedure. It is shown that the actual maximum moment and tension can be closely estimated by a simple formula.

1. Introduction

Because of the thermal dilation characteristics, the length of a bridge changes depending on the variation of temperature. Although the order of thermal dilation coefficient is 10^{-5} in the cases of concrete and steel, the end movement of a bridge can be significant. For a temperature change of 30 °C, the change on length of a 50 m span is about 1.5 cm. It is clear that if the length change of the bridge is restrained without having any expansion joints, its internal forces would develop significantly by variation of temperature [1–5].

Whenever vehicles run over an expansion joint which is placed typically at the top ends of bridge deck, the expansion joint is exposed to repeated impact of traffic loads [6,7]. Therefore its dynamic response and influence [8–11] and fatigue behavior [8,12,13] are important for the design of expansion joints. The way of calculating the dynamic amplification factor (DAF) can be found in the literature, too [8,11,14].

The finger-type expansion joint shown in Fig. 1 is one of the most popularly used expansion joints for bridges because of their simple structures. This type of joint is simply called finger joint [15,16]. We will use the term of finger-joint in the foregoing discussion. A finger-joint always consists of two plates, as shown in the figure. The expansion capacity of a finger joint is determined by the length of the fingers crossing over each other.

The design of a finger-joint can be carried out by a simple static analysis as shown in Fig. 1c. The finger-joint is idealized as a beam supported at points A and C which correspond to the positions of the anchor bolts and the end of the bridge deck, respectively. The thickness of the plate is determined by the moment at point C. The anchor bolts are designed according to the reaction force at point A [17–19]. To take into account any dynamic amplification, the moment and the reaction force are increased by a dynamic amplification factor (DAF) which is typically 1.0 [11].

$$\gamma(1+i)\frac{M_C}{I}\frac{t}{2} < \phi f_y \tag{1}$$

$$\gamma(1+i)R_A < \phi n f_y A_s \tag{2}$$

where γ is a load factor, ϕ is a strength reduction factor, i is the dynamic amplification factor, M_C is the moment of the finger plate at the end of the bridge deck as shown in Fig. 1c, t is the thickness of the plate, I is the second moment of inertia of the plate, f_y is the yield strength, R_A is the reaction of the anchor bolts, and n is the number of the anchor bolts within the width of the module under design.

Typically, finer-joints are designed by the concept of working stress design. Let us consider a design example in the literature [18]. The length l is 0.24 m, the thickness t is 45 mm, the load factor γ is 2.5, the impact factor i is 1.0, and the strength reduction factor ϕ is 0.5. Then, the safety factor becomes $\gamma(1+i)/\phi = 8$ which is

* Corresponding author. Tel.: +82 2 3290 3324.
E-mail address: g-zi@korea.ac.kr (G. Zi).
[1] Tel.: +82 2 3290 3836.

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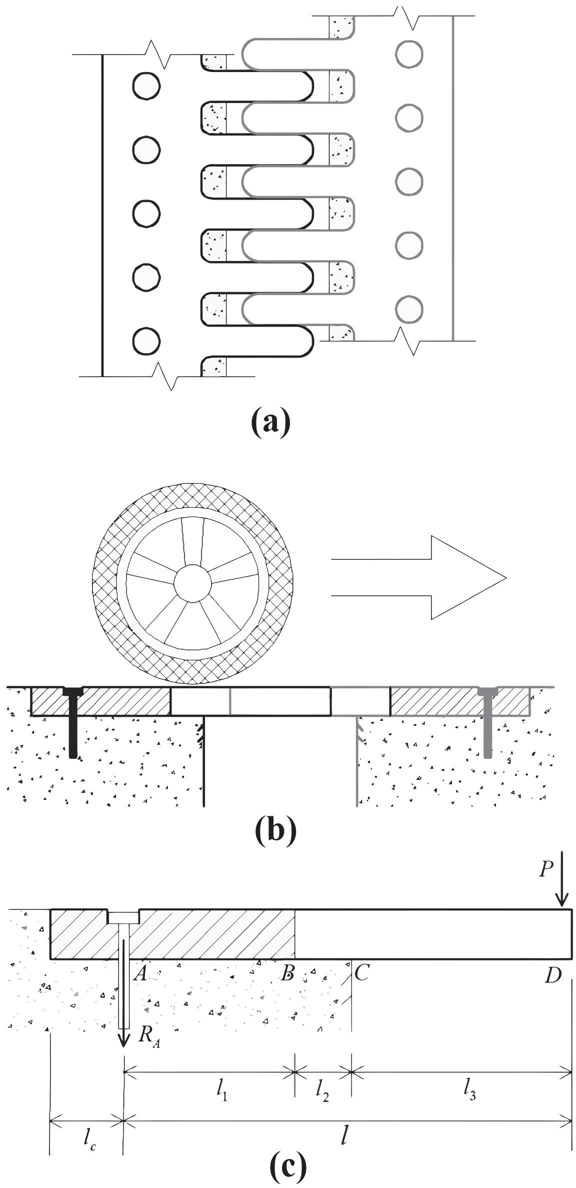

Fig. 1. Structure of a finger-type expansion joint: (a) plane view, (b) side view, and (c) idealized joint-plate for design.

very large. With such a large safety factor, it is hard to expect failure of finger-joints in the service condition. However, the failure of finger-joints can often be observed. Most of the failure is due to the failure of the anchor bolts rather than of the plate itself. Once the anchor bolts fail, the plate pops up as shown in Fig. 2.

Such a unexpected failure of the anchor bolts leads to many unjustified hypotheses to explain the mechanism. Some of them include that the failure of the anchor bolts would happen because of the direct impact of running tire to the end of the plate when the plate tilts excessively as shown in Fig. 3 due to the thermal gradient of the deck or long-term creep deflection. But according to the authors' calculation, the movement of the plate end due to the rotation of the deck is at most 5 mm for a typical 50 m span concrete box girder bridge, which is not enough to cause the failure of the anchor bolts by the wheel load at the end of the palte. This means that there must be another failure mechanism, rather than the load case considered in the typical design procedure.

In this paper, we propose an asymmetric vibration mode to be considered for the design of the anchor bolts of finger-joints. After

Fig. 2. Failure of the finger-joint in Young-Bong bridge II, Korea in which the right plate popped up because of the failure of the anchor bolts.

this introduction in Section 1, a discussion on the motion of finger-joint is given in Section 2 with a proposal on a simplified analysis method, based on the energy principle. That method is verified by the results of a small scale experiment in Section 3 and a three dimensional finite element analysis in Section 4. The conclusion for this work follows in Section 5.

2. Simplified analysis of finger-joint

2.1. Asymmetric vibration of finger joint

As mentioned in the previous section, the reaction itself caused by the tilt of the plate end is not significant enough to cause the failure of the anchor bolts. But the unevenness caused by the tilt makes the plate easy to vibrate. The vehicle load causes the maximum reaction of the anchor bolts when it is placed at the end of the finger joint as shown in Fig. 1c. Because the plate is supported at point A by the anchor and point C by the deck, the plate would deform as in Fig. 4a. This is the deflection shape assumed during the current design procedure.

Note that point C supports against downward displacement, not upward displacement. Therefore, the plate must pop up as shown in Fig. 4b by the conversion of deformation energy to kinetic energy as the load passes over the plate. Obviously, the motion is not symmetric but asymmetric. A precise description of this asymmetric vibration is very difficult because of its own nature. However we are still able to pursue a simplified method of the analysis.

2.2. Simplified solution of the finger joint

2.2.1. Hypotheses for the problem

According to the energy conservation principle of a deformable body, the sum of the kinetic energy and the deformation energy is constant, if any dissipation is neglected, i.e.

$$E(t) = K(t) + U(t) = \text{constant} \tag{3}$$

where E is the total energy of the system, K is the kinetic energy, U is the potential or deformation energy and t is the time. Therefore, the deformation energy measured at any two different times when the kinetic energy is zero should be identical to each other. For example, $U(t_1) = U(t_2)$ in the single degree-of-freedom problem shown in Fig. 5a, in which the acceleration of the mass diminishes to zero at t_1 and t_2.

This principle can also be applied to asymmetric vibration problems as shown in Fig. 5b. The asymmetric pendulum is supported at points A and C. If C does not exist, it is an ordinary symmetric