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Impedance-control technique for physical simulation of traffic vibration effects in monolithic bridge widening

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ABSTRACT

In monolithic bridge widening, a new deck is constructed alongside the existing deck and then a concrete stitch is cast to connect both decks. Due to practical reasons, it is often required to maintain traffic flow during placement of the concrete stitch. As a result, the curing concrete stitch would be subjected to traffic vibration, whose amplitude decreases as the concrete stitch gains strength and stiffness. There had been a lack of proper control algorithm to physically simulate such loading condition, and thus widely different results of vibration resistance of concrete stitches had been reported. To address this gap, an impedance-control technique for experimental simulation of traffic vibration effects has been developed. At any vibration cycle during physical testing, the load applied by the hydraulic actuator to the concrete stitch specimen is automatically determined from the force and displacement feedback signals in the previous vibration cycles. The actuation system is real-time computer controlled by a bespoke impedance-dependent control programme. With the use of this novel testing methodology, a series of concrete stitch specimens have been tested by subjecting to different vibration amplitudes for establishing reliable traffic vibration limits in bridge widening projects.

1. INTRODUCTION

The increase in traffic generated by urban development may saturate the traffic

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flow capacity of bridges and necessitate deck widening. Among various construction options, monolithic bridge widening, whereby a new deck is constructed alongside the existing deck with the clearance stitched by in-situ concrete slab (also referred to as concrete stitch), can provide a continuous riding surface and is often the favoured option (Manning 1981; Olesen 1995). Due to service requirements of highway bridge infrastructure, the existing bridge may have to be remained open to traffic during the casting and curing of the concrete stitch. This would subject the concrete stitch under construction to traffic vibration, whose amplitude decreases as the concrete stitch hardens and gains strength and stiffness (Guo et al. 2017). Such vibrations disturb the curing process and would potentially cause adverse effects on the concrete stitch such as cracking, debonding and strength reduction.

Previous studies (Hilsdorf and Lott 1970; Manning 1981; Furr and Fouad 1982) have attempted to reveal the threshold limit of vibration that would be resisted by the concrete stitch without inducing unacceptable damages. At this juncture, the vibration limit may be more consistently expressed in terms of threshold curvature corrected to a reference structural depth of stitching slab, which was suggested to be 200 mm (Ng and Kwan 2004; Ng et al. 2011a) based on a number of bridge widening projects cases. However, due to the lack of proper control algorithm to physically simulate the oscillatory traffic loading condition, widely different results of vibration limit had been reported in the literature among different researchers. For example, the threshold corrected curvature reported by Hilsdorf and Lott (1970) was 15.0×10^{-3} m^{-1}, whereas that reported by Furr and Fouad (1982) was 1.3×10^{-3} m^{-1}.

With regard to experimental investigation, the major issues identified by the authors are to properly simulate the following loading conditions: (1) the concrete stitch is mainly subjected to contraflexural loading with reversal of bending moment between the existing and the new decks, which have high rigidities in restraining rotations; and (2) as the concrete stitch hardens and its stiffness increases, the contraflexural deflection would decrease with time while the load induced in the stitching slab would increase with time. Numerical results from finite element analyses of various scenarios of bridge widening projects also reflected the above loading conditions (Kwan and Ng 2006; Ng et al. 2011b). Unfortunately, these loading conditions had not been duly simulated in the past (Du et al. 2008; Wang et al. 2008). To address this gap, an impedance-control technique for physical simulation of traffic vibrations has been developed by the authors. In this paper, the testing methodology is explicated with particular emphasis on the impedance-control algorithm. Furthermore, experimental results of concrete stitch specimens for establishing traffic vibration limits in practical bridge widening projects are presented.

2. DESIGN OF EXPERIMENTAL SET-UP

The schematic layout and photograph of the experimental set-up are depicted in Fig. 1. The design of experimental set-up was according to the following principles: Firstly, contraflexural loading is applied to the concrete stitch, whose two ends are restrained respectively by the existing and new decks from rotation. Secondly, loading magnitude in terms of displacement is decreased in response to increasing stiffness of the concrete stitch with time. Thirdly, loading frame for the test is self-reacting to eliminate possible errors arose from deformation of the foundation fixity.

The test specimen consists of two precast ends representing the new deck (fixed end or passive end) and the existing deck (movable end or active end), with reinforcing bars protruding into and spliced at the central in-situ portion representing the curing concrete stitch (Fig. 2). In order to simulate the traffic vibration, vertical movement is restrained at the fixed end, whereas the hydraulic actuator exerts cyclic vertical load to the movable end, so as to subject the concrete stitch portion to cyclic contraflexural loading. The actuator is positioned over the centre, i.e. the point of contraflexure of the specimen and applies loading through the tapered load-transfer beam. This configuration renders the experimental setup self-reacting. The whole set-up is mounted on a rigid ground beam, which supports the fixtures for clamping the fixed end, the roller guides for restraining the rotation of the movable end, and the servo-hydraulic actuator. More details about the experimental set-up have been reported in Kwan and Ng (2007).

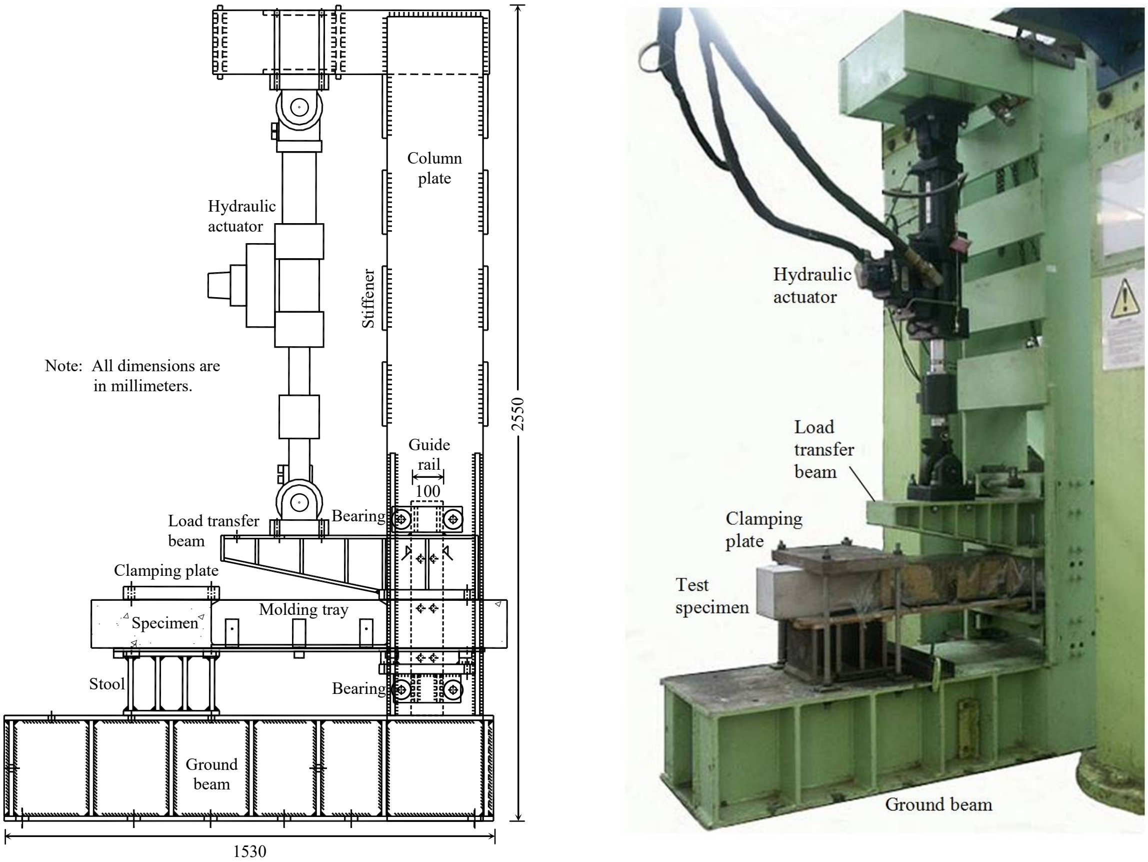


Fig. 1 Layout and photograph of experimental set-up

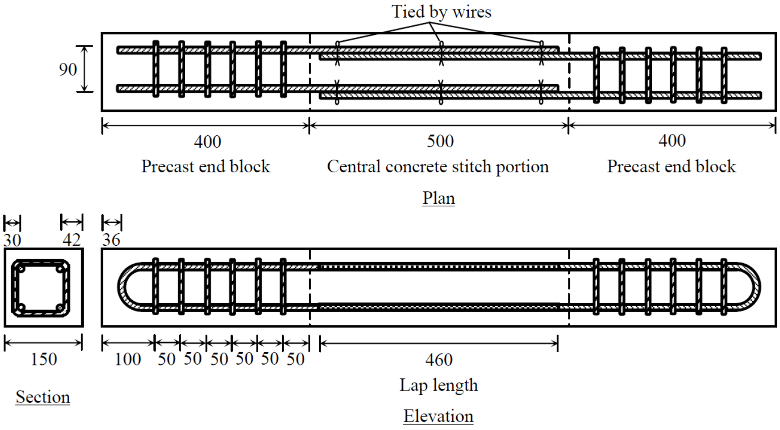


Fig. 2 Details of test specimen

3. IMPEDANCE-CONTROL TECHNIQUE

To simulate the variation of loading magnitude with the gain in stiffness of the concrete stitch in the same manner as what happens in the real structure, neither testing under constant force amplitude nor under constant displacement amplitude would be appropriate. Basically, as the concrete stiffens with time, the deflection of the concrete stitch should decrease while the load induced in the concrete stitch should increase. Since the rate of increase in stiffness is dependent on materials, environmental, and workmanship factors, the most reliable way to capture the change in stiffness is to directly measure the stiffness of the concrete stitch during the experiment. The actual stiffness so obtained is used for determining the load applied to the concrete stitch specimen. This forms the basis of the tailor-made impedance-dependent control programme.

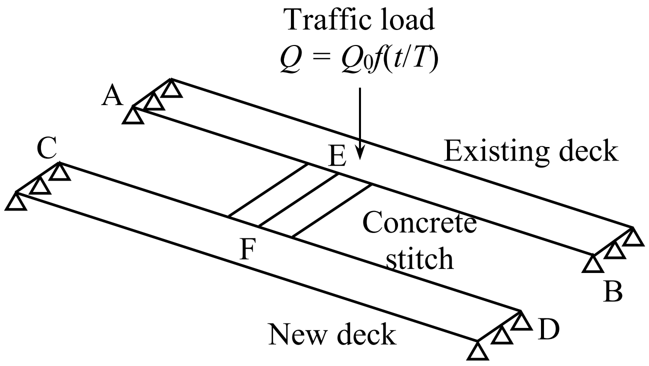
3.1 Equivalent Spring Model

A simplified structural model as shown in Fig. 3 is devised to represent the bridge widening. The existing deck and the new deck are modelled respectively by simply-supported beams AB and CD, while the concrete stitch is modelled by beam EF connecting the mid-points of beams AB and CD. A non-reversed cyclic load Q is applied to point E on beam AB to simulate the traffic load. Part of the load, denoted by Q_1, is carried by the existing deck and part of the load, denoted by Q_2, is transmitted through the concrete stitch and carried by the new deck. The sum of load components is equal to the applied load. Suppose the deflection of beam AB at E is u_1 and the deflection of beam CD at F is u_2, and denote the equivalent stiffness of beams AB and CD by k_1 and k_2 respectively, Eq. 1 can be established accordingly:

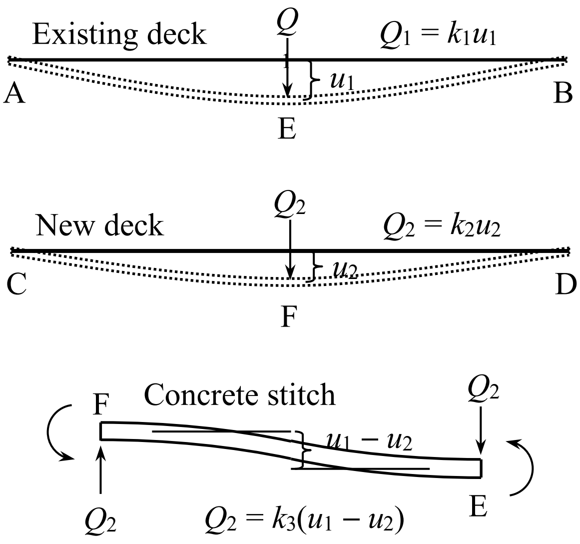
$$Q = Q_1 + Q_2 = k_1 u_1 + k_2 u_2 \qquad (1)$$

Further, as illustrated in Fig. 3, with reference to the load transmitted to beam EF and the corresponding deflection, and denote the equivalent stiffness of beam EF by k_3,

$$Q_2 = k_3 \left(u_1 - u_2 \right) \qquad (2)$$



(a) Structural representation of bridge widening



(b) Deflections of bridge decks and concrete stitch

Fig. 3 Simplified structural modelling

The widened bridge can be simplified to an equivalent spring model as illustrated in Fig. 4, where the aforementioned stiffnesses k_1, k_2 and k_3 become the spring stiffnesses. Substituting and solving the above equations reveal the following relations:

$$Q_1 = Q\left(\frac{1}{k_2} + \frac{1}{k_3}\right)\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1} \tag{3}$$

$$Q_2 = Q\left(\frac{1}{k_1}\right)\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1} \tag{4}$$

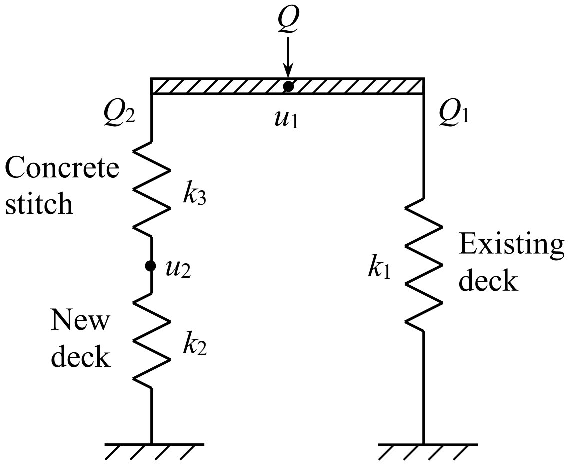


Fig. 4 Equivalent spring model of widened bridge

Denote Δ to be the differential deflection of the concrete stitch (i.e., $\Delta = u_1 - u_2$), Δ is given by:

$$\Delta = Q\left(\frac{1}{k_1}\right)\left(\frac{1}{k_3}\right)\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}\right)^{-1} \tag{5}$$

3.2 Control Algorithm

During testing of concrete stitch specimen, displacement control is adopted with Δ designated as the control parameter. It can be seen from Eq. 5 that the applied displacement amplitude Δ is dependent on k_1 (stiffness of existing deck), k_2 (stiffness of new deck), and k_3 (stiffness of concrete stitch). Altogether, these stiffness parameters describe the impedance characteristics of the structural system. It should be noted that while k_1 and k_2 have constant values, k_3 would increase as the concrete stitch hardens, such would cause gradual reduction of the Δ value.

Rational control of displacement amplitude should be based on the actual real-time measured value of k_3. In view of this, an impedance-dependent control algorithm is developed. The instantaneous stiffness value of k_3 is computed based on the feedback signals from force and displacement transducers during the test, and is used automatically for determining the value of Δ. At any time, Δ varies between its initial value Δ_o when the stitching concrete is fresh, and its final value Δ' when the stitching concrete has fully hardened. The mathematical derivation is as follows. Initially, when the concrete is fresh, $k_3 = 0$, and the initial deflection is given by:

$$\Delta_o = Q/k_1 \tag{6}$$

When the concrete has fully hardened, the final deflection Δ' can be obtained by substituting the maximum stiffness k_3' in lieu of k_3 into Eq. 5:

$$\Delta' = Q\left(\frac{1}{k_1}\right)\left(\frac{1}{k_3'}\right)\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3'}\right)^{-1} \tag{7}$$

Substituting Eq. 6 and Eq. 7 into Eq. 5, Δ can be expressed as:

$$\Delta = \frac{k_3'\Delta_o\Delta'}{k_3'\Delta' + k_3\left(\Delta_o - \Delta'\right)} \tag{8}$$

The simulated traffic load Q should satisfy the relation $Q = Q_o f(t/T)$, where Q_o is the amplitude of the non-reversed cyclic load, $f(t/T)$ is the wave function (for instance, sinusoidal or saw-tooth wave form may be used), t is the time and T is the period. Denote $\Delta(t/T)$ as the cyclic displacement to be applied to the specimen, the governing equation of the impedance-dependent control algorithm is stated as follows:

$$\Delta(t/T) = \frac{k_3'\Delta_o\Delta'}{k_3'\Delta' + k_3\left(\Delta_o - \Delta'\right)} f(t/T) \tag{9}$$

3.3 Feedback Signals for Control

The servo-hydraulic actuator is automatically controlled by the MTS Testar II computer control system under the direct digital control mode, where the applied load and/or displacement can be set as any computed function of the feedback signals from the transducers. With the impedance-control technique, feedback signals are obtained from the load cell and linear variable displacement transducer inside the hydraulic actuator. The instantaneous value of k_3 is computed as the measured force divided by the measured displacement. In each load cycle, the peak stage is considered, where the force and the displacement are respectively at their maximum. Moreover, the moving average technique is applied to the valuation of k_3 to even out any fluctuation in the calculated instantaneous values of k_3 in consecutive load cycles.

Consider the $(n)^{th}$ load cycle, suppose $(k_3)_{n-1}$ is the value of k_3 used in the $(n-1)^{th}$ cycle, and $(k_{3,est})_{n-1}$ is the estimated value of k_3 from the feedback signals measured in the $(n-1)^{th}$ cycle. The value of k_3 to be used for controlling the $(n)^{th}$ load cycle is given by:

$$\left(k_3\right)_n = (1-\gamma)\left(k_3\right)_{n-1} + \gamma\left(k_{3,est}\right)_{n-1} \tag{10}$$

in which γ is a weighting factor between 0.0 and 1.0. If the fluctuation of the estimated value of k_3 is small, a relatively high value of γ of 0.6 or 0.7 may be adopted. Conversely, if the fluctuation of the estimated value of k_3 is large, a relatively small value of γ of 0.3 or 0.4 may be adopted. Initially, the value of k_3 can be based on assumption.

4. EXPERIMENTAL SIMULATION AND RESULTS

Using the experimental set-up and novel testing methodology described above, a series of concrete stitch specimens have been subject to vibration testing to simulate traffic vibrations for a duration of 24 hours. The period *T* was set as 4-second. The curvatures corrected to reference depth of 200 mm at start of vibration testing ranged from 0 (control specimen) to 90×10^{-3} m^{-1} at intervals of 9×10^{-3} m^{-1}. After the 24-hour vibration, the specimens were examined for surface cracking. At 28 days of age of stitching concrete, each specimen was tested for its contraflexural loading capacity as shown in Fig. 5. The testing regime was described in detail in Ng and Kwan (2007). The traffic vibration limit is established as the tolerable vibration under which the crack width would not be unacceptably large and the 28-day contraflexural loading capacity (hereafter referred to as the contraflexural strength) would not be drastically impaired.

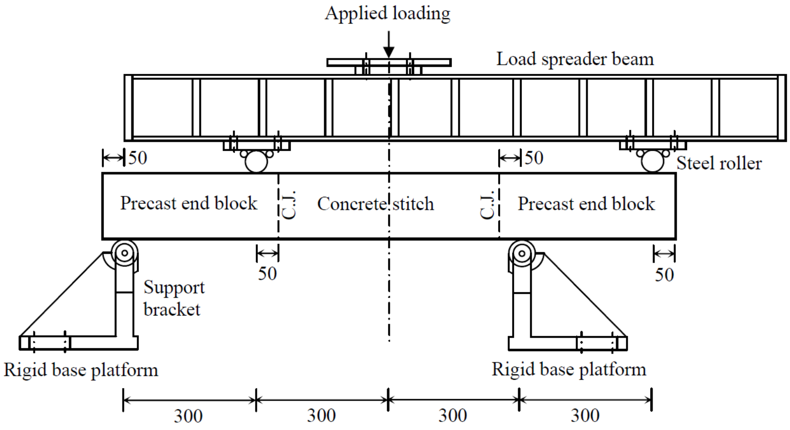


Fig. 5 Contraflexural loading test of concrete stitch specimen

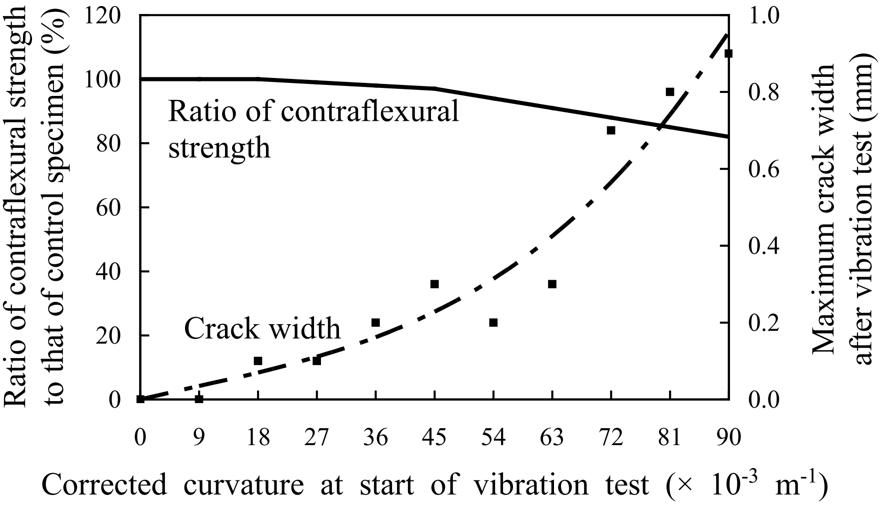


Fig. 6 Experimental results of crack width and 28-day contraflexural strength

The experimental results are presented in Fig. 6, from which it can be seen that the corrected curvatures at start of vibration testing to cause cracking in 0.1 mm and 0.2 mm crack widths are respectively 18×10^{-3} m^{-1} and 36×10^{-3} m^{-1}, whereas the 28-day contraflexural strengths were not detrimentally impaired by the vibration. From serviceability, durability and structural integrity viewpoint, it is considered that cracks of 0.2 mm or larger in width should be repaired. The traffic vibration limit should be set to reflect the acceptability of repairing cracks, while at the same time avoiding the occurrence of severe cracking. Practically, the traffic vibration limit (in terms of corrected curvature) is recommended to be 20×10^{-3} m^{-1} if repair of cracks is not favoured, and the limit may be relaxed to 40×10^{-3} m^{-1} if subsequent repair of cracks is envisaged.

5. CONCLUSIONS

The impedance-control technique to experimentally simulate the traffic load conditions of concrete stitch in monolithic bridge widening has been developed. By means of a tailor-made experimental set-up and an impedance-dependent control programme, the traffic vibration, which subjects the concrete stitch to contraflexural loading and decreases in amplitude as the concrete stitch stiffens, can be properly simulated. During the vibration testing, the instantaneous stiffness of the concrete stitch specimen is evaluated from the load cell and linear variable displacement transducer signals. By employing the moving average technique, the feedback signals from previous vibration cycles are used for controlling the applied displacement amplitude. A series of concrete stitch specimens have been tested. Based on the experimental results of cracking and contraflexural strength capacity, traffic vibration limits in practical bridge widening projects have been recommended.

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