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Analysis of piezoelectric effects on various loading conditions for energy harvesting in a bridge system

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ABSTRACT

This study examines the PE (piezoelectric) effects on various loading conditions for the possibility of harvesting energy from bridges by converting the potential energy of vibrating bridge systems into electric energy using PE material. A steel beam-slab type bridge specimen is fabricated and PE modules are attached at various positions, where different structural responses are expected under moving vehicles on the bridge. Considering the various traffic conditions, such as vehicle weight and moving speed, load test on the bridge specimen is performed with varying load amplitude and loading frequency. Generated voltage evaluation tests are also carried out in order to assess the PE characteristics of the adopted PE materials. The PE effects are examined under various structural response characteristics of the bridge members. The test results are compared with the well-known analytical formulations of PE effects. The test results indicate that the PE effects are affected sensitively by the strain increasing rate and peak strain of PE materials attached on the bridge members, which will be determined due to the moving speed and weight of moving vehicle on the bridge. Among the analytical formulations widely used to evaluate PE effects, the Euler–Bernoulli model is found to provide the most accurate estimation for the PE effects of the PE modules attached on the bridge members.

1. Introduction

Most highway bridge members vibrate due to the moving vehicles on the bridge and the vibration will continue as far as the consecutive vehicles move on, as shown in Fig. 1. This dynamic responses of bridge members will cause the dynamic strain status in the PE (piezoelectric) modules attached to the bridge members. Therefore, the dynamic energy of moving vehicles can be transformed to the electric energy through the bridge members and PE modules. Although available electric current cannot be obtained from PE material, energy harvesting systems can be implemented in practical applications using newly developed LEDs that require lower currents compared to past models [1]. Currently, various researches are being performed to harvest electric energy using PE materials. Poulin et al. are dealing with electromechanical systems to compare with electromagnetic system and PE system to conceive autonomous portable generators capable of harvesting human mechanical energy [2]. Feenstra et al. propsed a theoretical model of the PE buckle and performend experimental testing to validate the model accuracy and energy harvesting performance [3]. Fang et al. designed an MEMS-based composite PE cantilever structure for the vibration energy harvesting and evaluated Micro fabrication process and test of the device [4]. Howells studied tested and evaluated a small electric generator that utilizes PE elements to convert mechanical motion into electrical power for four proof-of-concept Heel Strike Units [5]. And other researches about piezoelectirc material for energy harvesting were perforemed to achieve high efficiency and to apply various conditions and system [6–9].

This fundamental study, before considering the economical efficiency of its application for energy harvesting, solely concentrates on the response and the efficiency of PE material applied to real structural system. Therefore, to examine the PE effects on various loading conditions for the possibility of energy harvesting in structures through the conversion of dynamic vibration and strain energy of bridge systems into electric energy using PE material, load testing on a steel beam-slab type bridge specimen attached PE modules was performed. The PE effects are evaluated and compared various structural response characteristics of the bridge members. The test results are compared with the well-known analytical formulations of PE effects. Additionally, generated voltage evaluation tests (LAB test) of the PE modules were carried out as a cantilever loading test type to assess the PE characteristics of the PE modules.

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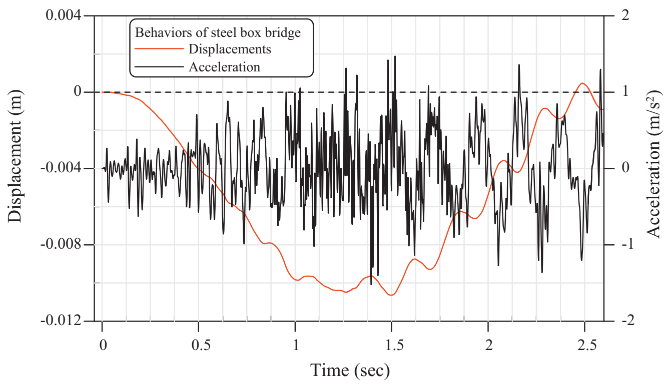

Fig. 1. Displacement and acceleration of a bridge caused by moving vehicles.

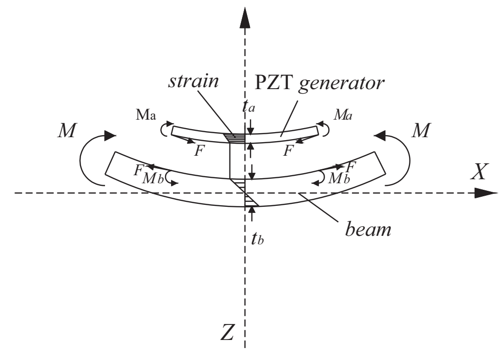

Fig. 3. Enhanced pin-force model of a unimorph-type PE module [6].

2. The generated voltage formulations of PE modules

When PE material is attached to a substrate member as Printed Circuit Board (PCB), the generated voltage of the PE module is determined by the stress and strain of the PE material, and it can be calculated using analytical formulations considering the stress and strain of the PE material. Some analytical formulations are presented to estimate the generated voltage of PE modules according to their dimensions, shape and their attached modules. These analytical formulations include the pin-force model, enhanced pin-force model, and Euler–Bernoulli model [10].

2.1. Pin-force model

The pin-force model deals with the mechanical force relationship of PE material and the substrate member to estimate the voltage generated in PE modules. Generally, PE material is attached to the substrate member as a pin connection. Therefore, the shear force acting on the PE material is designed to focus on the shear force at end of the pin connection. In this case, shear stress in the PE material is concentrated only in a small area at the end of the pin connection. The strain in the substrate member is derived by Euler–Bernoulli beam theory, but the strain in the PE material is assumed to be constant. Because of this constant strain, the pin-force model does not consider the bending stiffness of the PE materials.

Fig. 2 shows the pin-force model with a unimorph-type PE module and the strain distributions of PE modules—consisting of PE material and the substrate member as PCB. When a pin-force acts on the PE material attached to the substrate member by an external moment (M), as shown in Fig. 2, strain (ε_a) on the PE material can be expressed according to the relationship of stress (σ_a) and strain

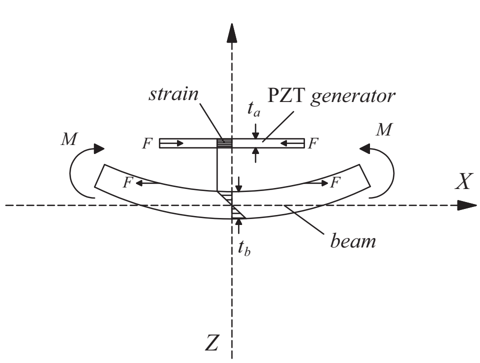

Fig. 2. Pin-force model of a unimorph-type PE module [6].

(ε_a) as Eq. (1). For the width (b) of PE material, strain can be edited as Eq. (2). In Eq. (2), F is the force on PE material by the external moment (M). The strain (ε_b) on the substrate member can be presented as Eq. (3) using the curvature (k) of the substrate member. If the PE material and the substrate member work as a single unit, their strain on the attached surface should be equal. Therefore, the curvature (k) of the substrate member can be expressed as Eq. (4), according to Eqs. (2) and (3). For the external moment (M), Eq. (4) can be modified as Eq. (5). Eq. (6) can be derived by relationship between Eqs. (5) and (4). I_b is the second moment of area of the substrate member in Eq. (5). Since the strain and stress of PE material can be presented as Eqs. (7) and (8), and the generated voltage on the poling surface of PE material can be expressed according to stress as Eq. (9), the generated voltage is derived as Eq. (10). Where, g_{31} is the PE constant, ψ is E_bt_b/E_at_a.

$$\varepsilon_a = \frac{\sigma_a}{E_a} \tag{1}$$

$$\varepsilon_a = \frac{F}{E_abt_a} \tag{2}$$

$$\varepsilon_b = \frac{-t_b}{2}k \tag{3}$$

$$k = -\frac{2F}{E_abt_at_b} \tag{4}$$

$$M_b = M - F\frac{t_b}{2} = (E_bI_b)\kappa \tag{5}$$

$$F = -\frac{6E_abt_aM}{3E_at_at_b - E_bt_b{}^2} \tag{6}$$

$$\varepsilon_a = \frac{6M}{b(3E_at_at_b - E_bt_b{}^2)} \tag{7}$$

$$\sigma_a = \frac{6E_aM}{b(3E_at_at_b - E_bt_b{}^2)} \tag{8}$$

$$V = g_{31}t_a\sigma_a \tag{9}$$

$$V = \frac{6g_{31}M}{bt_b(3-\psi)} \tag{10}$$

2.2. Enhanced pin-force model

An enhanced pin-force model is modified considering the bending strength of the PE material based on the pin-force model. In the enhanced pin-force model, the stress and strain of PE materials are determined by the deformation shape of the substrate member derived from the acting moments as shown in Fig. 3. In Fig. 3, the moment (M_b) acting on the substrate member is Eq. (11); moment (M_b) is equal to moment (M_a) and (E_aI_a) from the pin-force model. Force (F) can be derived as Eq. (12), depending on Eqs. (3) and (4).