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Numerical investigations on energy harvesting potential of thin PZT patches adhesively bonded on RC structures

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ABSTRACT

The reinforced concrete (RC) structures, such as bridges and flyovers, provide a viable platform for ambient vibration energy harvesting. Adhesively bonded thin piezoelectric ceramic (PZT) patches, operating in d_{31} mode, have recently been demonstrated capable of energy harvesting from ambient vibrations in RC structures in addition to structural health monitoring (SHM). Optimization of energy harvesting warrants detailed parametric investigations, which are, however, infeasible analytically or through experimentation, due to the complex piezo-structure interaction through the bond layer and the sheer large number of the parameters involved. This article investigates the effect of the adhesive bond and the related parameters on the energy harvesting capability of thin PZT patches operating in surface-bonded/embedded configurations bonded onto RC structures. Towards this end, a numerical model is generated for a real-life sized simply supported RC beam instrumented with (a) surface bonded piezo-sensor (SBPS), and (b) embedded PZT patch. Coupled field analysis is performed for both the configurations. Before employing for parametric study, the numerical model is validated with the previously developed analytical model as well as the experimental observations. The numerical model is utilized to investigate the effect of the varying load resistance, the piezo and the bond thicknesses, the patch's plan dimensions, the shear modulus of the adhesive layer and the presence of the adhesive covering on the voltage/close circuit power generated by the patch. The results of the study show that whereas the surface bonded condition generates higher voltage, the embedded configuration is more desirable from the point of view of dependence on piezo parameters, especially larger thickness, which promises definite beneficial effects. Further, covering the surface bonded patch with an adhesive layer not only offers protection to the patch but also aids in higher voltage and higher power output from it. The results of the study are crucial for practical deployment of PZT patches on RC structures for energy harvesting in addition to SHM.

1. Introduction

Currently, the sensors employed for structural health monitoring (SHM) invariably depend upon batteries for signal acquisition, data processing and transmission. Periodic replacement of batteries could be cumbersome and unsustainable in the long run for real-life structures, such as bridges. Hence, searching a realistic solution, which can act as a panacea for battery replacement, becomes need of the hour. Converting the ambient energy available in the form of sunlight, human motion, body heat, mechanical vibrations and radio-frequency into useful forms for direct/future use is termed as *energy harvesting*. In this paper, the mechanical vibrations experienced by the RC structures are considered as the ambient/input source of energy. Piezoelectric ceramic (PZT) sensor patches have proved their effectiveness in structural damage detection and quantification for both global and local techniques [1]. Current advances in low power consuming electronics have attracted researchers towards the use of these sensors for energy harvesting in addition to SHM. Recently published articles [2–8] cover a variety of techniques and formulations for energy harvesting from various commercially available piezo configurations, such as macro fibre composite (MFC), multilayer, quick pack, bimorphs, piezo fibres and flex tensional piezo composites, to name a few. It is a well established fact in literature [9] that piezoelectric energy harvesting faces a challenge that a sizeable fraction of the energy harnessed returns back to the excitation source in the form of reactive energy. Various analytical models for piezoelectric energy harvesting, incorporating the electrical and mechanical loads and electrical circuits, can also be found in the literature [5–7,10–17].

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The ambient vibrations normally encountered in bridges/flyovers are typically low-frequency and low-acceleration vibrations, often characterized by non-periodic nature [18,19]. Kaur and Bhalla [20,21] recently demonstrated the feasibility of energy harvesting utilizing the d_{31}-mode [stress applied in the axial direction triggering electric voltage development in perpendicular (thickness) direction] for surface bonded and embedded PZT patches in addition to SHM. Especially, for the embedded configuration, they demonstrated the feasibility of a specially designed concrete vibration sensor (CVS), for both SHM and energy harvesting [21]. The CVS [22], which operates in d_{31} mode when installed in an RC structure, is composite in fabrication, has sound compatibility with the surrounding concrete and can withstand the harsh conditions encountered typically encountered in the RC structures during casting. The vibration characteristics of civil structures under ambient sources augment d_{31}-mode of excitation in PZT patches, being more natural and simple form of excitation [23,24]. Additionally, this mode also adequately serves for SHM, via either the electro-mechanical impedance (EMI) technique or the global vibration technique or a fusion of the two [1]. The authors in their previous study [21] estimated and compared the power generated by a typical PZT patch installed in surface-bonded and embedded configurations on eight existing real-life bridges/flyovers across the world. Based on the electromechanical model developed and validated by the authors and utilizing the vibration data reported in the literature, the maximum power which could be harnessed via SBPS on real life steel bridges and embedded CVS on RC bridges was estimated as 26.154 μW (power density = 871.8 μW/cm^3) and 0.075 μW (power density = 2.5 μW/cm^3), respectively. It was demonstrated by the authors [20,21] that both configurations can enable energy harvesting in reasonable time sufficient enough to power commercially available miniaturized SHM devices, suitable for both global dynamic as well as local EMI techniques. It is realized that the use of the PZT patches in surface bonded and embedded configurations utilizing the d_{31} mode needs to be investigated further before the same could be employed for practical applications. At this stage, a detailed parametric study is lacking in the literature so as to optimize the various parameters associated with energy harvesting from PZT patches.

The main objective of this paper is to perform comprehensive numerical investigations on various parameters, including geometric properties of the PZT patch and the adhesive bond's stiffness and thickness, which possibly influence the power generated by the PZT patch. Two configurations have been considered for the PZT patch (a) surface bonded piezo sensor (SBPS) and (b) embedded, in form of CVS. Further, a comparative study has been carried out for the close-circuit power generated by the surface bonded and the embedded PZT patches. The analytical electro-mechanical model and the related experimental validation for the chosen configurations (SBPS and embedded CVS) have already been published by the authors [20,21]. Comprehensive parametric study, however, is not feasible analytically or experimentally due to the complex interaction mechanism between the patch and the structure and also the very large number of the governing parameters involved. Hence, in this paper, the detailed study has been carried out numerically through finite element (FE) method. This approach serves to circumvent the exceedingly large number of experiments which would otherwise have to be performed covering the large number of the parameters involved. However, before employing for the parametric study, the numerical models of the PZT patches in free and bonded configurations have been duly validated with the analytical and the experimental results. The results of the study shall pave way for optimal use of thin PZT patches from the purpose of energy harvesting. The following sections of the paper cover a brief description of the related analytical formulations and the development and validation of the numerical model, followed by detailed parametric studies.

2. Analytical model

The electro-mechanical model developed by the authors [20,21] for computing the voltage and the power generated by the SBPS and embedded CVS (Figs. 1 and 2) is briefly explained below. In these configurations, the voltage output from the PZT patch can be expressed as

$$V = S_1 K_p K_b S_q^* \tag{1}$$

where S_1 denotes the strain in the extreme fibre of the beam with SBPS and embedded CVS, given by, respectively

$$(S_1)_S = \frac{6D}{L^2} u(x,t)|_{peak} \tag{2}$$

$$(S_1)_E = \frac{12d'}{L^2} u(x,t)|_{peak} \tag{3}$$

where D denotes the overall depth of the concrete beam and d' the distance of the centre line of the embedded PZT patch from the neutral axis. $u(x,t)|_{peak}$ denotes the amplitude of the dynamic vibration of the beam based on the developments presented in [20,21], considering first n modes. K_p denotes the correction factor due to Poisson's effect and S_q^* the circuit sensitivity. The value of K_b, the adhesive correction parameter, is independent of the material properties of the sensor and depends only on its geometry and the properties of the adhesive layer. K_p, K_b and S_q^* are respectively given by,

$$K_p = \left(1 - \nu \frac{d_{31}}{d_{32}}\right) \tag{4}$$

$$K_b = \left(X_{eff}\right)\left(Y_{eff}\right) \tag{5}$$

and

$$S_q^* = \frac{d_{31} h Y^E}{\varepsilon_{33}^T} \tag{6}$$

where, ν is the Poisson's ratio of the host structure material and d_{31} and d_{32} the piezoelectric strain coefficients for the PZT patch. h, Y^E and ε_{33}^T have been defined with values in Table 1. (X_{eff}) and (Y_{eff}) are the effective length and width fractions for the PZT patch, respectively,considered along the length and the width of the PZT patch, as expressed by Eqs. (7) and (8) for SBPS and embedded CVS, respectively.

$$\left(X_{eff}\right)_S = 1 - \frac{\tanh\left(\Gamma_S L_p/2\right)}{\left(\Gamma_S L_p/2\right)} \tag{7}$$

$$\left(X_{eff}\right)_E = 1 - \left(\xi_E\right)_{L_p/2} \frac{\tanh\left(\Gamma_E L_p/2\right)}{\left(\Gamma_E L_p/2\right)} \tag{8}$$

where, the terms used for determining $\left(X_{eff}\right)$ in Eqs. (7) and (8) are well defined in [20,21]. Ignoring the shear lag effect along the width of the PZT patch, $\left(Y_{eff}\right)$ has been considered as unity for both for SBPS and embedded CVS. The next sections cover the development of the numerical model (Fig. 2) and its validation with the analytical formulations defined in this section.

3. Development of numerical model

The real life sized RC beam, shown in Fig. 1, earlier investigated by Kaur and Bhalla [21], is considered for numerical simulation. The beam has a length of 4 m and cross-section of 150 × 210 mm. Other related physical properties of the beam are listed in Table 2. The Rayleigh's damping coefficients (α = 11.86 s^{-1} and β = 1.1 × 10^{-4} s)