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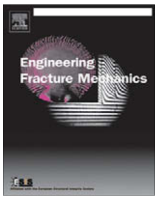

Boundary elements analysis of adhesively bonded piezoelectric active repair

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ABSTRACT

This paper presents the analysis of active piezoelectric patches for cracked structures by the boundary element method. A two-dimensional boundary integral formulation based on the multidomain technique is used to model cracks and to assemble the multi-layered piezoelectric patches to the host damaged structures. The fracture mechanics behavior of the repaired structures is analyzed for both perfect and imperfect interface between patches and host beams. The imperfect interface, representing the adhesive between two different layers, is modeled by using a "spring model" that involves linear relationships between the interface tractions, in normal and tangential directions, and the respective discontinuity in displacements. Numerical analyses performed on a cracked cantilever beam repaired by single and multi-layered patches are presented. It is pointed out that the adhesive deeply influences the performances of the repair as highlighted by an increasing of the repairing voltage values with respect to perfect bonding case.

1. Introduction

Piezoelectric materials exhibit the property known as piezoelectric effect which results from the coupling between the electric and mechanical properties of a material. When strain is applied to a piezoelectric material an electric field is produced (direct piezoelectric effect) and conversely when an electric field is applied strain occurs (converse piezoelectric effect). Due to the direct or converse piezoelectric effect these materials can be used in the design of many devices working as sensors or actuators, respectively [1]. For this reason piezoelectric materials are a primary concern in the field of smart-structure technology [2,3].

Recently, piezoelectric actuators have been studied in the field of repair technology. Based on the converse piezoelectric effect, the strain induced by an applied electric field across the piezoelectric patch can in fact help the structure to reduce the crack opening and consequently to increase its fatigue life [4]. It follows that piezoelectric patches can be potentially employed as an alternative to the most conventional repair methods involving bonded or riveted metallic or composite patches [5–7]. To exploit the potentiality of the "active repair" methodology a deeply characterization of their electromechanical behavior is needed. Studies on the piezoelectric active repair has been recently proposed by Wang et al. [8–10]. They developed an analytical model for a cracked beam, undergoing static or dynamic load, repaired with piezoelectric patches with the aim to reduce the singularity at the crack tip by inducing a local moment. Two-dimensional finite element analysis was performed by Duan [11], to study piezoelectric patches applied on delaminated beam, and by Liu [4,13], to study active repair for cracked structures by using multi-layered piezoelectric patches. Shape memory alloy wires have also been proposed as active structural repair by Wang [12]. In [13] Liu investigated two different repair criterion, the slope continuity criterion and

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Nomenclature

C_{ij}	elastic coefficients
D_i	electric displacement components
D_n	normal electric displacement
e_{ij}	piezoelectric constants
E	Young's modulus
E_i	electric field components
$\mathbf{F}$	generalized load vector
G	shear modulus
$\mathbf{G}$	influence matrix pertaining to $\mathbf{P}$
$\mathbf{H}$	influence matrix pertaining to δ
$\mathbf{k}$	local interface compliance matrix
k_I	stress intensity factor
k_{I0}	unrepaired structure stress intensity factor
k_N, k_T	adhesive spring compliance
$\mathbf{K}$	global interface compliance matrix
L	adhesive length
$\mathbf{N}, \Psi$	shape function matrices
P	current point
P_0	source point
$\mathbf{P}$	nodal displacement vector
t_a	adhesive thickness
t_i	traction components
$\mathbf{T}$	generalized traction vector
$\mathbf{T}^*$	fundamental solution traction kernel
u_i	displacement components
$\mathbf{U}$	generalized displacement vector
$\mathbf{U}^*$	fundamental solution displacement kernel
V	applied voltage
$x_i, i = 1, 2$	coordinates
γ_{ij}	strain components
ΔU_N	normal relative crack displacement
δ	nodal displacement vector
$\Delta\delta$	nodal displacement jump
ε_{ij}	dielectric constants
φ	electric potential
ν	Poisson's ratio
σ_{ij}	stress components
Ω	body domain
$\partial\Omega$	body boundary

the fracture mechanics criterion. According to the first one, the damaged structure is repaired when the slope discontinuity of the deflection, caused by the existence of the crack, is cancelled. Using the fracture mechanics criterion the crack is instead repaired when the strain energy density factor at the crack tip reaches its minimum value.

A better understanding of the performances of an "active repair" device can be achieved by studying the effect of the bonding layer between the host structures and the piezoelectric patches. The nature of the interface plays a decisive role in terms of strain/stress transfer mechanism. A good interface ensures in fact that effective actuation can be achieved avoiding the necessity of excessive voltage. Some studies including the finite-stiffness character of the interface between piezoelectric devices and the host structures can be found in literature. Crawley and de Luis [2], developing a theoretical framework for modeling extensional and bending deformations of a beam with PZT actuators, assumed that PZT patches were perfectly bonded to the host structure and characterized the adhesive layer by the only shear stresses. Luo and Tong [14] proposed a model for a PZT composite beam including the adhesive layers. They modeled the piezoelectric patches and the host structures as Euler–Bernoulli beams and the adhesive as a continuous spring with shear and peel stiffness. Later the same authors [15,16] developed a laminated beam element for PZT smart beams and a laminated plate element for PZT smart plates modeling the adhesive with both peel and shear stiffness.

In this paper a multidomain boundary integral formulation [17] is employed to analyze the active patches performances. The focus is to point out the effect of the adhesive layer whose influence, to the best authors' knowledge, has not been yet addressed in the literature. In the proposed approach, the characterization of the adhesive layer between the host structure and the piezoelectric patches is achieved by using a spring model which involves shear and peel stiffness and is based on the