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Piezoelectric beam element with embedded discontinuity

Matija Novak¹, Eduard Marenic³, Tomislav Jarak^{1,2}, Mijo Nikolic⁴

¹ *Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb
Ivana Lučića 5, 10 002 Zagreb, Croatia
E-mails: matija.novak.tomislav.jarak@fsb.hr*

² *ITAP, School of Industrial Engineering, EII. Paseo del Cauce 59 Valladolid
E-mail: tomislav.jarak@uva.es*

³ *Institut Clément Ader, CNRS UMR 5312, Université Fédérale Toulouse Midi-Pyrénées,
INSA/UPS/Mines Albi/ISAE, France
E-mail: marenic@insa-toulouse.fr*

⁴ *Faculty of Civil Engineering, Architecture and Geodesy, University of Split
Matice hrvatske 15, 21 000 Split, Croatia
E-mails: mnikolic@gradst.hr*

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1. Introduction

In modern times, many devices can be called “smart”. They are equipped with sensors and actuators so they can sense external stimuli and react to them in a predetermined way. Because of their ability to transform mechanical energy into electrical and vice versa, piezoelectric materials are often used as active parts of “smart” devices.

Most of the piezoelectric materials are quasi-brittle and subjected to mechanical and electrical loading, which can lead to mechanical damage or dielectric breakdown. If mechanical damage or dielectric breakdown occurs in an active part of a “smart” device, it can lead to the malfunction of the entire device. A reliable numerical model for predicting the damage behavior of piezoelectric materials can facilitate the prediction and extension of the service periods and the work life of “smart” devices.

One type of numerical models for the description of damage in brittle materials are lattice models [1], where continuum is represented by solid particles interacting by cohesive forces, represented in the model by one-dimensional finite elements. The softening of the lattice elements will cause the damage propagation through the material. This can be described objectively by introducing the displacement discontinuity at the integration points of the elements. In this work a piezoelectric beam finite element with embedded discontinuity is presented, which could be suitable for the use in lattice models for the description of damage in piezoelectric materials.

2. Piezoelectric beam finite element

Piezoelectric beam finite element, based on the Timoshenko theory, is a one-dimensional finite element with two nodes and four degrees of freedom in each node, two translational, one rotational and electric potential, as shown in Fig. 1. The polarization of a material can in general be in an arbitrary direction with respect to the element axial direction. Motivated by [2], the displacement and electrical discontinuities are added at the Gaussian point of the element, enabling the description of the crack propagation in the material. Consequently the displacement and potential fields contain regular and singular parts, where the singular parts are products of the Heaviside function and the displacement and potential jumps, respectively, as written in equation (1):

$$\mathbf{d}(x) = \begin{bmatrix} \bar{u}(x) \\ \bar{v}(x) \\ \bar{\vartheta}(x) \\ \bar{\varphi}(x) \end{bmatrix} + \begin{bmatrix} \alpha_u \\ \alpha_v \\ 0 \\ \alpha_\varphi \end{bmatrix} H_{x_c}, \quad (1)$$

where $\bar{u}(x), \bar{v}(x), \bar{\vartheta}(x)$ and $\bar{\varphi}(x)$ are regular parts of the displacement and electric potential fields, α_u, α_v and α_φ are displacement and electric potential jumps and H_{x_c} is the Heaviside function defined by $H_{x_c}(x) = 0$ for $x \leq x_c$ and $H_{x_c}(x) = 1$ for $x > x_c$, where x_c is Gaussian point of the element. From equation (1) it can be seen that the jumps occur in the longitudinal and transversal displacements as well as the electric potential, while the rotation remains continuous along the element.

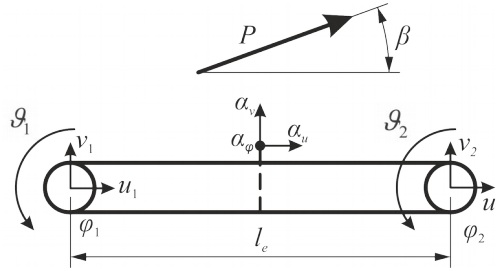


Figure 1. Piezoelectric beam element

The discontinuity in the longitudinal displacement field represents the mode I or tensile failure mode, while the discontinuity in the transversal displacement field represents the mode II or shear failure mode [1]. The discontinuity in electric potential field reflects the altered distribution of electrical fields due to the mechanical particles separation and is used to describe the electrical permittivity reduction in the material [2]. In our model, this electrical discontinuity is always triggered by the mechanical damage and can occur only at the places where the displacement jump arise due to mechanical damage.

Material behavior is linear-elastic until the stress reaches a critical value and then the discontinuities are activated. After satisfying the damage criterion, the material softening begins, described here by employing the exponential softening laws in both the longitudinal and transversal directions [1], as well as for the axial electrical displacements. The constitutive model is classical elastoplasticity, where total strains contain elastic component and contribution from the singular part related to the crack opening. The local algorithm is standard return mapping algorithm in plasticity, where internal variables related to the discontinuity are computed. With internal variables computed locally, global procedure is performed, where final stiffness matrix is formed through the static condensation.

References

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