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Numerical Studies of Smart Structure With Piezoelectric Actuators to Enhance Surface Integrity

Cédric Zaccardi^a, Aurélien Mazette^a, Ludovic Chamoin^b

^aEPF Graduate School of Engineering, 55 avenue du Président Wilson, 94230 Cachan, France

^bUniversité Paris-Saclay, ENS Paris-Saclay, CNRS, LMT - Laboratoire de Mécanique et Technologie, 91190, Gif-sur-Yvette, France

* Corresponding author. Tel.: +33-(0)1 41 13 01 53. E-mail address: cedric.zaccardi@epf.fr

Abstract

A major challenge linked to surface integrity is the ability to detect a crack and stop its expansion. Classical approaches seek to predict critical areas and design the structure accordingly. Nevertheless, this passive methodology usually leads to oversize the structure to maintain its integrity. On the other hand, smart material and structures show a growing interest for the last decade. In this contribution, we propose a smart structure capable of acting to improve its toughness. The idea is to use piezoelectric actuators in an effective way to delay the crack initiation in a material submitted to extreme loads.

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Keywords: Smart Structures ; Piezoelectric Actuators ; Toughness ; Crack Initiation

1. Introduction

The study of crack expansion is a key aspect of structure design. More precisely in shell structures, the initiation of crack can quickly lead to a complete failure. Over the last decades, crack initiation and propagation and their understanding have been extensively studied and several methodologies have been proposed to control them [1]. Two main approaches exist. The first is to calculate the operating time that leads to the initiation and sudden growth of a crack (depending on the geometry, materials and load cases). Following this principle, recent works have emerged to improve the relative resistance to fracture by "smartly" design the system, for example by taking advantage of 3D printers [2].

The second approach consists in a frequent inspection of the structure for cracks and determine if its critical length before the crack propagates rapidly could be reach before the next inspection. A wide range of non-destructive tests (NDT) are now available to perform these inspections. On one hand, whereas NDT is proven to be effective, a crack may not be detected during the inspection, a crack may reach its critical length faster than expected or a pre-existing defect may trigger the failure before the expected lifetime. In a classical engineering approach, these risks are listed, minimized and accepted as unlikely. How-

ever, they can still occur and have enormous consequences. For example, in transport, if the structure collapses during operation due to the sudden propagation of a crack, this can result in a large number of injuries or worse.

On the other hand, inspections and repairs of cracks are mainly done when the system is switched off or removed from the whole structure. To avoid this non-operating time, self-healing materials (with limited applications) have been developed [3]. To overcome these two points, a new approach, based on a smart structure, is proposed here. The main idea is to enrich the structure with an active and embedded system capable of detecting and acting to maintain the integrity of the surface and thus of the structure. The key points in the design of such a smart structure are based on :

- The placement of sensors that has to be done in an optimum way (to detect the critical phase) [4]
- The actuators that have to be able to act to delay the crack initiation
- Efficient and accurate digital twin models to predict the behavior in real time. Reduce model techniques for multi-scale problem are thus needed [5], coupling with control and error estimations [6] and using data driven models [7].

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2. On the use of Piezoelectric actuators in smart structure

2.1. Objectives

With regard to actuator capability, several studies have been carried out on shape control [8] [9]. They show that large stresses and/or strains can be applied to a structure using piezoelectric (PZT) actuators to change actively a shape in spatial structure applications for example. However, in these cases, shape control is often crossed with shape memory materials which can only adopt a finite number of states and cannot be applied to cracking problems due to the randomness of crack initiation.

For this purpose, an example of repair of a delaminated beam using PZT actuators have been proposed in [10]. A clamped beam is subjected to a bending force while two piezoelectric actuators are perfectly bounded to the top and bottom of the beam. The activation of the PZT lead to a reduction of the stress observed at the tip of the delamination. Nevertheless, the proposed work is limited to a laminated beam.

A novel approach is proposed here with the use of PZT as actuators in shell type structures. First works were dedicated to define a Proof of Concept of a smart structure in which PZT actuators are used to increase the fracture toughness of the material. Two simple numerical studies are performed to show the effect of the actuators on: the stress near the crack tip and on the critical energy release rate.

The proposed structure is a steel square subjected to plane constraints and containing a crack (see Fig. 1). This plate of $50 \times 50 \times 1$ mm is partially clamped on one side: x direction blocked on all the right edge ($u_x = 0$), and the middle point is fully blocked ($u = 0$). A surface load F_s is applied on the top and bottom of it to induce an opening mode I of the crack. One considers the Linear Elastic Fracture Mechanics (LEFM) hypothesis. The plate is made of stainless steel with a Young Modulus $E = 185$ GPa and a Poisson ratio $\nu = 0.3$. Two 2mm thick piezoelectric actuators are placed on the top and bottom edges along the length of the plate and perfectly bounded to the structure. Classical mechanical governing equations of the static equilibrium are used ($\nabla \cdot \sigma = 0$). The mechanical constitutive law which links the stress tensor to the strain tensor is given by:

$$\varepsilon = \frac{1 + \nu}{E} \sigma - \frac{\nu}{E} \text{tr}(\sigma) \mathbf{I} \quad (1)$$

Classical Finite Elements (FE) method has been used to simulate the given linear elastic model.

2.2. Classical crack problem approaches

To study the crack phenomenon, a large number of propagation criteria exist [1]. Two usual criteria are used in this contribution: the Stress Intensity Factor (SIF) criterion and the Griffith criterion [11]. The SIF represents the increase, in the vicinity of a defect or a singularity, in the value of the stress

applied to a structure. This increase in the stress field depends on several parameters, such as the geometry of the structure or of the defect, the material... Considering a crack as a defect, it also depends on its position in the structure (e.g. on an edge or in the middle), its length, its orientation with respect to the direction of the external load and the mode of opening. Then, when the SIF reaches the toughness of the material (which is an inherent characteristic of a material), the crack propagates. Thus, a decrease in stress at the crack tip caused by actuator induced "counter" loading could delay crack growth. This will be shown in the paragraph 2.3.

However, in the case of LEFM, it is known that the stresses near the crack tip are not accurately estimated in this area, due to the expected asymptotic solution. An other approach to deal with this aspect is to use the critical energy release rate described in the work of Griffith [11]. Indeed, it is based on an energy criterion that depends on global energy parameters instead of local parameters. It involves the energy release rate, which is a quantity that depends on the variation of the total deformation energy of the structure with respect to the crack zone. As the SIF leads to compute a material toughness, Griffith criterion considered a critical value of the energy release rate. The crack propagates when the input energy reach a critical level G_c that allow the expansion. This energy is computed as follow:

$$G = \frac{dE_c}{dA} = \frac{dE_s}{dA} - \frac{dW}{dA} \quad (2)$$

with

G : the Energy release rate [J/m^2]

E_c : the potential energy [J]

E_s : the strain energy [J]

W : the external loads work [J]

A : in [m^2] the infinitesimal crack area created because of the increasing load.

If $G < G_c$, the crack does not propagate but if G reaches G_c , the crack propagates. The global objective of the numerical proof of concept, described in 2.4, will be to show that the use of piezoelectric components will be able to decrease the energy release rate G and thus delay the crack propagation and improve the toughness of the surface.

2.3. A first simple model

In piezoelectric material, a coupling between electric field and mechanical strain field occurs. In this contribution, a simple coupling is used as the electric field in the direction x is linked to the strain ε_{xx} with the equation:

$$\varepsilon_{xx} = d_{xx} q_x \quad (3)$$

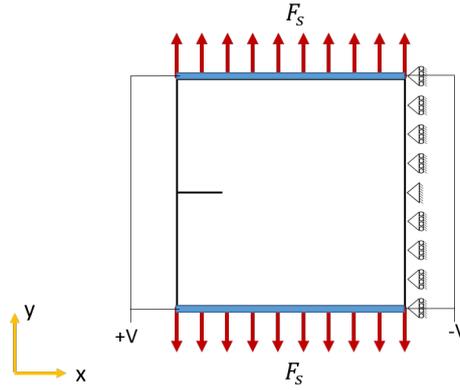


Fig. 1. Main problem: square steel with initial crack coupled with piezoelectric actuators (in blue) on the top and bottom edges.

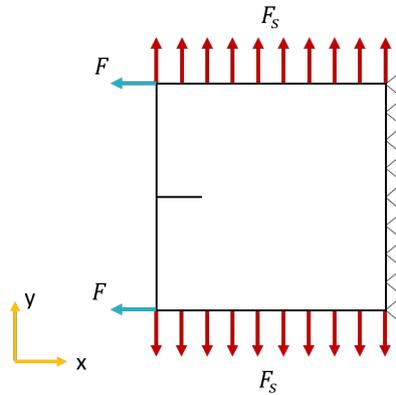


Fig. 2. A first numerical problem where the effect of PZT actuators is modeled by a force along x axis

where d_{xx} is the piezoelectric charge constant that can be seen as the mechanical strain ϵ_{xx} per unit of electric field applied in the x direction q_x (in V/mm).

In a first model, the piezoelectric is not directly modeled. Crawley and Deluis [12] relied the mechanical action induced by a perfectly bounded PZT actuator to the voltage. By following the work of Duan et al. [10], the effect of the actuator is introduced into the model by the force resulting from the activation of the PZT considering the classical beam theory. This hypothesis leads to an expression of a “shear” force applied at the plate/actuator interface, near the edge of the actuator. This force corresponds to the blue horizontal arrows in Fig. 2 and their magnitudes are defined by:

$$F = \frac{EHT}{(\psi + 6)\Delta} \quad (4)$$

where

$$\psi = \frac{EH}{E_p H_p} \quad (5)$$

and

$$\Delta = \frac{d_{xx}V}{H_p} \quad (6)$$

with

- E : the Young’s modulus of the steel plate [MPa]
- E_p : the Young’s modulus of the piezoelectric material [MPa]
- T : the thickness of the plate [mm]
- H : the height of the plate [mm]
- H_p : the height of the actuator [mm]
- d_{xx} : the piezoelectric constant defined in Eq. 3
- V : the voltage applied on the actuator [V]

In order to determine the effectiveness of the actuator, the Von Mises stress is computed by solving mechanical balance equations given previously with a classical finite element approach of the problem described in Fig. 2 and the values in the elements around the crack tip are observed (see Fig. 3 the 6 elements connected to the crack tip). To consider the effect of a piezoelectric actuator, the force F is calculated taking classical applied voltage and by using Eq. 4. In this contribution, simulation are performed with a force F of magnitude equal

to 15 N. When we add the F force generated by the actuator (with a magnitude of 0.05% of the F_s magnitude), we can see a decrease of 1.5% near the crack tip. For comparison, without PZT actuators, one needs F_s load increased by 1.5% to reach the initial stress.

The gain in F_s , and therefore in material toughness, is small but not negligible. Several elements of the methodology can still be improved. Firstly, the applied force F , represented by the piezoelectric actuator, was initially calculated using the beam hypothesis described in [10]. This assumption is far too strong for the study of a plate. Secondly, the output is, in this study, the Von Mises stress near the crack tip. As one knows, an energetic approach has to be followed to avoid the singularity in the LEFM. By modeling the piezoelectric actuator, it will be possible to rely the applied tension to the PZT with the energy release rate of the structure and thus the overall toughness.

2.4. A numerical proof of concept with piezoelectric actuators

The proposed numerical proof of concept consists in the static equilibrium of the structure described in Fig. 1 by modeling directly piezoelectric parts and using constitutive laws in Eq. 1 and Eq. 3. The piezoelectric actuators will affect the distribution of stress and energy in the structure.

Energy release rate is computed by the mean of Finite Element simulations and using Eq. 2. The potential energy is computed for several cases in which the crack length is increased step by step. First order derivative scheme is then used to estimate the energy release rate. As one still applies the LEFM, stress and strain at the crack tip are not taken into account for the computation of the energy.

Fig. 4 shows the relative improvement in G , when PZT actuators are subjected to a voltage of 1000 V, according to the resulting force of F_s on the edge. The gain decreases rapidly with the applied force but it is not negligible again. As previously for the SIF approach, the methodology can still be improved. Other parameters such as the position of the piezoelectric actuators, the number of actuators remain to be studied.

3. Conclusion

The local presence of defects such as cracks can lead to problems for the whole structure, making it a multi-scale problem. Smart materials could be a solution to improve the behaviour of structures with respect to these problems. Here, a first step to demonstrate the feasibility of such a material or structure through piezoelectric actuators has been proposed. These first feasibility studies show that the use of PZT actuators can increase the fracture toughness of the new "enriched" structure without changing the initial material. In this contribution, a simple numerical test has been performed: PZT actuators work in-plane and the whole structure can be modeled in 2D. In an imagined optimal configuration, the PZT actuators will be placed on the surface of on both sides of the hull to maximize their effect around the crack.

Moreover, the proposed numerical approach needs to be validated by an experimental proof of concept. Following works are planned to design an efficient smart physical structure to be tested by optimising the position and number of actuators according to the position of the crack tip. Coupled with a digital twin capable of predicting the behaviour, the smart structure will be able to react by imposing the optimal actuation according to the geometry of the host structure and the load cases and artificially increase its toughness to avoid dramatic failure.

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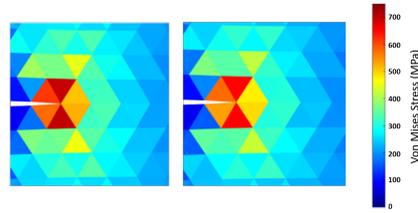


Fig. 3. Zoom on the Von Mises stress near the crack tip, without piezoelectric force on the left, with on the right.

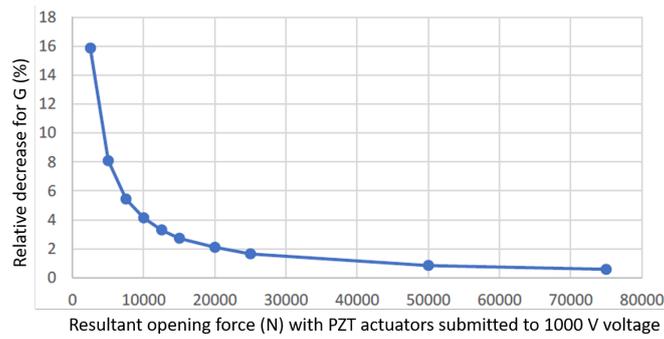


Fig. 4. Relative decrease of G after applying the voltage to the piezoelectric.