Reducing Stress Concentration Factor around a Hole on a Plate by Piezoelectric Patch

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Abstract: Using piezoelectric patches, the stress concentration around a hole on a plate under tension is reduced and controlled. For this purpose, two placements for piezoelectric patches around the hole are investigated. First, the piezoelectric patches are located at top/bottom of the hole with compression induced strain. This location controls the stress concentration directly. Then piezoelectric patches are located at left/right of the hole with tension induced strains to control the stress flow in plate and reduce the stress concentration indirectly. The result sprung from the above conditions is presented for host plate and piezoelectric patches, and by comparing the mentioned results, the advantages of locating the piezoelectric patches to control the stress flow in the host plate is investigated. Based on the related results, locating piezoelectric patches at left/right of the hole can affect the stress flow around the hole and control the stress concentration factor indirectly.

Keywords: Induced Strain, Piezoelectric, Plate with a Hole, Stress Concentration Factor

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1 INTRODUCTION

There have been many developments on high-performance structures known as smart structures in the recent years via using piezoelectric materials. The researchers have investigated on many subjects such as control the buckling, crack, vibration, shape and stress in structures. Rao and Singh proposed that by employing some piezoelectric actuators on a column, the critical load for buckling increases [1]. Wang worked on control and increase the buckling load of a column by attaching tow piezoelectric actuators on the surface of column [2]. Making precise attempts, he obtained the best position and voltage to achieve the maximum buckling load. Sridharan and Kim investigated on piezoelectric control of stiffened panels subjected to interactive buckling [3].

Repair of a notched beam with piezoelectric patch subjected to dynamic loading was studied experimentally by Wu and Wang [4]. They did set a piezoelectric patch near the notch as a sensor to monitor the stress concentration by measuring the output charge, and a piezoelectric patch around the notch as an actuator to reduce the stress concentration by induced prospered voltage. The repair of cracked beam under external load with piezoelectric patches is investigated by Wang et al. mathematically and numerically [5], [6]. Platz et al. presented an approach to evaluate the crack propagation reduction in aluminum panels by piezoelectric patches [7]. They discussed on proper placement and voltage to reduce the crack propagation in the panel. Li et al. worked on vibration control and plate modelling coupled with piezoelectric patch [8].

Based on the maximizing dissipation energy and through using genetic algorithm, the optimization placement of piezoelectric patches in a flexible smart structure is investigated by Zhang et al. [9]. A semi-analytical solution for a plate with piezoelectric patches subjected to static and dynamic loads is presented by Qing et al. [10]. Umesh and Ganguli worked on vibration and shape control of a smart composite plate with matrix cracks. Mehrabian and Yousefi-Koma presented a novel technique to control the vibration of a flexible fin as a smart structure with optimum placement of piezoelectric patches as actuators [11]. Zhang et al. developed a coupled electro-mechanical analysis for an elastic substrate with piezoelectric bounded [12], [13].

Using genetic algorithm, Silva et al. studied the shape control of a plate bounded with piezoelectric patches [14]. They investigated on optimum required voltages for piezoelectric patches so that the pre-defined shape of the plate is achieved. Sensharma et al. worked on reducing the stress concentration around a hole using applied induced strains such as piezoelectric patches [15], [16]. They proposed that piezoelectric patches and shape memory alloys may be used to induced strains in smart structures and control the stress and strain concentration factor. Kang et al. investigated the topology optimization for shape control of a plate bounded with piezoelectric patches [17], [18]. They used the error between desired and actuated shape as the objective function, and the best position for piezoelectric patch is presented via inducing the required voltages.

Sun et al. presented some methods to achieve the piezoelectric actuators pattern to control the shape of smart structures [19-21]. They controlled the voltage of piezoelectric to find the best pattern in which the desired predefined shape of a plate is achieved by the induced voltage. Jin et al. studied several simplification methods to control the shape of repetitive structures [22]. They used their method to find the optimal control voltage for shape of the structures. Nguyen et al. obtained a new evolutionary algorithm to control the shape of various smart composite plates with active piezoelectric actuators [23], [24]. They used linear least square method to find the applied voltage for control the shape of the composite plate. Shah et al. used piezoelectric actuators to reduce the stress concentration factor around a hole [25].

The present paper is focused on the location of piezoelectric patches around a hole on a plate to reduce the stress concentration factor (SCF). The plate is under tension and the piezoelectric patches are bounded on the top/bottom and left/right of the plate symmetrically. By considering the value of stresses in the plate and piezoelectric patches, the best position for piezoelectric actuators are obtained.

2 PROBLEM DEFINITION

A thin rectangular plate, (0.2 meter length, 0.1 meter width and 1 milimeter thickness) with a 20 mm diameter circular hole under uniaxial tensile loading $P=1\ Mpa$ was used throughout this study. The plate is made of aluminium with Poisson's ratio $\nu = 0.3$ and Young's modulus $E = 200\,GPa$. The rectangular piezoelectric patches with 10mm length, 5mm width, and 0.2 mm thickness made of PZT-4 are used in the current work as actuators. The material properties of piezoelectric patches are listed in table 1, where, C_{ii}, d_{ii} and K_{ii} are elastic, piezoelectric and dielectric constants of piezoelectric material respectively. Two positions for piezoelectric patches are considered. First, the piezoelectric patches are located at the top and bottom of the hole in the high stress concentration area. In this condition, the piezoelectric patches induced compression strains to control and reduce the stress concentration factor around the hole directly. In the second condition, the piezoelectric patches are located at the right and left of the hole in the low stress concentration area and by inducing tension strains, the stress concentration factor is reduced indirectly. In this location, the piezoelectric patches must be in the expansion and induced positive strains to affect the stress flow lines and reduce the stress concentration factors. A Python code was developed to simulate above conditions applying the Abaqus software. The aforementioned conditions and problem definition are shown in figure 1.

Table 1 Material property of PZT-4

Poisson Ratio=0.3		
Elastic Constants (GPa)		
C_{11}	C_{22}	C_{33}
139	139	115
C_{12}	C_{13}	C_{23}
74	74	74
C_{44}	C_{55}	C_{66}
25.6	25.6	25.6
Piezoelectric Constants (C/m^2)		
d_{31}	d_{32}	d_{33}
-5.2	-5.2	15.08
d_{24}	d_{15}	
12.71	12.71	
Dielectric Constants (C^2/Nm^2)		
k_{11}	k_{22}	k_{33}
6.75×10^{-9}	6.75×10^{-9}	5.87×10^{-9}

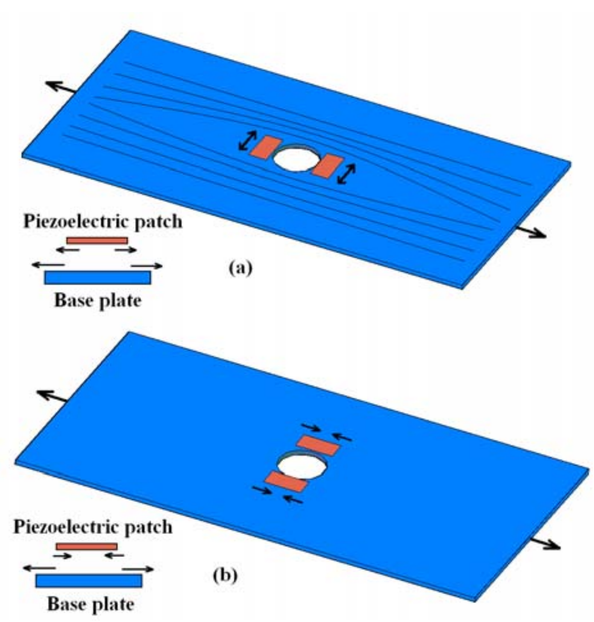

Fig. 1 Piezoelectric patches at (a) left/right (b) top/bottom of the hole

To validate the results, consider a plate without any piezoelectric patches. The stress concentration factor around the hole is obtained 3.115 from Python and FE code and is located at the top and bottom of the hole. The geometry ratio for plate and hole is $r/d = 0.2$ and the stress concentration factor goes along with those reported in the previous publication [26].

3 PIEZOELECTRIC PATCH AT TOP/BOTTOM OF HOLE

Let us consider as the first location that the piezoelectric patches are put at the top and bottom of the hole on both sides of the plate. The patches induced negative strains in the host plate at top and bottom of the hole. The voltage of piezoelectric patches is increased and the stress concentration factor is written respectively. Figure 2 shows the changes in stress concentration factor in the host plate and piezoelectric patches. In this figure, "S" is the stress at high stress concentration area and S_{ave} is the average stress in the plate. Obviously, SCF decreases in plate and the stress in the piezoelectric patches enhances when the induced voltages increases. Being desirable for plate, this condition is, however, undesirable for piezoelectric patches.

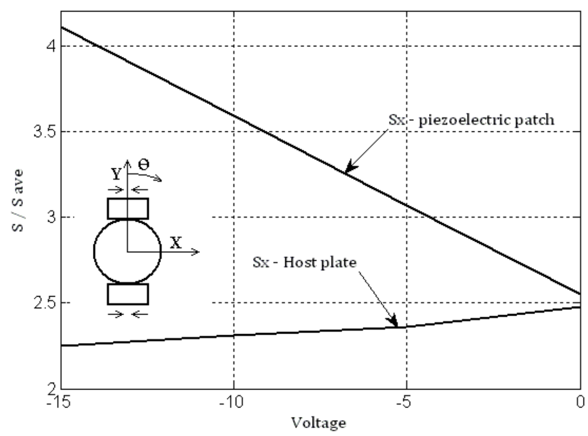

Fig. 2 Stress concentration factor reduction (piezoelectric patches at top/bottom of the hole)

Figure 3 shows the stress in X direction around the hole. It may be seen that increase of the voltage entails enhancement of the stress in high stress concentration area, and of course a change of the location of maximum stress concentration factor from top and bottom of the hole to a point in about 20 degree. This means that locating the patches at high stress concentration area may reduce the stress at these points, but for a safe reduction, the stress concentration in some other points of the host plate needs to be taken into account.

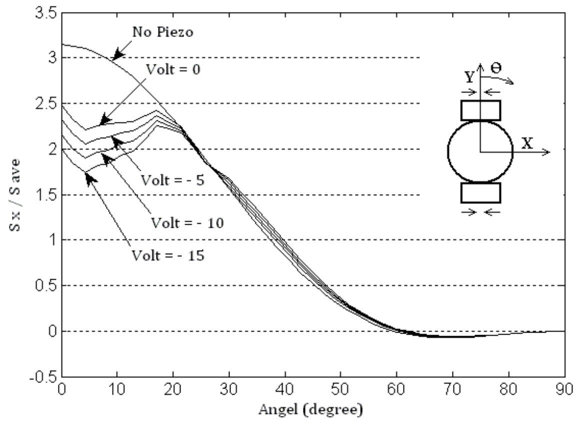

Fig. 3 Distribution of Sx along the circumference of the hole for top/bottom location of patches

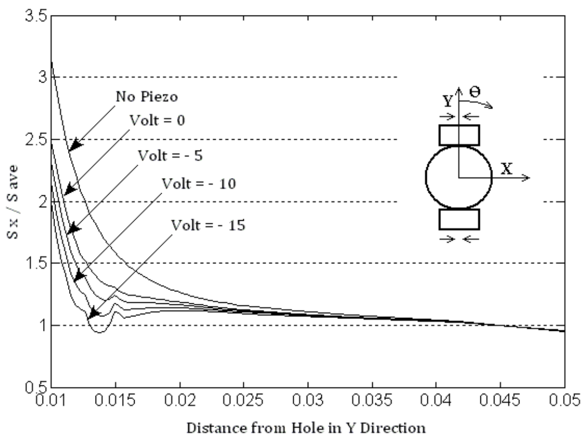

Fig. 4 Distribution of Sx along the X axis of plate for top/bottom location of patches

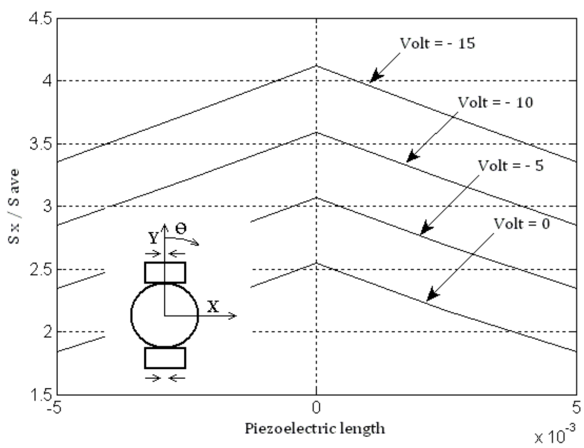

Fig. 5 Distribution of Sx in piezoelectric patches for top/bottom location of hole

Figure 4 shows the stress in X direction along the Y axis on plates. This figure demonstrates that induced strains affect less at points far from the piezoelectric patch, and that the piezoelectric patches affect the stress in points near the induced strain areas.

Figure 5 shows the stress along the piezoelectric patches. It may be seen easily that a rise in the voltage can increase the stress in the piezoelectric patches and the points with maximum stress in the patches located at top/bottom of the hole.

4 PIEZOELECTRIC PATCH AT RIGHT/LEFT OF HOLE

As the second location, consider that the piezoelectric patches are set at the left and right of the hole in both sides of the host plate. The main idea is that if the piezoelectric patches located at the left and right of the hole, expanded and induced positive strains to the host plate, the stress flow turns into smooth, resulting in a reduction in the stress concentration. By implementing this idea, it is observed that bearing the desired effect, the new location of piezoelectric patches reduces the stress concentration factor.

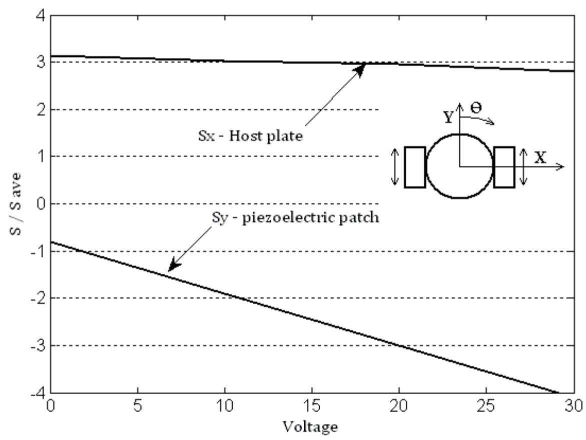

Fig. 6 Stress concentration factor reduction (piezoelectric patches at left/right of the hole)

Figure 6 shows the effect of increasing the voltage on stress concentration in host plate and piezoelectric patches. According to the mentioned figure, by increasing the voltage, the stress at top and bottom of the hole is decreased while the stress in piezoelectric patches is enhanced in compression zone. Figure 7 shows the stress in Y direction around the hole. It can be observed that by increasing the voltage, the stress in host plate under the patches location is increased.

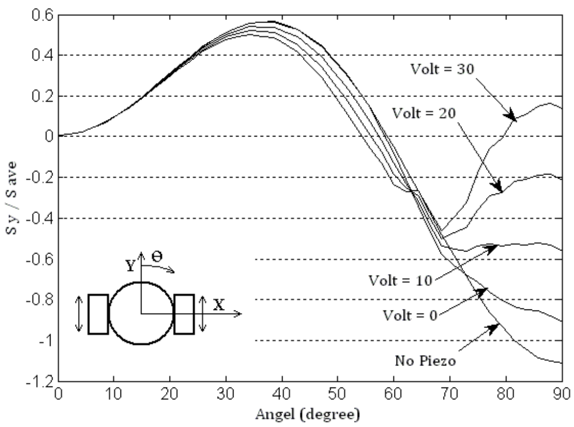

Fig. 7 Distribution of Sy along the circumference of the hole for left/right location of patches

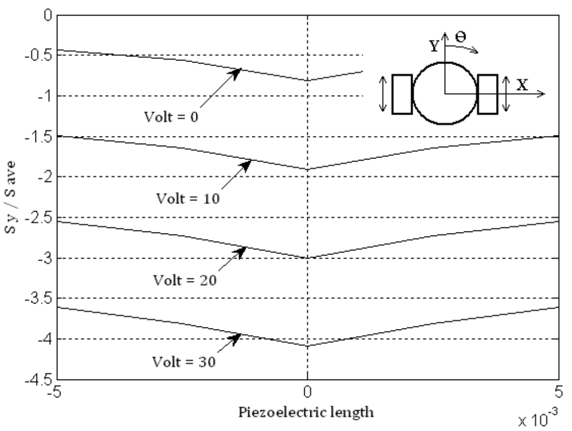

Fig. 8 Distribution of Sy in piezoelectric patches for left/right location of patches

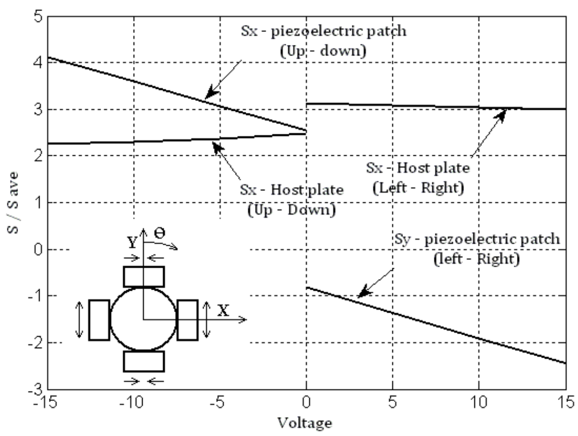

Fig. 9 Comparison of the stress around the hole regarding placements of piezoelectric patches at left/right and top/bottom of the hole

Figure 8 shows the stress in Y direction for piezoelectric patches. Respecting the figure, if the piezoelectric patches are set at left/right of the hole and the piezoelectric patches are induced positive strain to the host plate, the negative stress in piezoelectric is produced and increased by the voltage rise.

5 RESULTS AND DISCUSSIONS

To select the best location for piezoelectric patches around the hole, let us consider figures 2 and 6 simultaneously within the figure 9. This figure shows the effect of increasing the voltage on stress in host plate and piezoelectric patches for locating the piezoelectric patches at top/bottom and left/right locations around the hole. Obviously, for top/bottom location of patches, when no voltage is induced to patches, the stress concentration is about 2.5 and this reduction in stress concentration factor occurs because of reinforcement effect of patches. A rise to the induced voltage, however, leads to a linear increase in piezoelectric patches. So this placement for piezoelectric patches is not desirable.

On the contrary, setting the piezoelectric patches at the left/right of the hole makes them free from any reinforcement effect. However, by increasing the voltage, the stress in host plate is decreased while it gets increased in piezoelectric patches in compression. According to this fact that piezoelectric materials are strong in compression versus tension, it can be suggested that by selecting appropriate material for piezoelectric patches, setting them at proper placement, and considering adequate voltage to control the stress flow in a plate, the stress concentration factor may be reduced and controlled.

6 CONCLUSION

This paper investigates two placements for piezoelectric patches, in order to reduce the stress concentration factor in a plate under tension with a hole by applying induced strains with piezoelectric patches. The first location of patches is top/bottom and the second is left/right of the hole. The results indicate that locating piezoelectric patches at top/bottom of the hole, and inducing contraction strain, the stress in the host plate is decreased while it is increased in the piezoelectric patches. This placement for piezoelectric patches, therefore, is not suitable. In the second location, the piezoelectric patches are embedded at left/right of the hole in host plate and expansion strains induced to control the stress flow in the plate. In this condition, the stress concentration factor in the host plate is reduced while it is increased in piezoelectric patches in compression values. According to the fact that piezoelectric materials are strong in compression versus tension, it is suggested that through applying appropriate voltage, material and location of piezoelectric patches, the stress concentration factor in the plate may be reduced and controlled.

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