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Investigating the Effect of Stiffness/Thickness Ratio on the Optimal Location of Piezoelectric Actuators Through PSO Algorithm

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ABSTRACT

This article has studied the effect of ratio of stiffness and thickness between piezoelectric actuators and host plat has been explored on optimal pattern for placement of piezoelectric work pieces around a hole in thin isotropic plate under static loading to reduce stress concentration. The piezoelectric actuators reduce directly or indirectly the stress concentration by applying positive and negative strains on the host plate. For this purpose, various modes as the thickness/stiffness ratios of the plate to the piezoelectric patches as ≥ 1 or ≤ 1 were considered. Then, a Python code was developed using particle swarm optimization algorithm in order to achieve the best model of piezoelectric actuators around the hole for maximum reduction in stress concentration factor. Also, the maximum stress concentration on the top and bottom of the hole was moved to another point around the edge by changing the location of piezoelectric patches. The results obtained from software solutions were confirmed by experimental tests.

Keywords : Optimization; Piezoelectric patches; Stiffness; Particle swarm optimization.

1 INTRODUCTION

IN recent years, much progress has been made in smart structures One of high-performance structures that are frequently used includes piezoelectric materials. Many studies of the use of piezoelectric material in subjects such as control the vibration, buckling and stresses in structures have been done by researchers. Wang and Wu [1] presented active electromechanical properties of the piezoelectric material. They also presented active mechanical-thermal properties of shape memory alloys and their application for structural repairing. Kang et al. [2,3] investigated on simultaneous optimal distribution of material structure and trilevel actuation voltage using topology optimization for a static shape control. Mehrabian and Yousefi- Koma [4] introduced a new method to optimize the location of piezoelectric actuators for the vibration control of flexible structures. They investigated the vibration control of a flexible fin. Huang and Kim [5] studied controlling the free-edge inter laminar stresses in composite plates using smart structures. They found that by using piezoelectric actuators bonded on the surface or embedded in the composite laminates, Stress significantly reduced in plate. Also location of piezoelectric actuators affects the stress distribution in composite laminates. Platz et al. [6] studied reduction in crack propagation in aluminum panels, by using piezoelectric actuator near the crack tip applying a compressive force to the panel surface. Repairing of a

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notched beam using piezoelectric actuator was investigated by Wu and Wang [7] .They used a small piezoelectric actuator as a sensor for controlling stress concentration, placed near the cracks. Another piezoelectric was placed near the notch to reduce stress concentration. A new evolutionary algorithm for shape controlling of smart composite plates using piezoelectric patches was provided by Nguyen et al. [8-10]. They were able to optimize the electric field and obtain the location and size of piezoelectric actuators for desired structures. Hsu et al. [11] studied energy harvesting by piezoelectric from kinetic energy structure, such as structural vibrations to convert the electrical energy. Buckling control of rigid panels using piezoelectric materials presented by Sridharan and Kim [12]. They used piezoelectric actuators on surface of the panel to prevent buckling. Correia et al. [13] investigated increasing buckling load of a laminated composite plate, using a piezoelectric actuator. Chee et al. [14] and Lin and Nien [15] worked on static shape control of composite plates. They investigated the effect of the piezoelectric actuator and its place on shape control. Zhang et al. [16] used genetic algorithm for optimal control of flexible smart structures and optimization of piezoelectric actuator placement in a desired structure. A semi-analytical solution for static and dynamic analysis of a laminated aluminum plate that was attached by piezoelectric patches was provided by Qing et al. [17]. Using genetic algorithm, Silva et al. [18] studied on shape control of composite plates using piezoelectric patches. They describe the behavior of structure and piezoelectric actuator using finite element model. Nakasone and Silva [19] worked on development of topology optimization formulation for dynamic design of laminated piezoelectric plates for the purpose of harvesting energy. Rafiee et al. [20] worked on nonlinear analysis of piezoelectric functionally graded carbon nanotubes on the mechanical and thermal loading, with the aim of energy harvesting. Using genetic algorithm, Roy et al. [21] studied optimal vibration control of a smart composite shell. They formulated finite elements layered shell for coupled electromechanical analysis of a composite structure integrated with piezoelectric patches. Wu and Wang [22] investigated a method for repairing the vibrating delaminated beam structures using piezoelectric actuators. Kumar et al. [23] presented a finite element formulation for dynamic and static response of a laminated composite shell, including piezoelectric actuators subjected to thermal, mechanical and electric loads. Quintero et al. [24] investigated optimization design through modeling of a thinned bulk-PZT-based vibration energy harvester on a flexible polymeric substrate. Kurata et al. [25] studied a method to find damage for a sensing system by monitoring seismic damage in steel structures. Jadhav et al. [26] studied forced and free vibration analysis of functionally graded materials. They used piezoelectric actuator at the top and bottom to control the vibration of the plate. Sensharma et al. [27,28] worked on reducing stress concentration in a plate with a hole using piezoelectric actuators. Their aim was to achieve maximum reduction in stress concentration in the plate by using piezoelectric patches near the hole. The use of piezoelectric patches to reduce the stress concentration factor in a plate with a hole was presented by Shah et al. [29]. They showed if the piezoelectric patches were placed in area beraing a high stress, the stress in the plate would be decreased while the stress in piezoelectric patches would be increased. They proposed that by locating the actuators in the compression area and inducing positive strain in the host plate, the stress flow through the host plate is changed and consequently leads to reducing the stress in plate, indirectly. The optimum pattern for patches placement around the hole in a plate under tension was presented by Jafari Fesharaki and Golabi [30]. They used particle swarm optimization algorithm to show the best location for piezoelectric actuators around the hole.

Regarding the relationship between the stiffness and thickness of the piezoelectric patches and the host plate, two modes are provided to reduce the stress concentration factor using piezoelectric patches. In the first mode, the stress concentration is reduced directly, by creating positive strain in the host plate. In the second mode, the stress concentration is reduced by creating negative strain in the host plate and disrupting the flow of strain in the host plate. Then, the best model for the integration of piezoelectric patches around the hole is investigated to reduce the maximum stress concentration in the different stiffness/thicknesses ratios. None of researchers has examined the relationship ratio of stiffness and thickness between piezoelectric actuators and base plate for finding optimal placement of piezoelectric actuators around the hole and also their effect on reducing stress concentration factor in previous studies. For these two purposes, an optimization Python code has been developed based on the particle swarm algorithm. The obtained results, have validated by some experiment tests.

2 PARTICLA SWARM OPTIMIZATION (PSO) ALGORITHM

Particle swarm optimization (PSO) is an evolutionary computation method based on the behavior of a colony that proposed by Kennedy and Eberhart [31]. In this algorithm, each particle has three characteristics: particle position, particle velocity and fitness function. The initial position of each particle is located randomly. The initial velocity of each particle sets to zero. Also, during the implementation of the PSO optimization algorithm, each particle wanders in the design space while remembers the best previous position. All particles share their information to other particles and affect their positions and velocities. The main steps for implementation the PSO algorithm are considered as follow [32]:

1. Assume the number of particles "N".
2. Consider the initial position for each particle "X" in the upper and lower range randomly as "$X_1, X_2, ..., X_n$". Hereafter, the location of "j" particle and its velocity in iteration "i" are specified as $X_j^{(i)}$ and $V_j^{(i)}$, respectively. Thus the initial position of the particles is specified as $X_1^{(0)}, X_2^{(0)}, ..., X_n^{(0)}$.
3. Evaluate the values of objective function corresponding to the particles as $f\left(X_1^{(0)}\right), f\left(X_2^{(0)}\right), ..., f\left(X_N^{(0)}\right)$.
4. Set the iteration number as $i = 1$ and find the velocity of all particles. The initial velocity of all particles is assumed to be zero.
5. Find the best historical value of particle $X_j^{(i)}$ as $P_{Best,j}$ in the i^{th} iteration, with the highest value of the objective function $f\left(X_j^{(i)}\right)$, encountered by particle j in all the previous iterations.
6. Find the best historical value of $X_j^{(i)}$ as G_{Best}, in the i^{th} iteration with the highest value of the objective function $f\left(X_j^{(i)}\right)$, encountered in all the previous iterations by any of the N particles.
7. Find the velocity of particle j in the i^{th} iteration as follows:

$$V_j^{(i)} = V_j^{(i-1)} + c_1 r_1 \left[P_{Best,j} - X_j^{(i-1)}\right] + c_2 r_2 \left[G_{Best} - X_j^{(i-1)}\right];\ \text{j=1,2,...,N}$$

where, C_1 and C_2 are the individual and group learning rates respectively and are usually assumed to be 2, And r_1 and r_2 are selected randomly in the range 0 and 1.

8. Find the position of the j^{th} particle in i^{th} iteration as:

$$X_j^{(i)} = X_j^{(i-1)} + V_j^{(i)}\ ;\ \text{j=1,2,....,N}$$

9. Find the objective function values due to each particle as $f\left(X_1^{(i)}\right), f\left(X_2^{(i)}\right), ..., f\left(X_N^{(i)}\right)$.
10. The method is assumed to have converged if the positions of all particles converge to the same set of values. If the convergence criterion is not satisfied, the iteration number set as $i = i + 1$ and step 5 is repeated by updating and by computing the new values of $P_{Best,j}$ and G_{Best}.

3 MODEL AND PROBLEM DEFINITION

Two methods for controlling the stress in a plate with hole were provided previously [29]. At the first proposed method, stress is directly decreased in the plate by placing piezoelectric actuators at the points with high stress, and by applying positive strain on the host plate. The problem of this method is that as the stress concentration factor reduces in the host plate, the stress increases in the piezoelectric actuators. In the second method, by redistributing the stress flow line in the host plate using piezoelectric actuators and by creating a negative strain, the stress in the host plate is reduced indirectly.

In previous researches, the effect of thickness and stiffness ratio of piezoelectric actuators and the host plate on the location of piezoelectric patches and reduction in stress concentration factor has not been studied. However, the thickness ratio and stiffness ratio of piezoelectric patches and host plate effect on the location of piezoelectric patches and the decrement rate of stress concentration factor. Stiffness ratio (*Rs*) and thickness ratio (*Rt*) of the piezoelectric patches and plate are defined as follow:

$$\text{Stiffness ratio } (Rs) = \frac{(E)_{Plate}}{(\mathrm{E}_0)_{Piezo}}$$

$$\text{Thickness ratio } (Rt) = \frac{(t)_{Plate}}{(\mathrm{t}_0)_{Piezo}}$$

To investigate two proposed method and analyze the effect of stiffness ratio and thickness ratio of the host plate and piezoelectric patches on locating the piezoelectric actuators and reducing the stress concentration factor around the hole, seven conditions listed in Table 1. are considered.

Table1
Seven condition for stiffness ratio and thickness ratio.

Condition Number:	NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7
Stiffness ratio (*Rs*)	*Rs* =1/4	*Rs* =1/3	*Rs* =1/2	*Rs* =1	*Rs* =2	*Rs* =3	*Rs* =4
Thickness ratio (*Rt*)	*Rt* =1/4	*Rt* =1/3	*Rt* =1/2	*Rt* =1	*Rt* =2	*Rt* =3	*Rt* =4

For the host plate, a thin rectangular plate subjected to uniform tension 1*Mpa* is considered. The geometry of the plate is presented in Fig.1. Because of accruing the stress concentration around the hole to achieve the maximum reduction in stress concentration factor, piezoelectric actuators should be placed near the hole. Therefore a virtual grid mesh near the hole for the location of the piezoelectric patches as a circle sector with a 15 degree radius and a 4 *mm* width is considered. The piezoelectric patches are polarized in the thickness direction. To simulate and analyze the mentioned problem, a python code is developed.

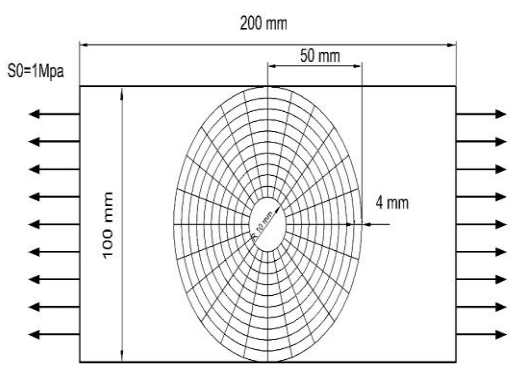

Fig.1
The geometry of plate and grid mesh.

To simulate the case and use the particle swarm optimization algorithm to locate the piezoelectric patches around the hole, a Python code was developed. To find the best location for piezoelectric patches and the optimum voltage around the hole, the PSO algorithm was used for different thicknesses/stiffness ratios. At first, in this code the number of piezoelectric patches was introduced to be located to the software, and after the program was converged, its output was extracted as the optimum voltage and location for piezoelectric actuators around the hole. The flowcharts of the PSO algorithm implementation and optimization procedure are shown in Fig.2.

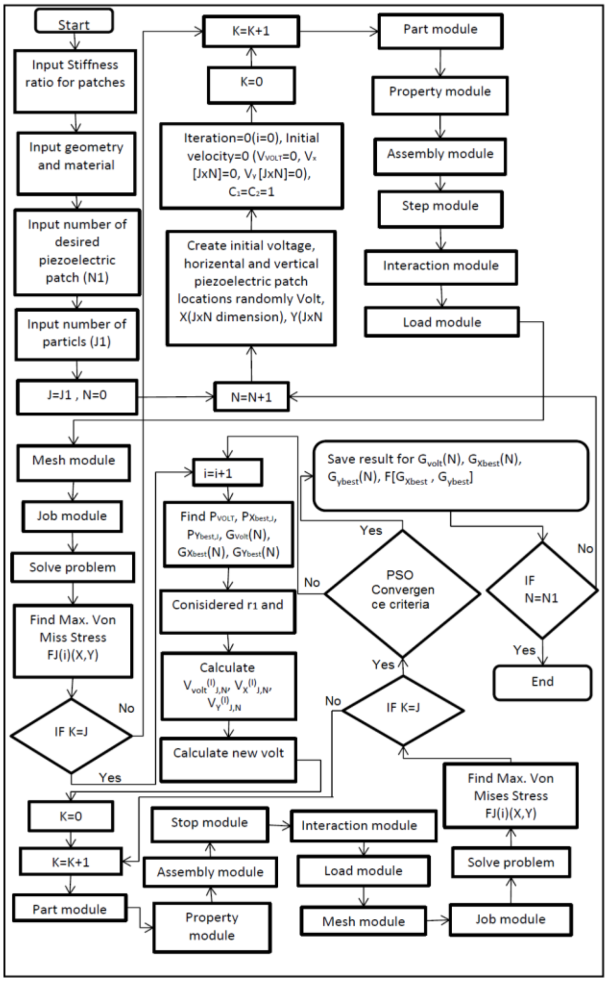

Fig.2
Flowchart of PSO for consideration problem.

4 VALIDATING RESULTS

Two experiments have been carried out to examine results of Finite Element Method (FEM) analysis and their results are shown in Table 2. One of tests has been designated for induction of positive strain into host plate by piezoelectric actuators and another, was considered for induction of negative strain into the given host plate. The plates are made of aluminum and piezoelectric type (Pzt-4). The actuators have been placed at specified points in these tests and strain-gauges were positioned at top and bottom of the hole. The output strain from strain- gauges that was exerted to piezoelectric actuators is extracted by data-logger by exertion of tensile force to base plate. These cases have been also conducted by the aid of the following software and results were extracted in order to be compared with empirical results. Fig 3. shows schematic view of empirical test.

As it is clear from the results in Table 2., there is acceptable consistency between the experimental results and the finite element analyses. However, the existing error between the results could be caused by the adhesive layer between the actuators and the host plate in experimental test. It was also impossible to attach strain gauges exactly on the top and bottom of the hole. Both above cases can influence on the difference between the experimental results and analyses by software.

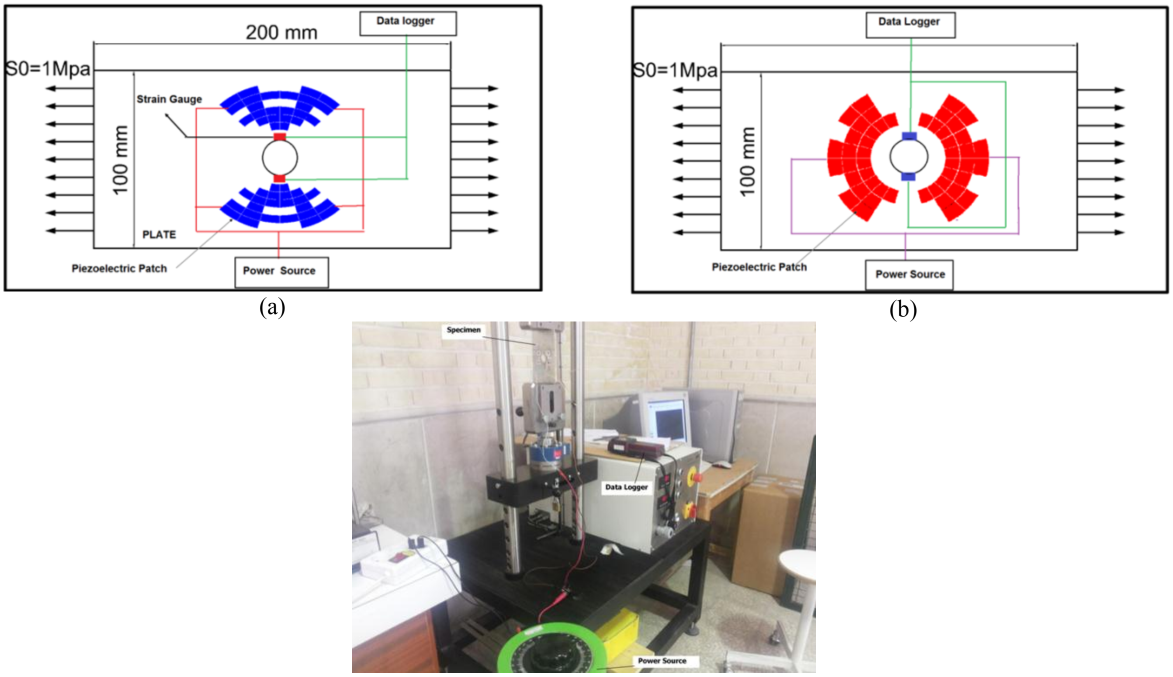

Fig.3
Schematic of experimental tests, a) Negative strain b) Positive strain.

Table 2
Comparison the results of the test and analysis.

Condition	Volt	Strain from analysis	Strain from Test	Error
	0	48.582×10^{-6}	46.258×10^{-6}	4.783%
	16.75 (E_0)	42.98×10^{-6}	40.785×10^{-6}	5.1%
A	33.5 ($2E_0$)	37.85×10^{-6}	36.015×10^{-6}	4.84%
	50.25 ($3E_0$)	32.25×10^{-6}	30.45×10^{-6}	5.58%
	67 ($4E_0$)	26.73×10^{-6}	25.14×10^{-6}	5.94%
	0	34.743×10^{-6}	33.25×10^{-6}	4.28%
	16.75 (E_0)	24.93×10^{-6}	23.78×10^{-6}	4.61%
B	33.5 ($2E_0$)	21.784×10^{-6}	20.53×10^{-6}	5.75%
	50.25 ($3E_0$)	18.25×10^{-6}	17.56×10^{-6}	3.78%
	67 ($4E$)	15.78×10^{-6}	14.96×10^{-6}	5.196%

5 OPTIMIZATION RESULTS

5.1 The first mode

The placement of piezoelectric patches under tension was studied around the hole in this mode. In this case, by applying a negative strain on the host plate through affecting the lines of stress, the piezoelectric patches reduced the stress concentration coefficient.

Fig.4 shows the placement of piezoelectric actuators at stiffness ratios of ≥ 1. In these figure the piezoelectric actuators are shown at the left and right sides of the hole as well as around the longitudinal axis of the plate. Fig.5 shows the placement of piezoelectric actuators at stiffness ratios of ≤ 1. These figures show that the piezoelectric actuators are placed at a longitudinal direction by an angle of about 60°. Approaching from the thickness ratio 1 to 1/4, the actuators are placed at an angel lower than 60° and the longitudinal direction is increased. This is shown in Fig. 6.

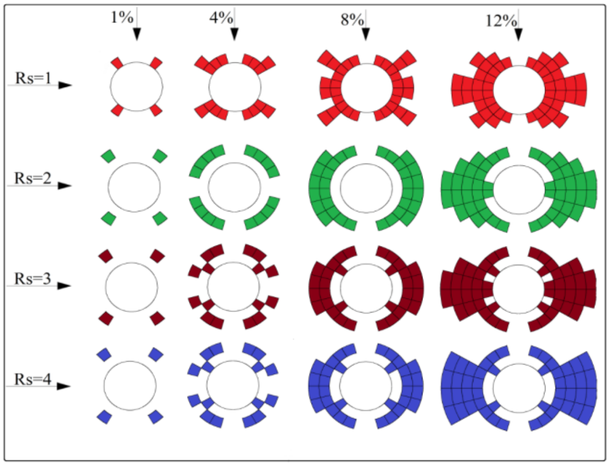

Fig.4
Optimum pattern of piezoelectric patches around the hole for stiffness ratio *Rs*≥ 1.

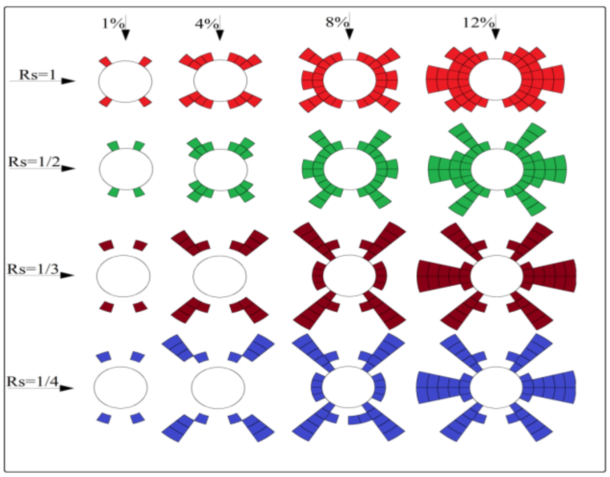

Fig.5
Optimum pattern of piezoelectric patches around the hole for stiffness ratio *Rs*≤ 1.

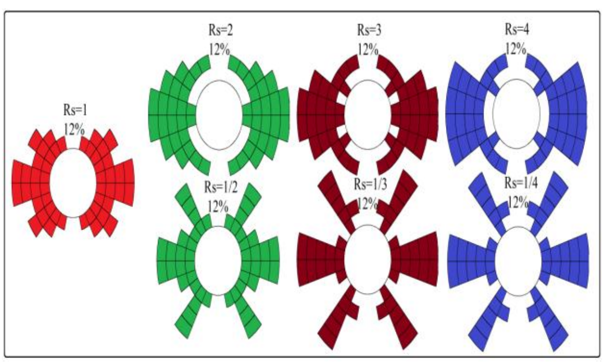

Fig.6
Best pattern of patches for different stiffness ratio.

The piezoelectric actuators are shown in Fig.7 at the thickness ratios of ≥ 1. As this can be seen, the actuators are at the left and right sides of the hole. Fig. 8 shows the piezoelectric actuators at the thickness ratios of ≤ 1. As seen, the piezoelectric actuators are placed at a longitudinal direction by an angle of about 60°. Approaching from the thickness ratio 1 to 1/4, the actuators are placed at an angel lower than 60° and the longitudinal direction is increased. This is shown in Fig. 9.

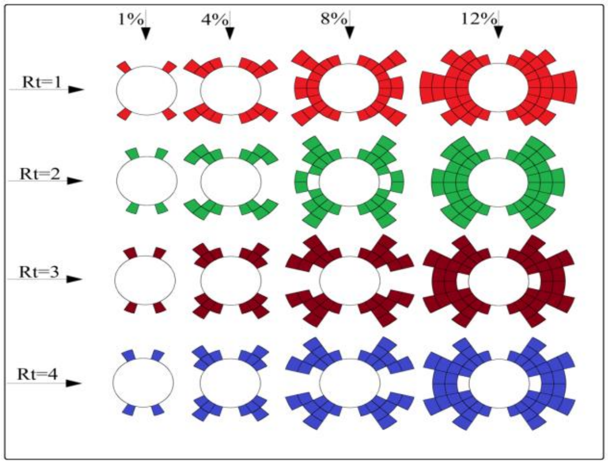

Fig.7
Optimum pattern of piezoelectric patches around the hole for thickness ratio $Rt\geq 1$.

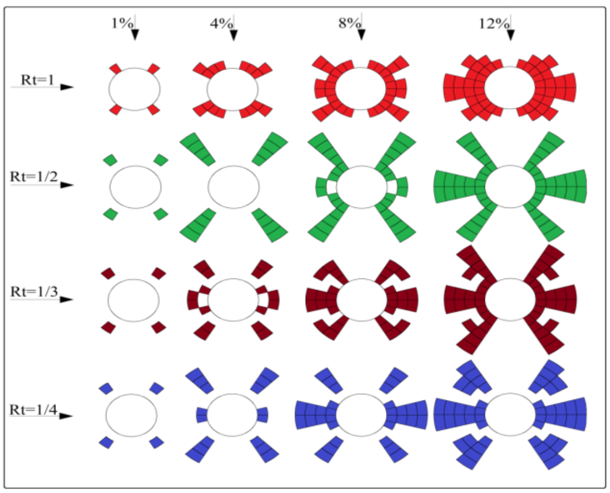

Fig.8
Optimum pattern of piezoelectric patches around the hole for thickness ratio $Rt\leq 1$.

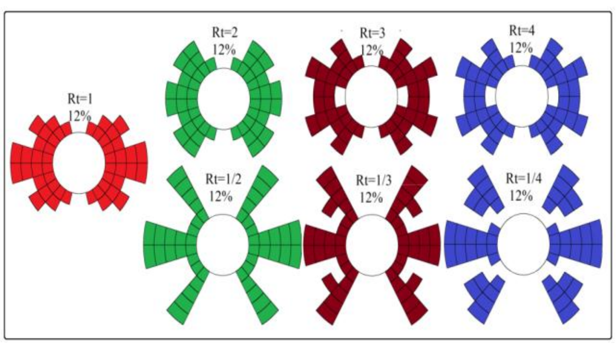

Fig.9
Best pattern of patches for different thickness ratio.

Figs. 10 to 13 show the effect of the voltage and the stiffness/thickness ratio between the piezoelectric actuators and the host plate on the reduction of the stress concentration factor around the hole. This study shows that the voltage has a significant effect in reducing the stress. But it is remarkable that an adequate increase in the voltage displaces the maximum stress at the top and bottom of the hole to other points around the hole.

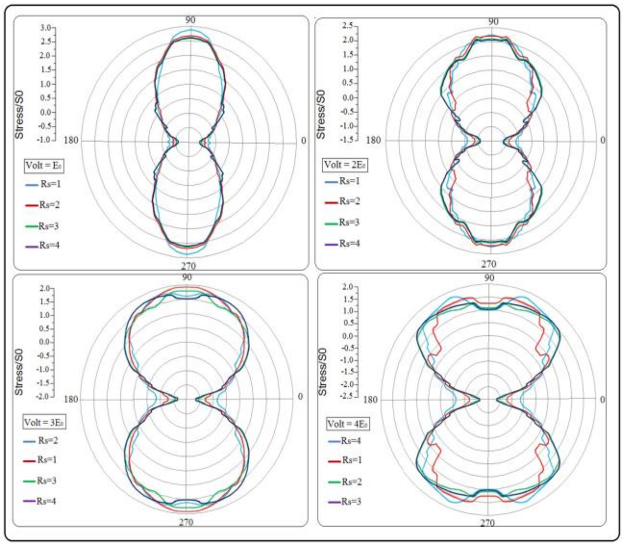

Fig.10
Effect of stiffness ratio and voltage on stress concentration for *Rs*≥ 1.

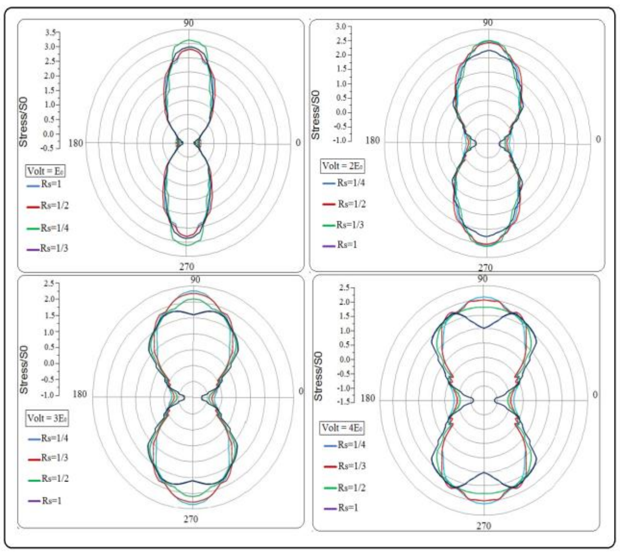

Fig.11
Effect of stiffness ratio and voltage on stress concentration for *Rs*≤ 1.

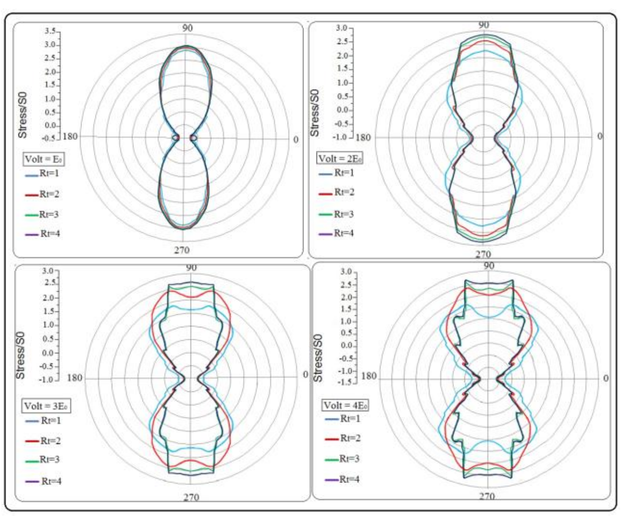

Fig.12
Effect of stiffness ratio and voltage on stress concentration for *Rt*≥ 1.

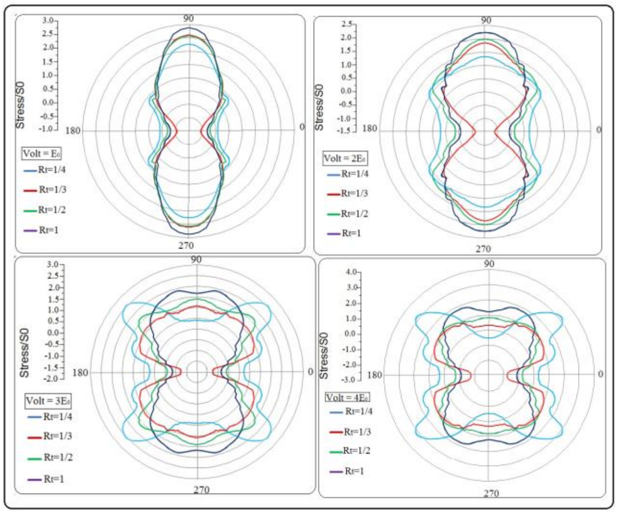

Fig.13
Effect of stiffness ratio and voltage on stress concentration for $Rt \leq 1$.

Figs.14 and 15 compare the capability of the piezoelectric actuators with different stiffness/thickness ratios in reducing the stress concentration factor. The reduction of the stress concentration factor for different thickness ratio is shown in Fig. 14. At thickness ratios less than 1, more reduction in the stress concentration factor occurred. Besides, the maximum reduction in the stress concentration factor is seen at the thickness ratio of 1/4, equal to 82%.The thickness ratio of 4 shows the least reduction in the stress concentration factor, i.e. approximately 19%. Fig.15 shows the reduced stress concentration factor at different stiffness ratios. The stiffness ratios greater than 1 shows greater reduction in the stress concentration factor, with a maximum reduction at the stiffness ratio of 4, i.e. about 85%.

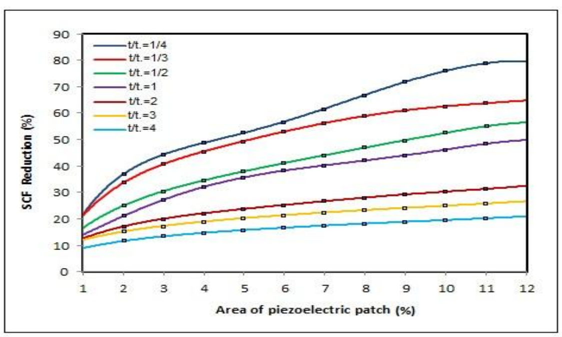

Fig.14
Effect of Thickness ratio on stress concentration reduction.

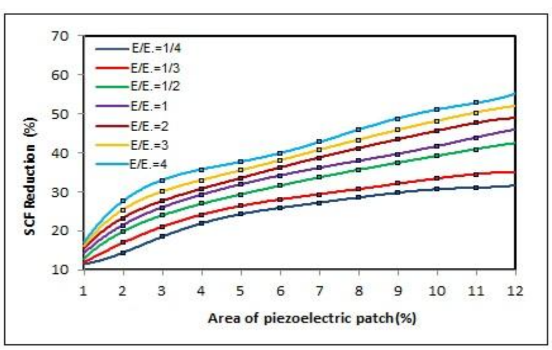

Fig.15
Effect of stiffness ratio on stress concentration reduction.

In Figs. 16 and 17, the amount of stress in the piezoelectric patches is shown in different thickness/stiffness ratios. In Fig. 16, among different thickness ratios, in thickness ratios less than 1, the piezoelectric actuators bear less stress; and in greater ratios, there is more increase in stress in the piezoelectric actuators. In Fig.17, among different stiffness ratios, at stiffness ratios greater than 1, the piezoelectric patches bear less stress, and in the lesser ratios, there is more increase in stress in the piezoelectric actuators.

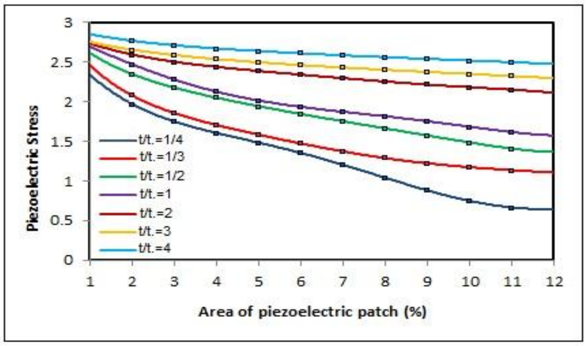

Fig.16
The stress piezoelectric actuators of different thickness ratio.

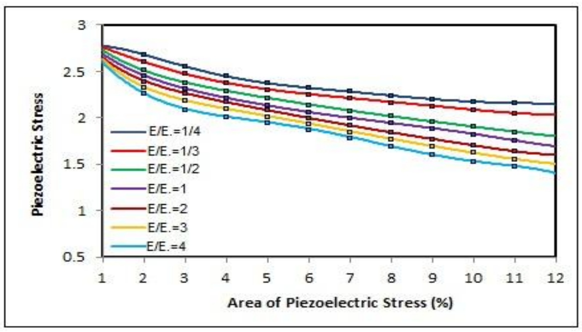

Fig.17
The stress piezoelectric actuators of different stiffness ratio.

5.2 The second mode

In this mode, the placement of piezoelectric patches around the hole is examined when they are in compression. In this case, the piezoelectric patches reduce directly the stress concentration factor by creating positive strain on the host plate.

Fig.18 shows the placement pattern of the piezoelectric actuators at stiffness ratios of ≥ 1. As seen in these figure, the piezoelectric actuators are placed at the top and bottom of the hole and around the transversal axis of the plate. The placement of the piezoelectric actuators at the stiffness ratios less than 1 is shown in Fig.19. In these figures, it is observed that the actuators are located at the top and bottom of the hole and away from the transversal axis of the plate at an angle of 45º to 75º. Approaching from the thickness ratio 1 to 1/4, the actuators are placed at an angel lower than 75° and the longitudinal direction is increased. This is shown in Fig. 20.

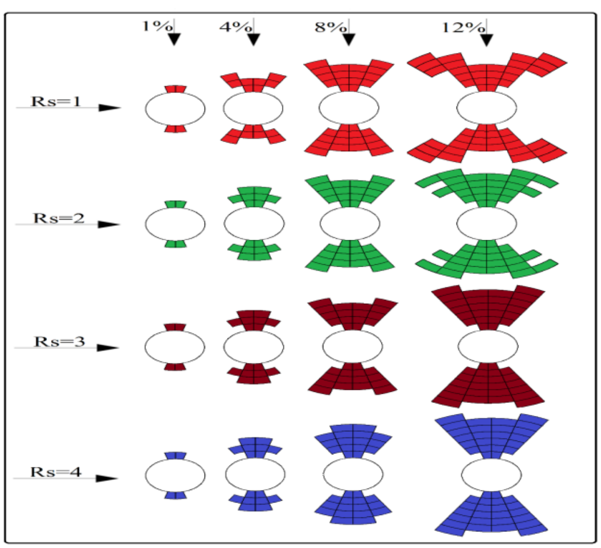

Fig.18
Optimum pattern of piezoelectric patches around the hole for stiffness ratio *Rs*≥ 1.

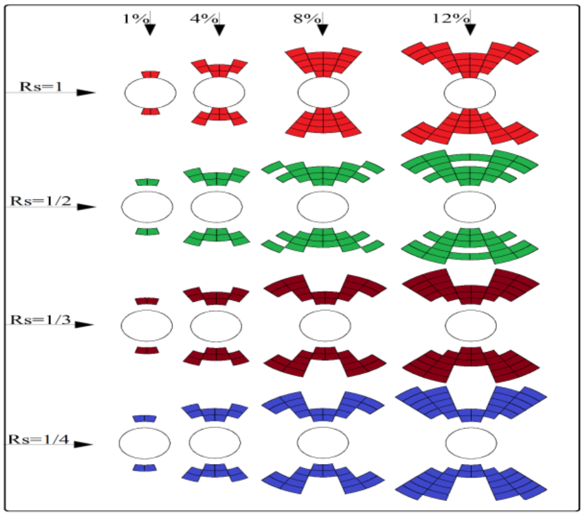

Fig.19
Optimum pattern of piezoelectric patches around the hole for stiffness ratio $Rs\leq 1$.

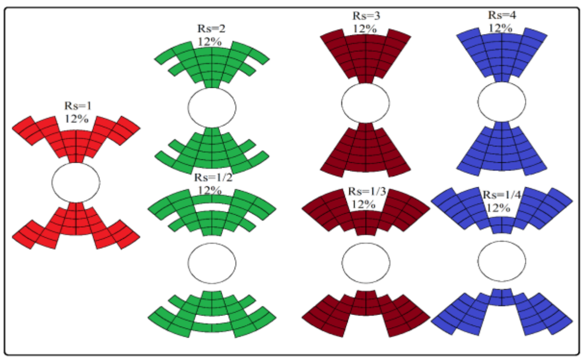

Fig.20
Best pattern of patches for different stiffness ratio.

Fig. 21 shows that piezoelectric actuators are located at the thickness ratios of ≥ 1. As seen, the actuators are located at the top and bottom of the hole. In Fig.22, it is shown that the placement of the piezoelectric actuators at the thickness ratios less than 1. As can be seen, the piezoelectric actuators are located at the top and bottom of the hole at the transversal axis of the plate. The piezoelectric actuators are at an angle of 45º to 75º away from the transversal axis of the plate. Approaching from the thickness ratio 1 to 1/4, the actuators are placed at an angel lower than 75° and the longitudinal direction is increased. This is shown in Fig. 23.

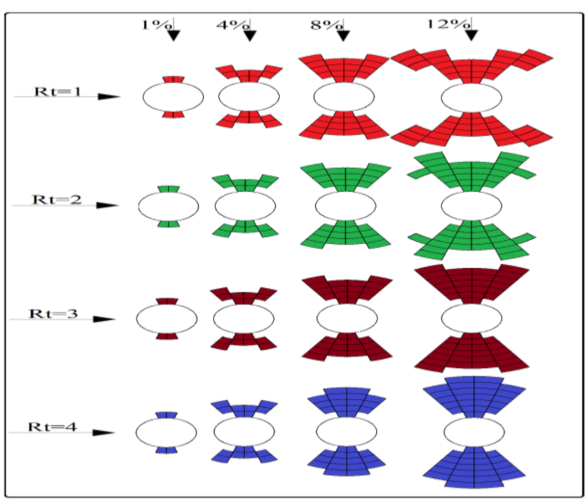

Fig.21
Optimum pattern of piezoelectric patches around the hole for thickness ratio $Rt\geq 1$.

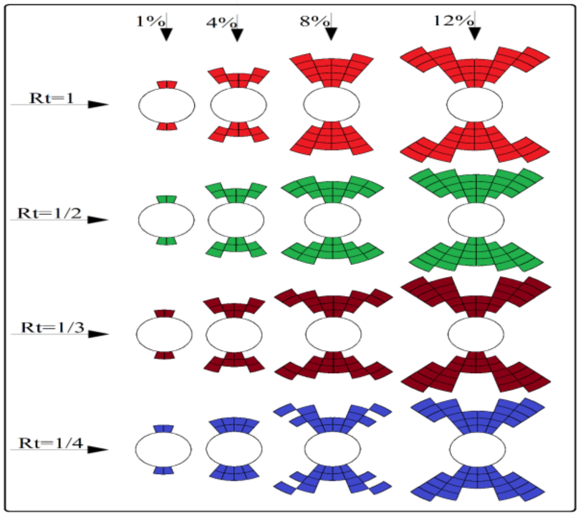

Fig.22
Optimum pattern of piezoelectric patches around the hole for thickness ratio $Rt\leq 1$.

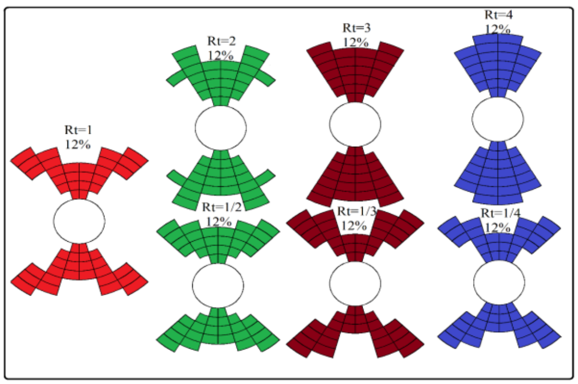

Fig.23
Best pattern of patches for different thickness ratio.

Figs. 24 to 27 show the effect of the voltage and the stiffness/thickness ratio between the piezoelectric actuators and the host plate on the reduction of the stress concentration factor around the hole. Experimental tests show that the voltage has a significant effect on reducing the stress. But it is remarkable that the sufficient increase in the voltage displaces the maximum stress at the top and bottom of the hole to other points around the hole. The increase in the voltage also raises the stress in the piezoelectric actuators, so applying the voltage to the actuators is limited.

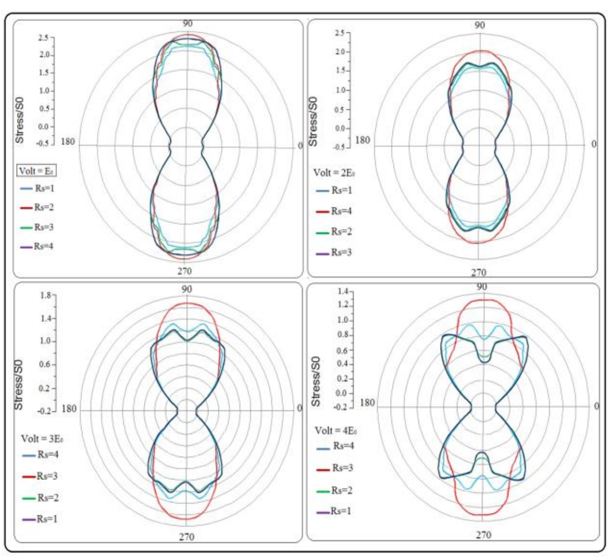

Fig.24
Effect of stiffness ratio and voltage on stress concentration for $Rs\geq 1$.

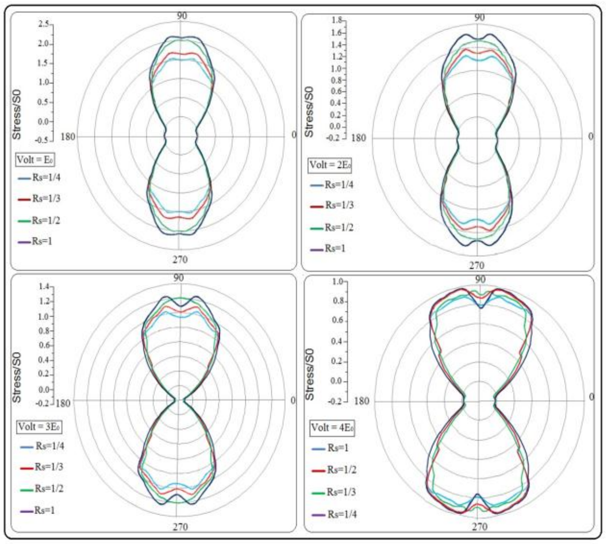

Fig.25
Effect of stiffness ratio and voltage on stress concentration for *Rs*≤ 1.

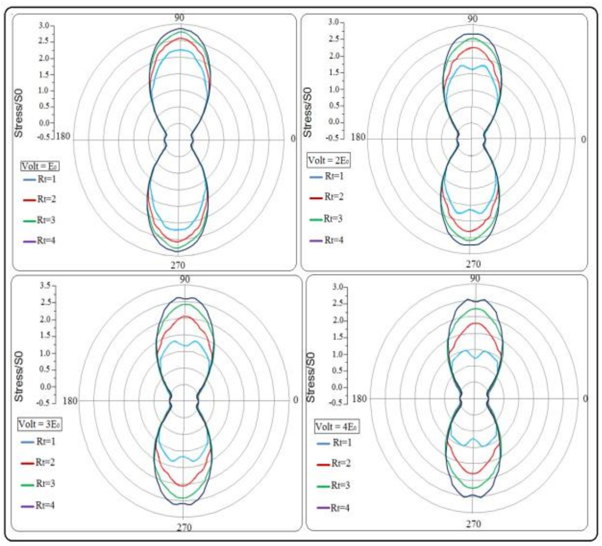

Fig.26
Effect of stiffness ratio and voltage on stress concentration for *Rt*≥ 1.

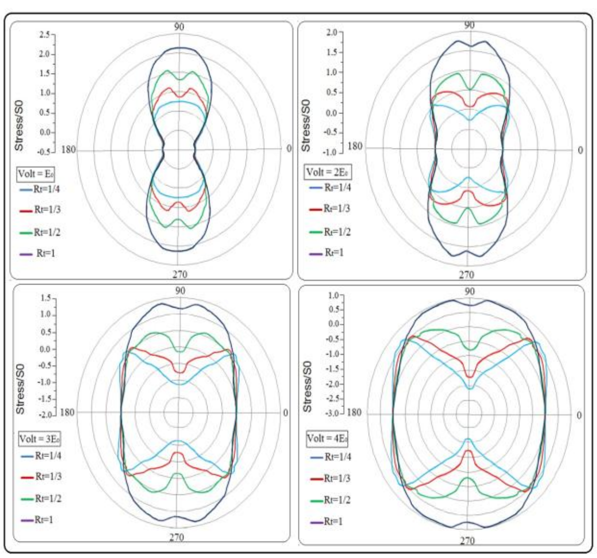

Fig.27
Effect of stiffness ratio and voltage on stress concentration for *Rt*≤ 1.

In Figs. 28 and 29, the capability of piezoelectric actuators with different stiffness/thickness ratios in reducing the stress concentration factor is compared. In Fig.28 the reduction in the stress concentration factor for different thickness ratios is displayed. For thickness ratios less than 1, more reduction in the stress concentration factor is observed and the maximum reduction in stress concentration factor is seen at the thickness of 1/4, equal to 37%. Also, the minimum reduction in stress concentration factor is seen at the thickness of 4, equal to 11%. The reduced stress concentration factor at different stiffness ratios is observed in Fig.29. The stiffness ratios less than 1 display more reduction in stress concentration factor, and the maximum reduction occurs at the stiffness ratio of 1/4, i.e. about 53%.

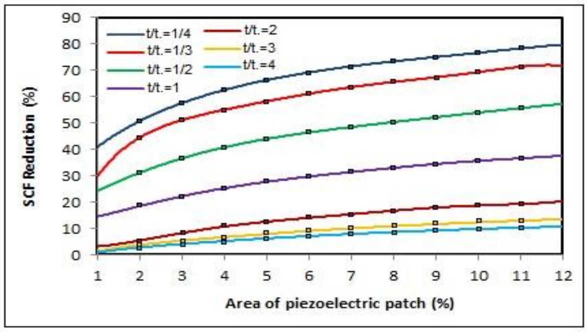

Fig.28
Effect of Thickness ratio on stress concentration reduction.

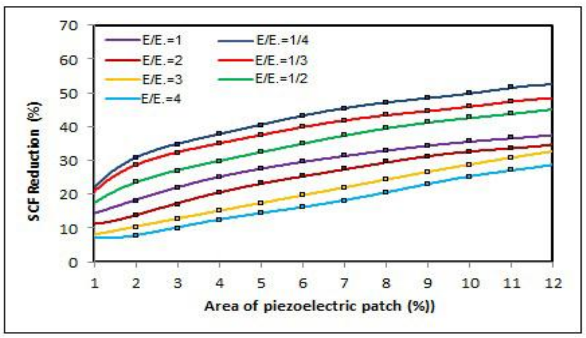

Fig.29
Effect of stiffness ratio on stress concentration reduction.

Figs. 30 and 31 show the amount of stress in the piezoelectric patches at different stiffness/thickness ratios. In Fig.30, among different thicknesses ratios, at the thickness ratio less than 1 the piezoelectric actuators show less stress, while at greater ratios, there is the more increase in stress in the piezoelectric actuators. In Fig.31, among different stiffness ratios, at the stiffness ratio less than 1, less stress in the piezoelectric actuators is seen, and at the greater ratios, the more stress is observed in the piezoelectric actuators.

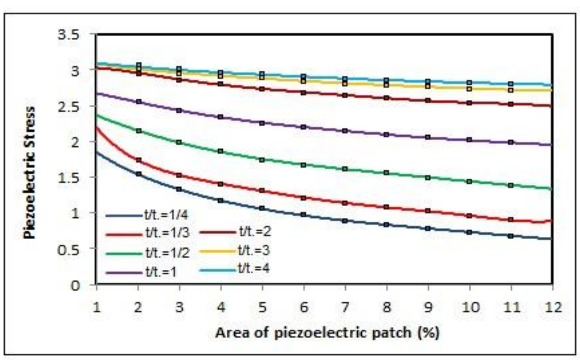

Fig.30
The stress piezoelectric actuators of different thickness ratio.

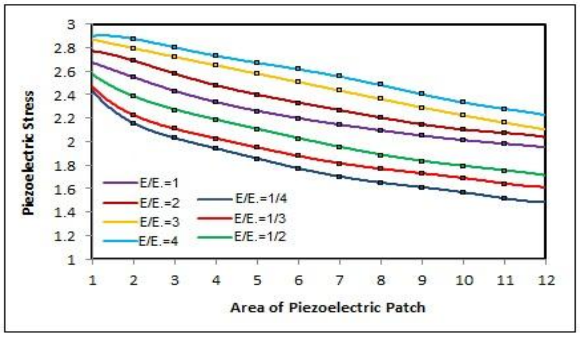

Fig.31
The stress piezoelectric actuators of different stiffness ratio.

6 CONCLUSIONS

In this paper the effect of stiffness and thickness between the plate and piezoelectric patches on optimum location of piezoelectric actuators is presented. For this purpose some various modes as the thickness/stiffness ratio of the plate to the piezoelectric patches as ≥ 1 or ≤ 1 are considered. Using PSO algorithm the best locations of patches are presented for considered ratios. The results show that by changing in stiffness or thickness of actuators, the location of patches are changed and the maximum stress concentration point is moved from top/bottom of hole to another point around the hole. It is shows that to select patches for reducing the stress in a plate, the thickness and stiffness of piezoelectric patches must be mentioned. The results are validated by some experimental tests.

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