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Research Article

Design and Optimization of Piezoresistive MEMS Pressure Sensors Using ABAQUS

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A b s t r a c t

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In this paper, optimization of a piezoresistive Micro Electro Mechanical System (MEMS) pressure sensor has been intended. The aim of this study is to find an optimal diaphragm shape by Finite Element Method (FEM) using ABAQUS®, which is the most suitable software in this area. Optimal diaphragm shape is a one, that results in reasonable output stimuli with maximal deflection and minimal stress. Three different shapes of diaphragms are considered in this study, they are circular, square and rectangular diaphragms. Another purpose of this study is to find out the effect of holes in these diaphragms. With respect to applied stress and sensor output, results were showing that circular shaped diaphragms are performing much more efficient than other shapes. Moreover Rectangular holes have better influence on the function of diaphragms too.

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1. Introduction

Pressure sensors are widely used in automotive, medical and various types of industrial applications [1, 2]. MEMS devices have very low power consumption; besides they require very low space.

In this work, it is assumed that Wheatstone bridge configuration has been used to sense the stress developed in a diaphragm. The stress is sensed by measuring the change in piezoresistors which are connected in Wheatstone bridge configuration that are situated on a pressure sensor diaphragm. The pressure is converted into an electrical signal by the use of resistance change phenomena due to the stress or strain of the piezoresistors. The stress or strain causes electrical signal fluctuations in two ways, one way is by structural deformation induced resistance variations, and the other way is by the quantum physical phenomena induced resistivity variations.

Three different shapes of diaphragms have been compared together. Stress, deflection, sensor output voltage and sensitivity of Circular, square and rectangular shapes of diaphragms have been examined.

The diaphragm shapes that have been simulated in FEM software are shown in Figure 1. The dimensions of the diaphragm are such that the area is same in all the three cases.

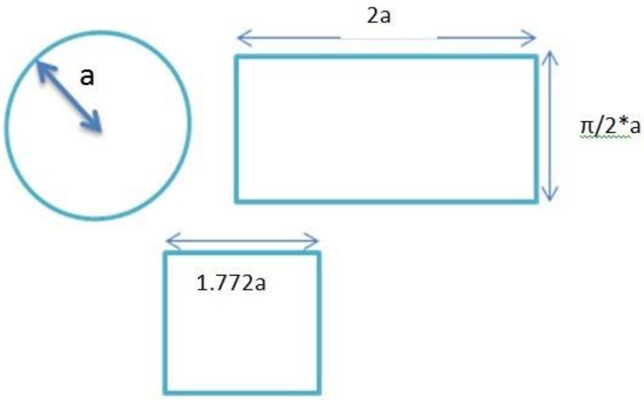

Fig. 1: Circular, square and rectangular diaphragms and their relative dimensions used in simulations

2. Sensor diaphragm design

In order to model the silicon pressure sensor diaphragm, it is assumed that the diaphragm has a uniform thickness, with perfectly clamped edges. In the steady state, the diaphragm deflection is governed by the Lagrange equation as in Eq. (1) which allows calculating the out-of-plane membrane deflection $w(x,y)$ as a function of position [3-4]. In this case, Cartesian coordinates are chosen for analysis as the diaphragm is rectangular in shape.

$$\frac{\partial^4 w(x,y)}{\partial x^4} + 2\alpha_{si}\frac{\partial^4 w(x,y)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y)}{\partial y^4} = \frac{P^4}{Dh^3} \qquad (1)$$

Where, P represents the differential pressure applied on the membrane of h thickness; the anisotropy coefficient α_{si} depends on the crystallographic orientation and D is a rigidity parameter which depends on material properties given by Eq. (2)

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad (2)$$

Where, E is the Young's modulus whereas ν is the Poisson's ratio. The factor G is called the shear modulus and it describes the reaction of the material to the shear stress. α_{si} Can be calculated using Eqs. (3) and (4):

$$G = \frac{E}{2(1+\nu)} \cdot \tag{3}$$

And

$$\alpha_{\mathrm{si}} = \nu + \frac{2G(1-\nu^2)}{E} \cdot \tag{4}$$

However the exact solution of Eq. (1) does not exist and one of the approaches used to analyze the basic shapes is the Polynomial approximation [5-6]. This approach is used to analyze the deflection and stress for the different shapes of diaphragms.

2.1. Circular diaphragm

Considering the isotropic circular membrane of radius "a" as shown in Figure 1, this is characterized by the axial symmetry. So in order to simplify calculations, the out of plane deformation $w(r)$ is considered to be dependent only on the distance from its center r and is given by [7]:

$$w(r) = \frac{Pa^4}{64D}\left[1-\left(\frac{r}{a}\right)^2\right]^2 \cdot \tag{5}$$

2.2. Square diaphragm

The solution to Eq. (1) for a square diagram with side length of $\sqrt{\pi}\, a$ as shown in Fig. 1 (a), with appropriate approximations and simplification yields the displacement of a square diaphragm which changes with uniform pressure (P), is given by [7]:

$$w(x,y) = \frac{Pa^4}{47D}\left(\frac{1-x^2}{\pi\, a^2}\right)^2\left(\frac{1-y^2}{\pi\, a^2}\right)^2 \cdot \tag{6}$$

2.3. Rectangular diaphragm

In case of a rectangular diaphragm, the deflection in the diaphragm can be simplified as in Eq. (7). The width of rectangular diaphragm is $0.5\,\pi\, a$ and a length is $2a$ as shown in Fig. 1.

$$w(x,y) = \frac{P(1-\nu^2)}{2Eh^3}\left[\frac{(\pi^2 a^2/16)-x^2}{(\pi^4 a^4/256)+a^4}\right]^2 (a^2-y^2)^2 \cdot \tag{7}$$

2.4. Sensor design

A pressure sensor is designed to measure a pressure from 1 MPa to 100 MPa. The diaphragm thickness (h) is estimated as 30 μm and has been made on plane of single crystalline silicon. For the rectangular diaphragm design, a length to width ratio of 1.25 is assumed. Various diaphragm dimensions are shown in Table 1. The Young's modulus (E) of Si is 2×1011 Pa and Poisson's ratio (ν) is 0.28 [8].

Table 1: Dimensions of various diaphragms in the design

Diaphragm Type	Dimensions (µm)
Circular	250 (radius)
Square	443 (side)
Rectangular	396×500 (length×width)

2.5. Sensor circuit design

A Wheatstone bridge circuit as shown in Fig. 2 is used for sensing the output voltage [9]. Four piezoresistors namely R_1, R_2, R_3 and R_4 form the bridge circuit.

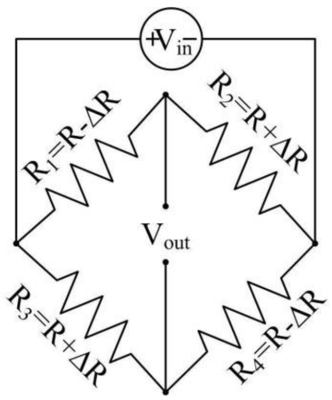

Fig. 2: Wheatstone bridge configuration to measure output voltage due to change in resistances on the sensors

The length, width and thickness of the piezoresistors are 200 µm, 10 µm and 10 µm, respectively. The piezoresistors are placed with an offset (distance from the edge of the diaphragm) of 13 µm in the longitudinal direction and 10 µm in the transverse direction. The electrical resistivity of each piezoresistor is $0.5\times10^{-4}\ \Omega\mathrm{m}$. When no pressure is applied, the bridge is under balance and ΔR is zero and the output voltage of the sensor is zero. When a pressure is applied, the resistance of the piezoresistors will change, thus the bridge is not balanced , and it leads to a voltage at the output. As the applied pressure results in more diaphragm deflection, that causes more stress and more output voltage. Thus the bridge output voltage is a direct indication of the applied pressure.

3. Stress concentration region

Another thing that is considered in this area is the effect of holes on the diaphragms. The main concept for this approach is to increase stress that occurred on diaphragms. SCR (Stress Concentration Region) is an approach where defects or holes are made in order to increase stress. To produce SCR, no extra high tech equipment is needed; because it just involves etching and mask design. Therefore, this approach appears to be the most suitable for enhancing the sensitivity of piezoresistive MEMS since the piezoresistive material has good sensitivity to stress and no additional complicated equipment or process are required [9-12].

In this paper the effect of three different shapes of hole have been studied in all considering diaphragms. Maximum stress, maximum deflection and maximum sensitivity in each case had been calculated.

4. Application mode using ABAQUS

In this paper, we introduce an implementation of the extended finite element method for structural mechanics analysis. Applied approach in this article enables the use of available ABAQUS capabilities (interactive FEM mesh generation, finite element libraries and so on) in order to solve the problems presented in previous sections [15, 16].

5. Results and discussion

In this section, deflection and stress and sensitivity for all the three mentioned diaphragms are compared. Stress contours of each situation are also presenting in this section.

5.1. Effect of diaphragm's geometry

All of the three diaphragms are simulated using ABAQUS and various results are compared. Figure 3 shows a comparison of Stress, maximum Sensitivity and maximum deflection in various diaphragm shapes while applied pressure is constant. It can be observed from Figure 3 that the deflection is more in circular diaphragm. As observed in Figure 3 the rate of changing of deflection is more in case of circular diaphragm, while rate of changing of stress in rectangular shape is more than the two others.

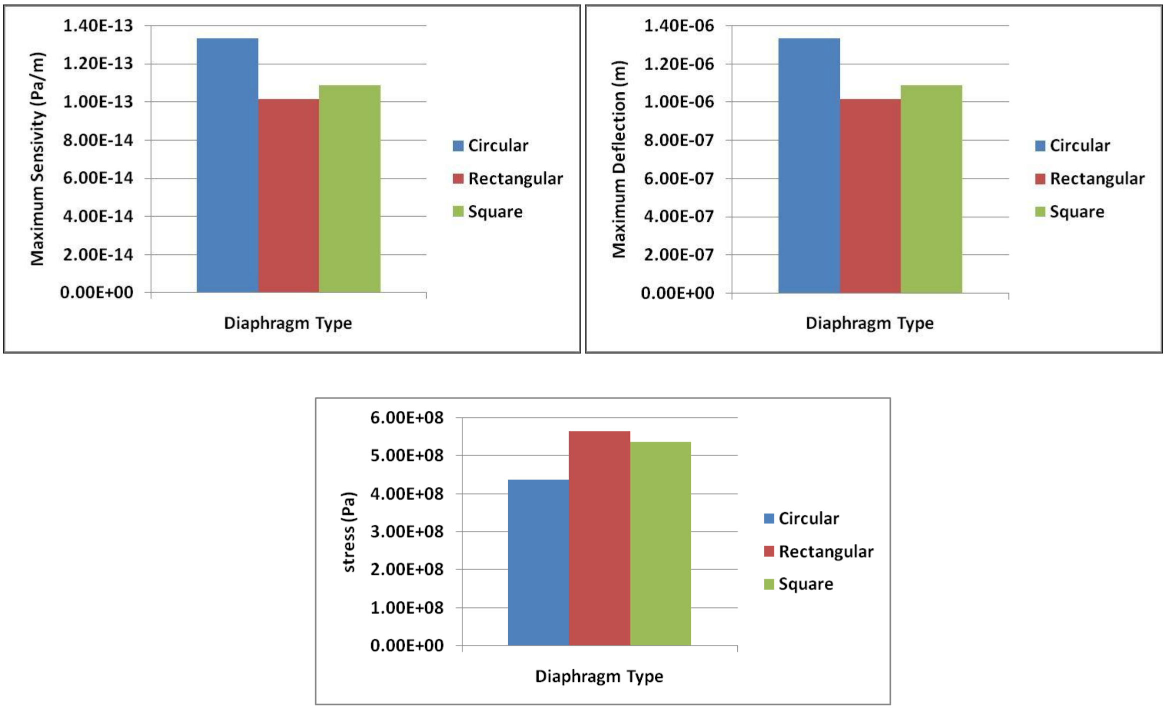

Fig. 3: Maximum sensitivity, maximum deflection and stress in three different shapes of diaphragm

Figure 4 shows a comparison of the maximum stress and deflection in various diaphragm shapes as the applied pressure is changed. It can be observed from Figure 4 that the stress is more in rectangular shaped diaphragm.

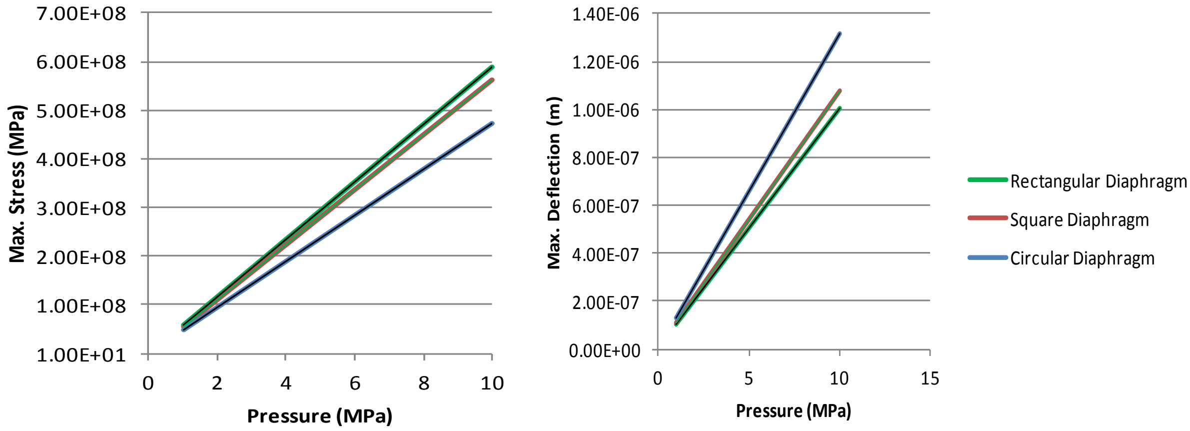

Fig. 4: Maximum stress and maximum deflection in three different shapes of diaphragm

Table 2 provides a comparison between the maximum deflections in all the three different diaphragms at an applied pressure of 10 MPa. It can be noted that in a rectangular diaphragm, the stress is much bigger compared to other diaphragm shapes. This is due to the fact that, the diaphragm structure is more asymmetric.

Table 2: Maximum stress, maximum deflection and maximum sensitivity at 10 MPa applied pressure

Diaphragm Type	Applied Pressure (MPa)	Maximum Stress (Pa)	Maximum Deflection (m)	Maximum Sensitivity
Circular	10	4.37E+08	1.33E-06	1.33E-13
Rectangular	10	5.65E+08	1.01E-06	1.01E-13
Square	10	5.37E+08	1.08E-06	1.08E-13

5.2. Mechanical analysis of the effect of holes on diaphragms

Table 3 summarizes the analysis result of stress, deflection and sensitivity difference for different types of SCR holes in each diaphragm type. In Figures 5 to 8 stress contours in three shapes of diaphragms with different kinds of hole have been compared together.

Table 3: Maximum stress, maximum deflection and maximum sensitivity in three shapes of diaphragms with 3 kinds of hole and without hole

Maximum Sensitivity	Maximum Stress	Maximum Deflection	Hole Type	Geometry of Diaphragm
1.437E-13	4.854E+8	1.437E-6	Rectangular	**Circular**
1.282E-13	4.260E+8	1.282E-6	Hevagonal	
1.273E-13	4.204E+8	1.273E-6	Circular	
1.330E-13	4.371E+8	1.330E-6	without hole	
1.058E-13	5.188E+8	1.058E-6	Rectangular	**Rectangular**
1.007E-13	5.387E+8	1.007E-6	Hevagonal	
1.002E-13	5.299E+8	1.002E-6	Circular	
1.013E-13	5.649E+8	1.013E-6	without hole	
1.361E-13	5.542E+8	1.361E-6	Rectangular	**Square**
1.078E-13	5.136E+8	1.078E-6	Hevagonal	
1.074E-13	5.064E+8	1.074E-6	Circular	
1.084E-13	5.367E+8	1.084E-6	without hole	

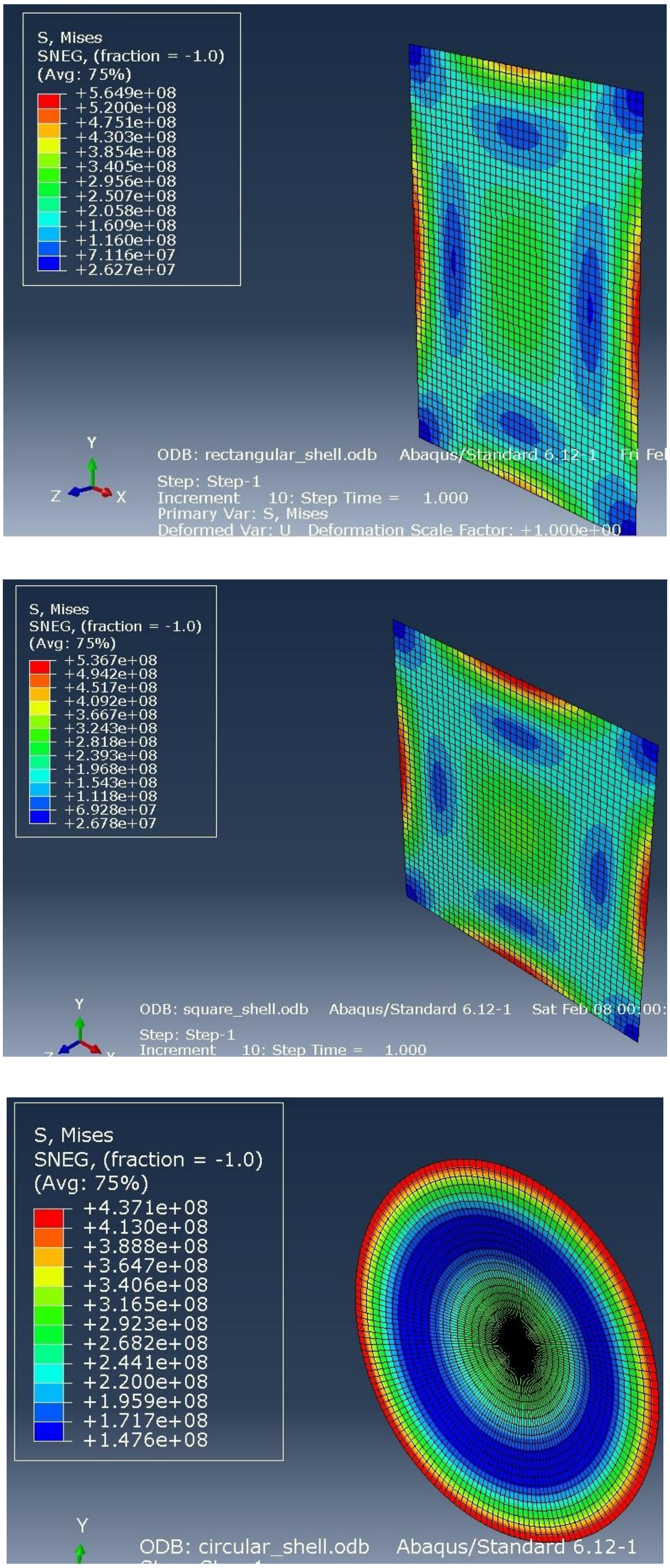

Fig. 5: Stress contours in three shapes of diaphragms

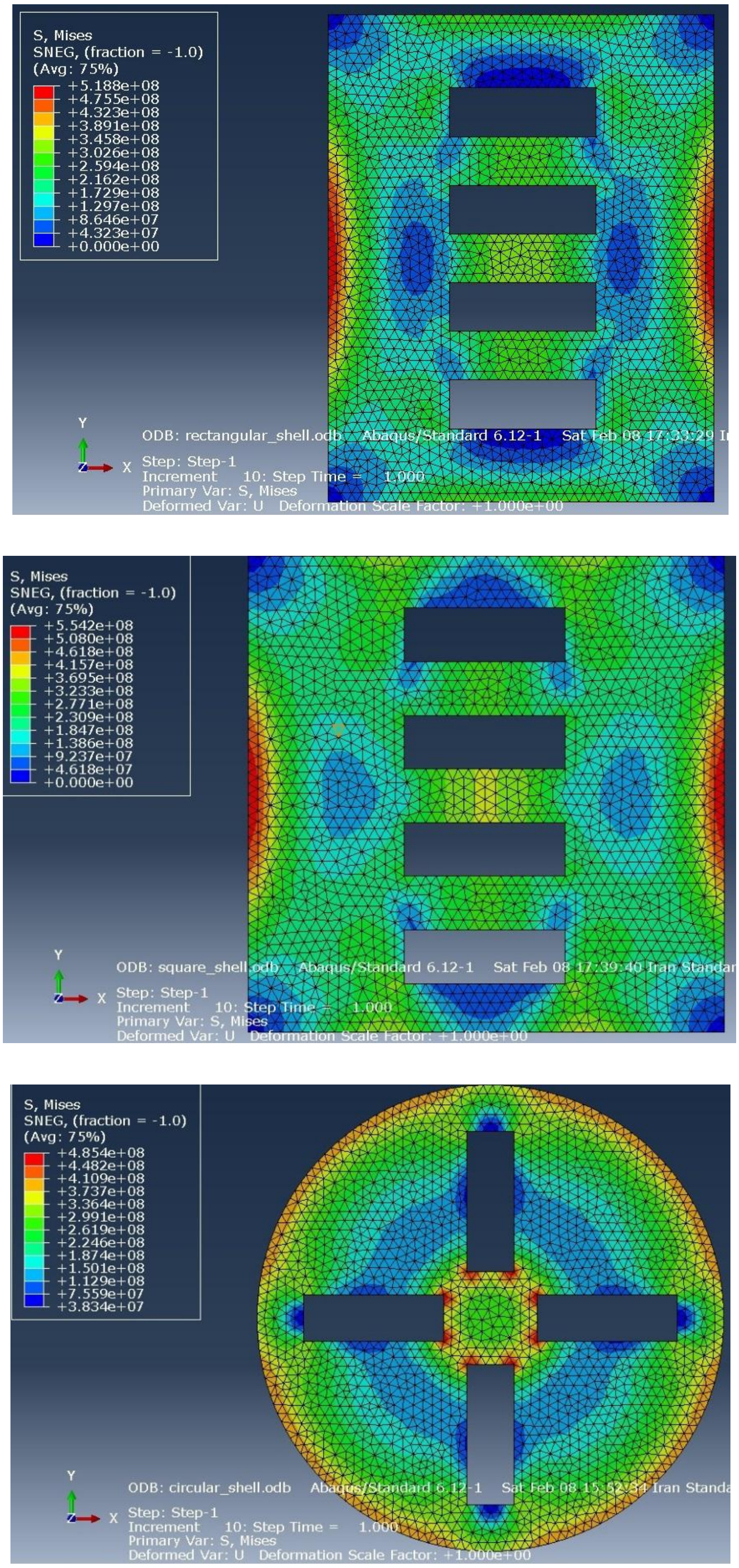

Fig. 6: Stress contours in three shapes of diaphragms with rectangular holes

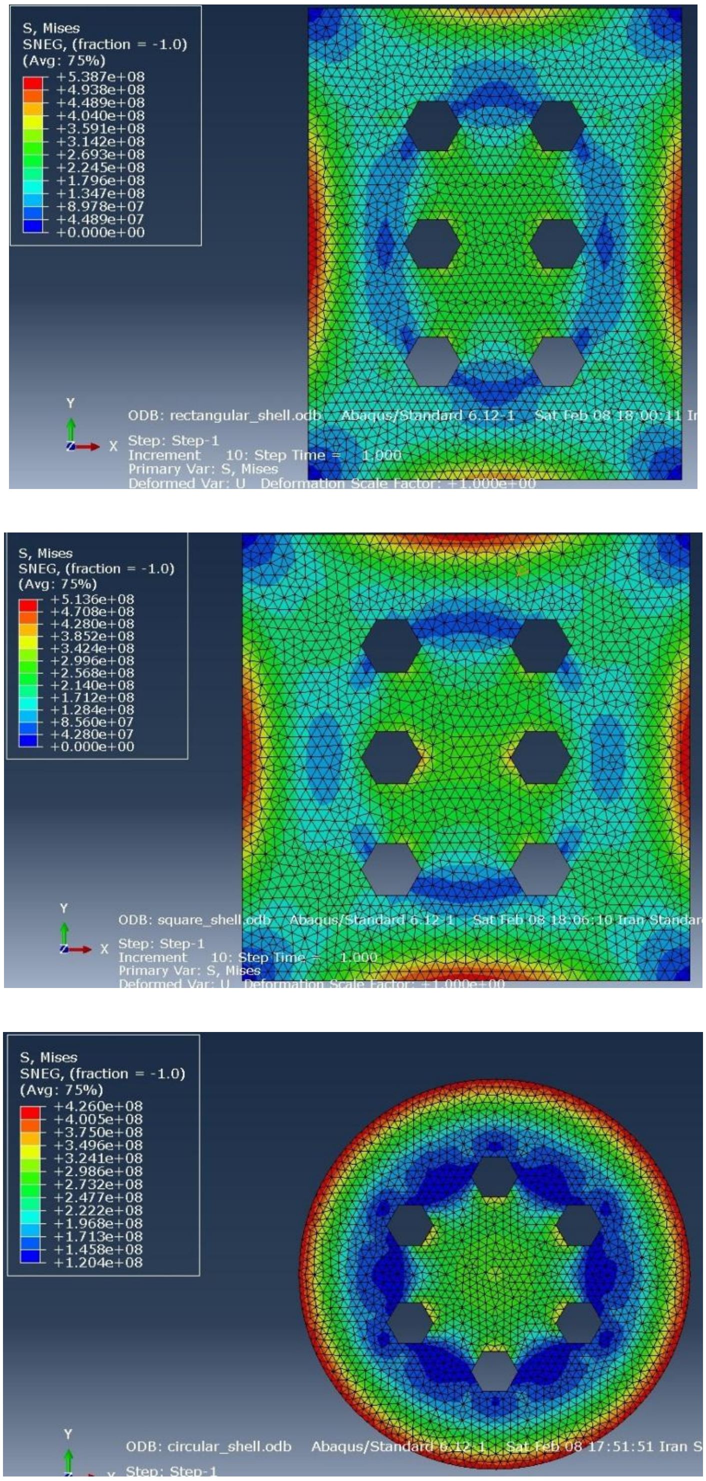

Fig. 7: Stress contours in three shapes of diaphragms with hevagonal holes

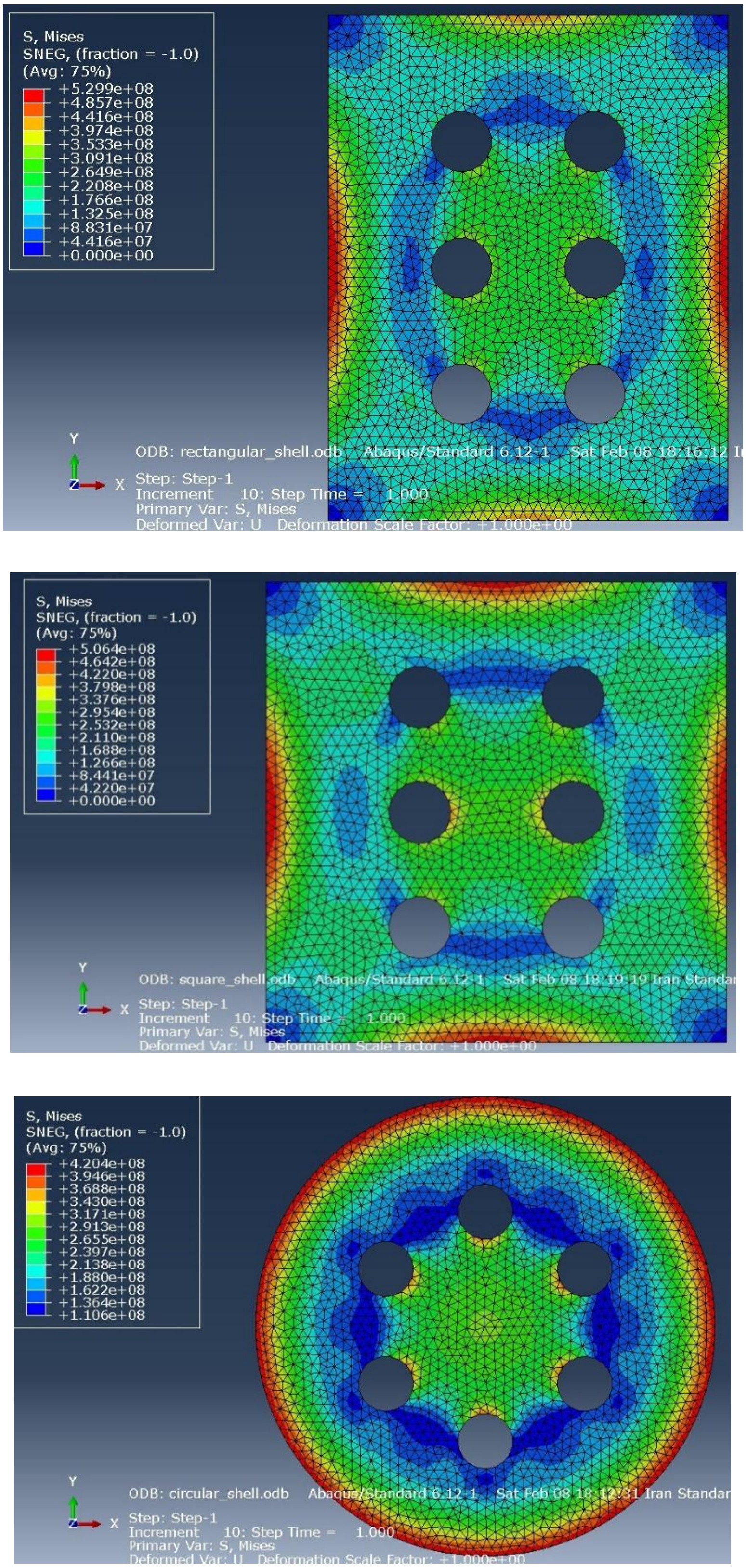

Fig. 8: Stress contours in three shapes of diaphragms with circular holes

6. Conclusions

In this research, three different shape of diaphragms have been simulated in ABAQUS. From FEA results, circular type diaphragm had better function and was more efficient. This subsumption is based on the comparison between stress and deflection results in these three kinds of diaphragms. However, when the stress in the diaphragm is considered, the rectangular diaphragm is under more stress compared to the square diaphragm. Thus, the probability of the sensor breakdown is more in the rectangular diaphragm in comparison with the square diaphragm. To reduce stress, one can increase the diaphragm thickness. In conclusion circular typed diaphragms are more preferred than the other two shapes, namely square and rectangular diaphragms.

From another view when we added holes in diaphragms, significant differences have been observed. The piezoresistive MEMS with circular diaphragms and rectangular holes had more sensitivity compared to other situations.

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