Influence of Shape Design of MEMS (Micro-Cantilever Based Sensor) on High-Sensitivity

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ABSTRACT

In this paper, a novel analysis was carried out on the biosensor micro-cantilevers in order to increase the sensitivity of a micro- cantilever based biosensor piezoresistive. Holes were made and compared with the basic rectangular (R), triangular (T), and step(S) profile cantilever. Effect of changing the micro-cantilevers profile and its cross-section shape was investigated. A finite element ANSYS was used to analyze these models. The micro-cantilevers are made of silicon with elastic modulus 130Gpa and poisson’s ratio 0.28. Several cases were studied by making one, two and three holes in each biosensor piezoresistive micro-cantilevers (rectangular (R), triangular (T), and step(S) profile cantilever). Results showed that triangular micro-cantilever with two holes (T22) has the better sensitivity, also showed T12 respectively 61.7% and 65% higher sensitivity than R12, S12.

Keywords: Micro-cantilevers, Sensitivity, Biosensors, Piezresistive.

تاثير تصميم شكل المستشعر الكابولي الادق على زيادة التحسس

الخلاصة

فى هذا البحث تم اجراء تحليل مبتكر على (**Micro-Cantilever based sensor**) لغرض زيادة التحسس من خلال عمل ثقوب دائريه فى عتبات المستشعر التي هى بمقطع مستطيل مثلث ومتدرج. لغرض اجراء المقارنه بينهما من خلال دراسة تاثير تغير مقطع شكل العتبه على اداء المستشعر .و تم استخدام مادة السليكون والذي له معامل المرونة 130 Gpa و نسبة بويسن 0.28 لتصنيع المتحسسات ولغرض تحليل هذه النماذج تم استخدام طريقة ANSYS. تم دراسة عدة حالات من خلال وجود ثقب واحده او ثقبان او ثلاثة ثقوب فى كل من المقاطع الثلاثه مثلث، مستطيل ومتدرج. اظهرت نتائج الدراسه بان العتبه (المستشعر) ذات المقطع المثلث(T22)مع وجود ثقبان هى الاكثر تحسس للاجهادات واظهرت ايضا بان(T12) اكثر بالتتابع من R12 ، S12 بنسبة %61.7 و %65 هى الاكثر تحسس للاجهادات.

Symbols

R10,R20	Rectangular basic and modified profile micro-cantilever model without holes respectively.
R11,R21	Rectangular basic and modified profile micro-cantilever model with one hole.
R12,R22	Rectangular basic and modified profile micro-cantilever model with two holes,

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R13,R23	Rectangular basic and modified profile micro-cantilever model with three holes,
T10,T20	Triangular basic and modified profile micro-cantilever model without holes.
T11,T21	Triangular basic and modified profile micro-cantilever model with one hole.
T12,T22	Triangular basic and modified profile micro-cantilever model with two holes.
T13,T23	Triangular basic and modified profile micro-cantilever model with three holes.
S10,S20	Step basic and modified profile micro-cantilever model without holes.
S11,S21	Step basic and modified profile micro-cantilever model with one holes.
S12,S22	Step basic and modified profile micro-cantilever model with two holes.
S13,S23	Step basic and modified profile micro-cantilever model with three Holes.

INTRODUCTION

In many applications the micro-cantilevers are highly used special in physical, biological, and chemical portions by transducing changes in temperature, mass, electromagnetic field or surface stress on the micro-cantilever[1]. The marriage of micromachining technology and traditional biosensing technologies provides a new generation of biosensors with advantages of miniaturized and high sensitivity. In the recent years many efforts were devoted to develop various biosensors depend on micromachining technologies [2].

The fabrication of the micro-cantilever biosensors are simple, and the mechanical displacement of the cantilevers requires complicated optical or electronic approaches. The microcantilever biosensors which are working in the environmental liquid requires more investigations.

One of the simplest MEMS transducer micro-cantilever are the clamped suspended (cantilevers). Firstly used as atomic force microscope AFM probes and then Cantilever– based, sensor have been proved to be quite versatile and sensitive devices and have been used mainly in the trace detection of bio-chemical materials as detectors of surface stresses and resonance frequency [1-5] .The important parameter of the microcantilever is the geometry of the device.

S.Sukuabol et al.,2005 are executing using liquid specimens and completed sensors work better in the liquid environmental, knowing that the silicon are used as a cantilever material because this material is itself water proof and therefore eliminates the need for an encapsulating layer required for silicon based cantilever sensors. It was concluded that the best shaped cantilevers were T shape [6].

Xiaomei Yu et al., 2005 studied a design of silicon – based biosensor with Piezoresistor layer cantilever is realized by boron ion implantation with the estimated depth of 0.2 um and with 6 rectangular holes are opened on looped the piezoresistor legs, the stresses are concentrated around the holes, which is 1.5 times higher than that of rectangular cantilevers under the same design and simulation parameters . Measurement results on the cantilever displacement sensitivities show a 1.3 times increase [7].

Muhammad A. Bhatti et al., 2007 studied a paddle type cantilever with different number of rectangular holes modeled from silicon is used. The placement of the holes was found to be critical and results in improvements of piezovesistive displacement and force sensitivity, the stresses around the holes are higher with 1.55 times than that of rectangular cantilevers under similar design [8].

Fabian T.Goericke and William P.King, 2008 studied the location for the piezoresistive area and suggested to be at the center of clamped base, where the elevated stress difference levels extend the Farthest along the cantilever length dimension and it targeted at designing the piezoresistive cantilevers for both atomic force microscope (AFM) applications and also for the applications of the biochemical sensing ,the sensor areas designed with boron doped silicon (P-type) and cantilever width is an important parameter in this sensor [9].

Rosminazuim Ab. Rahim, et al.,2008 studied a comparison of polySi and SiO_2-based piezoresistive microcantilever incorporated with stress concentration region(SCR) they concluded that the rectangular shaped and minimum thickness more suitable to be used as a highly sensitive cantilever sensor [10].

Mohd. Zahid Ansari, et al.,2009 studied the analyses and compares the deflection and vibration characteristics of rectangular and trapezoidal profile microcantilever. Results show that the paddled trapezoidal profile have better sensitivity [11].

Mohd. Zahid Ansari, and Chongdu Cho, 2009 studied the deflection, Frequency and stress characteristics of Rectangular, triangular and step profile microcantilever for Biosensors separately and together, finite element code ANSYS is used, with 0.05N/m stress applied to the top surface of cantilevers and with silicon material. Results show the triangular and step cantilevers have been better deflection and frequency characteristics than rectangular ones [12].

This paper investigated the vibration analysis for calculating the sensistivity values of rectangular, triangular, and step profile microcantilever with and without holes near their free end in basic and modified shapes. The stress concentration regions are achieved by introducing structural holes into the piezoresistive cantilever structures, which make discontinuities in the cantilever. These discontinuities increase the stress difference in the longitudinal and transverse detections that in turn increase the sensitivity of the cantilevers. The surface stress in microcatilevers was modeled by applying tensile force at the top free edge of the cantilever a commercial finite element method (FEM) software ANSYS is used .

SENSITIVITY MODELS OF MICRO-CANTILEVER

Finite element method is used for the modeling to consider mechanical deformation in different shape of the silicon cantilever cross section with and without holes as shown in Figure (1). The piezoresistor region is 50µm, of thickness 0.3µm, and located flush with the cantilever base, these dimensions are typical for cantilever sensor applications [13].

Figure (1) presented all models of micro-cantilevers which are analyzed in this study, in addition to the models with holes (1,or 2,or 3) holes near their free ends, circular holes of size 25µm radius in the middle of their widths, with100µm part from the free ends and between each holes if there are more than one holes.

The relative resistance change (ΔR/R) of a piezoresistive cantilever (sensitivity) due to the cantilever deflection is described by the following expression [14].

$$\frac{\Delta R}{R} = \beta \frac{3\pi_{L(l-v)}}{t}(\sigma_1 - \sigma_2) \quad (1)$$

Where $\pi_L$is the piezoresistive confficient of silicon along the <110> axis, σ_1 and $\sigma_2$and the longitudinal stress and transverse stress receptively, t is the cantilever thickness,ν is the Poissons ratio, and $\beta(0\ to\ 1)$ is a factor that adjust for the thickness of the piezoresistor [10]. The displacement sensitivity of piezoresistive cantilever is then defined as

$$\frac{\Delta R}{R}/D\Pi = \frac{(\sigma_1 - \sigma_2)}{D} \quad (2)$$

Where $\Pi = \beta \frac{3\pi_{L(l-v)}}{t}$ is the piezoresistive coefficient, D is the vertical displacement of the cantilever. From Eq.(1) and Eq.(2) it can be seen that apart from the geometry and the material characteristics, the displacement sensitivity of the piezoresistive cantilever is proportional to the different stress$(\sigma_1 - \sigma_2)$ therefore the deflection signal can be increased by maximizing the different stress [15].

The applying tensile force of 5×10^{-6} N at the top free edge of all type models. The simulation assumed the cantilevers are made of silicon and have elastic modulus of 130Gpa and a poissons ratio of 0.28, respectively. In simulations, mesh size convergence test was performed to eliminate any mesh size effect on the analysis. The FEM models were meshed by (solid 95) and (solid226) to the peizoresistive elements as in Figure (2).

RESULTS AND DISCUSSION

Figures (3,4,5 and 6) show the equivalent stresses distribution in all the micro-cantilever models, in this study the maximum stress and the maximum deflection are indicated in the top left corner of the photos. The cantilever size and deflection which are expressed in micrometers ,and stress are in (Mpa). The maximum induced stresses range from a minimum of (2.75Mpa) for model (S10) to a maximum of (35.77Mpa) for model (T20). Stresses are comparison between models (R1,R2),(T1,T2) and (S1,S2) show that the values of the stresses and the deflections for modified profile cantilever model (R2,T2,S2) are higher than that of basic profile cantilever model(R1,T1,S1)for all models with or without holes.

This behavior is expected because the changes in the cantilever profile or shape will lead to a change in the area. Also the stress distribution of basic design cantilever as example in model R1 change from 2.45 to 5.94 (Mpa) and for modified model R2 change from 35.77 to 34.95 (Mpa).The sharp corners and holes in model can raise the stress concentration factors which increasing their deflection and frequency characteristics of the cantilevers which then increased the sensitivity of microcantilever biosensor, also the stiffness of cantilever made an important role in the sensitivity in which its increased with increasing the stiffness due to increasing the resonance i.e. the resonant frequency increases as a function of increasing stiffness and decreasing mass of the cantilever and the stiffness decreasing with increasing holes in the cantilever.

Tables (1, 2 and 3) show the maximum stress distribution and the sensitivity of all micro-cantilever models. However in these models T10 the sensitivity of 2.14 and it increased to 7.43 for T12. Also it is shown that models T1 and T2 have the highest values of the stress and the sensitivity than that of models R1, R2 and S1, S2. To select the best cantilever model, it can be chosen one that has the highest sensitivity value.

From tables (1, 2 and 3) it is obvious that the design sensitivity of micro-cantilever can be improved by simply changing the micro-cantilever profile design. For instance, comparing the sensitivity indicated by T12 with R12 and S12, the sensitivities are increased by 61.7 % and 65% respectively. Further noted in tables when comparing the sensitivity indicated by T22 with R22 and S22 the sensitivity increased by 87.06% and 57.40% respectively. Fig.(7) shows the different equivalent stress distributions along the longitudinal axes next to the holes for the cantilevers and compared it with an ordinary one which shown T13, T23 have the highest stressed.

Figure (8) shows the simulation results of sensitivity of the micro-cantilever for all models, it can be concluded that the design sensitivity of the micro-cantilever used in biosensors can be improved by changing the cantilever profile and/or shape to triangular or step designs.

Figure (9) shows the simulation results for the micro- cantilever designs analyzed in this study, it can be improved the design sensitivity of the cantilevers used in biosensor by replacing the rectangular profile cantilever by a triangular or step profile cantilever (1 without hole,2 with one hole, 3 with two holes and 4 with three holes).

The different stress distribution of longitudinal and transverse along the longitudinal axes next to the holes for cantilevers are shown in Fig.(10). In order to make the comparisons, the stress distributions of an ordinary basic rectangular cantilever with the same dimension and modeling parameters are also plotted in Figure (9) at the same time.

Obviously, the stress can be localized near every region by adding hole. Three "peaks" are observed for the micro-cantilever with three rows of holes. The stresses near the holes increase or decrease sharply as moved away from the holes position. Between every two adjacent peaks, minimum stress regions are observed, which are almost in the same shape stress as that of the rectangular cantilever. The simulated stress near the hole regions are about 2 times higher than that of the rectangular cantilever at the same distance position.

Its shown that the sensitivity of a micro- cantilever base biosensor, piezoresistive cantilevers with stress concentration holes were designed by ANSYS, and this design can obviously result in an improvement on the sensitivity of the micro- cantilever. Fig.(10) illustrates the comparison between the published results [12] with obtain results for the step basic profile micro - cantilever model without holes, and its found that the average of discrepancy was 7.4%.

CONCLUSIONS

Many of the biosensors are used in the clinical applications. Many of them have already been used in the detection of diseases. In this paper the investigation improving the overall sensitivity of the micro-cantilevers that can be used in biosensors by increasing their deflection characteristics of the cantilevers. To improve it the studying of basic and modified design rectangular (R), triangular (T) and step (S) profile cantilevers are done. This work has described of silicon based piezoresistive cantilever. Holes are opened on part regions of the cantilevers.

ANSYS was used to complete work. The stresses are concentrated around the holes, and the model which have the highest value of stresses and sensitivity is T22**,** alsoT1,T2 and S1,S2 have respectively 40% and 20% less mass than R1,R2 and show T12 respectively 617% and 65% higher sensitivity than R12,S12

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Table (1) Comparison between normalized values of maximum induced stress and sensitivity for rectangular basic model design R1 and modified model. design R2.

Model	σ max (MPa)	$\frac{\Delta R}{R}$
R10	3.1	0.9
R20	33.95	2.76
R11	4.36	1.32
R21	33.94	2.8
R12	4.19	1.26
R22	33.69	2.69
R13	4.22	1.23
R23	33.995	2.8

Table (2)Comparison between normalized values of maximum induced stress and sensitivity for triangle basic model design T1 and modified model design. T2.

Model	σmax (MPa)	$\frac{\Delta R}{R}$
T10	2.96	2.14
T20	35.77	20.7
T11	5.85	6.78
T21	34.89	20.64
T12	5.91	7.43
T22	35.58	20.87
T13	5.94	6.96
T23	34.96	20.37

Table (3) Comparison between normalized values of maximum induced stress and sensitivity for step basic model design S1 and modified model design S2.

Model	σmax (MPa)	$\frac{\Delta R}{R}$
S10	2.76	1.13
S20	30.99	8.8
S11	4.63	2.01
S21	31.5	8.98
S12	4.2	1.91
S22	31.3	8.89
S13	4.3	1.92
S23	31.12	8.784

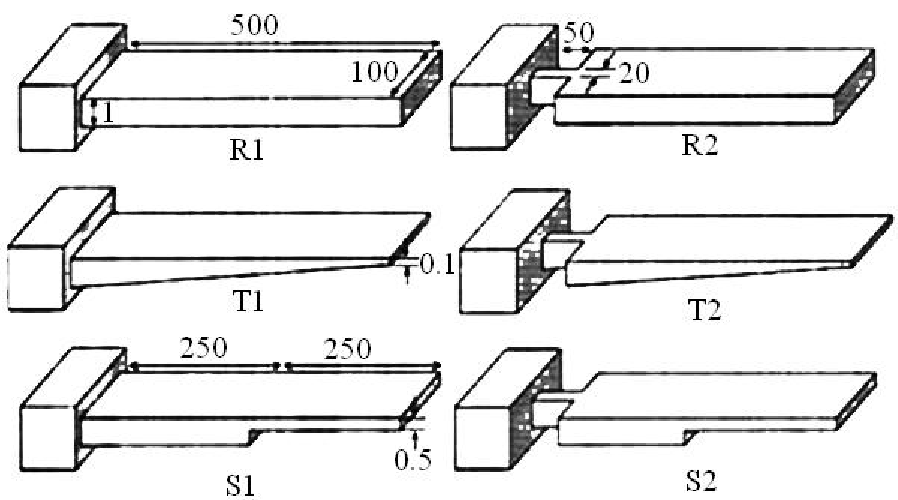


Figure (1) The schematic designs for the rectangular(R), triangular (T), and step(S) profile cantilevers. All models have equal length, width, and fixed-end thickness. (All dimensions in micro meter).

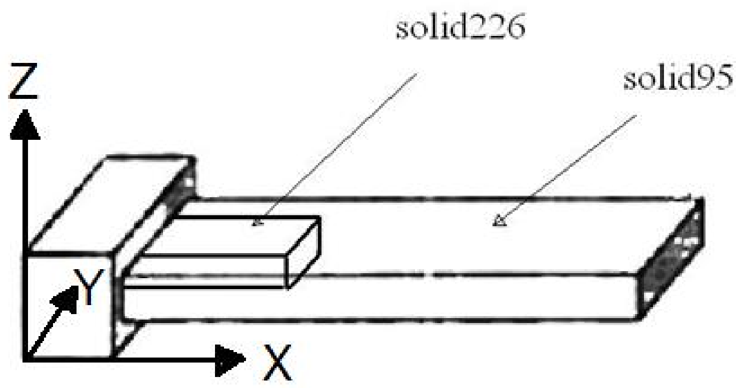
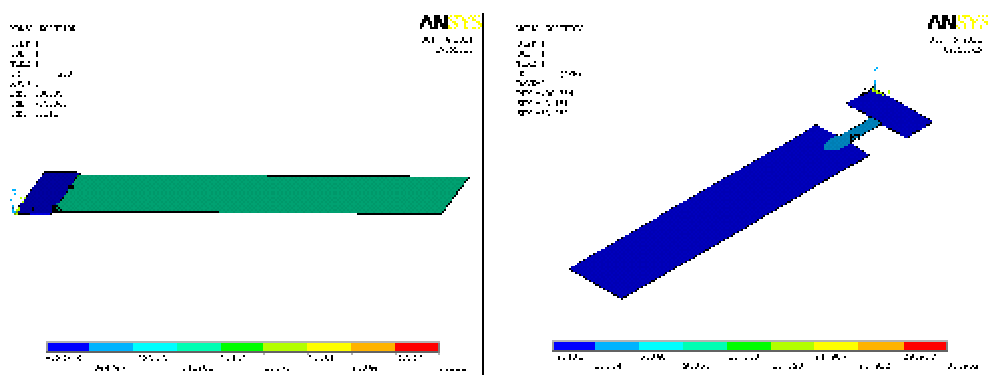
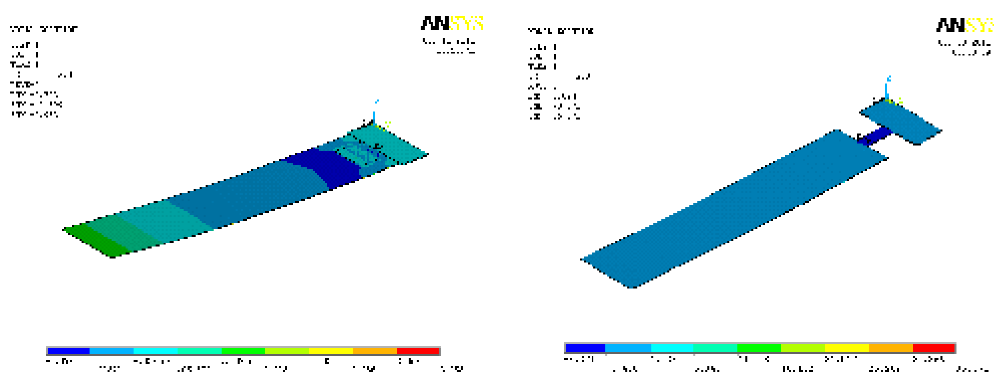


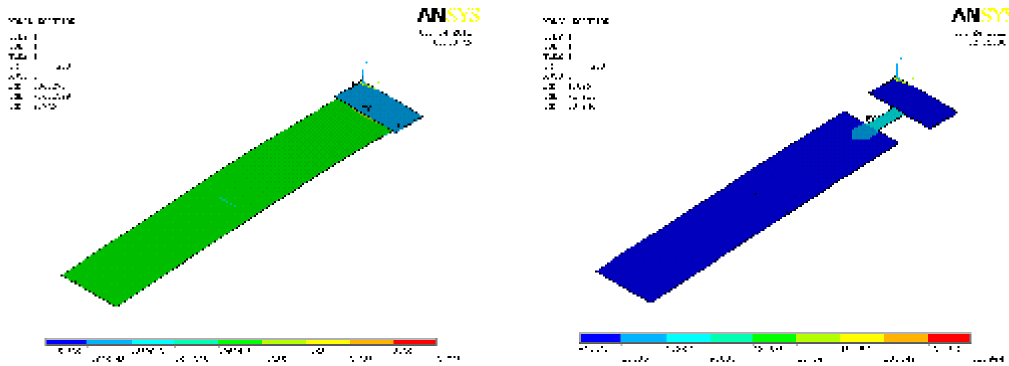
Figure (2) The element's model used in the analysis.



Rectangular(R)

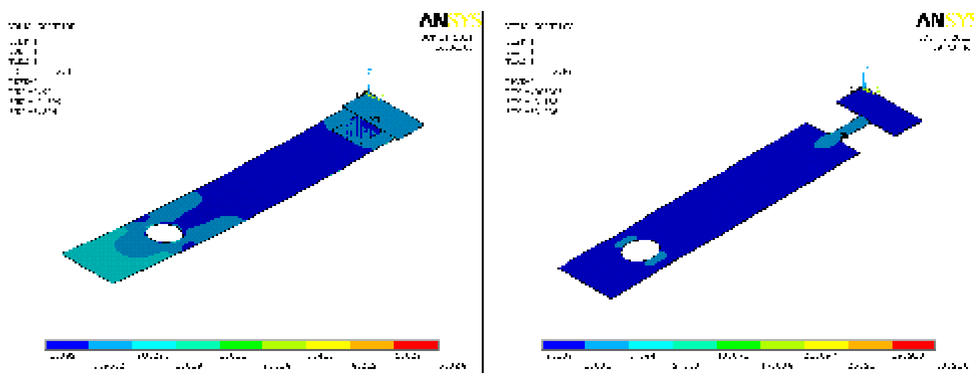


Triangular (T)

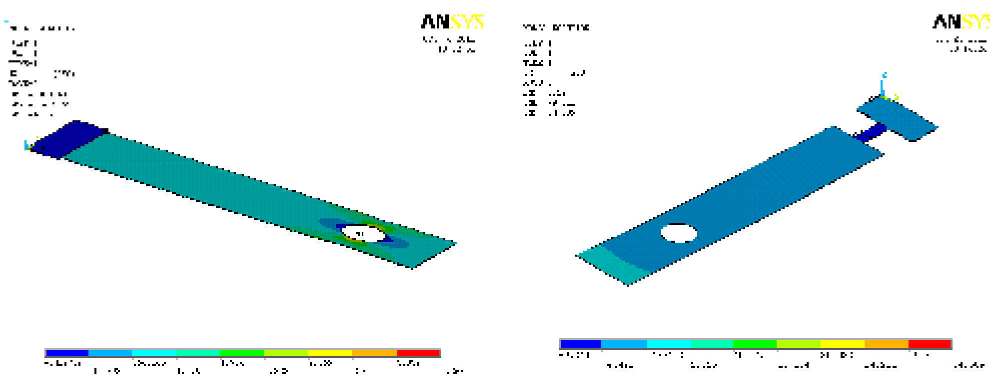


Step (S)

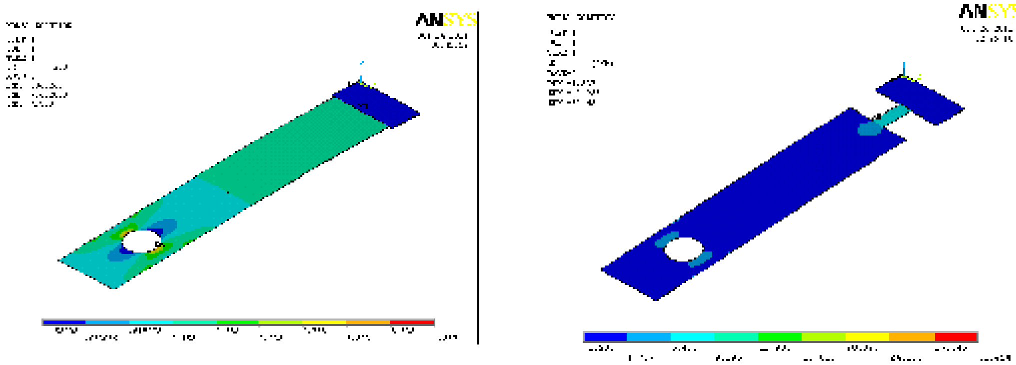
Figure (3) Equivalent stress distribution in the micro-cantilever models, R10,R20;T10,T20;S10,S20.



Triangular

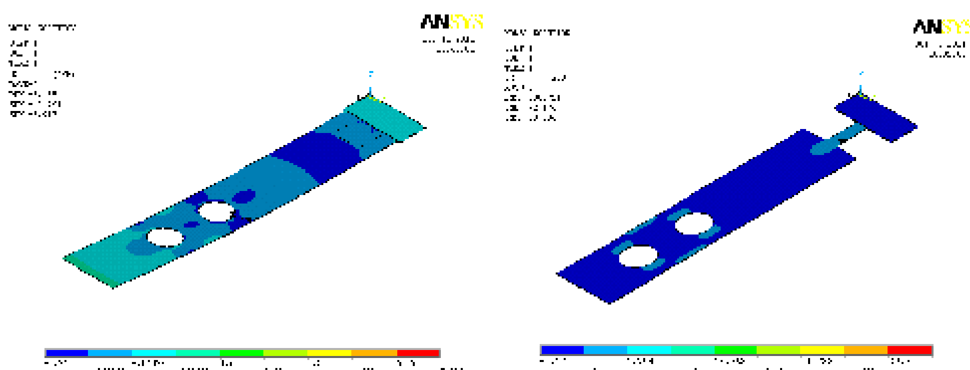


Rectangular

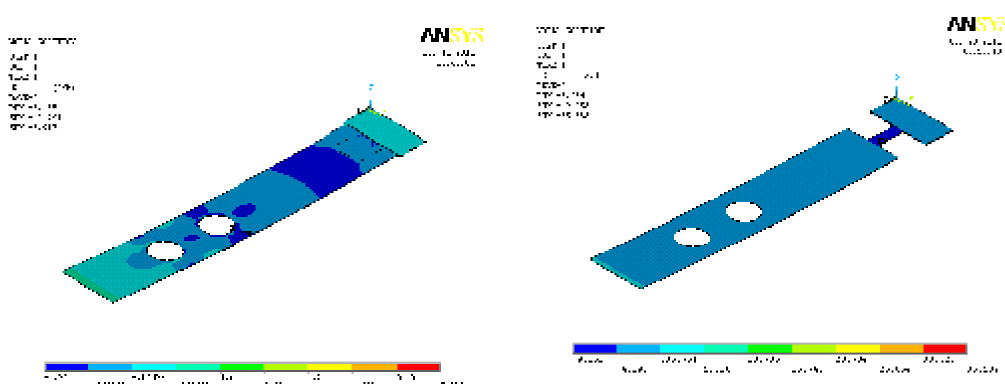


Step

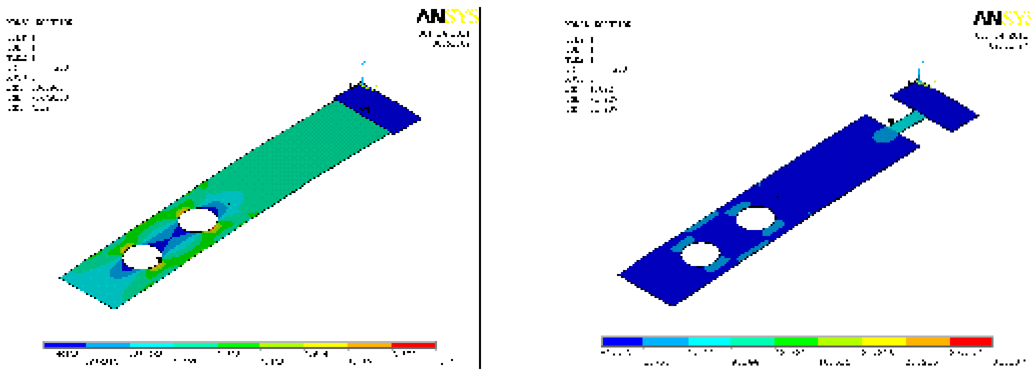
Figure (4) Equivalent stress distribution in the micro-cantilever models R11,R21;T11,T21;S11,S21.



Rectangular

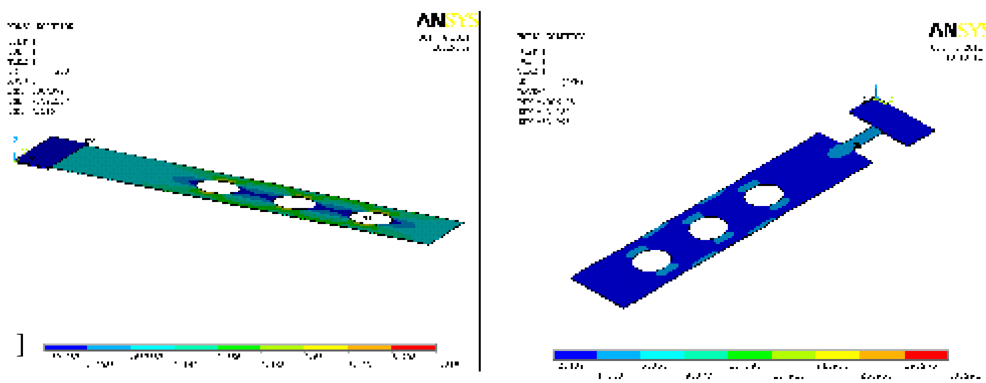


Triangular

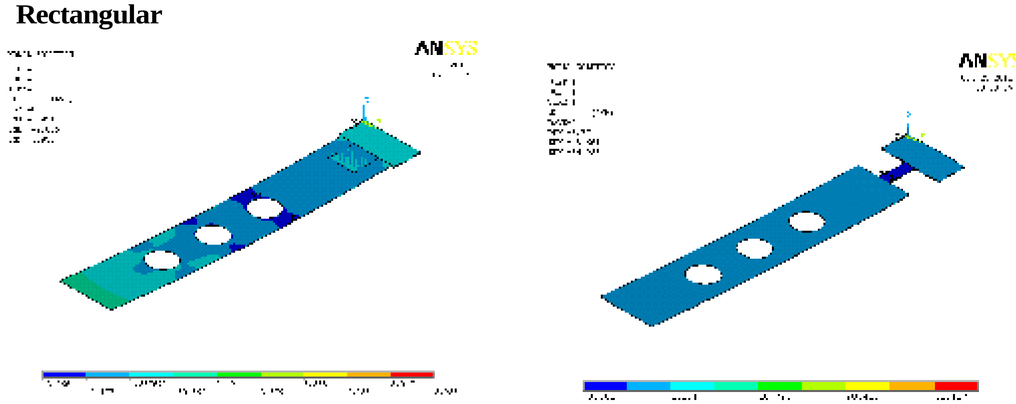


Step

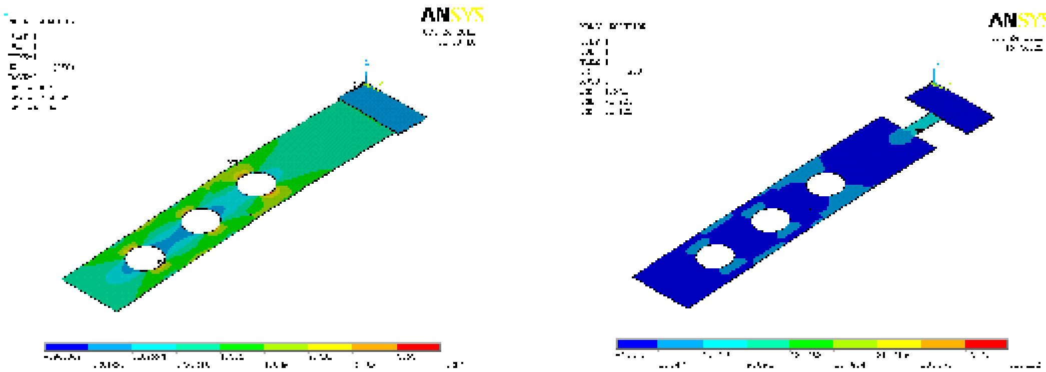
Figure (5) Equivalent stress distribution in the micro-cantilever models R12,R22;T12,T22;S12,S22.



Rectangular



Triangular



Step

Figure (6) Equivalent stress distribution in the micro-cantilever models R13,R23;T13,T23;S13,S23.

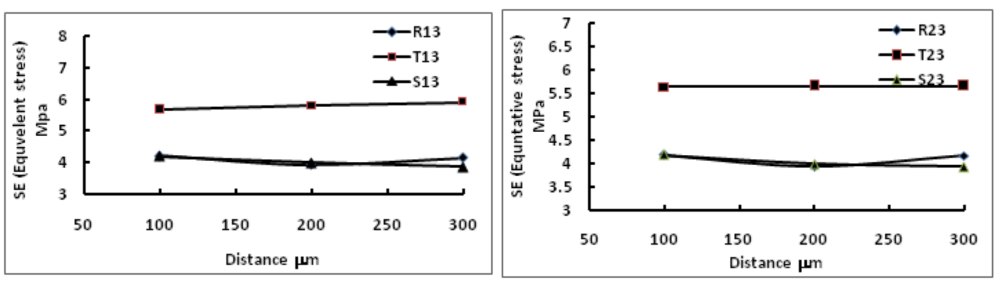


Figure (7) The different stress distributions of longitudinal and transverse along the longitudinal axes next to the holes for all models with three holes.

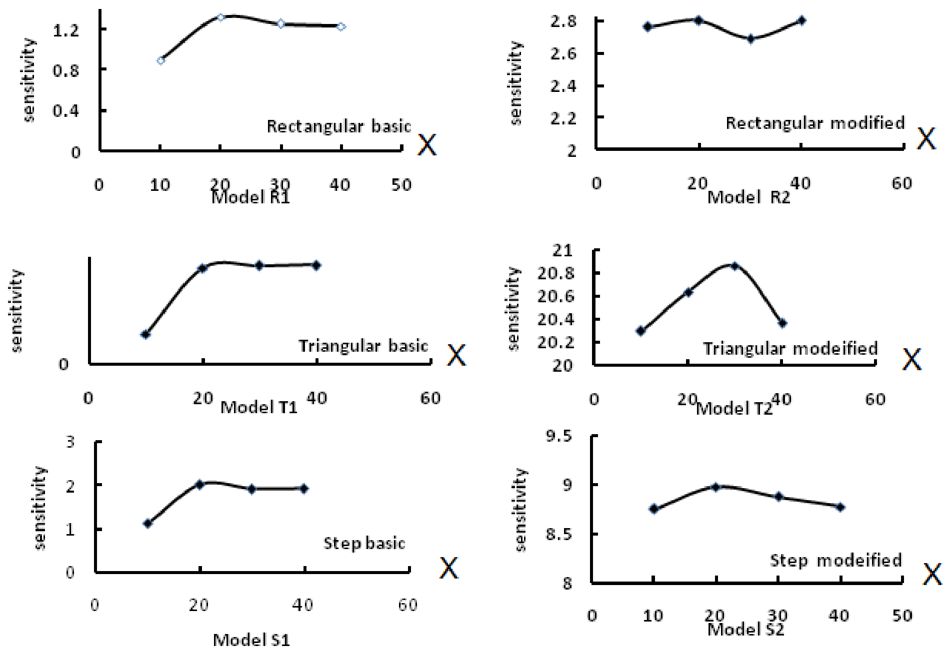
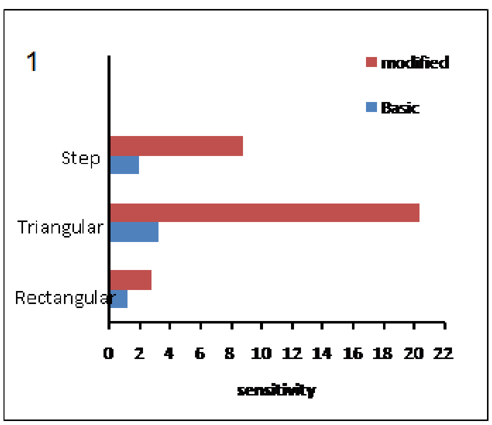
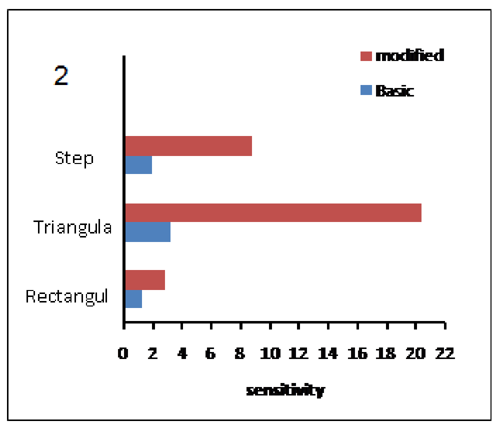


Figure (8) The results of sensitivity of the micro-cantilever for all cases (R1, R2), (T1, T2) and (S1, S2).





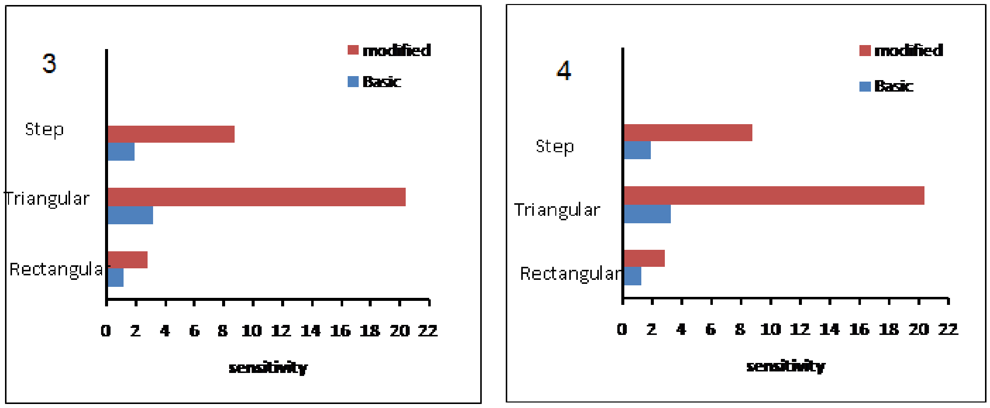


Figure (9) Results showing the sensitivity values for the basic and modified design rectangular, triangular and step profile cantilevers(1-without hole,2-with one hole,3-with two holes and 4-with three holes).

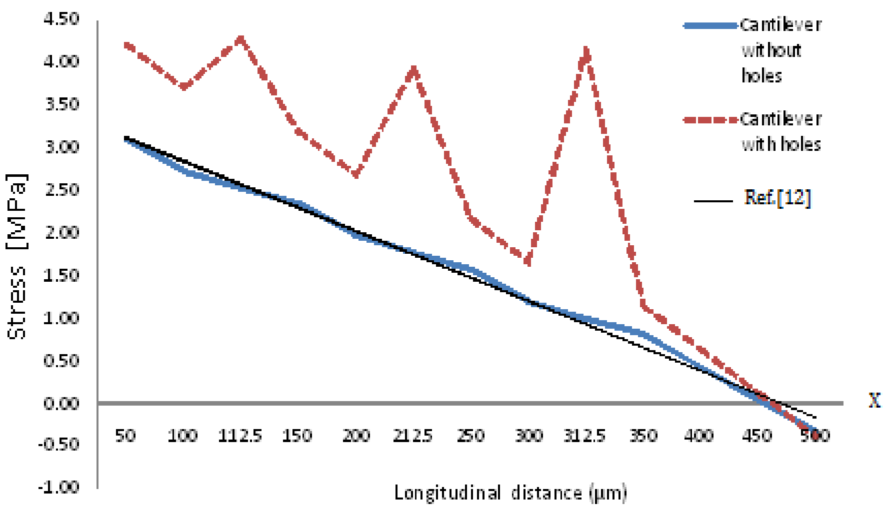


Figure (10) Equivalent stress distribution of micro-cantilevers along the longitudinal axis.