Influence of Structural Parameters on Stress/Strain Amplification Property of Biomimetics Membrane-In-Recess Si Microstructure

Dedy H. B. Wicaksono, Nawale Gharbage, Lu-Jun Zhang, Yue Chen, and Patrick J. French

***Abstract*—Strain sensor used in new applications, e.g. implant medical instrumentation, smart structures, etc., should have a high sensitivity (i.e. high gauge factor) and be integrated within the structure, that it can detect the slightest stress implied on the surface of a structure. A biomimetic membrane-in-recess microstructure inspired from natural strain sensor, i.e. the *Campaniform Sensillum* of insects is a potential stress/strain amplifier to be utilised in such strain sensor. Furthermore, an implementation of such microstructure, using Semiconductor MEMS technology is applicable. This paper reports our investigation on further optimising the microstucture in order to get the highest possible stress/strain information amplification. The structural parameters being varied in our investigation are: *D*: diameter of the hole-opening; *t*: thickness of the membrane; h_1: the recess from the surface; The figures of merit to be compared are the maximum von-Misses stress, the maximum strain energy density the z-displacement of the central point of the structures, as well as the in-plane strain (ε_{xx} and ε_{yy}). The relative stress/strain amplification is obtained by dividing these entities at each structural variation to the bulk chunck structure [i.e. when D=0, t=h_1=0, h_2=h]. The structure is modeled and simulated as being attached to another structure (e.g. plate, see figure 3) where the load is applied onto. This model is to resemble the actual experimental setup. Numerical simulation and analysis was then carried out. Different kinds of loading were applied: a) concentrated load with the clamped plate, b) 3-point bending load, c) axial push and pull load. Numerical simulation results show that a membrane-in-recess microstructure with D = 1000 μm, t = 500 nm, and h_1 = 13 μm, can amplify the stress with 3.21 factor. Further the structure has an inherent directional sensitivity, implying that transducer for sensor application should be put in the correct direction to sense stress coming from certain direction with high sensitivity. The highest amplification occures at θ=90° (i.e. perpendicular) to the incoming bending moment or stress.**

***Index Terms*—Biomimetics, Stress/Strain sensor, Stress/Strain Amplification, Silicon Microstructure, Numerical modeling**

I. INTRODUCTION

Nature has long been a source of inspiration for the engineering world [1]. In the world of sensor engineering, more natural sensors are being studied as inspirations for building better perfomance sensors for highly-demanding applications [2]. Among those natural sensors is the *Campaniform sensillum*, one of the various mechanoreceptors found in insects [3]. Campaniform sensillum is a strain-sensing organ used by insect for its proprioception, i.e. to coordinate and sense the movement of its limbs [4-6]. Despite its small size (diameter ~10μm) and exocuticle's material stiffness (~10^9 Pa), campaniform sensillum is very sensitive towards tiny displacement [7]. A cross-section illustration of campaniform sensillum is shown in figure 1.

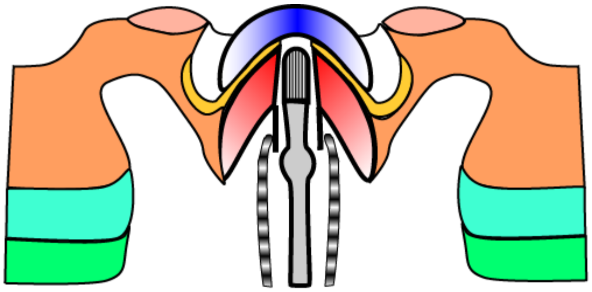

Figure 1. Cross-section illustration of Campaniform sensillum

The high sensitivity of campaniform sensillum could be attributed to its unique structure of a membrane with a dome-shaped cap located inside a surrounding blind-hole structure with collar ring. The blind-hole structure concentrates stress, as conventionally understood from mechanics [8]. In campaniform sensillum this concentrated stress is transduced into lateral deformation of the collar and membrane, as well as vertical indentation of the cap, squeezing the neurotubules of the neuron cell located in the middle [9]. The cap transduces

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and amplifies the concentrated strain/stress from surrounding exocuticle, through collar and membrane deformation.

Our initial biomimetics strain-sensing structure tries to utilise this stress-concentrating mechanical property of the blind-hole/notch structural feature from campaniform sensillum, to amplify stress and strain, thus gaining higher strain-sensing performance, with the final goal of realising a novel high-performance MEMS strain sensor.

This paper reports the continuation of our effort to analytically [10] and numerically [11] model and simulate our biomimetics strain-sensing microstructure and its experimental setup as described elsewhere [12]. The aim of this modeling and simulation are firstly to understand and confirm the true underlying mechanism of the strain amplification in campaniform sensillum, and secondly to further optimise the artificial Si-based biomimetics membrane-in-recess structure inspired from it, for future stress/strain sensor application as previously mentioned.

II. METHODS

A. *Structure Design*

The design of the biomimetic membrane-in-recess structure inspired from the structure of the Campaniform sensillum, is illustrated in figure 2 [11].

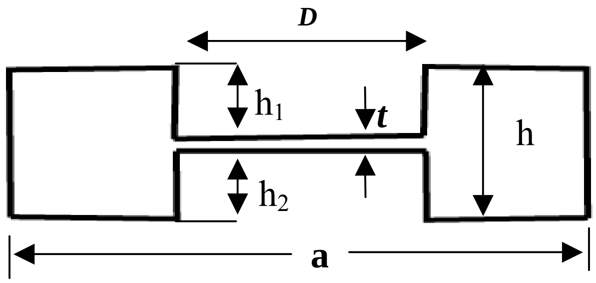

Figure 2. Biomimetics Membrane-in-recess Structure

The structural parameters being investigated in our design are *D*: the diameter of the circular hole opening, *t*: the thickness of the membrane, *h*: the thickness of the whole wafer [constant at 525 µm], h_1: the recess from surface, and $h_2 = h-h_1-t$, respectively. While *a* is the size of the structure chip, which is 3 mm. The biomimetics membrane-in-recess structure utilises the stress-concentrating property of blind-hole structural feature, and the mechanical movement transducing property of the membrane structural feature. Both structural features are observed in the campaniform sensillum natural strain sensor of insect [*cf.* 3,13]. The modeling and simulation carried out in this report, will hopefully provide more insights into what actually influence the strain-stimuli transduction to further optimise the structure for strain-sensor application.

B. *Experimental Setup Design*

The modeling and simulation was performed according to the actual experimental setup, as illustrated in figure 3 [12].

The designed biomimetics strain-sensing microstructure (shown in figure 2) is attached to a larger plate structure. Here, both the numerical simulation, and the experimental are carried out while keeping in mind that the end goal is to utilise the structure as a strain-sensing device attached to a larger structure whose strain is to be measured. Three kinds of investigations were carried out, as explained in the next three subsections. In all of these investigations, numerical simulation and calculation were perfomed using the assumption that both the biomimetics structure and the plate was built using homogeneous linear isotropic Silicon material with Young Modulus of ~130GPa. The main figure of merit to be compared in our modelling is the von Misses stress distribution on the surface of each structure, especially where the hole or the membrane is located in the structure chip. Other figure of merits that were used include the strain energy density, displacement, and strain at particular direction, as needed in particular cases. Numerical Modelling and simulation were performed using a finite element software.

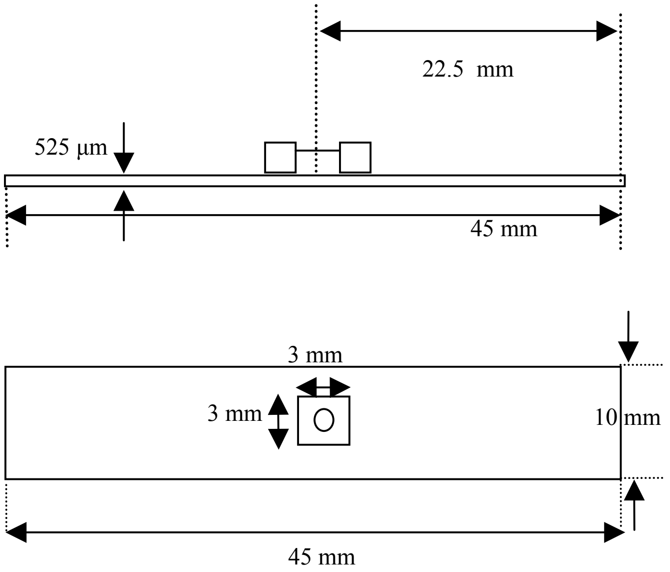

Figure 3. Experimental setup as the basis for numerical model

C. *Structural Parameters Influence under Concentrated Displacement Loading*

The first performed investigation used a concentrated point displacement with clamped-clamped boundary condition for the plate. The point displacement is 50 µm displacement (comparable to ~1.664 N force load, see appendix I) from behind the plate, at its center, as shown in figure 4. To optimize the structure, i.e. to know how the combinations of varied structural parameters could give the best strain/stress amplification, we vary the *D*, h_1, and *t*. Various kinds of strain-sensing structures, thus, were investigated: Bulk chunk,

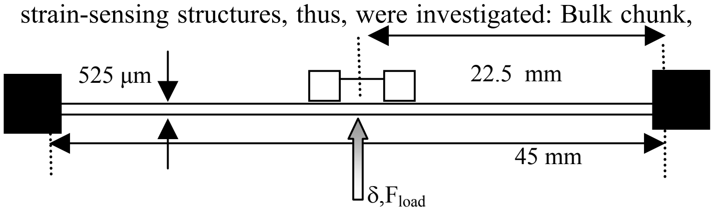

Figure 4. Loading and boundary condition for 1st investigation

Through-Hole, Blind-Hole, Membrane-on-Surface (MoS), and the biomimetics Membrane-in-Recess (MiR) structures. The parameter variations for these different bio-inspired structures are shown in table 1.

TABLE 1. PARAMETER VARIATIONS IN DIFFERENT STRUCTURE MODELS

Structure Name	h (in µm)	h_1 (in µm)	t (in µm)	D (in µm)
Plate only	0	0	0	0
Bulk chunk	525	0	0	0
Through-Hole	525	525	0	1000
Blind-hole	525	13	512	1000
Membrane on Surface	525	0	50	1000
Membrane in Recess-1	525	175	50	1000
Membrane in Recess-2	525	83	50	1000
Membrane in Recess-3	525	50	50	1000
Membrane in Recess-4	525	50	50	500
Membrane in Recess-5	525	13	0.5	1000

D. *Three-Point Bending Load*

A second type numerical simulation was further carried out to compare the perfomance of biomimetics Membrane-in-Recess (MiR) structure with biomimetics Membrane-on-Surface (MoS) structure for lateral stress/strain sensing. In this modelling and simulation, the thickness of the membrane is set to be 10 µm, and the diameter is 500 µm. The MiR structure's membrane is recessed 13 µm from the surface. Then a 3-point bending force load was applied from behind, as illustrated in figure 5. The values of the load are 4N (tensile) and -4N, (compressive). The two ends of the plate are simply–supported.

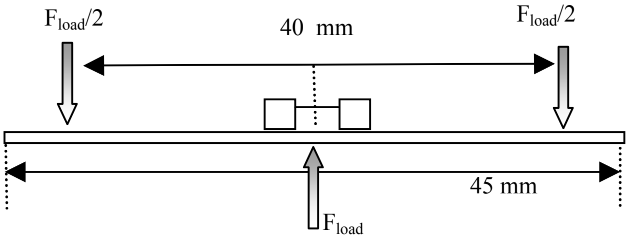

Figure 5. Three-Point Bending load and boundary condition for 2nd investigation

E. *Axial Push-Pull Load*

Finally, an investigation was also carried out using axial loading applied at both end of the plate (figure 6). Currently, the force applied (within the simulation) was quite small. A normal stress σ_{xx} of ±5000 Nm^{-2} (both tensile and compressive) were applied. Considering the cross section area of the plate which is equal to wh = 5.25 x $10e^{-6}$ m^2, thus the force applied at each end is calculated using equation

$$F_x = \sigma_{xx} \times A = \sigma_{xx} \times wh \tag{1}$$

whose result is F_x = 0.02625 N.

In axial load case, only MiR structure with structural parameters as described in the previous section, was being investigated.

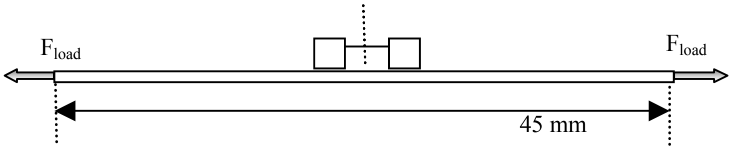

Figure 6. Loading and Boundary condition for 3rd investigation

III. RESULTS AND DISCUSSION

A. *Influence of Structural Parameters to Stress Amplification under Point Displacement Bending Load*

The first numerical simulation was performed with point displacement load of +50 µm, while the two ends of the plate (fig. 3) are clamped. Thus, a bending tensile stress occurs on the surface of the plate.

The calculated von-Misses stress distribution of through-

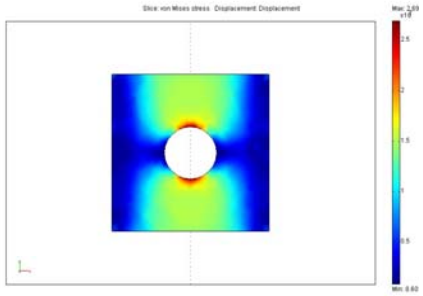

Figure 7. Von-Misses Stress distribution response in Through-Hole structure.

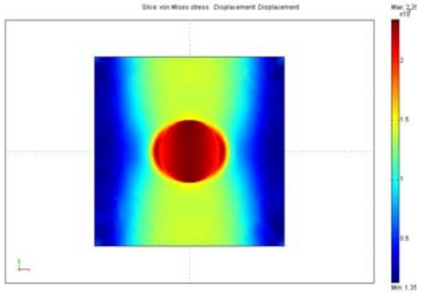

Figure 8. Von-Misses Stress distribution response in MoS structure.

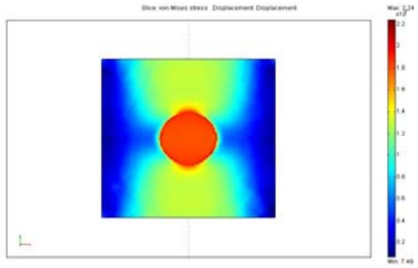

Figure 9. Von-Misses Stress distribution response in MiR3 structure.

hole, MoS, and biomimetic MiR3 structures are shown in figure 7, figure 8, and figure 9, respectively. The rainbow colors illustrate the value of the von-Misses stress, with blue color showing lower value, and red color showing higher value, respectively.

Figure 7 illustrates the stress- concentrating and amplifying property of a hole structure, as commonly understood in mechanics [8]. The bending moment, and the stress accordingly, change as a function of angle θ, measured from the positive x-axis, if the center of the hole was taken as the center of the coordinates. This variation is modelled analytically by Savin in equation (2) [8]:

$$M\theta = M\left[1 - \frac{2\left(1+\upsilon\right)}{3+\upsilon}\cos 2\theta\right] \qquad (2)$$

Largest value of M_θ is when $\theta = \pm 90°$. The stress concentration coefficient σ_θ for any value of θ will be between 1.667 and 1.857 [8]. The analytically calculated stress concentration on the vicinity of a hole is shown in figure 10.

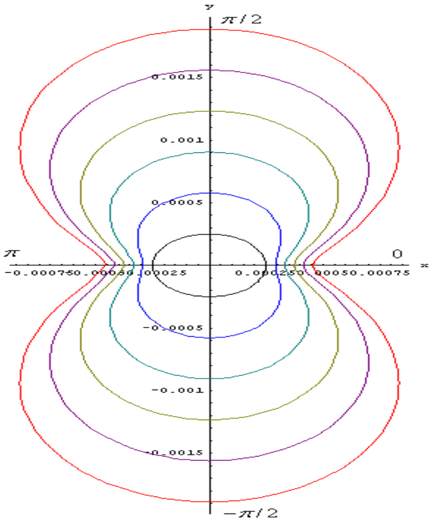

Figure 10. Qualitative Analytical calculation of stress distribution on the vicinity of hole from equation 2

This stress-concentrating property shown in figure 10 is also owned by the Membrane-in-Recess (MiR-3) structure as shown in figure 9. The highest stress value is found in the edge of the membrane at θ = 90°, i.e. at the ±y axis. The Membrane-on-Surface (MoS) structure, although having the highest Von-Misses stress observable among the three structures shown figures 7, 8, and 9, respectively, lacks this stress-directionality sensing.

A comparison of the calculated maximum von-Misses stress observable from the structure-models described in table 1, is shown in table 2. From the table, we see that the biomimetic membrane amplifies the stress/strain implied from the load. This stress-amplifying property of the biomimetics structure can be thought of as a property similarly owned by the through-hole structure, as explained previously. However, the through-hole structure does not interest us for future strain-sensor application since it is difficult to put an electromechanical transducer on/in it. The region where the stress is highly concentrated is also relatively small compared to MoS or MiR structures. Furthermore, the through-hole can become a crack initiator in itself, preventing it for long-term usage as a sensing structure.

TABLE 2. SIMULATION RESULTS EXPLAINED WITH COMPARISON OF MAXIMUM VON-MISSES STRESS

Structure Name	VM stress (ir Pa)	Relative Stress Amplification to Plate Only	Relative Stress Amplification to Chunk
Plate only	2.62×10^7	1	N/A
Bulk chunk	1.338×10^7	0.51	1
Through-Hole	2.693×10^7	1.03	2.01
Blind-hole	1.95×10^7	0.74	1.46
Membrane on Surface	2.354×10^7	0.90	1.76
Membrane in Recess-1	1.598×10^7	0.61	1.19
Membrane in Recess-2	2.313×10^7	0.88	1.73
Membrane in Recess-3	2.247×10^7	0.86	1.68
Membrane in Recess-4	2.863×10^7	1.09	2.14
Membrane in Recess-5	4.293×10^7	1.64	3.21

From the calculated simulation results shown in table 2, by comparing MiR-1, MiR-2, MiR-3 the stress amplification factor in MiR structure will increase as h_1 is lowered, i.e. the membrane approaches the surface. The stress amplification also increases if the diameter of the hole-opening is reduced, as can be compared from MiR-3 and MiR-4 results. Thinning the membrane also will increase the stress amplification factor, as we compare results from MiR-3 and MiR-4, with that of MiR-5. The effect of thinning the membrane also seems to be more influential than decreasing the diameter of the hole opening.

The MoS structure, although also has high stress-amplification, yet, lacks in providing stress-directionality. Thus, MoS structure is good for out-of-plane strain sensing application (e.g. in pressure sensors), yet, disadvantageous for in-plane strain-sensing application.

B. Membrane-in-Recess and Membrane-on-Surface under Bending Load

The result of the second type of loading simulation of MoS and MiR with 10 μm membrane thickness is shown in figure 11-14. Figure 11 shows the von Misses stress of a 4 N tensile-bended MoS structure, while figure 12 shows the response of the MiR structure towards the same loading. Figure 13 and 14 shows the von Misses distribution under 4 N compressive bending, for MoS and MiR structures respectively. The results show that MiR structure is slightly superior than the MoS in amplifying the stress. Both structures amplify the stress to a level of ~ 1×10^8 Pa, from a –4 N 3-point bending force load, comparable to 340 μm displacement of the center of the plate (see Appendix B). The MiR, however, is quite superior than MoS in concentrating the stress to certain direction, i.e. towards θ = 90° from the incoming bending moment. This can be seen from the color distribution, representing the von-Misses stress distribution.

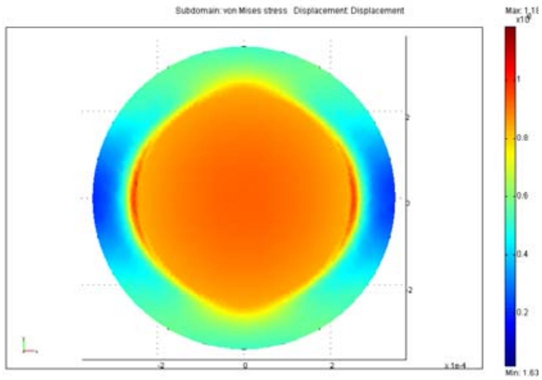

Figure 11. Von-Misses stress of MoS in under 4 N tensile bending load

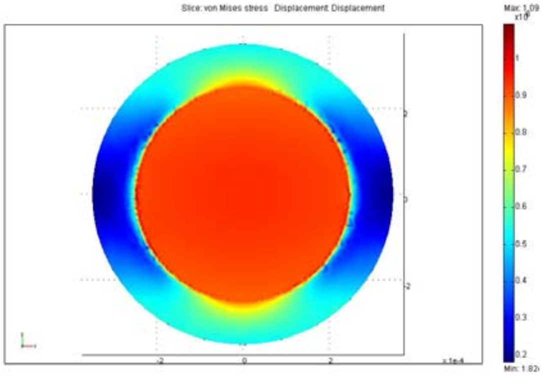

Figure 12. Von-Misses stress of MiR in under 4 N tensile bending load

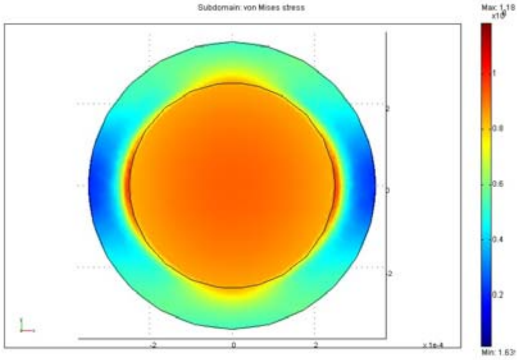

Figure 13. Von-Misses stress of MoS in under 4 N compressive bending load

C. *Membrane-in-Recess under Small Axial Load*

Under small axial tensile and compressive loading of 0.02625 N, the lower structural plate undergo an axial stress of 5000 Pa. The stress is being concentrated by the Membrane-in-Recess structure to ~6000 Pa, an amplification by a factor of 1.2. Both von Misses stress distribution for tensile and compressive load are similar, as shown in figure 15. The small amplification factor might be attributed to the relatively large diameter/chip size (D/a) ratio. If the diameter is small enough compared to the distance from the edge of the hole to the edge of the chip, than a bigger stress amplification might be achieved [14].

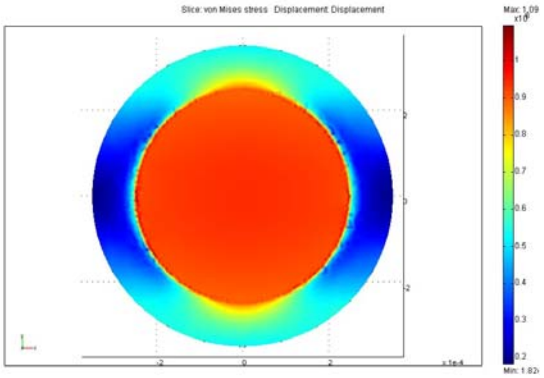

Figure 14. Von-Misses stress of MiR in under 4 N compressive bending load

D. *Stress Concentrated Region and Stress Contrast*

Besides, the stress amplifying property of the biomimetics Membrane-in-Recess structure, i.e. how the structure amplifies nominal stress (σ_{nom}), there is another interesting property that is beneficial for strain/stress sensing application. By looking at figure 9, 12, 14, and 15, we could see how on the membrane and its vicinity a contrast of stress is being collected. The membrane has a uniformly very high stress, as well as the vicinity at an angle $\theta = 90°$ from the incoming stress 'flow' direction; while at $\theta = 0°$ and $\theta = 180°$, we have a large area of minimum stress. By putting the correct piezoresistors at the correct location, direction and orientation, and combining them in a bridge circuitry, this stress concentration property can be utilised as a high sensitive stress/strain sensor.

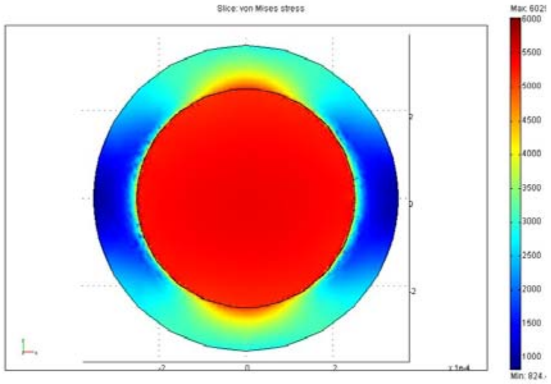

Figure 15. Von-Misses stress distribution of Membrane-in-Recess structure under axial compressive 5000 Pa load. The distribution under tensile load is similar.

IV. CONCLUSION

In this paper, we have reported an on-going research to reveal the underlying mechanism of a highly sensitive natural strain sensor, while at the same time putting the knowledge onto a real world application as a novel strain sensor. The bioinspired/biomimetics membrane-in-recess structure proved to be very potential as a mechanical transducer and amplifier. The structure has a promising possibility to be used in a MEMS-based integrated force/strain sensor. Many works are still need to be carried out, though, to further elucidate other structural properties inherent in the *campaniform sensilla* that make it into a very reliable sensitive and robust strain sensor. The study of such natural sensors will hopefully open the way to build better engineered sensors for future demanding applications.

APPENDIX A

For the doubly clamped plate (Fig.4), a point load, **F**, is applying at the central point of the plate, the maximum deflection which is the deflection at the central point of the plate, δ, can be calculated as follow,

$$\delta = \frac{FL^3}{192EI} \tag{A.1}$$

Thus,

$$F = \frac{192EI\delta}{L^3} \tag{A.2}$$

Where, L means the length of the plate, I means flexural rigidity, which is $wh^3/12$ for this case. w, h is the width and thickness of the plate, respectively. And E is the Young Modulus of the plate.

APPENDIX B

For three-point bended plate (Fig.4), with load, **F**, the maximum deflection which is the deflection at the central point of the plate, δ, can be calculated with the following formula,

$$w(x)_{\max} = \delta = \frac{FL^3}{48EI} = \frac{FL^3}{4wh^3E} \tag{B.1}$$

Where, L means the length of the plate, I means flexural rigidity, which is $wh^3/12$ for this case. w, h is the width and thickness of the plate, respectively. And E is the Young Modulus of the plate.

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