Strain Amplifying Property of Bioinspired Membrane-in-Recess Microstructure: Analytical Modelling

Yue Chen, Dedy H.B. Wicaksono, Lu-Jun Zhang, Julian F.V. Vincent, and Paddy J. French

Abstract*— Nowadays natural sensors with relatively better performances are increasingly being studied to meet the demands for rapidly expanding sensor engineering. This paper describes the continuation of our work based on [1-2]. The unique sensing mechanism of the strain-sensing organ used by insects, i.e. *campaniform sensillum*, has been investigated in the previous report [1]. In this paper, the analytical modelling is presented to interpret a more quantitative understanding for the stain amplifying property of silicon membrane-in-recess microstructure inspired from the campaniform sensillum. We are also trying to utilise the strain amplifying property of this microstructure to obtain higher strain-sensing performance with the final goal of realizing a novel high-performance MEMS strain sensor. The analytical modelling is performed based on actual experimental setup described in [2], which has been divided into three stages. Firstly, several mechanical test models based on the silicon rectangular plate are theoretically analyzed and performed. These models are three-point bending test for simply supported plate, bending and tensile tests of plate with clamped edges. Secondly, clamped circular membrane under a concentrated load has been theoretically analyzed and then tested by Atomic Force Microscope (AFM). Strain distributions along the surface of each structure are also presented through analytical modelling, respectively. The final stage of analytical modelling is performed by fixing the Membrane-in-Recess microstructure on the central point of silicon rectangular plate surface, from which the strain amplification property is indicated.

***Keywords*— Strain amplification, Biomimetic sensor, MEMS**

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I. INTRODUCTION

IN the world of engineering, the great nature has a long history providing the blueprints for solving many problems faced by engineers. Nowadays natural sensors with relatively better performances are increasingly being studied to meet the demands of rapidly expanding sensor engineering. *Campaniform sensillum* is a strain-sensing organ used by insect. Deformation in the insect's cuticular layer can be sensed by the campaniform sensillum. Despite its small size (diameter ~10 μm) and exocuticula's material stiffness (~ 10^9 Pa), campaniform sensillum is very sensitive to tiny displacement [1]. Previous work by one of the authors [2-3] reported that the opening or the hole in the sensillum structure of fly amplifies the local deformation. A cross-section illustration of campaniform sensillum is shown in Fig. 1.

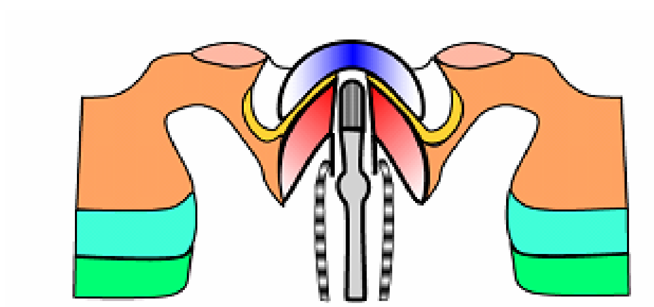

Fig. 1. A model of campaniform sensilla, showing different parts of the sensor.

The structure of the campaniform sensillum shows a dome-shaped cap which locates inside a surrounding blind-hole structure with a collar ring. The high sensitivity of campaniform sensillum could be attributed to this unique structure. From the initial study in mechanics [4], it has been known that holes concentrate stress to initiate failure and is usually regarded as weakening a load-bearing structure. However, in campaniform sensillum this concentrated stress is further transduced into lateral and vertical displacement of the cap, resulting in squeezing the neurotubules of the neuron cell located in the middle. Thus, the cap transduces and amplifies the concentrated strain/stress [1] from surrounding exocuticle. The amplification was utilized for strain-information gathering. Initial biomimetic Membrane-in-Recess (MiR) and

Membrane-on-Surface (MoS) microstructures inspired from the structure of campaniform sensillum have already been fabricated and experimentally characterized [2].

Previous work from one of authors has illustrated that MiR microstructure is slightly superior to the Membrane-on-Surface (MoS) one in amplifying the stress [5]. Therefore, in this paper, the analytical modelling will be only based on the MiR microstructure. The analytical modelling and simulation carried out in this report will hopefully provide more insight into what actually happened during the strain-stimuli transduction. Thus, further optimization of the structure can be planned carefully, with the final goal of realizing a novel high performance MEMS strain sensor.

II. STRUCTURE DESIGN

The biomimetic MiR structures inspired from the structure of campaniform sensillum has been designed by one of the authors [2]. As shown in Fig.2, the parameters ***D*** and ***R*** mean the diameter and radius of the circular membrane in recess the hole opening, respectively, ***t*** and ***h*** are the thickness of the membrane and the whole chip, respectively. ***d*** is the dimension of the square chip, h_1 is the membrane recess depth from the surface of the wafer, and h_2 is equal to $(h-h_1-t)$.

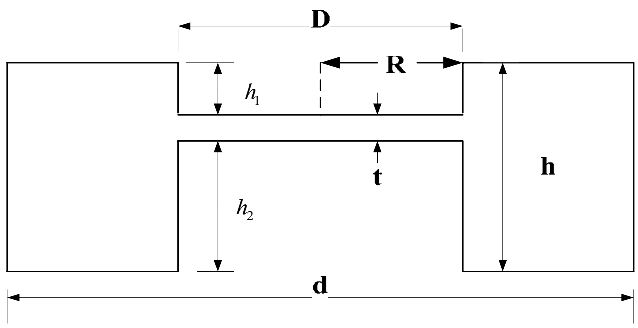

Fig. 2. Biomimetic Membrane-in-Recess (MiR) structure.

The analytical modelling and simulation is carried out on actual experimental setup [2], which is illustrated in Fig.3. The designed biomimetics strain-sensing microstructure (shown in Fig. 2) is attached to a larger silicon plate structure. The parameters of ***L***, ***w*** and ***H*** are the length, width and thickness of the silicon plate, respectively. In this paper, both the analytical modelling and numerical simulation are carried out on this setup. Our essential goal is to utilise this structure as a strain-sensing device attached to a larger structure in which the strain will be measured.

III. ANALYTICAL MODELLING

A. Silicon Plate

At the first stage, in order to get the value for the Young's modulus of the plate, the three-point bending test was used. The test structure was built as shown in Fig.4 with point **a.** and point **c**. moving downward with the same force and point **b.** fixed. It is obvious that the elongation along the width direction

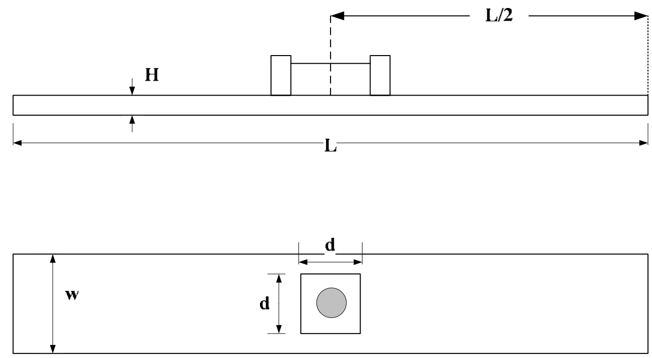

Fig. 3. Experimental setup as the base of analytical modelling.

(z-axis) can be neglected. So, this test model can be simplified to a two dimensional structure ($x-y$ plane). The formula for the Young's Modulus under the three-point bending is very classical and can be easily derived from Timoshenko's method [6].

$$E = \frac{L^3}{4wh^3} \cdot \frac{F}{\delta} \tag{1}$$

where ***E*** is the Young's modulus of the silicon plate, ***F*** is the force at the central point of the load, ***δ*** is the maximum deflection of the plate, which indicates the deflection at the ends of the plate during this test.

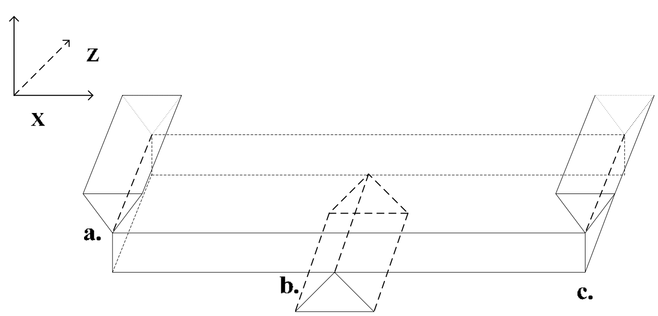

Fig. 4. Scheme for three-point bending test analytical model

B. Circular membrane

In order to obtain the value of the Young's modulus of the circular membrane, clamped circular membrane under a concentrated load has been theoretically analyzed and then tested by Atomic Force Microscope (AFM). The size of sample circular plate and the test model are shown in Fig.5, in which the load ***P*** is applied at point A with the distance ***b*** from the center point O of the clamped circular plate. By following Timoshenko's analysis [7], the formula for the deflection at the central point of the circular membrane (δ) is shown as following,

$$\delta = \frac{P}{16\pi D}\frac{(R^2-b^2)^2}{R^2} = \frac{3P(1-\nu^2)}{4\pi Et^3}\frac{(R^2-b^2)^2}{R^2} \tag{2}$$

where ***D*** is the flexural rigidity ($Et^3/[12(1-\nu^2)]$), ν is the Poisson's ratio. The values for the load and deflection can be obtained while scanning the circular membrane with AFM tip. Thus, the Young's modulus can be gained by using eq. (2).

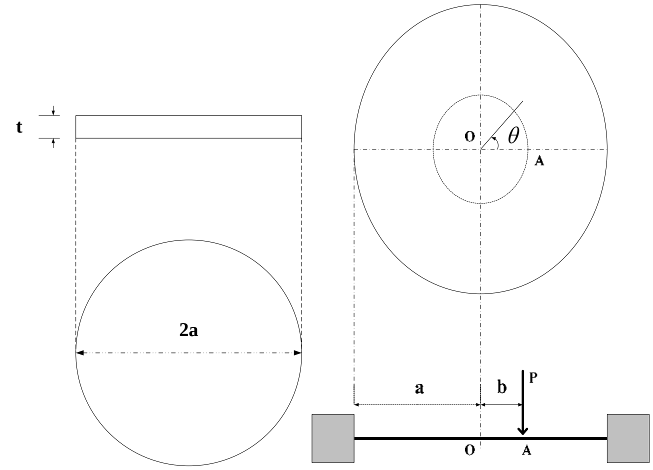

Fig. 5. Dimensions of the circular plat (left) and sketch for the clamped circular plate under a concentrated load (right).

C. Membrane-in-Recess microstructure

Dual-pull load model was analyzed as the start point for the analytical modelling of the MiR microstructure. As shown in Fig. 6 and 7, the experimental setup (Fig.3) is doubly clamped at the edges of silicon plate. Pull load ***F*** is applied in opposite directions on the clamped edges. Initial numerical simulation result indicates that the stress at the bottom of the chip (σ_p) is uniform and can be calculated with the following equation,

$$\sigma_p = \frac{2F}{wH} \tag{3}$$

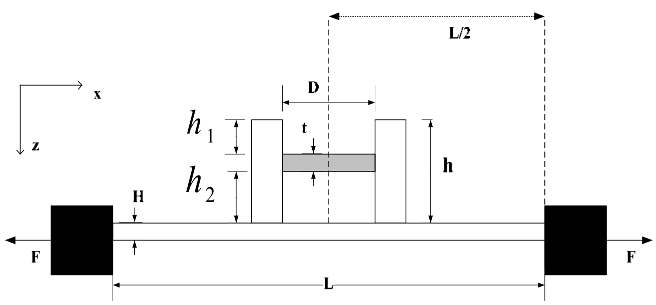

Fig. 6. MiR microstructure modelling under pull load (x-z plane).

Thus, the strain at the bottom of the chip (ε) is,

$$\varepsilon = \frac{\sigma_p}{E} = \frac{2F}{EwH} \tag{4}$$

where ***E*** is the Young's modulus of the plate. The chip is moved by axial tensile stress according to $\tau << \sigma_p$, in which τ is

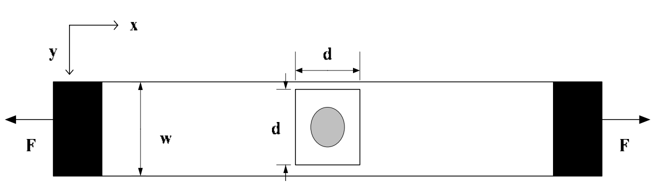

Fig. 7. MiR microstructure modelling under pull load (x-y plane).

the shear stress, so axial tensile stress (σ_c) applied on the chip is:

$$\sigma_c = \varepsilon E_c \qquad (E_c = E) \tag{5}$$

where E_c is the Young's modulus of the chip, in which has the same Young's modulus with the plate. Then the stress applied on the chip

$$\sigma_c = \sigma_p = \frac{2F}{wH} \tag{6}$$

According to the calculation in [8], the stress along the edges of the circular membrane (σ_e) is,

$$\sigma_e = \sigma_c(1-2\cos 2\theta) + \sigma_c \Delta^2 \cdot n \cdot \zeta^{n-2}[(2n-1)\zeta^n - n + 1] \cdot \sum_{i=1}^{2} \{[1-(q+i-1)\log R]\lambda_{1i} + (\lambda_{2i} + 2\lambda_{3i})\log R\} \cos 2\theta \tag{7}$$

where $\Delta = h/D$, the expponts ***q,n*** as well as the values of $\lambda_{\alpha i}$ (α=1,2,3; i=1,2) which depend upon Δ and ν, are given in Tables 4,5,6 in [8]. θ is the angle showing in Fig.5. For the MiR structure, Δ is 1.05, thus, from [8], ***q*** and ***n*** are approximately 2.3 and 2.2, respectively. The values of $\lambda_{\alpha i}$ are showing in Table I.

TABLE I.
VALUES OF $\lambda_{\alpha i}$

Symbol	Quantity
λ_{11}	0.0306
λ_{21}	0.4276
λ_{31}	-0.1451
λ_{12}	0.02403
λ_{22}	0.03868
λ_{32}	0.07669

According to the theory for nonlinear analysis of plates [9], when the value of the compression edge stress exceeds a certain value, i.e. critical value for bulking and postbulking, the circular membrane will have a postbulking variation. In order to guarantee the MiR structure with relatively large strain amplification, the clamped circular membrane under postbukling will be analytical modeled. The basic equations of the postbuckling modelling of the circular plate can be found in [9], which were expressed by dimensionless parameters.

$$\begin{cases} x \dfrac{d}{dx}\dfrac{1}{x}\dfrac{d}{dx}\left(x\dfrac{d\Omega}{dx}\right) = -g\dfrac{d\Omega}{dx} \\ x \dfrac{d}{dx}\dfrac{1}{x}\dfrac{d}{dx}(xg) = \dfrac{1}{2}k^2\left(\dfrac{d\Omega}{dx}\right)^2 \end{cases} \tag{8.a,b}$$

where,

$$x = \frac{r}{R}, \quad \Omega = \frac{\omega}{t}, \quad g = -\frac{Rk^2}{Et^2}\frac{d\Phi}{dr},$$

$$\sigma_\theta^m = \frac{d^2\Phi}{dr^2} = -\frac{E_m t^2}{R^2 k^2} \cdot \frac{dg}{dx}, \quad k = \sqrt{12(1-\nu^2)}$$

And ***Φ(r)*** is the stress function, ***r*** is the radial coordinate. For the clamped plate, the boundary conditions at the edge assume the following forms,

$$\frac{d\Omega}{dx} = 0,\ g = 0,\ \Omega \text{ is finite} \qquad \text{at } x=0 \tag{9}$$

$$\Omega = 0,\ \frac{1}{x}\frac{d\Omega}{dx} = 0,\ g = \xi \qquad \text{at } x=1 \tag{10}$$

where,

$$\xi = -\frac{R^2 k^2 \sigma_e}{E_m h^2} \qquad (\xi > 0)$$

The complicated function system eq. (8)-(10) can be solved by Newton-Raphson iterative method [10] [11]. The solutions from the first and second iteration [11] are illustrated as following. The formula for the deflection of the membrane (***ω***) can be illustrated as

$$\omega = t\sqrt{\frac{\frac{\xi}{\xi_0}-1}{\beta[\sum_{j=0}^{\infty}(j+1)C_j]}}\left(1+\beta\sum_{j=0}^{\infty}A_j x^{2j+2}\right) \tag{11}$$

in which the parameter of ***β, ξ₀, C_j*** and ***A_j*** are defined by Appendix (a-c). From [12], the central deflection of postbuckling clamped circular plate (***δ***) can also be easily expressed as

$$\frac{\sigma_e}{\sigma_{cr}} = 1 + 0.205\left(\frac{\delta}{t}\right)^2 \tag{12}$$

where $\boldsymbol{\sigma_{cr}}$ [13] is the critical compression stress for the clampe d circular plate, which can be expressed as,

$$\sigma_{cr} = \frac{14.68\,E t^3}{12 R^2 (1-\upsilon^2)} \tag{13}$$

The cicumferential membrane compression stress [11] is

$$\sigma_\theta^m = \frac{-Et^2}{12R^2(1-\nu^2)}\frac{d}{dx}\cdot\left(\xi x + \sqrt{\frac{\frac{\xi}{\xi_0}-1}{\beta\left[\sum_{j=0}^{\infty}(j+1)C_j\right]}}\cdot\sum_{j=0}^{\infty}B_j x^{2j+1}\right) \tag{14}$$

where $\boldsymbol{B_j}$ is defined by Appendix (b).

IV. RESULTS AND DISCUSSION

The dimensions of the sample structure are shown in Table II. The three points bending microtest experiment was processed by using the tensile stage produced by Deben UK

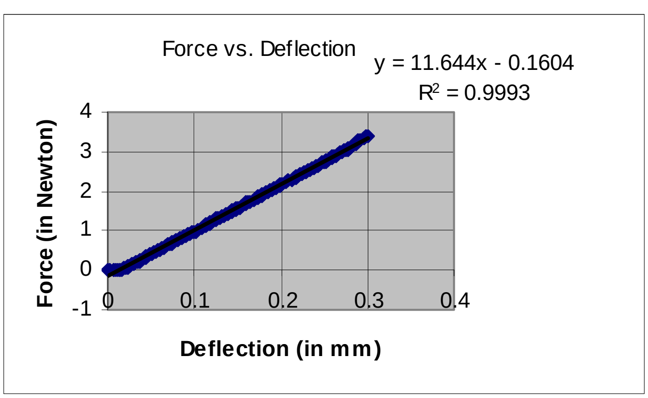

Fig. 5. Three points bending test experiment result.

TABLE II.
DIMENSIONS OF THE SAMPLE STRUCTURE

Symbol	Value
L	40 mm
w	10mm
H** and **h	525 μm
d	3 mm
R	0.25 mm
t	0.5 μm
h_1	13 μm
h_2	511.5 μm
υ	0.27

Ltd.. The test analytical model has been described in section III.A. The test duration was 88.5 s; the maximum for deflection was 2.55mm which was shown by the readout software of the microtest stage. The experiment result is shown in Fig.8. The calculation results are in conformity between experimental results and theoretical calculation. The slope of the linear line for force vs. deflection was 11.644. Young's Modulus of the sample plate indicated by the slope of the linear line (11.644) in Fig.5 is 129 GPa by using eq. (1). From the database of FEMLAB 3.1, Young Modulus of homogeneous linear isotropic Silicon approximately equal to 131GPa. The errors between the experimental results and the theoretical calculations were probably from the measurement scale of the software, temperature, the measurement for the virtual length of the samples during bending. For further numerical modelling with MATHEMATICA 5 and simulation with FEMLAB 3.1, the value of 131 GPa for Young's modulus is assumed for the silicon plate.

AFM was used to scan the surface of the circular membrane in the MiR structure samples (Fig.2). The principle of AFM relies on the use of a sharp, pyramidal tip mounted on a cantilever, which is brought into close proximity to the surface where intermolecular forces acting between the tip and the surface cause the cantilever to bend (Fig.6). The recorded cantilever deflections, as detected by a laser beam focused on the top of the cantilever, as well as the forces measures between the tip and the sample during scanning were obtained by the

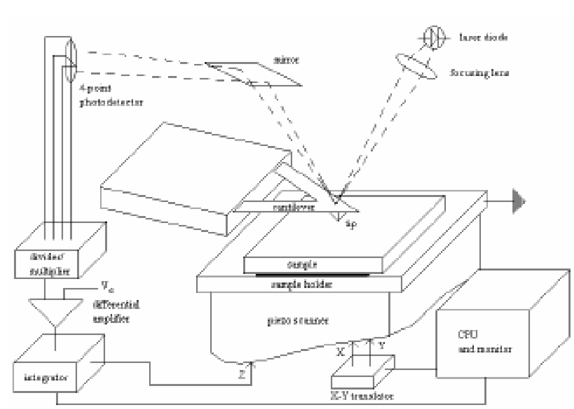

Fig. 6. AFM scan setup, where small Van-der-Waals repulsion forces are measured between the tip and the sample during scanning. These forces cause vertical movement of the cantilever, which are monitored by a laser beam

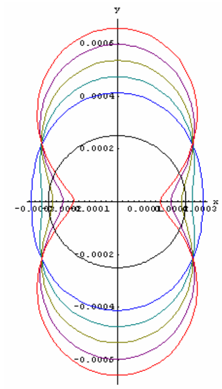

Fig. 7. Qualitative Analytical calculation of stress distribution on the vicinity of hole from eq. (7) .

readout software of AFM. Therefore, with known deflections and forces, the Young's modulus of the membrane can be calculated by eq. (2). However, when this paper had to be submitted, the experiment data have not been full analyzed. Due to this reason, for all the numerical modelling, LPCVD-grown SiN thin film with Young's modulus of ~320 GPa is assumed as the material of the circular membrane ($\boldsymbol{E_m}$).

The analytically calculated stress concentration on the vicinity of a hole is obtained from eq. (7) and illustrated in figure 7. The highest tensile stress value is found in the edge of the membrane at $\boldsymbol{\theta} = \pi/2$ and $3\pi/2$, i.e. at the $\pm y$ axis, which corresponds well with the discussion in [14]. For the dual-pull load modelling, the applied force $\boldsymbol{F}$ is assumed to be 3 N.

The numerical modelling of MiR with 0.5 µm membrane thickness under dual-pull load can be then treated as a simplified model, i.e. a clamped circular membrane with distributed tensile stress. However, the analytical modeling used in [9] to obtain eq. (11) and (14) was actually based on a circular plate with uniform radial in-plane compression.

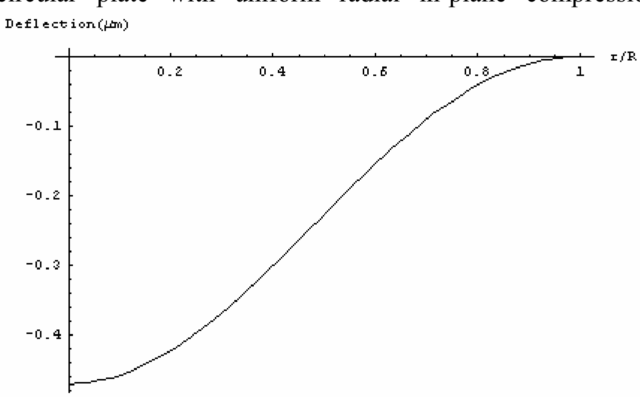

Fig. 8. The defelection diagram of the membrane under dual-pull load modeling.

Having the solutions from eq. (11) and (14) at $\boldsymbol{\theta} = \pi/2$ and 0, our initial analytical modeling results can be obtained by superposition, which are illustrated in figure 8.and 9. The results show that MiR structure amplified the stress to a level of $\sim 1 \times 10^6$ Pa and indicated the bulking behaviour with deflection in a level of 0~0.5 µm.

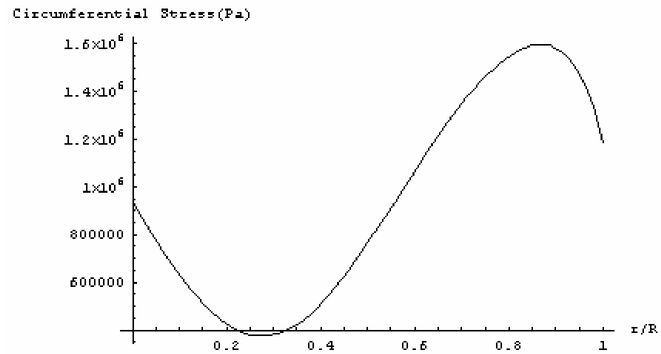

Fig. 9. The stress distribution of the membrane under dual-pull load modelling.

V. CONCULSIONS

We have carried out the numerical modelling and initial numerical simulation of bioinspired membrane-in-recess strain-sensing structure. The results have indicated that even with dual-pull load, the high stress amplification property can be well achieved by the thin membrane postbuckling mechanics. Analytical modelling for the experimental setup (Fig.3) with more complicated test models, i.e. three-point bending test and dual-push load test, are still under processing. Efforts are also made to obtain further simulation with ANSYS and experimental test results. We believe that with these quantitative understanding for its mechanical properties, this bioinspired MiR structure can be further improved and can be utilized further for developing a new type of high-sensitive MEMS-based strain sensor.

APPENDIX

Parameters definition for eq.(10) and (11),

$$A_0 = 1 \qquad A_{j+1} = \frac{-\xi_0 A_j}{(2j+4)^2}$$

$$\sum_{j=0}^{\infty}(2j+2)A_j = 0 \qquad 1 + \beta \sum_{j=0}^{\infty} A_j = 0 \tag{a}$$

where the value of the coefficient β is -2.617 [11], and the value of ξ_0 is 14.68 [11].

$$\begin{cases} B_{j+1} = \frac{1}{2} k^2 \beta^2 \left[\frac{\sum_{n=0}^{j} (2n+2)(2j-2n+2) A_n A_{j-n}}{(2j+3)^2 - 1} \right] \\ B_0 = -\sum_{j=1}^{\infty} B_j \end{cases} \tag{b}$$

$(j = 0, 1, 2, 3, ...)$

$$C_j = \frac{\sum_{n=0}^{j} (2n+2) A_n B_{j-n}}{(2j+2)(2j+4)^2} \tag{c}$$

VI. ACKNOWLEDGMENT

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REFERENCES

[1] D.H.B. Wicaksono, W.A. van Duyl, J.F.V.Vincent and P.J. French, “Preliminary study on the design of a new micromachined silicon strain sensor based on the Campaniform sensillum of insects”, *in Proc. Semiconductor Advances for Future Electronics 2003, SAFE 2003,* Netherlands, 2003, pp. 721–725.

[2] D.H.B. Wicaksono, J.F.V. Vincent, G. Pandraud, G. Craciun, and P.J. French, “Biomimetic strain-sensing microstructure for improved strain sensor: fabrication results and optical characterization,” *J. Micromech. Microeng.*,vol. 15, 2005, pp. 72-81.

[3] D.H.B. Wicaksono, G. Pandraud, and P.J. French, “Simple optical characterisation for biomimetic micromachined silicon strain-sensing structure,” *in Proc. of SPIE* 5852, part 2, Singapore, 2004, pp.788-795.

[4] G.N. Savin, *Stress Concentration Around Holes,* Oxford: Pergamon Press, 1961.

[5] D.H.B. Wicaksonol, L-J. Zhang, N. Gharbage, Y. Chen, J. F.V. Vincent, and P.J. French, “Numerical Modelling of biomimetics strain-sensing microstructure,” in Proc. of EuroSensors XX, T2B, Sweden, pp. 13-16.

[6] S.P. Timoshenko and J.M. Gere, *Mechanics of Materials*, New York: Van Nostrand, 1972, pp. 114-116.

[7] S.P. Timoshenko, *Theory of Plates and Shells*, 1st ed., New York: McGraw-Hill, 1940), Sec.50, pp. 266-269.

[8] E. Sternaberg, M.A. Sadowsky and ILL. Chicago, “Three-dimensional solution for the stress concentration around a circular hole in a plate of arbitrary thickness,” *J. Appl. Mech.*, vol.16, 1949, pp. 27–36.

[9] C-Y. Chia, *Nonlinear Analysis of Plates,* New York: McGraw-Hill, 1980, pp. 174-181.

[10] A. Wang, “Axisymmetric postbuckling and secondary bifurcation buckling of circular plates”, *Int’l J. Non-Linear Mech.*, vol.35, no.2, 2000, pp. 279-292.

[11] D.Li, (1991), “Application of the modified iteration method to nonlinear postbuckling analysis of thin circular plates” *Appl. Math. Mech. (English Edition)*, vol. 12, 1991, pp. 1143-1148.

[12] F. Bloom and D. Coffin, *Handbook of thin plate buckling and postbuckling,* Boca Raton: Chapman and Hall, 2001, pp. 221-225.

[13] S.P. Timoshenko and J.M. Gere, *Theory of elastic stability*, 2nd ed., New York: McGraw-Hill, 1961, pp. 389-390.

[14] S.P. Timoshenko and J.N. Goodier, *Theory of Elasticity*, 3rd ed., New York: McGraw-Hill, 1970, pp.90-92.

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