VERIFICATION OF FEM ANALYSIS OF LOAD-DEFLECTION METHODS FOR MEASURING MECHANICAL PROPERTIES OF THIN FILMS

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ABSTRACT

Accurate models are an essential element for determining the mechanical properties of thin films from load-deflection experiments. Analytical models are desirable because of their simplicity. Finite element method (FEM) models have the potential to be more accurate. Through an extensive FEM analysis of the load-deflection methods, we have confirmed that while the functional form of the analytical result is correct, three constants in the model must be corrected by as much as 30%. Experimental measurements of the deformed membrane shape have been made and they match the FEM results, verifying the accuracy of the FEM models. Experimental values, extracted from load-deflection analysis, for the biaxial modulus and the residual stress of thin films of Dupont PI2525 and Hitachi PIQ13 are presented.

INTRODUCTION

The load-deflection method has previously been developed for the measurement of the mechanical properties of thin films [1-6]. In this technique, the deflection of a suspended film is measured as a function of applied pressure (Fig. 1). The biaxial modulus and the residual stress of the film can then be extracted from the data using various mathematical models. The models for both square and circular membranes have been developed using both analytical and finite-element methods (FEM).

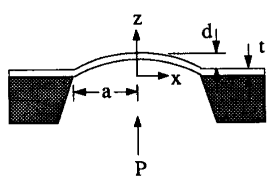

Figure 1: Deflection of a suspended membrane in response to an applied pressure.

In the case of the analytical model, a functional form of the deflected shape is assumed, and the total strain energy minimized to find the load-deflection behavior. A hemispherical cap is assumed as the deflected shape of the circular membranes [2], whereas a cos(kx)cos(ky) form is assumed for the square membranes [7-8]. These choices are often made to simplify the mathematics at the expense of modeling accuracy.

The FEM models are generated by inputting a set of geometric and material parameters into a FEM program and simulating a load-deflection experiment. By noting the effect of variations of each material parameter on the simulation, a model can be derived.

In all cases the load-deflection behavior is of the form:

$$P = \frac{C_1 t}{a^2}\sigma_o d + \frac{C_2 f(\nu) t}{a^4}\frac{E}{1-\nu}d^3 \qquad (1)$$

where P is the applied pressure, d the center deflection, a the radius/half-edge length of the membrane, t the thickness, E the Young's Modulus, ν the in-plane Poisson Ratio, σ_o the residual stress, and $E/(1-\nu)$ the biaxial modulus. The dimensionless constants C_1 and C_2 and the dimensionless function $f(\nu)$ are geometry and model dependent.

It can be seen from (1) that the biaxial modulus and residual stress can be evaluated from the experimental pressure-deflection data and the membrane dimensions provided that C_1, C_2, and $f(\nu)$ are known. Accurate values for these constants are therefore essential for the accurate determination of the mechanical properties. The choice of modeling method affects the values of these constants. Our goal in this study is to show that in contrast to the analytical models, which have to assume a shape function, the FEM model yields the shape function, and this shape function is in good agreement with experiment.

ANALYTICAL MODELS

In the analytical model, a functional form of the deflected shape must be assumed and the total strain energy minimized to find the load-deflection behavior. For square membranes, a one-term Fourier approximation of the actual deflected shape can be assumed. The form is from Allen [7-8]:

$$z = d\cos\left(\frac{\pi x}{2a}\right)\cos\left(\frac{\pi y}{2a}\right) \qquad (2)$$

where x and y are the distances in the x- and y-axes away from the center, z is the deflected height at (x,y), a is the half-edge length, and d is the center deflection.

The analytical shape for the circular case is assumed to be a hemispherical cap [2]. The equation is:

$$z = d - R + (R^2 - r^2)^{1/2} \qquad (3)$$

where r is the distance from the center, R is radius of curvature of the deflected membrane, and d is the center deflection. The value of R can be calculated from

$$R = \frac{a^2 + d^2}{2d} \qquad (4)$$

where a is the radius of the membrane.

With these assumptions for the deflected shape, the minimization of the strain energy in the presence of a residual tensile stress is straightforward [2,7-8]. The resulting values for C_1, C_2, and $f(\nu)$ are shown in Table II. Note that a simplified linear fit to the actual $f(\nu)$ for square membranes is given in the table. The actual equation can be found in the references [4,7-8].

FINITE ELEMENT METHOD

Finite element modeling of square and circular suspended membranes was carried out using both ABAQUS and ADINA. Agreement between the two programs was excellent. In order to check the consistency of the FEM models, several types of elements were used to solve this problem, and their results were compared.

The types of elements and the number of nodes selected for this work are shown in Table I. Three different types of elements were used for square membranes: 4-node and 16-node shell elements, and 20-node 3D solid elements. For circular films, 4-node and 16-node shell elements and 8-node 2D solid axisymmetric elements were used. Fig. 2 shows the schematic geometry of the different elements. Nonuniform grids were also used in some cases to put more nodes near the edges of the membranes. These elements are labeled as ratioed elements in Fig. 2.

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TABLE I
The element types and the number of nodes per element used in FEM analysis.

membrane shape	element type	nodes per element	number of elements	ratioed elements
circular	shell	4	1200	no
	shell	16	105	yes
	2D solid	8	960	no
square	shell	4	324	no
	shell	16	64	yes
	3D solid	20	256	yes

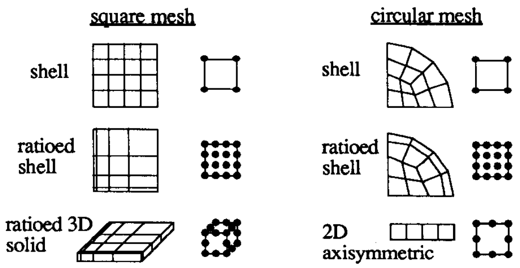

Figure 2: The schematic geometry of FEM elements.

Ratioed elements were used for the 16-node shell and the 20-node 3D solid elements in order to accurately model the behavior of the membrane near its boundaries. The smallest size for the shell elements was 0.047mm or about 1.2% of the half edge length; for the 3D solid elements it was about 0.058mm or 1.5%. The deflected shape for a square membrane as a function of element type is shown in Fig. 3. The variation in both the deflected shape and the center deflection for the different elements is less than 0.3%.

The results for a circular membrane are shown in Fig. 4. Again the variation in the results is less than 0.3%. This indicates that our FEM analysis converges to the same answer regardless of the element type. We found the best balance between accuracy and computation time to be a grid of 576 4-node shell elements for square membranes and 250 8-node 2D solid elements for circular membranes.

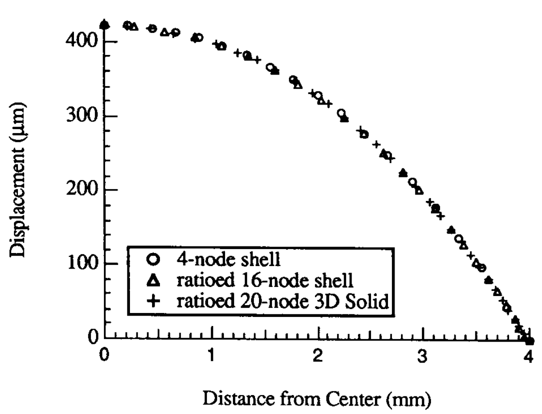

Figure 3: FEM-calculated deflected shape along center-to-midside for a square membrane as a function of element type.

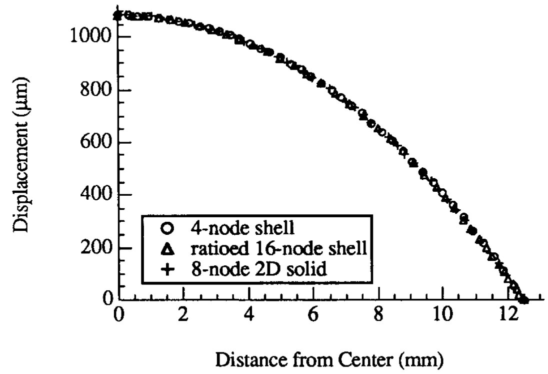

Figure 4: FEM-calculated deflected shape along radius of a circular membrane as a function of element type.

By computing the deflection vs. pressure for assumed values of σ_0, E, and ν for a sequence of applied loads, and fitting the results to Equation (1), it is possible to determine C_1 and the product $C_2 f(\nu)$. For convenience, we assign C_2 as the value assigned to the analytical model when ν=0.25; i.e. $f(\nu)$ is scaled such that $f(\nu=0.25) = 1$. The results of extensive fittings are shown in Table II. The values are accurate to within 1%.

For the circular case, the FEM value for $f(\nu)$ differs from the analytical value by 12% at ν=0.4. C_1 and C_2 are the same for both models. For square membranes, the FEM and analytical values for C_1 differ by 12% while $f(\nu=0.4)$ varies by 33%.

TABLE II
Modeled values of C_1, C_2, and $f(\nu)$ for both square and circular membranes.

Membrane Shape	Model	C_1	C_2	$f(\nu)$
Circular	Analytical	4.0	2.67	1.0
	FEM	4.0	2.67	$(1.026 + 0.233\nu)^{-1}$
Square	Analytical	3.04	1.37	$1.075 - 0.292\nu$
	FEM	3.41	1.37	$1.446 - 0.427\nu$

EXPERIMENTAL PROCEDURE

Fabrication of Samples

Square membranes of BTDA-MPDA/ODA (Dupont PI2525) were fabricated using micromachining techniques [5]. A combination of oxide mask, p^+ etch stop, and KOH etchant was used to define a thin silicon membrane on an <100> n-type silicon wafer. The polyimide was then spun cast onto the wafer and the silicon membrane etched in an SF_6 plasma. The final structure was cemented to an aluminum plate for pressure testing.

Circular membranes were made from Hitachi PIQ13 films using a variation of the technique outlined in [6]. PIQ13 was spun cast onto a bare silicon wafer. Using 6:1:1 $HF:HNO_3:CH_3COOH$, a hole was then etched through the center of the wafer, leaving a suspended polyimide membrane. The membrane was then transferred to a machined Vespel ring by epoxying the ring to the membrane and cutting it free from the silicon support. Finally, the ring was cemented to an aluminum plate to facilitate testing.

Measurement of the Mechanical Properties

The thicknesses of the films were taken from Dektak measurements. The dimensions of the membranes were measured with a Nikon UM-2 measuring microscope equipped with two Boeckeler model 9598 digital micrometers connected to a Metronics Quadra-Chek II digital readout box. The maximum error in each axis for the calibrated xy stage was less than 3 microns.

The samples were clamped into a custom-designed pressurizing jig for testing. Computational routines inside the Quadra-Chek II were used to locate the center of the membrane under test. The deflection resulting from varying pressure loads for each membrane was then measured with the microscope [5-8]. A 40X objective with a numerical aperture of 0.5 provided the sub-micron depth of focus needed to locate the surface of the membranes. A 543-series Mitutoyo digimatic indicator was used to track the z-axis movement of the microscope head. The total measurement error in the deflection was less than 2 microns. Pressure readings accurate to 0.02 psi were made with a MICRO SWITCH 142PC05G pressure sensor.

All measurements were done at room temperature in dry air (dew point < -46° C). The strain in the sample was never allowed to exceed 1%. Ten to twenty pressure-deflection measurements were taken, and the points were fit to equation (1) using the FEM constants to determine the residual stress and biaxial modulus.

A ν of 0.4 was assumed for all calculations. We can check this assumption by comparing the Young's modulus predicted by this assumption against published values. The Young's modulus of PI2525 has been measured from uniaxial tests to be 3.2 ± 0.16 GPa [6]. The predicted biaxial modulus of 5.22 GPa combined with the assumed Poisson ratio of 0.4 yields a value of 3.13 GPa for E, so our computations are consistent. The results for two membranes are shown in Table III. The accuracy of the values is estimated to be ±5%.

TABLE III
Measured residual stress and biaxial modulus for two membranes.

Membrane Shape and Dimensions	Residual Stress (MPa)	Biaxial Modulus (GPa)
Square t = 5.2 µm, a = 4826 µm (Dupont PI2525)	32.2	5.22
Circular t = 11.4 µm, R = 12610 µm (Hitachi PIQ13)	35.2	5.37

Measurement of Deflected Shapes

The same apparatus as above was used to measure the deflected profiles. The calibrated xy stage allowed us to locate the center of the membranes and accurately translate the sample along the appropriate path. The results are plotted against the modeled results in Figures 5-6. The residual stress and biaxial modulus derived using the indicated model and the measured thickness, edge length/radius, and pressure were used to generate the modeled results.

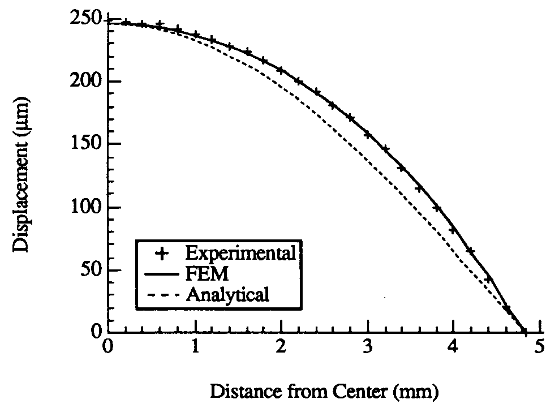

Figure 5a: Experimental deflected shape vs. FEM results and analytical model for center-to-midside of square membrane.

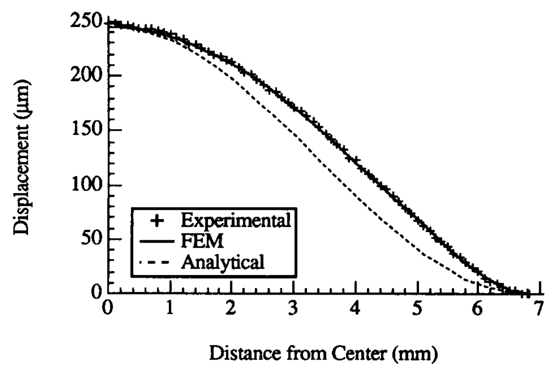

Figure 5b: Experimental deflected shape vs FEM results and analytical model for diagonal of square membrane.

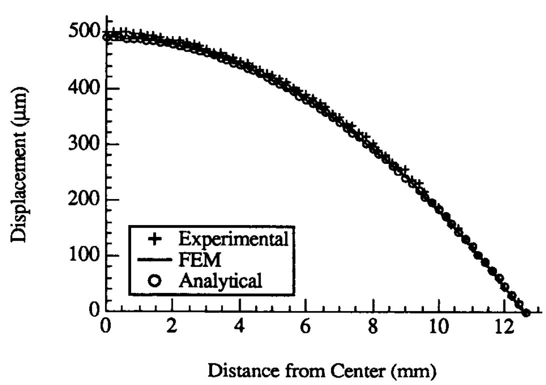

Figure 6: Experimental deflected shape vs FEM result and analytical model for radius of circular membrane.

DISCUSSION

The center-to-midside deflected shape for a square membrane is shown in Fig. 5a; the deflected shape along the diagonal is given in Fig. 5b. The agreement between the experimental data and the FEM results is within 0.5% in both cases. The difference between the experimental data and the analytical solution is over 10% at the x-position of 4000μm.

Figure 6 shows the predicted and measured deflected shapes for circular membranes. Note that both the FEM result and the analytical result are within 3% of the experimental data. This indicates that the actual deflected shape is very close to a hemispheric function.

On the basis of this experimental confirmation of the FEM-predicted deflected shapes, we can conclude that the FEM values of C_1, C_2, and $f(\nu)$ given in Table II are the correct values to use for load-deflection analysis.

CONCLUSION

Through a careful study of FEM modeling accurate values for C_1, C_2, and $f(\nu)$ in Eqn. (1) have been found. These values are substantially different from those predicted by analytical models. By direct experimental observation, we have verified that FEM modeling yields the correct deformed shape, and, hence the values of the constants obtained from FEM provide a reliable basis for using load-deflection data to measure the mechanical properties of materials.

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REFERENCES

[1] E. I. Bromley, J. N. Randall, D. C. Flanders, and R. W. Mountain, "A technique for the determination of stress in thin films," J. Vac. Sci. Technol. B, vol. 1, no. 4, pp. 1364-1366, Oct.-Dec. 1983.

[2] J. W. Beams, "Mechanical Properties of Thin Films of Gold and Silver," in Structure and Properties of Thin Films, C. A. Neugebauer, Ed. New York: Wiley, 1959, pp. 183-192.

[3] J. A. Hinkley, "A Blister Test for Adhesion of Polymer Films to SiO_2," J. Adhesion, vol. 16, pp. 115, 1983.

[4] O. Tabata, K. Kawahata, S. Sugiyama, and I. Igarashi, "Mechanical Property Measurements of Thin Films Using Load-Deflection of Composite Rectangular Membrane," Micro Electro Mechanical Systems: An Investigation of Micro Structures, Sensors, Actuators, Machines, and Robots, IEEE,1989, pp.152-156.

[5] M. G. Allen, M. Mehregany, R. T. Howe, and S. D. Senturia, "Microfabricated structures for the in situ measurement of residual stress, Young's modulus, and ultimate strain of thin films," Appl. Phys. Lett, vol. 51, no. 4, pp. 241-243, July 1987.

[6] F. Maseeh and S. D. Senturia, "Elastic Properties of Thin Polyimide Films," in Polyimides: Materials, Chemistry and Characterization, C. Feger, M. M. Khojasteh and J. E. McGrath, Eds. Amsterdam: Elsevier Science Publishers B. V., 1989, pp. 575-584.

[7] M. Mehregany, M. G. Allen, and S. D. Senturia, "The Use of Micromachined Structures for the Measurement of Mechanical Properties and Adhesion of Thin Films," Technical Digest, IEEE 1986 Solid-State Sensors Workshop, Hilton Head, S. C., June 1986.

[8] M. G. Allen, M. S. thesis, Department of Chemical Engineering, Massachusetts Institute of Technology, May 1986.

[9] M. G. Allen and S. D. Senturia, "Analysis of Critical Debonding Pressures of Stressed Thin Films in the Blister Test," J. Adhesion, vol. 25, pp. 303-315, 1988.