STATIC AND DYNAMIC BEHAVIOR OF

STRESS COATED MEMBRANES

By

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NOMENCLATURE

Following nomenclatures are for the abbreviations used in this paper.

EXP	Experimental results
EXP_U	Experimental results for uncoated membrane
EXP_C	Experimental results for coated membrane
FEA	Results obtained from finite element analysis (FEA)
FEA_U	Results obtained from FEA for uncoated membrane model
FEA_C	Results obtained from FEA for coated membrane model
FEA_C_NCS	Results obtained from FEA for coated membrane model, with no coating stress used in the model
MSU	Montana State University
SFP	Stress fitting parameter

ABSTRACT

Large space mirrors need to be made of ultra-lightweight materials (membranes) that have very low densities and high flexibility (compliance) for packaging. A coating application necessary for optical reflectivity may also impart to these ultra-lightweight materials a desired shape and to help maintain that shape in the harsh environment of space. When a coating is applied on the membrane substrate, stresses develop in the coating due to atomistic processes. These stresses are fundamental to the final shape of the substrate. Coatings applied to the substrate in order to maintain a particular shape are known as the 'stress coating prescription'.

As there is no way one could directly measure stresses in the coatings experimentally, in this work it will be explained how finite element analysis (FEA) was used in estimating stresses in the coatings. This work mainly comprises static pressure-deflection tests (bulge tests) on the coated and uncoated membranes, and a comparison of the experimental results to FEA findings in order to estimate the stresses in the coatings. Before FEA results are matched with the experimental results, an analytical solution to the problem in hand will be derived. Uncertainties due to variation in coating thicknesses and difficulties in coating process have led to various uncertainties in this work, and these uncertainties are also discussed. The ability to use changes in vibration frequency as a measure of coating stress is also investigated.

1. INTRODUCTION

Use of gossamer or ultra-lightweight structures in space technology has promised high performance deployable membrane mirrors among other applications (see Figure 1). Light-weight mirrors are ideal for space related applications; polymer membranes of very low density, such as a Kapton membrane coated with SiO_2, could be used to form a light-weight mirror. Optical efficiency of these light-weight mirrors, just as any mirror, mainly depends on an ability of that mirror to have a precise curvature.

| (a) | (b) |
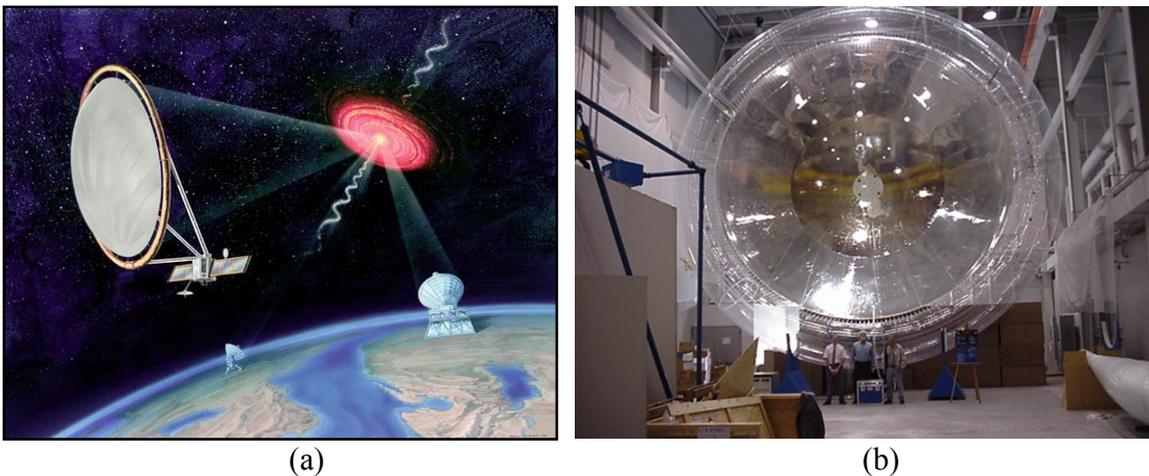
Figure 1: (a) Gossamer space reflector[1]; (b) 10 m SRS inflatable reflector mirror[2]

Mirrors made up of these membranes also have an advantage of high packaging efficiency since they are thin and have high structural compliance. As these ultra-lightweight space mirrors are made up of membranes that do not have flexural rigidity, they lack an intrinsic ability to maintain their precise curved shape. In addition to this, membranes having a thickness in the range of a few micrometers are very challenging to manufacture and are prone to have intrinsic stresses due to the curing process.

The existence of intrinsic stresses could result from thermal mismatch or evaporation during curing. However use of stress-coatings could be helpful in overcoming these intrinsic stresses and in maintaining the desired geometry of the overall membrane.

In this thesis, static and dynamic behavior of coated membranes will be studied. For comparison to experimental data, either an analytical solution or finite element analysis (FEA) result, or both, will be used. As dynamic experimental work is not done, the study of frequency behavior of the membrane will be based on a comparison of analytical solution with the FEA results. A flowchart of this whole procedure can be seen in Appendix – A.

2. BACKGROUND

History

For some time now, gossamer structures have been of great interest for space applications. One main reason behind that is their low mass; gossamer structures are also readily packaged and deployed. They are of interest for many applications, such as satellite antennas or solar reflectors. Often times these ultra light-weight antennas are made of thin membranes. These properties of the membranes make them suitable for space applications as there are restrictions on the payload size and weight that can be launched into space. The Echo II balloon (ca. 1960) seen in Figure 2(a) was slightly more than 30 m in diameter, consisting of 12 micron Mylar coated with 2000 Angstrom (Å) vapor-deposited aluminum[3]. The 1996 Inflatable Antenna Experiment (IAE) can be seen in Figure 2(b).
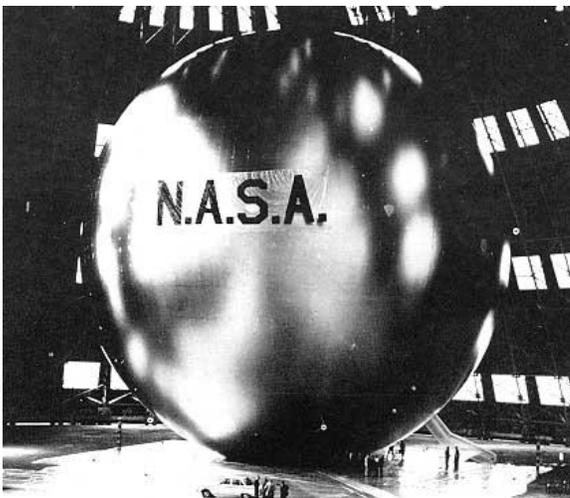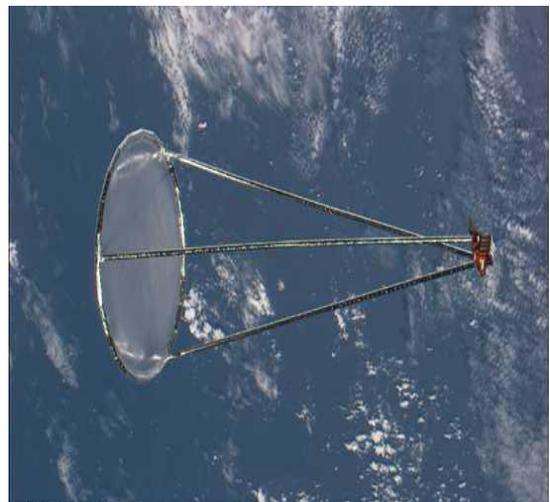
(a)   (b)

Figure 2: (a) Echo II balloon[4]; (b) IAE on orbit[5]

Stress Coatings

Stress in thin membrane mirrors is of importance because it affects the shape and other mechanical behaviors. Typically these membranes are coated, mainly to provide a reflective surface. Stresses developed in the coating mainly depend on the amount of restraint supplied by the substrate, which is used to derive the shape of the mirrors, against the expansion or contractile nature of coating. When such coatings are applied to a substrate with compliant properties, one could also obtain a surface with curvature. This curvature is obtained when the forces in the coating and in the substrate form a couple or moment. These stress coatings could be used to alter the shape of substrates with small thicknesses. The intrinsic coating stress can be achieved through two ways during coating application:

 a) by packing particles of the coating very densely, or

 b) by packing particles of the coating sparsely.

When the coating particles are packed very densely, they will try to reach equilibrium position. Inter-particle repulsion forces develop and two neighboring particles will repel each other (expansive), thereby producing compressive stresses in the coating. Similarly, when the coating particles are sparsely packed, they will attract each other (contractile) producing tensile stresses. This effect is illustrated in Figure 3.

Inter-particle distance is < normal	Inter-particle distance is normal	Inter-particle distance is > normal

	Coating	
	Substrate	

Coating is expansive and results in compressive stresses	Coating has no stresses	Coating is contractile and results in has tensile stresses
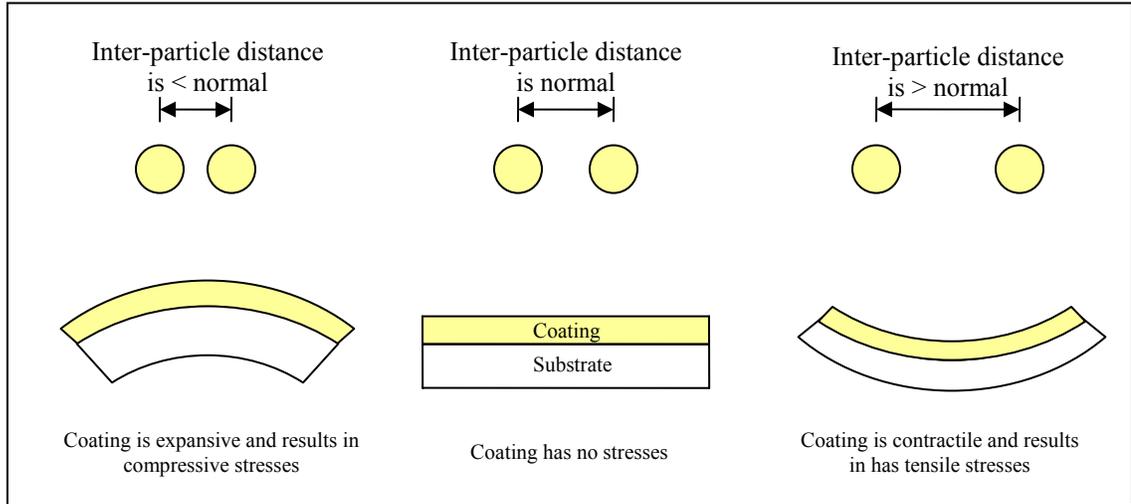
Figure 3: Stress formation in the coating

The type of coating (expansive or contractile) makes a membrane softer or stiffer. A stiffened membrane is one which has a contractile (tensile) coating. As the membrane is stiffened by the tensile coating stress, it will have less deflection to a particular pressure than it would have had when it was uncoated. On the other hand, a softened membrane will have more deflection to same uniform pressure than it would have when it was uncoated.

From basic vibration theory, we can say that a stiffer membrane will have higher natural frequency. This behavior can be thought to be similar to that of a guitar string. As one tightens (tensions) the string, its frequency increases. Similarly, when the tension in the string is decreased, its natural frequency decreases. Similar behavior can be expected when the membrane is coated with the expansive or contractile coating. "Since the stress in the coating cannot be directly controlled (there is no 'stress knob'), it is difficult to 'dial in' the exact desired stress."[6] Hence, the aim of this work is to understand how coatings affect the static and dynamic behavior of membranes.

3. ANALYTICAL SOLUTION

Before any experimental or FEA analysis was done, an analytical approach was taken towards the problem at hand. A membrane, with coating applied, behaves as a plate (it gains rigidity). Hence, a plate formulation could be used to model a coated membrane, by including the small resistance to bending in the formulation. This is explained in the following sections.

Analytical solutions for the static deflection theory and frequency behavior of laminated (coated), as well as non-laminated (uncoated), plates were obtained. For verifying the FEA results with analytical solutions for static tests (discussed in Chapter 4), various theories were considered and their results were matched with the FEA solutions.

Classical Plate Theory

Consider a circular plate of radius 'a' and thickness 'h' (see Figure 4). This plate is clamped at the edges and applied with a uniform lateral pressure 'p' which results in an out-of-plane deflection 'w_0' at the center of the plate.
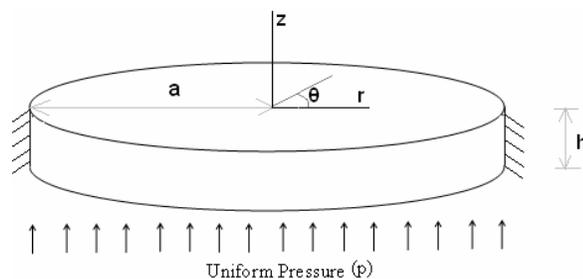
Figure 4: Non-laminated plate definition sketch

Classical plate theory applies to deflections of plates when the deflection is small as compared to the thickness of the plate itself, or: [7]

$$w_0 \leq 0.2h \qquad (3.1)$$

Large Deflection Plate Theory

In classical linear plate theory straining of the mid-plane of the plate is not considered. When the deflections are large, i.e., when

$$w_0 > 0.2h \qquad (3.2)$$

straining of the mid-plane is important to consider. Inclusion of mid-plane strains leads classical plate theory to Large Deflection Plate theory (LDT).

In the case of very thin plates, the out-of-plane deflection may become very large in comparison with the thickness. In such cases, the resistance of the plate to bending can be neglected, and can be treated as a flexible membrane[7]. The general equations for such a membrane are obtained from the two equations of equilibrium modified by A. Nádai[7] as follows:

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \frac{u}{r^2} = -\frac{1-v}{2r}\left(\frac{dw}{dr}\right)^2 - \frac{dw}{dr}\frac{d^2w}{dr^2} \qquad (3.3)$$

$$\frac{d^3w}{dr^3} + \frac{1}{r}\frac{d^2w}{dr^2} + \frac{1}{r^2}\frac{dw}{dr} = -\frac{12}{h^2}\frac{dw}{dr}\left[\frac{du}{dr} + v\frac{u}{r} + \frac{1}{2}\left(\frac{dw}{dr}\right)^2\right] + \frac{1}{Dr}\int_0^r prdr \qquad (3.4)$$

Where w is out of plane deflection, u is radial coordinate, v is Poisson's ratio, and D is flexural rigidity of the plate

The first approximation for dw/dr is

$$\frac{dw}{dr} = C\left[\frac{r}{a} - \left(\frac{r}{a}\right)^n\right]$$ (3.5)

where C is a constant and w vanishes for r=0 and r=a in compliance with the boundary conditions of clamped edges. As discussed before, plates of very small thickness can be modeled as membranes. Left-hand side of Equation (3.4) adds bending resistance terms in the equation. As membranes lack flexural rigidity, left-hand side of the Equation (3.4) can be replaced by zero. Deflection at the center (w_0) of the plate is given by[7]:

$$\frac{w_0}{h} + 0.583\left(\frac{w_0}{h}\right)^3 = 0.176\frac{p}{E}\left(\frac{a}{h}\right)^4$$ (3.6)

If the ratio of deflection at the center to the thickness of the plate is more than 2, an approximate solution of the resulting equations is obtained by neglecting the first term on the left-hand side of Equation (3.6) as

$$\frac{w_0}{h} \ll 0.583\left(\frac{w_0}{h}\right)^3$$ (3.7)

After solving Equations (3.5), the following expression for the maximum out-of-plane deflection w_0 at the center of the membrane is obtained.[7]

$$w_0 = 0.665a\sqrt[3]{\frac{pa}{Eh}}$$ (3.8)

where p is out-of-plane pressure applied and E is Young's modulus

A similar solution of the same problem was given by H. Hencky[7]

$$w_0 = 0.662a\sqrt[3]{\frac{pa}{Eh}}$$ (3.9)

Equation (3.9) was used in the present work to calculate the analytical solution for static behavior of laminated and non-laminated plates. An effective Young's modulus was calculated for laminated plates as explained in following section.

Structurally Orthotropic Plates

A laminated plate was considered and an analytical solution for an effective modulus was obtained. Because of the presence of two adjoining sections of different material properties, the overall plate becomes 'structurally orthotropic' even though the coating and substrate materials are isotropic themselves. Hence, a combined flexural rigidity of the plate was calculated. Figure 5 provides a definition sketch of the laminated plate.
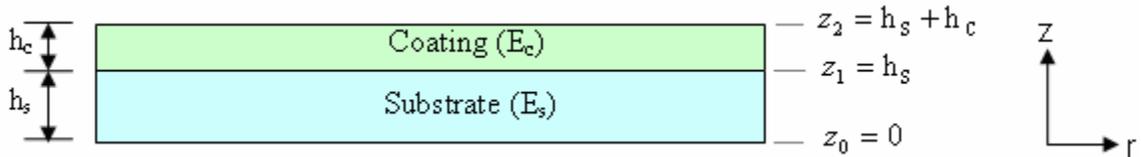
Figure 5: Coating and substrate in a laminated plate

In this case, the coating modulus E_c is different from the substrate modulus E_s. Notice that, the flexural rigidities of coating and substrate will generally be different. The effective flexural rigidity was calculated from the following formula.[8]

$$\text{Effective flexural rigidity} = D^* = \frac{A \cdot C - B^2}{A} \tag{3.10}$$

where

$$A = \frac{E_s}{1 - v_s^2}(z_1 - z_0) + \frac{E_c}{1 - v_c^2}(z_2 - z_1) \tag{3.11}$$

$$B = \frac{E_s}{1-v_s^2} \frac{\left(z_1^2 - z_0^2\right)}{2} + \frac{E_c}{1-v_c^2} \frac{\left(z_2^2 - z_1^2\right)}{2} \qquad (3.12)$$

$$C = \frac{E_s}{1-v_s^2} \frac{\left(z_1^3 - z_0^3\right)}{3} + \frac{E_c}{1-v_c^2} \frac{\left(z_2^3 - z_1^3\right)}{3} \qquad (3.13)$$

v_s & v_c are Poisson's ratios for the coating and substrate, respectively.

An effective Young's modulus E* is calculated by

$$E* = \frac{12 \cdot D * \left(1 - v^2\right)}{h^3} \qquad (3.14)$$

where flexural rigidity of the plate is given by

$$D = \frac{Eh^3}{12\left(1 - v^2\right)} \qquad (3.15)$$

where v is Poisson's ratio.

Frequency Behavior of Plates

Background

As previously discussed, knowledge of stresses in the coating is very important in predicting the curvature of the resulting mirror. Apart from a static analysis (bulge test), a frequency analysis could be carried out in order to determine the coating stresses. Stresses in the coating can be determined by looking at the variation in frequency of the vibration of membranes due to the applied coating.

Isotropic Plate

Consider a circular plate of radius a, where r and θ are polar coordinates, ω is the circular frequency, and w is the total displacement in the z-direction (see Figure 4). For free vibrations, the differential equation is given by[9],

$$D\nabla^4 w + \rho h \frac{d^2 w}{dt^2} = 0 \qquad (3.16)$$

where $\nabla^4(\ ) = \dfrac{\partial^2}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial}{\partial r} + \dfrac{1}{r^2}\dfrac{\partial^2}{\partial^2\theta}$,

ρ is the density of the plate material, and t is the time.

Solving the Equation (3.16) for axisymmetric vibration and applying boundary conditions for a circular plate with clamped edges, the following solution is obtained:[9]

$$\omega_i = \frac{(\beta_i a)^2}{a^2}\sqrt{\frac{D}{\rho h}} = 2\pi f_i, \qquad i = 0,1,2,..\infty \qquad (3.17)$$

where for 1st fundamental mode of vibrations $\beta_0 a = 3.1961$. Then the 1st fundamental cyclic frequency of free vibration can be calculated from Equation (3.17) formula as:

$$f_0 = \frac{1}{2\pi}\frac{(3.1961)^2}{a^2}\sqrt{\frac{D}{\rho h}} \qquad (3.18)$$

The frequency of a laminated circular plate (coated membrane) can be calculated using the Equations (3.18). To solve for D* in Equation (3.14), h=h$_c$+h$_s$ was used.

Frequency Variation due to Coating Thickness and Stress

Of interest here are effects the coating thickness and stress in the coating have on the frequency of the laminated plate. Frequency 'f 'of free vibrations of a beam is proportional to the square root of the stiffness over mass ratio:

$$f \sim \sqrt{\frac{k}{m}} \qquad (3.19)$$

where k and m are bending stiffness and mass of the beam, respectively.

For the case at hand, the bending stiffness will be replaced by the flexural rigidity of the circular plate. The frequency of vibration of a beam is also related to the tension in the beam (frequency of a guitar string increases as one tightens it). Hence, the frequency of a laminated plate is expected to be related directly to pre-stress and the thickness of the lamination (coating) and inversely related to the plate mass.

4. FINITE ELEMENT ANALYSIS

Overview on FEA Model

Finite element analysis (FEA) becomes necessary to use in this research as there is no direct way to measure stress in the coatings experimentally. The FEA model mainly consists of an axisymmetric shell model. In order to simulate the stresses in the coating, as well as substrate pre-stress, a coefficient of thermal expansion (CTE) was assigned to the elements of the model. As CTE used here has no physical meaning in the problem at hand, it will be called as stress fitting parameter (SFP). With applied 'temperature field' and fine adjustment of the SFP value, desired pre-stress and stress values can be obtained. This is done in order to mimic experimental results and then back out the values for other parameters which can not be calculated from the experimental work alone. A schematic diagram for the FEA model used in this work can be seen in Figure 6.
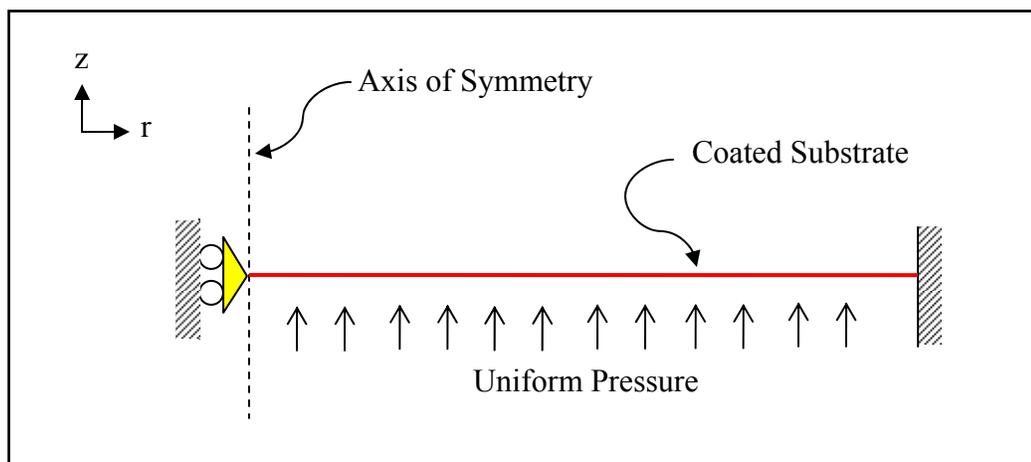
Figure 6: Schematic diagram for FEA model

As the thickness of the membrane is very small, the FEA model with elements of plate/shell formulation can be used for simulating the membrane.

ABAQUS Model Parameters

A FEA model was prepared in ABAQUS/CAE 6.5-1. Two input files were used, one for the uncoated membrane model and another for the coated membrane model.

Table 1: Parameters used for ABAQUS models

Parameter	Substrate	Coating
Young's Modulus (E)	2.5×10^9 Pa	1.5×10^{11} Pa
Density (ρ)	1420 kg/m^3	8200 kg/m^3
Poisson's ratio (ν)	0.34	0.3
Thickness (t)	12.7×10^{-6} m	1.1×10^{-7} m (maximum)
Temperature (K)	1 degree	1 degree

Mesh convergence studies for deflection at the center of the plate and for the first natural frequency of vibration were carried out and it was observed that use of 161 nodes gave sufficiently close approximate solution. A convergence graph can be seen in Figure 7 for the static problem.
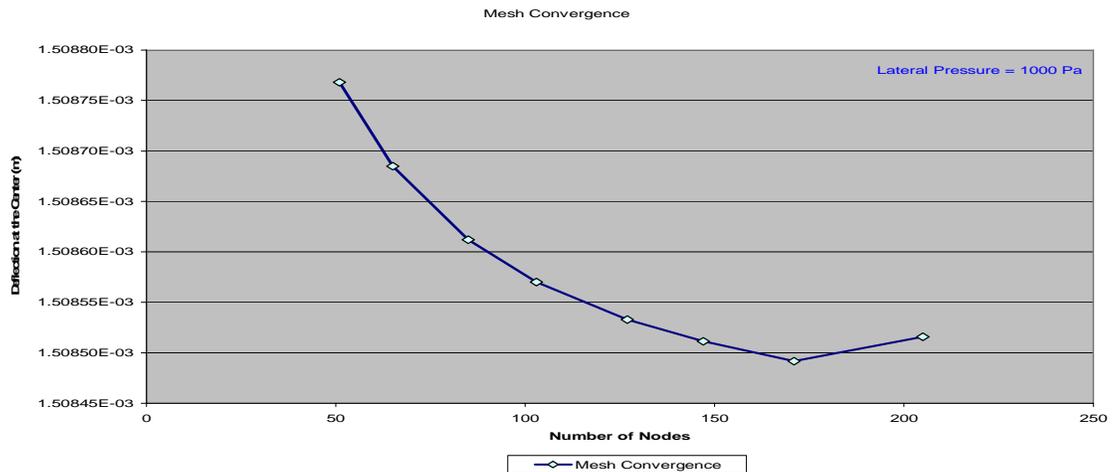
Figure 7: Mesh convergence for static deflection under pressure loading

Table 2: Data for mesh convergence

Number of nodes	Deflection at the center (m)	Percentage Error (%)	Frequency (Hz)	Percentage Error (%)
51	1.50877E-03	-	182.08	-
65	1.50869E-03	-0.0055	182.09	0.0055
85	1.50861E-03	-0.0048	182.09	0
103	1.50857E-03	-0.0028	182.09	0
127	1.50853E-03	-0.0025	182.09	0
147	1.50851E-03	-0.0014	182.09	0
161	1.50849E-03	-0.0013	182.09	0
205	1.50852E-03	0.0016	182.09	0

Percentage error was calculated as follows:

$$\text{Percentage error} = \frac{\text{Previous value} - \text{New value}}{\text{Previous value}} \times 100 \qquad (4.1)$$

It can be seen from Table 2 that frequency values converge very fast. The convergence of the displacement values takes more nodes. The ABAQUS model used for both coated and uncoated FE analysis use 161 nodes and 80, 2-D axisymmetric shell elements (SAX2).

Intrinsic Stress Modeling

The axisymmetric model was given a nominal temperature field of +1 degree Celsius. To model pre-stress in the substrate, the substrate was given a negative coefficient of thermal expansion (SFP), thus contracting and resulting in tensile stresses developed in the substrate. The SFP in the uncoated membrane model was adjusted in such a way that it matched with the experimental data.

This adjusted value of SFP was then used for the substrate in the coated membrane model. In order to look at the stiffening effect of the coated membrane solely due to the

addition of coating thickness, coating SFP was first kept to zero (no coating stress) and results were tabulated.

Then, the SFP of coating was adjusted in such a way that it matched with results from coated membrane experiments. Stresses in the coating could then be calculated from the SFP value (or one can just look at the field output values in FEA results). Input files for both the models are included in Appendices – A and B.

While matching the FEA curve with experimental curve, it was difficult to have all the data points match (due to mismatch in the slopes). Hence, a Least Square Method was used to compute the error between FEA and experimental data sets. Several FEA curves were used to match with a particular uncoated membrane experimental result, and one with least error was chosen for coating stress calculations. As slopes of FEA curves did not match with curves obtained from experimental results for coated membrane, curves were matched using a single point. A deflection value corresponding to the pressure of 622.72 Pa (midpoint of pressure range) was selected for matching the curves.

5. EXPERIMENTAL SETUP

Overview of Bulge Test

A bulge test is a type of 'deflection technique' that may be used in determining properties of thin films (coatings and membranes)[10]. Basically, a thin film is pressurized in order to bulge out the film and deflection at a particular point (usually at the center) is noted with respect to its initial (un-pressurized) position. A schematic of a bulge test can be seen in Figure 8. Bulge tests have been proven sufficiently accurate and have been accepted by many scientific organizations[11].
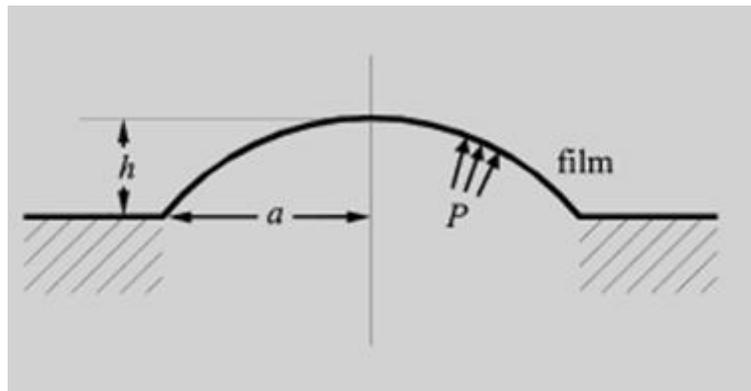
Figure 8: Schematic diagram of bulge test[12]

Specimen Preparation

In this work, membrane specimens were prepared on the MSU campus. 12.7 μm (0.5 mil) thick Kapton membrane was used. During the previous work done by Gunderson et al.[13], mismatch in pretension had led to high of variations in uncoated membrane behavior. A new idea was brought into practice during this current work[13]. An

oversized membrane was glued to a ring of specific weight (actually a bicycle rim). The weight of this ring would be directly related to the tension imparted to the membrane. The ring and membrane assembly would then be placed on a mandrel that would contact only the membrane (see Figure 9) thus pre-tensioning the membrane. The mounting ring (bearing spacer) would then be attached to the tensioned membrane. This method would reduce the uncertainty in and variation of tension in the mounted membrane.
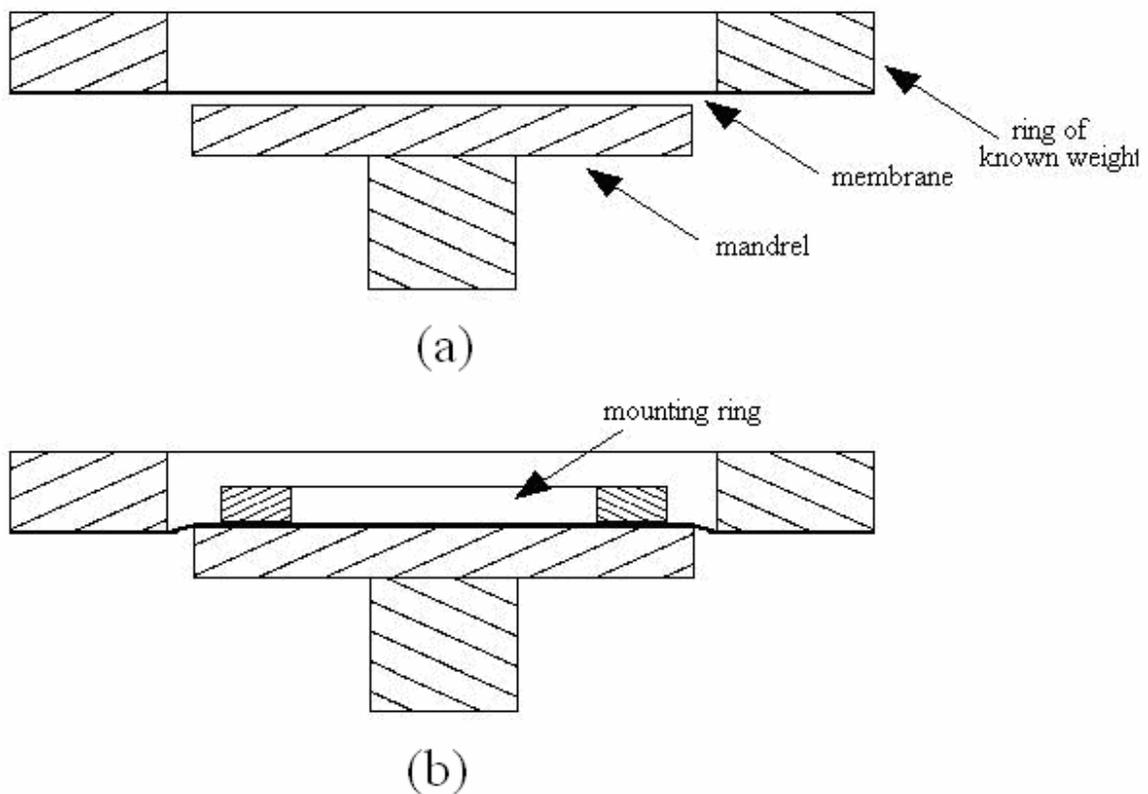
Figure 9: Design for membrane tensioning structure[13]

The membrane attached to the tensioning ring (bicycle rim) can be seen in Figure 9(a). A stretched membrane with mounting ring (bearing spacer) is shown in Figure 9(b). Actual preparation for the specimen is explained as follows.

At first, a piece of membrane was laid down on the table as shown in Figure 10 (a). Care was taken so as not to damage or place fingers on the membrane surface. A bicycle rim (0.55 m diameter, 0.44kg) was then adhered on this membrane using epoxy (ITW Devcon, 2 Ton/clear Weld Epoxy, part no: 47609/31345) as shown in Figure 10 (b).
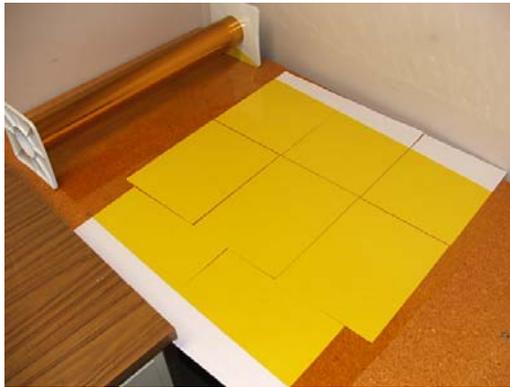
(a)   (b)

Figure 10: Membrane adhered to rim

After adhesive was cured and the unwanted outside portion of the membrane was removed, the rim with adhered membrane was placed on an aluminum mandrel shown in Figure 11.

(a)   (b)

Figure 11: (a) Aluminum mandrel; (b) membrane attached to rim placed on the mandrel

Thrust bearing spacers (Timken Company, part no: TRA3244) were used as mounting rings to make the membrane specimens. The smooth surface of these spacers was made rough using sand-paper, and then cleaned with Acetone before adhering to the membrane using epoxy. Weights were used to put uniform pressure on the rings for 24 hours. One of the bearing spacers and the pressure/adhesion process can be seen in (a) and (b), respectively.

(a)   (b)
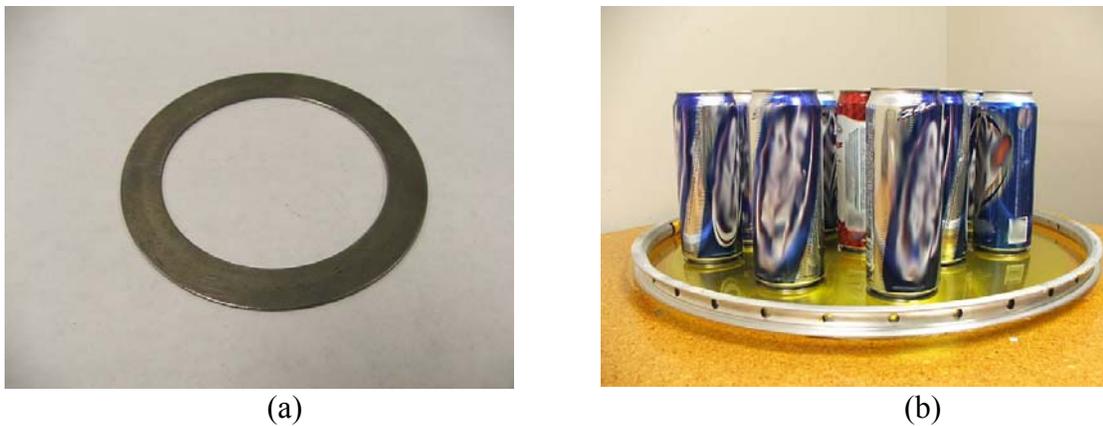
Figure 12: Specimen preparation, (a) bearing spacer; (b) pressure/adhesion process

A complete finished specimen can be seen in Figure 13.

Figure 13: A finished specimen

To analyses the strength of membrane-to-ring bond, a failure test was conducted. A specimen was put under a uniform pressure and released repeatedly to see at what point plastic deformation and failure occurs. Working pressure range for this experiment was from 0 to around 1000 Pascal. At a pressure of ~3000 Pa, the membrane went into plastic deformation. This can be seen in Figure 14.

(a)   (b)
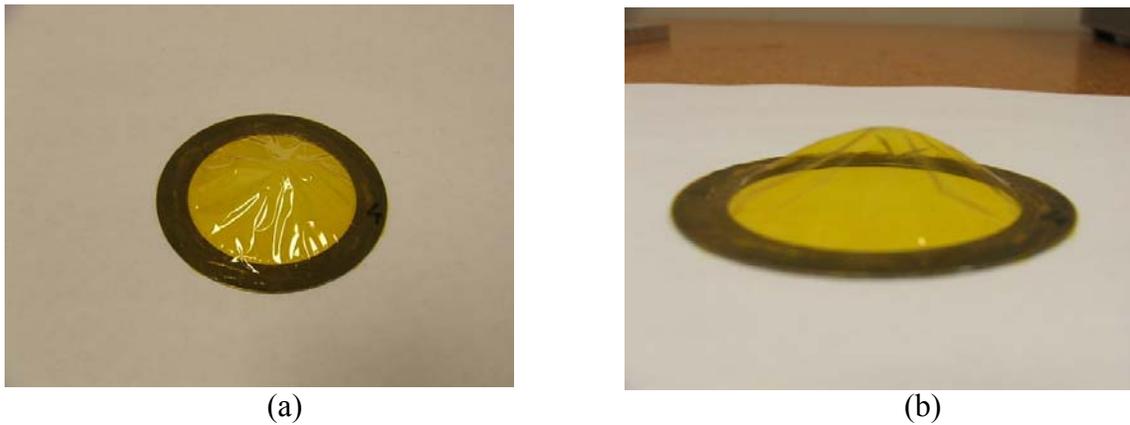
Figure 14: Plastic deformation (a) top view; (b) side view

Final failure occurred at very high pressure (the pressure transducer used could not read such high pressures). Although the membrane tore, the membrane-to-ring bond did not fail (see Figure 15).

Figure 15: Failure due to high pressure

Experimental Setup

Bulge testing equipment in this research work mainly requires a pressure chamber, pressure sensor, air vacuum/pressure pump, and a displacement sensor. The open-ended chamber was made air-tight by placing a circular membrane across the opening. A uniform pressure was created inside the chamber. Air could be either removed or pumped into the chamber to create a bulging out or bulging in of the membrane. In this work, membranes were pressurized by pumping in some air using a syringe. Deflection at the center of the membrane was measured from its initial position for each pressure reading. A laser displacement sensor (Keyence, model: LK-G3001V, resolution: 0.1μm) was used to take deflection readings while a differential pressure transducer (Omega, model: PX655, range: 0-±10 inches of water) was used to measure the pressure. A block diagram of the experimental setup can be seen in Figure 16.
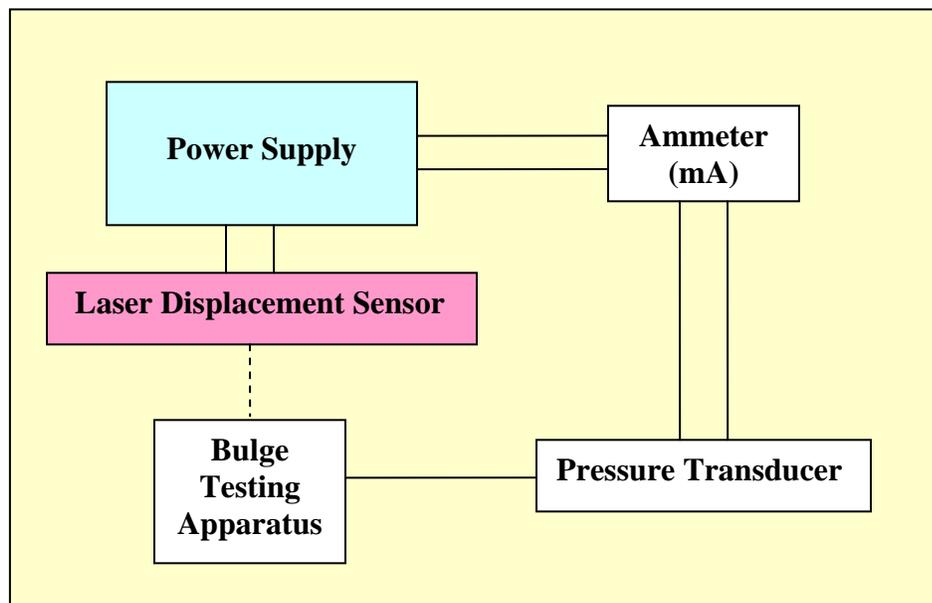
Figure 16: Block diagram for bulge test experiment

The experimental setup can be seen in Figure 17.
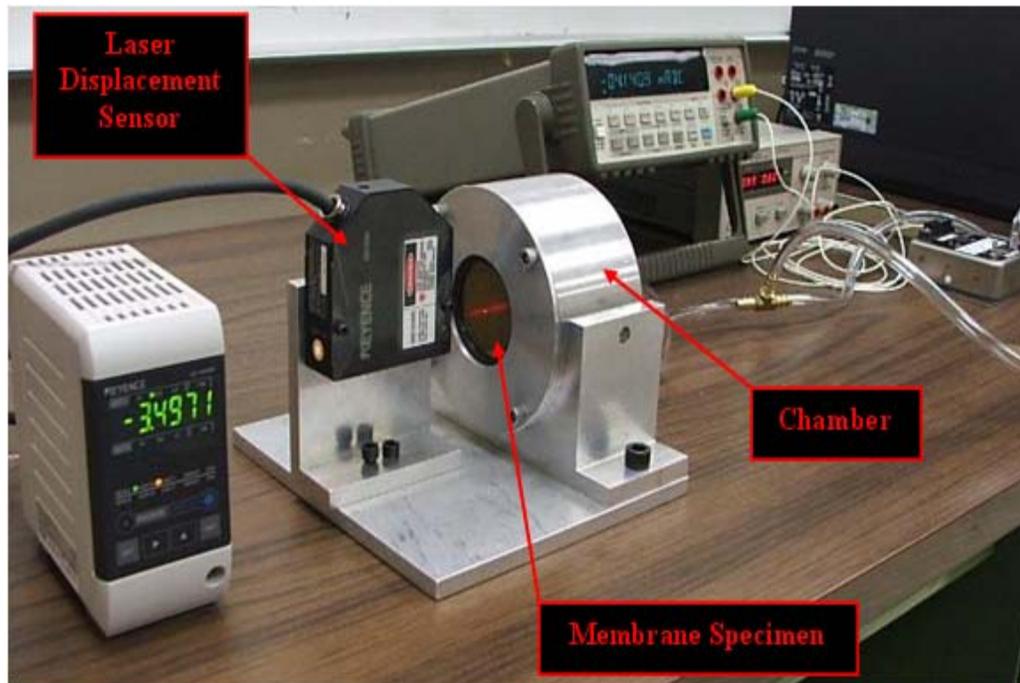
Figure 17: Actual experimental setup

To ensure that the membrane specimen and the chamber form an air-tight space between

them, rubber gaskets and cover plates were used as shown in Figure 18.
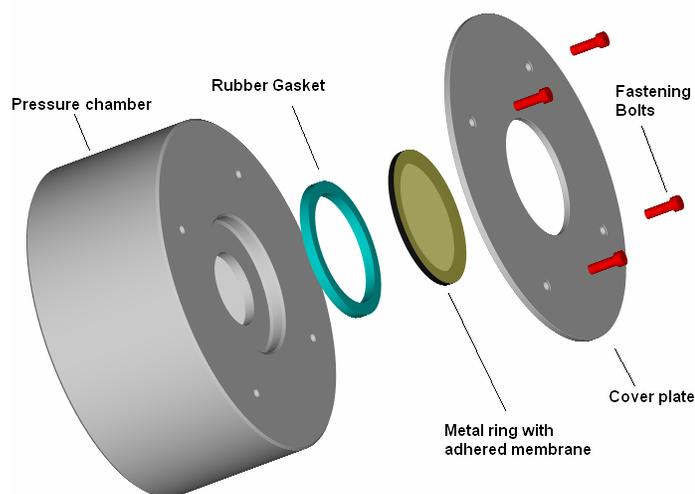
Figure 18: Bulge test apparatus

Experiment Procedure

An uncoated membrane specimen was placed in the bulge test apparatus and an initial (flat membrane surface) displacement reading W_1 was noted. Pressure was then created inside the chamber using a syringe and finely adjusted to get a desired value. A displacement sensor reading W_2 was again noted (Initially, a micrometer was used for the uncoated specimens and adjusted in such a way that the tip of the micrometer just touched the bulged membrane at its center. As it was not easy to set the micrometer to when it 'just touched' the membrane surface, some error in the readings was expected. Hence, four sets of readings were taken and standard deviation was calculated (see Figure 19).
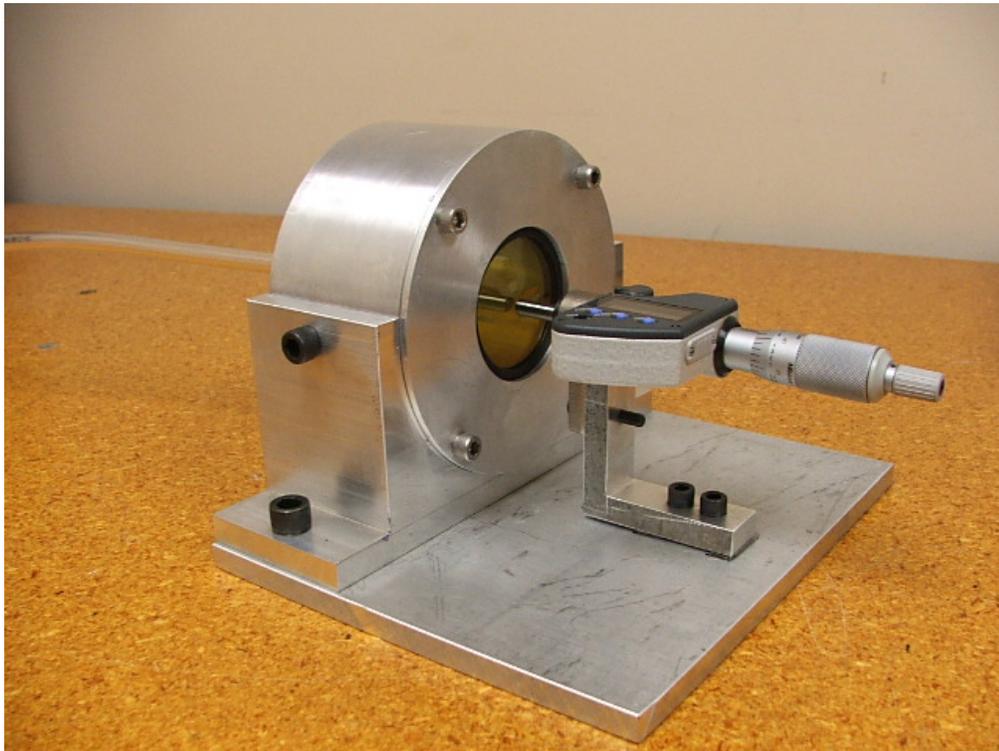
Figure 19: Micrometer arrangement for initial bulge testing

Deflection at the center of the membrane can be calculated as:

$$\text{Deflection at center} = w_0 = W_2 - W_1$$

Four sets of data were taken by repeating the experiment for a range of pressure from 0 to 1089.76 pascal. Standard deviation was calculated and verified that the experiments were repeatable. FE analysis was performed and pressure vs. deflection curves were fit to the experimental results.

After getting good agreement between experimental and FEA results, the specimens were shipped to Alameda Applied Sciences for coating (Ta_2O_5) application (see Table 3 for coating thickness information). Coated specimens were again tested using bulge testing equipment with same range of pressure and deflection values similarly noted. Behavior of a coated membrane was plotted on the same chart with respect to its behavior before coating. Just by looking at these graphs their stiffening or softening behavior could be assessed. After coating was applied on the uncoated membrane specimens, wrinkles were developed on the surface of coated membrane. This suggested that coating stress should be compressive. New FE analysis was done for coated membrane model and results were matched with the coated experimental results to ascertain the stresses in the coating.

Table 3: Coating data

Date Coated	Sample#	Avg. Thickness (Å)
3/2/2006	6,7,8	1100.79
3/3/2006	9,11,12	777.81
3/6/2006	13,14,15	251.69
3/7/2006	16,17,18	604.84
3/8/2006	19,20,21	334.3

6. RESULTS

Analytical and FEA Solutions for Static Analysis

Uncoated Membrane

Analytical solution obtained for uncoated and coated membrane model was solved for

and FEA results were compared (see Table 4).

Table 4: Data for comparison study between LDT and FEA results for uncoated
membrane

	Analytical solution	FEA solution	
Pressure (Pa)	w_0 (mm)	w_0 (mm)	% Error
50	0.5751	0.5771	0.35
100	0.7245	0.7278	0.45
200	0.9128	0.9177	0.53
300	1.0449	1.0510	0.58
400	1.1501	1.1580	0.68
500	1.2389	1.2470	0.65
600	1.3166	1.3260	0.71
700	1.3860	1.3960	0.72
800	1.4491	1.4600	0.75
900	1.5071	1.5190	0.78
1000	1.5609	1.5740	0.83

It can be seen in Figure 20 that an analytically solved solution matches very well with the

solution obtained from FEA results.

Comparison between Analytical and FEA solution for Uncoated Membrane
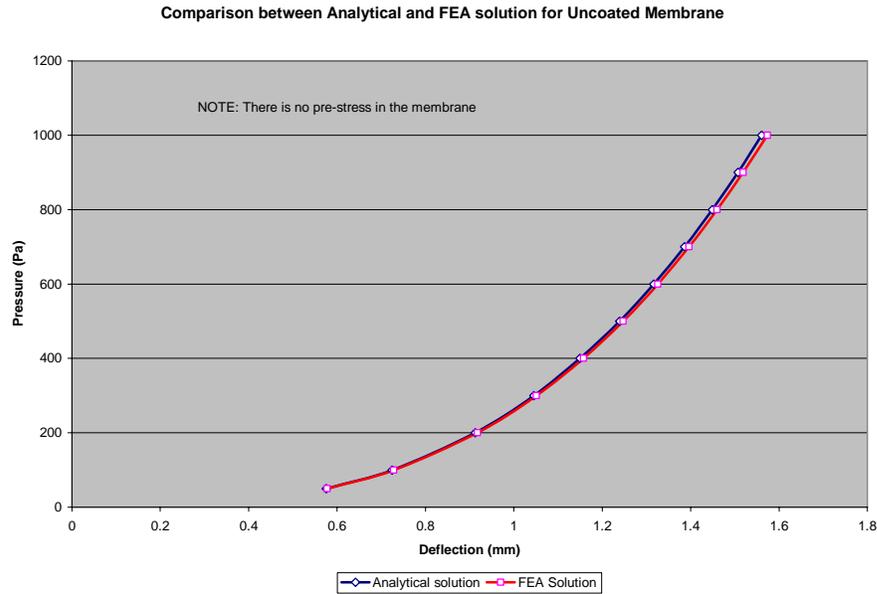
Figure 20: Comparison between analytical and FEA solution for uncoated membrane

Coated Membrane

Similar calculations were done for the coated membrane. After carrying out the finite element analysis, the following results were obtained.

Table 5: Data for comparison study between LDT and FEA results for coated membrane

Pressure (Pa)	Analytical solution w_0 (mm)	FEA solution w_0 (mm)	% Error
50	0.323	0.322	-0.25
100	0.407	0.406	-0.16
200	0.513	0.512	-0.08
300	0.587	0.587	-0.05
400	0.646	0.646	0.00
500	0.696	0.696	0.01
600	0.739	0.740	0.03
700	0.778	0.779	0.06
800	0.814	0.814	0.06
900	0.846	0.847	0.09
1000	0.877	0.877	0.09

It can be seen in Figure 21 that an analytically solved solution matches well with the solution obtained from FEA.
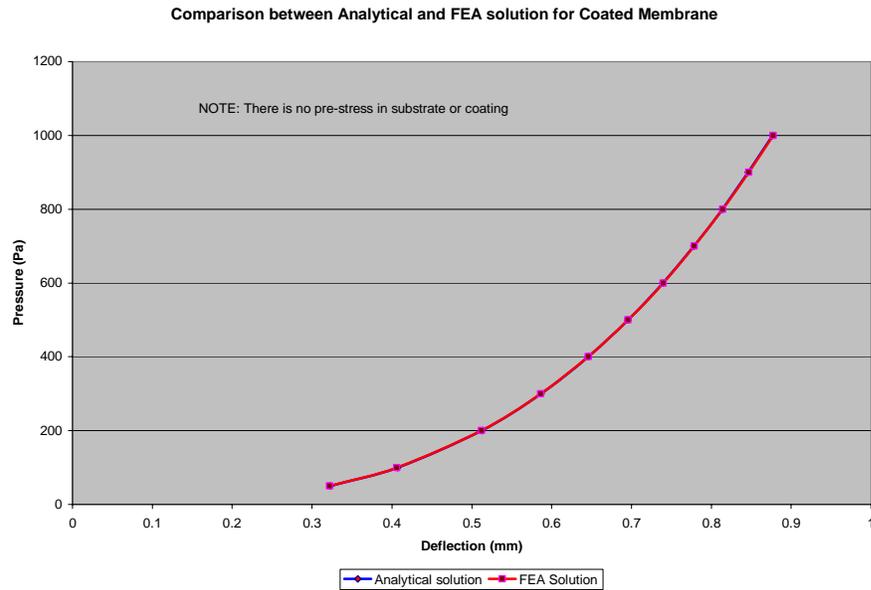
Figure 21: Comparison between analytical and FEA solution for coated membrane

Analytical and FEA solutions for Dynamic Analysis

Uncoated Membrane

Analytical solution for the 1st fundamental frequency of uncoated membrane was found to be $f_0 = 13.035\,\text{Hz}$. This value has been verified with the value obtained by FEA. Data can be seen in Table 6.

Table 6: Analytical and FEA results for uncoated membrane vibration

Uncoated Membrane	Analytical Solution	ABAQUS solution	% Error
1st natural frequency of vibrations	**13.035 Hz**	**13.036 Hz**	**0.007**

<u>Coated Membrane</u>

After carrying out the calculations for analytical solution and performing FEA for the coated membrane model, following results were obtained. Data can be seen in Table 7.

Table 7: Results for coated membrane vibration

Coated Membrane	Analytical Solution	ABAQUS solution	% Error
1st natural frequency of vibrations	**24.772 Hz**	**24.784 Hz**	**0.012**

It can be seen that ABAQUS results fairly matched with the analytical solutions.

<u>Variation in Frequency of Vibration with Thickness of Coating</u>

During the FEA, at first only the variation of frequency with change in coating thickness was investigated, i.e., no stress was present in the coating (but substrate was prestressed). Trend can be seen in the Figure 22.
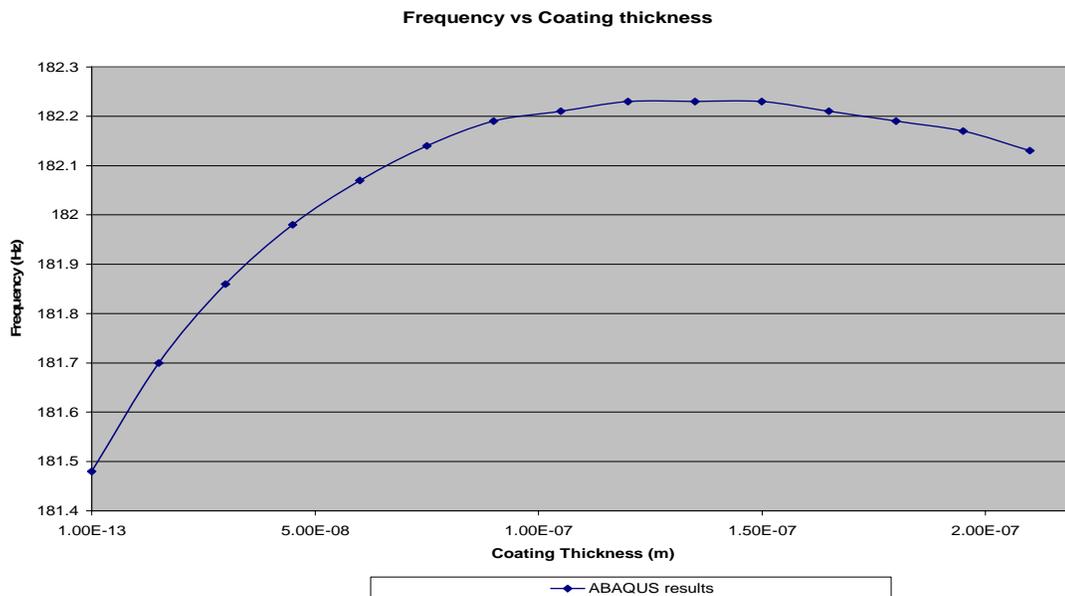
Figure 22: Variation of frequency with increase in coating thickness (no pre-stress)

It can be seen that, at the beginning frequency of coated membrane increases as thickness of coating increases. After coating thickness reaches the value of 0.12 µm, the frequency almost remains constant until the coating thickness becomes 0.17 µm, and then starts decreasing. For an unstressed membrane, the frequency should be a linear function of thickness. The behavior seen in Figure 22 may be a result of the substrate stress.

Next, the variation of frequency with a change in the coating thickness, as well as coating stress (both compressive and tensile), was considered. Results can be seen in Figure 23. This graph was helpful in knowing the range and least resolution of a laser vibrometer that would be needed for this kind of frequency analysis. Frequency of the pre-stressed uncoated membrane is around 182 Hz.

Variation of Frequency with Coating thickness and the Stress in the coating
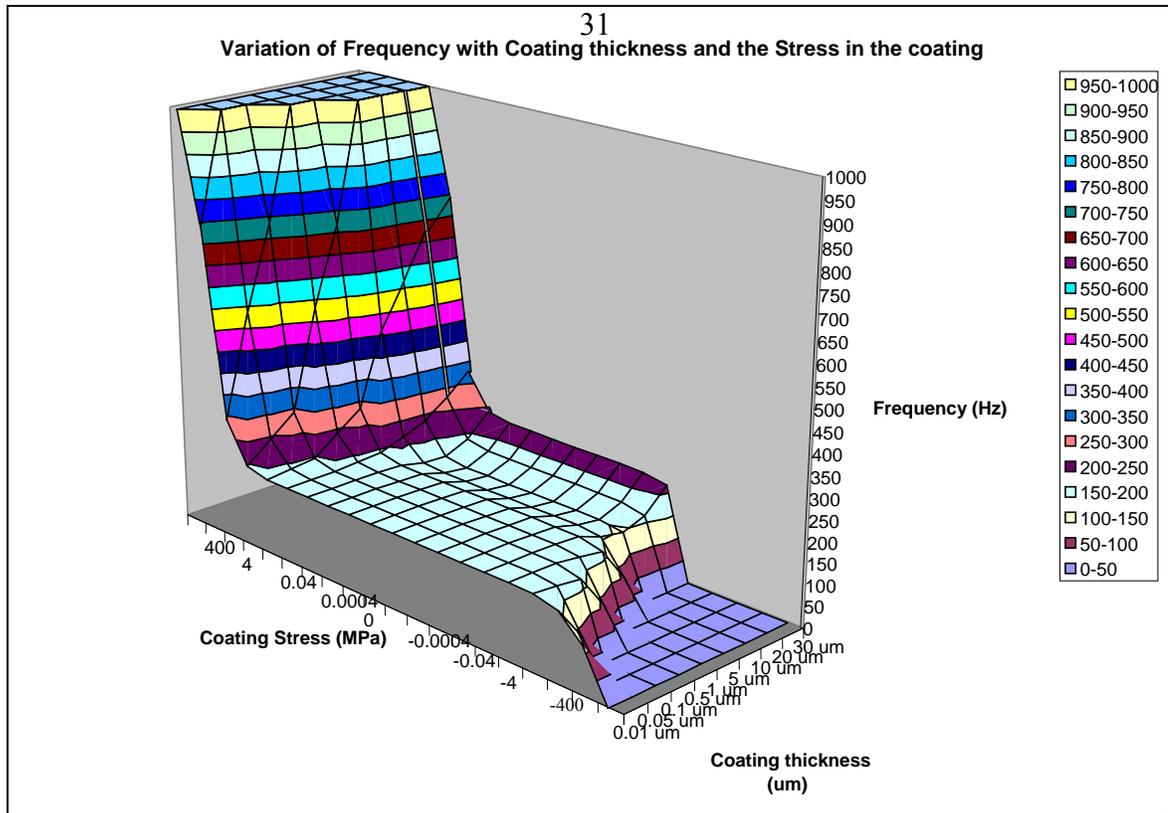
Figure 23: Variation of frequency with coating thickness and stress in the coating

It can be inferred from the above graph that when coating has higher compressive stresses than pre-stress present in the substrate, the frequency of the coated membrane is zero, irrespective of the coating thickness. This can be explained by showing that net axial force in the coated membrane is compressive.

Coating Stress Calculation Procedure

FEA and experimental analysis were done on selected 13 membranes (both uncoated and coated). All the specimens used were from the same pre-tension process. However, some variation in pre-stress was observed and all the uncoated membranes, though similar, behaved slightly differently. Experimental results for all uncoated membranes can be seen in Figure 24.

EXPERIMENTAL DATA FOR UNCOATED MEMBRANES
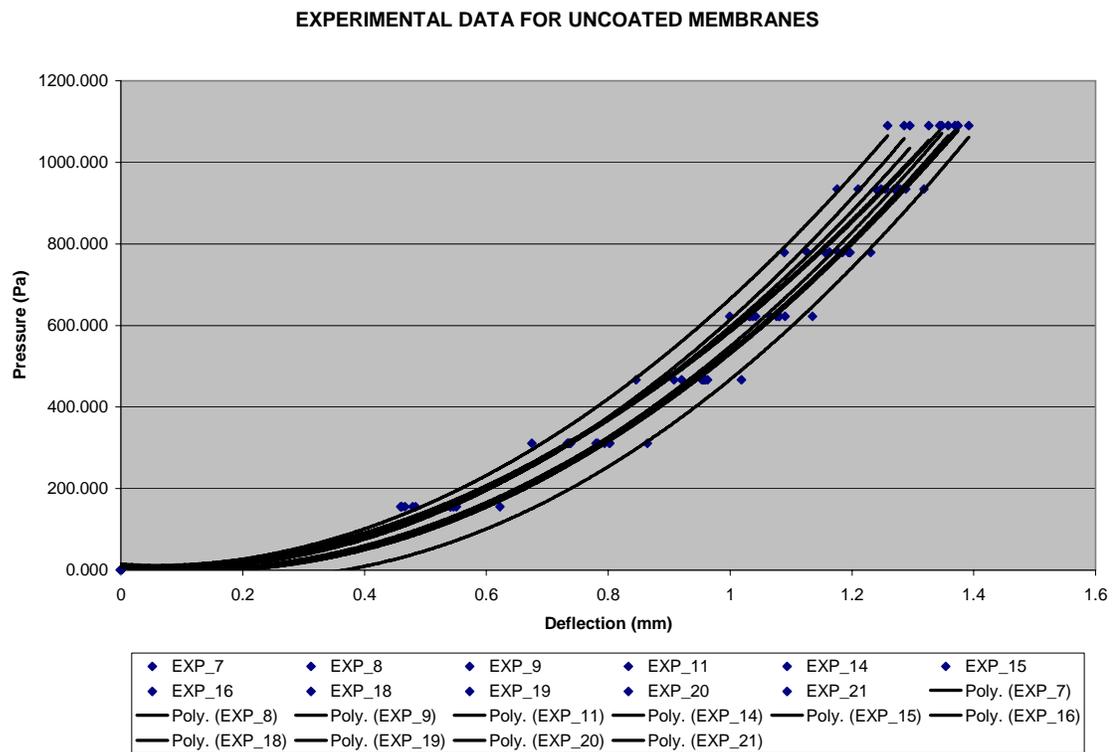
Figure 24: Experimental results for uncoated membranes

As the curves differed from each other, FEA models need to be individually "tuned" to each of the experimental results for uncoated membrane specimens.

When the coated membranes were experimentally characterized and after carrying out FEA on all of the membrane samples, four of the specimens showed very strange behavior (e.g. specimen# 6, 10, 12, and 17). This strange behavior could be because of variation in thickness of Kapton membrane. Such specimens were further omitted from analysis. Hence, this study mainly focuses on specimens # 7, 8, 9, 11, 14, 15, 16, 18, 19, 20 and 21. Experimental results can be seen in Figure 25 for both coated and uncoated specimen #8.
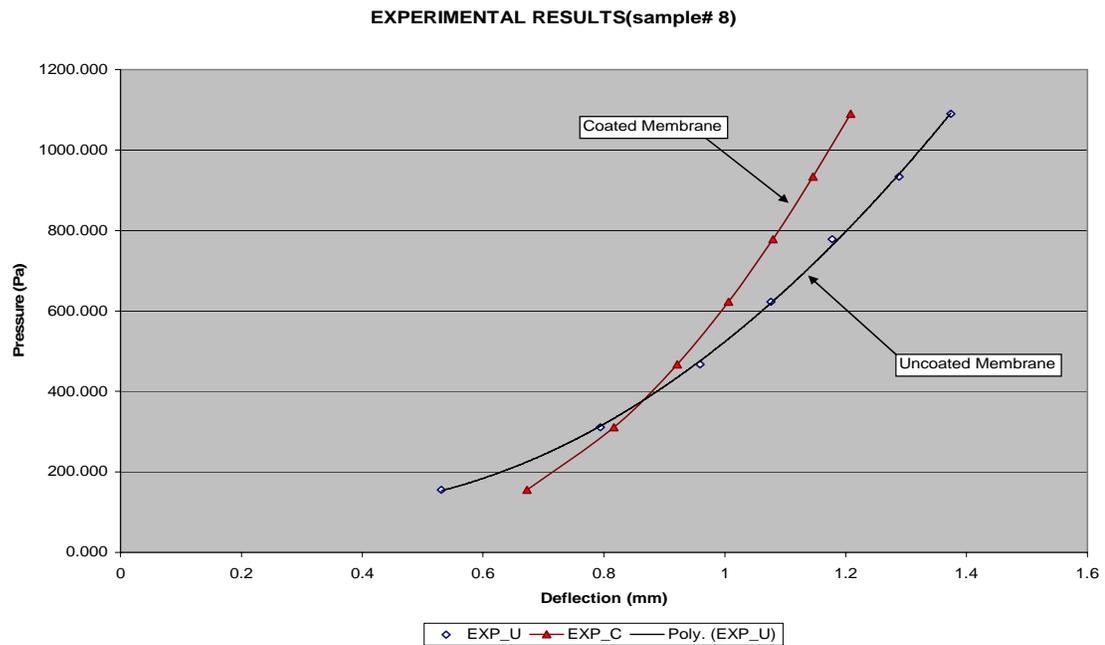
Figure 25: Experimental results for specimen #8

It can be clearly seen that coated membrane shows softening behavior at the beginning and becomes stiffer as the pressure value goes up. Similar trends were observed in other specimens. Reasons behind such a peculiar behavior were investigated

during this study. At first the FEA model was curve-fit to the experimental
uncoated membrane results as shown in Figure 26.

EXPERIMENTAL RESULTS(sample# 8)
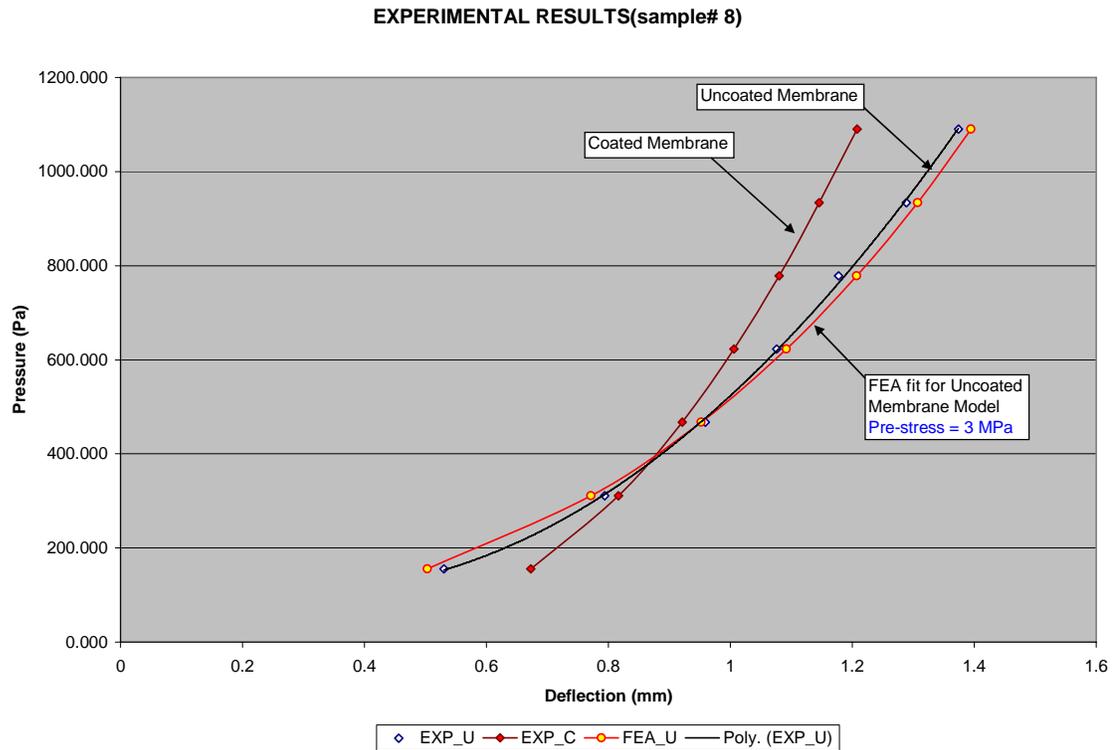
Figure 26: FEA fit for uncoated membrane model for specimen #8

Uncoated membrane model was given a SFP of -0.0008 to get the best fit for
uncoated experimental curve on the basis of Least Square Method. Pre-stress calculated
from the FE results was found to be nearly 3 MPa.

The same value of SFP for the substrate was used in the coated membrane model.
At first, behavioral change of the coated membrane due solely to coating thickness was
observed. Hence in this case of FE analysis of coated membrane model, there was a
substrate SFP (value obtained from FE uncoated membrane model) but SFP for coating is
zero. Results can be seen in Figure 27.

EXPERIMENTAL RESULTS(sample# 8)
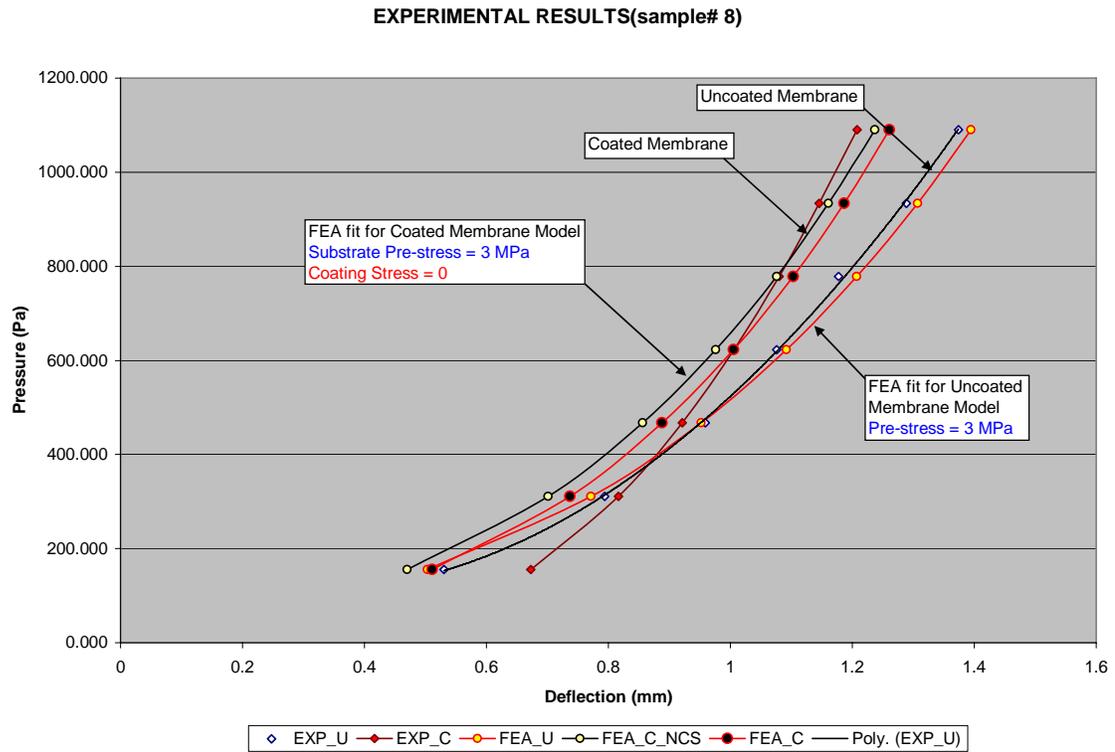
Figure 27: FEA curve for coated membrane model with no coating stress

It is quite clear from Figure 27 that, due to the coating thickness, coated membrane has become stiffer than the uncoated one. Next, the coating is assigned a non-zero SFP value such that FEA results fit with the experimental coated membrane curve. Results can be seen in Figure 28. There is no unique way the FEA results could be curve-fit to coated membrane experimental results as slopes of the curves obtained from experimental and FEA results do not match. Hence, the deflection with respect to the pressure of 622.72 Pa (midpoint of the pressure range) was taken as point for matching of curves. In Appendix – C, details of the matching of FEA curves with experimental results of coated membrane are discussed.

EXPERIMENTAL RESULTS(sample# 8)
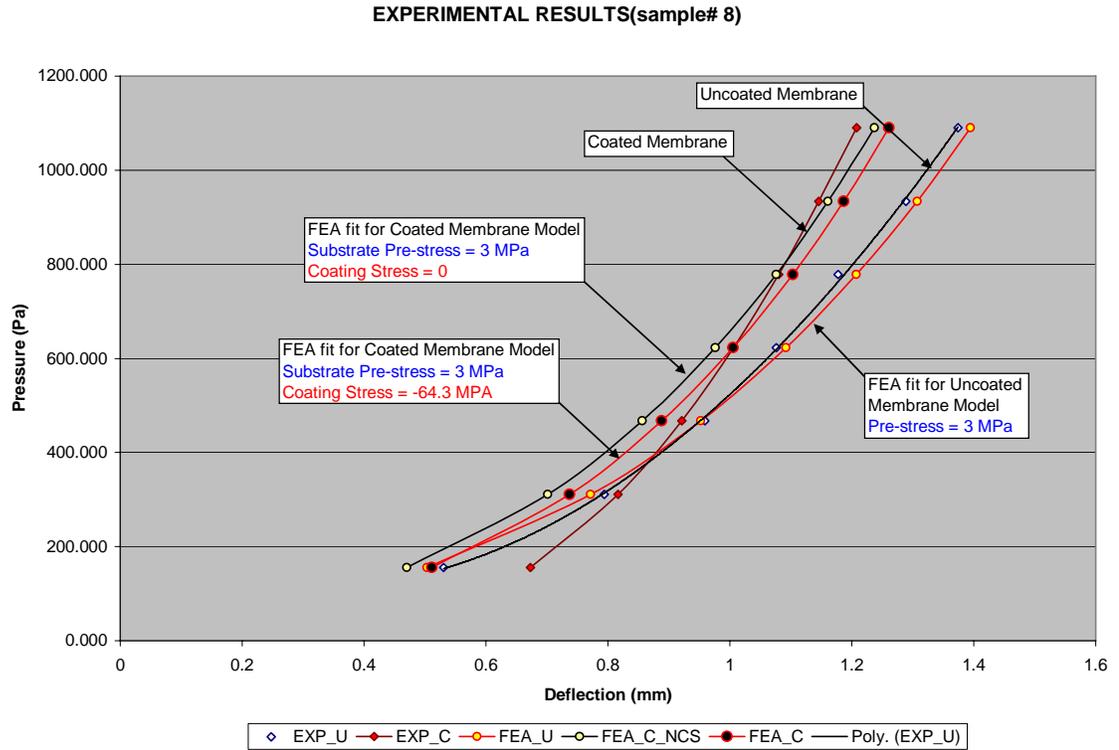
Figure 28: FEA fit for coated membrane results

Coated membrane model with coating stress is slightly softer than coated membrane model with no coating stress. This gives the first impression that coating was an expansive coating (compressive stresses in the coating). The results for all the membrane specimens can be seen in Table 8.

Table 8: Result for coating stress values

Membrane#	Coating Thickness (Å)	Substrate Stress (Pa)	Coating Stress (Pa)
7	1100.79	3.79E+06	-7.93E+07
8	1100.79	3.03E+06	-6.43E+07
9	777.81	4.55E+06	-5.81E+08
11	777.81	3.03E+06	-1.29E+08
16	604.84	3.79E+06	2.36E+08
18	604.84	3.03E+06	2.14E+07
19	334.3	3.03E+06	1.33E+09
20	334.3	3.03E+06	1.41E+09
14	251.69	3.41E+06	2.25E+09
15	251.69	3.03E+06	9.43E+08

It can be seen from these results that as the specimen# 14 & 15, which have least coating thickness, show stiffening effect while specimen #7 & 8, which have highest thickness of coating with compressive stresses in the coating, should show softening behavior. But on the contrary, specimen# 7 shows stiffening effect (see Figure 29).
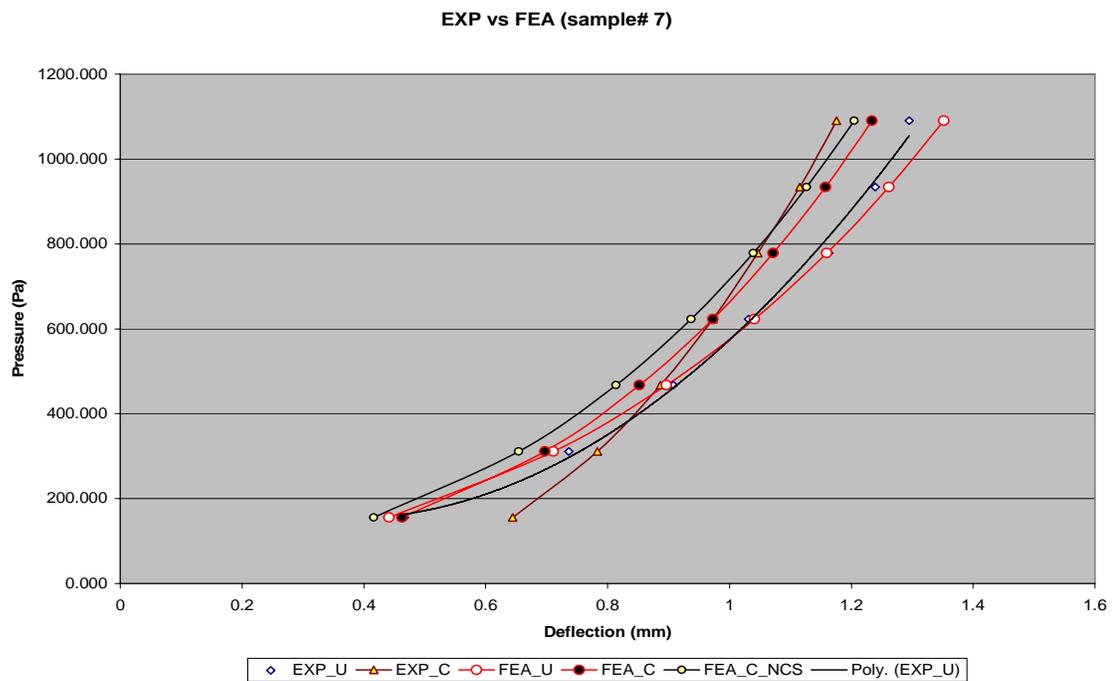
Figure 29: Stiffening effect of specimen# 7

After all the FEA and experimental results were obtained, coupon cut-out tests were performed. At first, two coupons from the membrane specimen with highest and lowest coating thicknesses were cut. Results can be seen in Figure 30 (a) and (b).

(a)   (b)
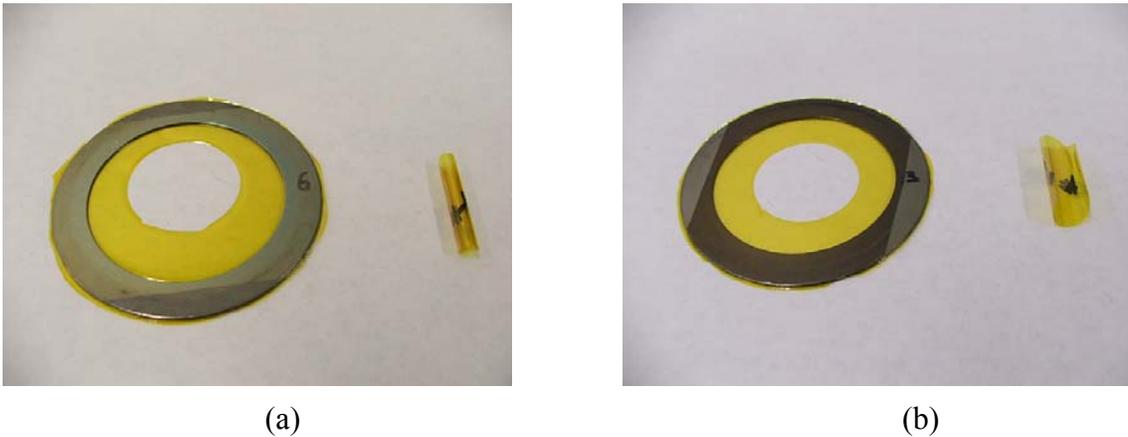
Figure 30: Coupon cut-out test for specimens #6 and #13

Results from coupon cut-out tests are very encouraging. As can be seen in Figure 30 (a), coated membrane specimen #6 has highest coating thickness and coupon cut from it has curled up much more than coupon from specimen #13 (see Figure 30(b)), which has least coating thickness. Coupon cut-outs from both specimens have curled with the coating side on the convex portion (see Figure 3), indicating good agreement with the type of coating behavior observed from experimental and FEA solutions. Results for coupon-cutout tests for all other coated membrane specimens can be seen in Figure 31. After careful examination it can be concluded that all the specimens have actually, expansive coating, i.e. compressive stresses in the coating. Specimens with higher coating thicknesses have shown compressive stress in the coating while the specimens with lesser coating thickness have failed to show compressive coating stresses. This was not understood.
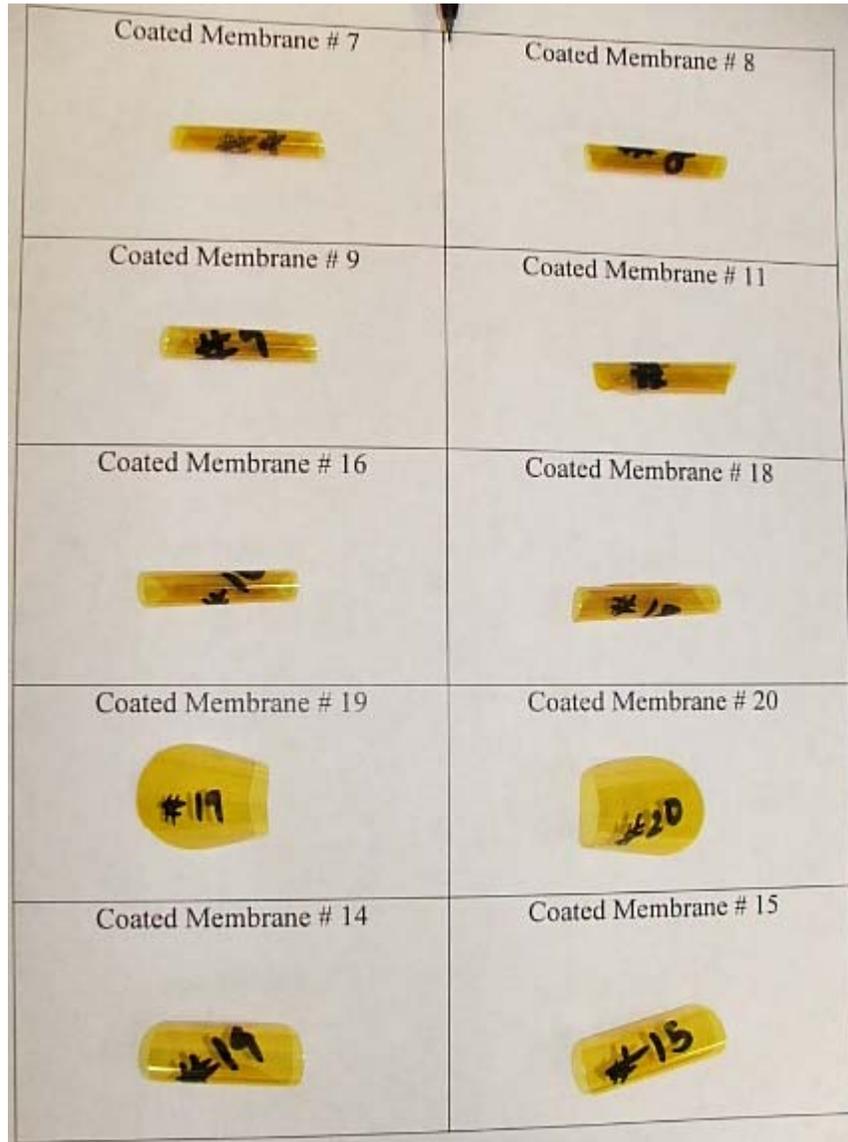
Figure 31: Results of coupon cut-out tests

It was noticed that all the coated membrane specimens have curled with their coating side on convex side. This suggests that coating indeed had compressive stresses.

The existence of compressive stresses in the coating can be again proved by looking at the configuration of coated membrane surface after they were got back from coating application. Coated membrane specimen# 6 (see Figure 32), which has highest coating thickness, was noticed to be having highest amount of wrinkles. This is nothing but an indication that coating must have been trying to expand (as pre-stressed substrate did not let this happen) there by wrinkling the surface.

Figure 32: Wrinkles on coated membrane specimen# 6

7. CONCLUSION AND RECOMMENDATION

Observations

During the experimental and FE analyses, the following observations were made:

1) During the sample preparations, it is necessary to have perfectly flat surface which the membrane is laid on. Otherwise it could lead to uneven pre-tension.

2) Continuously varying air pressure inside the building makes it very hard to maintain precise value of pressure while doing bulge tests on the specimens.

3) Use of micrometer during the uncoated membrane experiments has contributed to some errors in the deflection readings as it was hard to see when micrometer tip 'just touches' the membrane surface. Laser Displacement Sensor is ideal for the work at hand.

4) Unavailability of the exact value for Young's modulus of coating material used, i.e. Tantalum Oxide (Ta_2O_5), has led to further uncertainty in the obtained results.

5) As slopes of FEA curve and the curve obtained from experimental results for coated membrane differ considerably, they intersect at only one point. Matching of two curves using only one point as a basis may not be very convincing.

6) Coated membrane samples had developed wrinkles after coating applications. This means that, pre-stress in the substrate was not high enough to prevent coating from buckling. This demand for higher pre-stress for future work.

Conclusion

Static deflection test during this work have shown a good agreement with the FEA results, particularly for uncoated membrane behavior. Static deflection tests, in themselves, are very delicate to perform and are prone to various kinds of errors. However, a reasonably consistent estimate of stress in the coating was obtained in this work. Vibration tests to determine coating stress were not performed, but analysis show that this method has potential as a test method.

Recommendations

As explained before, variation in air pressure inside the laboratory needs to be minimized. This may be achieved by performing experimental work in a controlled environment (for example, enclosed chamber housing the bulge test equipment).

A more controlled system should be used for pre-tensioning the uncoated membranes. This may be achieved by either using heavy pre-tensioning ring or by using a number of pre-tensioning rings (of different diameters). Hence, instead of pre-tensioning the membrane only once, it could be pre-tensioned more than once, subsequently minimizing the error in pre-stress.

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APPENDICES

APPENDIX A

FLOWCHART FOR THE FEA AND EXPERIMENTAL WORK

Appendix − A**:** Flowchart for the FEA and experimental work
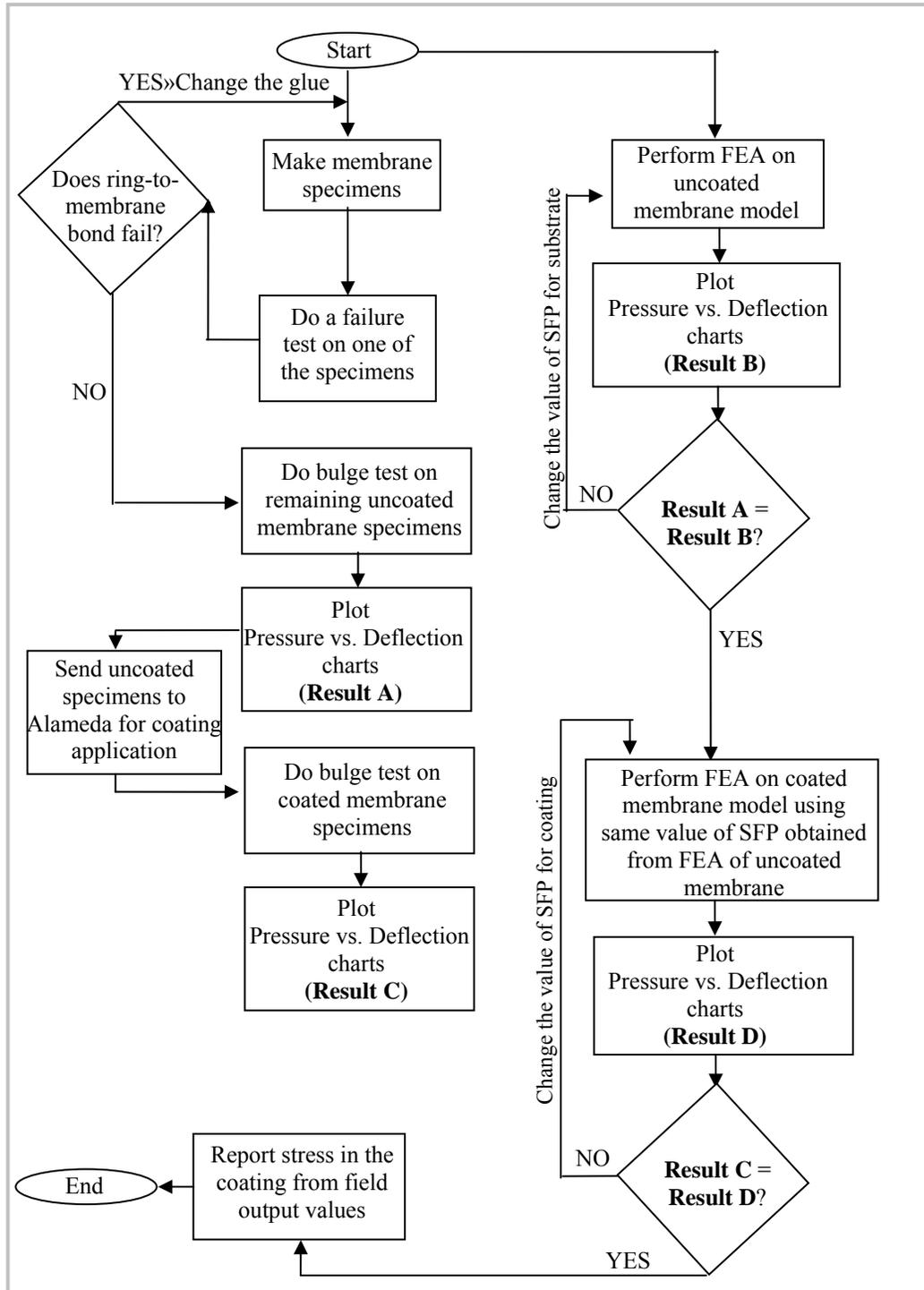
APPENDIX B

CURVE FITTING PROCEDURES AND ISSUES

Appendix – B: <u>Curve Fitting Procedures and Issues</u>

Slope of the FEA curve for the coated membrane model would ideally be matched with the slope of curves obtained from experimental results for coated membrane. In order to do so, Young's modulus of the coating material required a higher value than the nominal value of 150 GPa (this made coated membrane model stiffer). Results can be seen in Figure C1.

EXPERIMENTAL RESULTS(sample# 8)
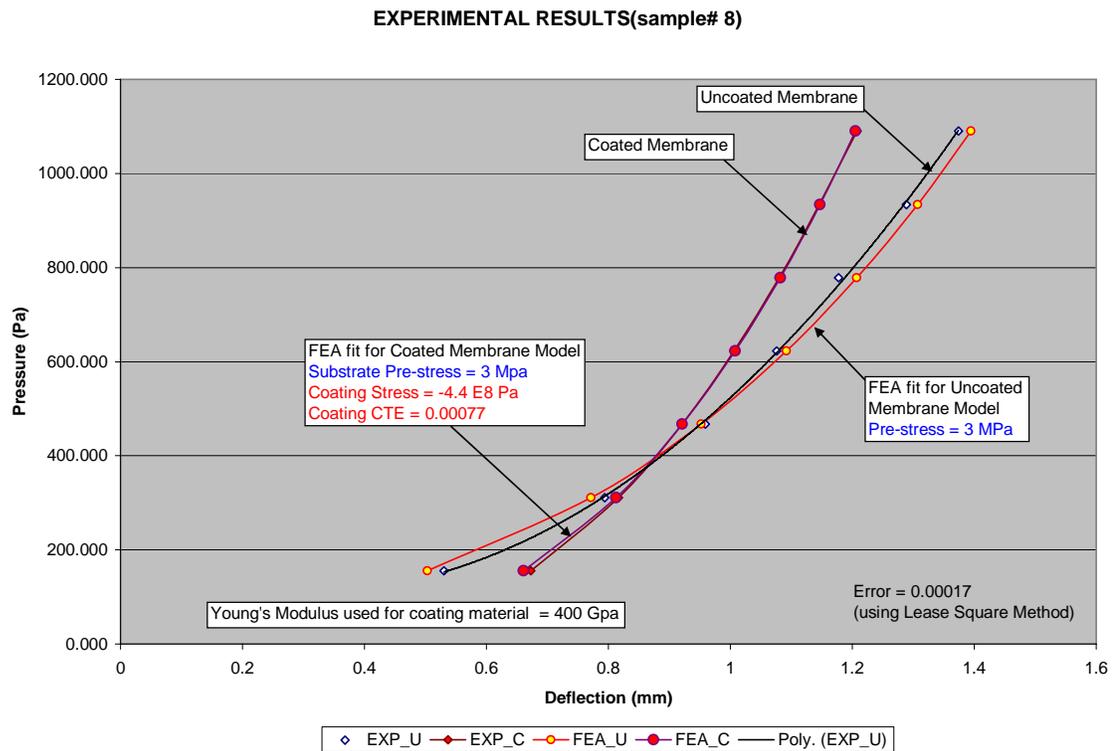
Figure C1: FEA curve fit for coated membrane model

It is observed that the FEA curve matched very well with curve obtained using results obtained from coated membrane experiments. The coating stress value obtained by using the higher value for Young's modulus (400 GPa) is almost 7 times higher than that would

have obtained using the value provided by Alameda Applied Sciences which was 150 GPa. Also the Young's modulus of bulk Tantalum is 186 GPa[1]. Hence, the value provided by Alameda (150 GPa) seems reasonable and was used for the results obtained in this thesis work.

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[1] http://www.matweb.com/search/SpecificMaterial.asp?bassnum=AMETa00

APPENDIX C

ABAQUS INPUT FILE FOR UNCOATED MEMBRANE MODEL

Appendix – C**: ABAQUS input file for uncoated membrane model

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*Heading
 Substrate has a CTE of -0.00087
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*Preprint, echo=NO, model=NO, history=NO, contact=NO
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*Part, name="Uncoated Membrane"
*End Part
** ASSEMBLY
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*Instance, name=Uncoated-1, part="Uncoated Membrane"
*Node
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    2, 0.000317500002,        0.
    3, 0.000635000004,        0.
    4, 0.000952499977,        0.
    5, 0.00127000001,        0.
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   159, 0.0246062502,        0.
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*Element, type=SAX2
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 2,  2,  83,  3
 3,  3,  84,  4
 4,  4,  85,  5
 5,  5,  86,  6
**Not all the element coordinates have been shown
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77,  77, 158,  78
78,  78, 159,  79
79,  79, 160,  80
80,  80, 161,  81
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  1, 161,   1
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*Density
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*Elastic
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*Expansion
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** Name: Center Type: Displacement/Rotation
*Boundary
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** Name: End Type: Displacement/Rotation
*Boundary
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_PickedSet4, 2, 2
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*Initial Conditions, type=TEMPERATURE
_PickedSet16, 0., 0., 0., 0., 0.
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*Step, name=Temperature, nlgeom=YES
Temperature Field of 1 degree is applied and propagated till the end of Analysis
*Static
0.1, 1., 1e-05, 1.
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
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*Temperature
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1, , , 2, 30
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*Static
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** LOADS

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*End Step
** --
** STEP: Press_04
*Step, name=Press_04, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_03   Type: Pressure
*Dsload, op=NEW

** Name: Press_04   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 622.722
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** --
** STEP: Press_05
*Step, name=Press_05, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_04   Type: Pressure
*Dsload, op=NEW
** Name: Press_05   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 778.403
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** --
** STEP: Press_06
*Step, name=Press_06, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_05   Type: Pressure
*Dsload, op=NEW
** Name: Press_06   Type: Pressure
*Dsload, op=NEW

_PickedSurf17, P, 934.083
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** --
** STEP: Press_07
*Step, name=Press_07, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_06   Type: Pressure
*Dsload, op=NEW
** Name: Press_07   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 1089.76
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step

<u>APPENDIX D</u>

ABAQUS INPUT FILE FOR COATED MEMBRANE MODEL

Appendix – D: <u>ABAQUS input file for coated membrane model</u>

```
*Heading
 coating has -0.0006 CTE while Substrate has CTE of -0.00087
** Job name: CoatedMembrane Model name: Coated_1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
** PARTS
*Part, name="Coated Membrane"
*End Part
** ASSEMBLY
*Assembly, name=Assembly
*Instance, name=Uncoated-1, part="Coated Membrane"
*Node
    1,        0.,        0.
    2, 0.000317500002,        0.
    3, 0.000635000004,        0.
    4, 0.000952499977,        0.
    5, 0.00127000001,        0.
**Not all the nodal coordinates have been shown
  157, 0.0239712503,        0.
  158, 0.0242887512,        0.
  159, 0.0246062502,        0.
  160, 0.0249237493,        0.
  161, 0.0252412502,        0.
*Element, type=SAX2
 1,  1,  82,  2
 2,  2,  83,  3
 3,  3,  84,  4
**Not all the element coordinates have been shown
78,  78, 159,  79
79,  79, 160,  80
80,  80, 161,  81
*Nset, nset=_PickedSet2, internal, generate
  1, 161,   1
*Elset, elset=_PickedSet2, internal, generate
 1,  80,  1
*Nset, nset=_PickedSet3, internal, generate
  1, 161,   1
*Elset, elset=_PickedSet3, internal, generate
 1,  80,  1
*Nset, nset=_PickedSet4, internal, generate
  1, 161,   1
*Elset, elset=_PickedSet4, internal, generate
 1,  80,  1
*Nset, nset=_PickedSet5, internal, generate
  1, 161,   1
*Elset, elset=_PickedSet5, internal, generate
 1,  80,  1
** Region: (Coated_Ta2O5:Picked)
```

*Elset, elset=_PickedSet5, internal, generate
 1, 80, 1
** Section: Coated_Ta2O5
*Shell Section, elset=_PickedSet5, composite, section integration=GAUSS
1.27e-05, 5, Kapton, 0.
3.343e-08, 5, Ta2O5, 0.
*End Instance
*Nset, nset=_PickedSet4, internal, instance=Uncoated-1
 81,
*Nset, nset=_PickedSet5, internal, instance=Uncoated-1
 1,
*Nset, nset=_PickedSet6, internal, instance=Uncoated-1, generate
 1, 161, 1
*Elset, elset=_PickedSet6, internal, instance=Uncoated-1, generate
 1, 80, 1
*Nset, nset=_PickedSet16, internal, instance=Uncoated-1, generate
 1, 161, 1
*Elset, elset=_PickedSet16, internal, instance=Uncoated-1, generate
 1, 80, 1
*Elset, elset=__PickedSurf17_SNEG, internal, instance=Uncoated-1, generate
 1, 80, 1
*Surface, type=ELEMENT, name=_PickedSurf17, internal
__PickedSurf17_SNEG, SNEG
*End Assembly
** MATERIALS
*Material, name=Kapton
*Density
1420.,
*Elastic
 2.5e+09, 0.34
*Expansion
 -0.00083,
*Material, name=Ta2O5
*Density
1400.,
*Elastic
 1.5e+11, 0.3
*Expansion
 -0.0006,
** BOUNDARY CONDITIONS
** Name: Center Type: Displacement/Rotation
*Boundary
_PickedSet5, 1, 1
_PickedSet5, 6, 6
** Name: End Type: Displacement/Rotation
*Boundary
_PickedSet4, 1, 1
_PickedSet4, 2, 2
_PickedSet4, 6, 6
** FIELDS
** Name: Initial   Type: Temperature
*Initial Conditions, type=TEMPERATURE
_PickedSet16, 0., 0., 0., 0., 0.
** --

```
** STEP: Temperature
*Step, name=Temperature, nlgeom=YES
Temperature Field of 1 degree is applied and propagated till the end of Analysis
*Static
0.1, 1., 1e-05, 1.
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
** STEP: Frequency
*Step, name=Frequency, perturbation
First Natural Frequency Extraction Step
*Frequency, eigensolver=subspace, normalization=displacement
1, , , 2, 30
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-2
*Output, field, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
** STEP: Press_01
*Step, name=Press_01, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_01   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 155.681
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
```

*End Step
** ---
** STEP: Press_02
*Step, name=Press_02, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_01   Type: Pressure
*Dsload, op=NEW
** Name: Press_02   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 311.361
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** ---
** STEP: Press_03
*Step, name=Press_03, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_02   Type: Pressure
*Dsload, op=NEW
** Name: Press_03   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 467.042
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** ---

```
** STEP: Press_04
*Step, name=Press_04, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_03   Type: Pressure
*Dsload, op=NEW
** Name: Press_04   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 622.722
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
** STEP: Press_05
*Step, name=Press_05, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_04   Type: Pressure
*Dsload, op=NEW
** Name: Press_05   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 778.403
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
** STEP: Press_06
*Step, name=Press_06, nlgeom=YES
```

Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_05   Type: Pressure
*Dsload, op=NEW
** Name: Press_06   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 934.083
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step
** --
** STEP: Press_07
*Step, name=Press_07, nlgeom=YES
Lateral Pressure Step
*Static
1., 1., 1e-05, 1.
** LOADS
** Name: Press_06   Type: Pressure
*Dsload, op=NEW
** Name: Press_07   Type: Pressure
*Dsload, op=NEW
_PickedSurf17, P, 1089.76
** FIELDS
** Name: Initial   Type: Temperature
*Temperature
_PickedSet16, 0., 0., 0., 0., 0.
** Name: Temperature   Type: Temperature
*Temperature
_PickedSet6, 1., 1., 1., 1., 1.
** OUTPUT REQUESTS
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1
*Output, field, variable=PRESELECT
** HISTORY OUTPUT: H-Output-1
*Output, history, variable=PRESELECT
*End Step