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UNIAXIAL AND BIAXIAL TENSIONING EFFECTS ON THIN MEMBRANE MATERIALS

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SUMMARY

Thin laminated membranes are being considered for various surface applications on future large space structural systems. Some of the thin membranes would be stretched across or between structural members with the requirement that the membrane be maintained within specified limits of smoothness which would be dictated by the particular application such as antenna reflector requirements. The multiaxial tensile force required to maintain the smoothness in the membrane needs to be determined for use in the structure design. Therefore, several types and thicknesses of thin membrane materials have been subjected to varied levels of uniaxial and biaxial tensile loads. During the biaxial tests, deviations of the material surface smoothness were measured by a noncontacting capacitance probe. Basic materials consisted of composites of vacuum-deposited aluminum on Mylar and Kapton ranging in thickness from 0.00025 in (0.000635 cm) to 0.002 in (0.00508 cm). Some of the material was reinforced with Kevlar and Nomex scrim. The uniaxial tests determined the material elongation and tensile forces up to ultimate conditions. Biaxial tests indicated that a relatively smooth material surface could be achieved with tensile force of approximately 1 to 15 Newtons per centimeter, depending upon the material thickness and/or reinforcement.

INTRODUCTION

The tensioned structure has long been recognized as an efficient and practical configuration which could be used to achieve structural objectives such as large antenna or solar reflectors in space (ref. 1). Thin plastic metal-coated membranes are being considered for the surface applications of these large space structural systems. The membrane material would be stretched across or between the structural segments which would provide the tensile loads to maintain the membrane within specified limits of surface smoothness required for the particular antenna and/or solar reflector application. The multiaxial tensile loads required to maintain the membrane surface smoothness need to be determined for use in the structure design.

This paper presents the results of an investigation which subjected several types and thicknesses of thin membrane materials to uniaxial and biaxial tensile loads. In the uniaxial tests, 1-inch wide strips of each material were pulled to maximum elongation and ultimate load. During the biaxial test, deviations from flatness of the material surface were measured as a function of increasing biaxial load. Materials consisted of composites of aluminum, Mylar, Kapton, Kevlar, and Nomex scrim, ranging in thickness from 0.00025 in (0.000635 cm) to 0.002 in (0.00508 cm).

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Numerous investigators have used uniaxial and biaxial test equipment to determine mechanical behavior of various materials such as solid propellant, fabrics, and plastics, some of which had been metalized (refs. 2 - 6). One of the major problems encountered in these investigations has been support of the specimen so that the forces applied can be evenly distributed along the sides. The specimens were supported by hooks, clamps, rings, eyelets, and/or strings. Force application was by a whiffletree arrangement in reference 2. To generate biaxial loads in reference 3, a small specimen was attached to a pressurized cylinder. In reference 4, weights were attached to several pull points around the circular membrane. In reference 5, individual strain gage load cells were attached to several eyelets around the sides of the membrane. These load cells were fastened to a pair of right-angle, L-shaped interconnected frame assemblies which were designed to move apart biaxially when pulled uniaxially by an INSTRON machine.

In the present investigation, the biaxial tensile loads and support procedures resembled the methods in references 5 and 6, respectively. The membrane was supported by seven mounting eyelets on each of the four sides. The eyelets were attached to adjustable rods which were, in turn, attached to the test frame. On two sides of the specimen, an electrical strain gage load cell was mounted to measure the load at each pull point. These load cells could be set individually for the specified static load conditions. As in reference 5, it is believed that applying load over small segments of the specimen, and being able to measure that segment load, result in a more uniform load distribution in the thin membrane.

Materials used in this investigation are production run, purchased commercially, and were not like any of the materials tested and reported on in the reference documents described above. Therefore, a test program was necessary to determine material characteristics such as multiaxial tensile load data needed for use in the design of the tensioned space structure described above. Material surface smoothness, as a function of varying tensile load, was not measured in the previous work.

The biaxial test equipment was designed, constructed, and operated for the investigation at the Langley Research Center. Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

APPARATUS

The basic mechanical and electrical apparatus set up along with schematics of the test sample, load, and material surface deviation measuring system, and loading system are shown in figures 1 through 3. A typical test sample along with load cells and load application points are shown in figure 2(a). The number of load application points was determined from the theoretical curve shown in figure 4. With equal loads in the X and Y directions, this curve represents the fractional region of the test sample at constant stress. Each sample had 24 eyelets for mounting to the biaxial tension fixture. However, to prevent wrinkling of the sample material in the corners due to biaxial loading, the corner eyelets were used to load in both the X and Y directions. Therefore, the total number of loading points was considered to be 28 which results in an a/b ratio of 0.57. Thus, for the 10 in (25.4 cm) square sample, the area considered to be at constant stress is shown in figure 3(a) as the inner dotted square. This region was considered the test area across which surface deviations were measured.

Tensioning of the test sample was accomplished by the apparatus shown in the schematic in figure 3(b). A coarse load was applied through a cable and pulley arrangement to a slide bar to which was attached seven load cells which were, in turn, attached to the test sample through threaded turnbuckles, rods, and clamps. The turnbuckle allowed a load "fine" adjustment. The load was applied on two sides of the test sample and in the plane of, and perpendicular to, the test sample. A support structure supported the weight of the adjustment rods, clamps, load cells, etc. Teflon tape was used between sliding surfaces to reduce friction.

The load measuring system is shown in figure 2(b). The load cell output signal was conditioned by the balance box, amplified by the neff amplifiers, and displayed on the digital voltmeter.

The material surface deviations were measured by the noncontacting capacitance probe and associated equipment shown in figure 2(c). The capacitance probe (gage) is based upon the principle that a voltage applied across two plates which are electrically isolated from each other permits a charge to accumulate on the plates, thus causing the formation of an electric field. The charge accumulation, i.e., the capacitance, is determined by the physical parameters of the system; it is directly proportional to the area of the plates and the dielectric constant of the intervening medium, and inversely proportional to the distance between the plates. Therefore, in order to measure capacitance changes due to displacement, it is necessary to fix the probe diameter (area) and dielectric constant in a manner that permits variance only in the separation distance between the probe (one plate) and the material test sample (the other plate). In the present investigation, the dielectric medium was air, and the probe sensing diameter was 0.21 in (0.53 cm) with a nominal spacing for zero at 0.0225 in (0.057 cm) above the material surface; the measuring range was ±0.01 in (0.0254 cm) about the zero spacing. The output of the capacitance probe (surface deviations) along with the probe position (see fig. 3(a)) along the test sample surface was recorded by the X-Y plotter.

The uniaxial tests were performed on an INSTRON Model 115 TT-D testing machine on which the cross-head moved at a constant rate of 0.2 in/min (0.508 cm/min). Gage length for the 1 in (2.54 cm) wide specimens was 2 in (5.08 cm).

MATERIALS

Mylar and Kapton, two polymide film materials, were used for the tests in this investigation. Each film had a thin layer (approximately 1 μ) of pure aluminum vacuum deposited on one side. Nomex and Kevlar organic fiber scrim was used to reinforce some of the material. The scrim had a denier of 195 to 200 (see table 1) and was attached to the unaluminized surface in the warp and woof direction with the scrim approximately 1/4 in (0.635 cm) apart. The scrim in the warp direction was attached to the material surface only at the intersections of the glued-down scrim in the woof direction. Material reinforcing was a manufacturing procedure and was not optimized for the present tests. Film thickness, excluding the scrim, varied from 0.25 to 2.0 mils.

DISCUSSION OF RESULTS

Several combinations of thin membrane aluminum-coated Mylar and Kapton materials, some reinforced with Kevlar and Nomex scrim, have been subjected to a range of uniaxial and biaxial tensile load conditions. The uniaxial tests were conducted to determine the strength and elongation characteristics of the basic materials with and without scrim reinforcement. The biaxial tests were conducted to determine surface quality smoothness as a function of biaxial loads. A noncontacting capacitance gage was used to measure the surface smoothness.

Uniaxial Tensile Tests

Figures 5 and 6 and table 1 show comparisons of the membrane material strength and elongation characteristics with and without reinforcement to ultimate load. Each curve in the figures is the result of averaging the strength data from five test samples. Each sample tested was 1-in (2.54 cm) wide with a 2 in (5.08 cm) grip separation. Each reinforced sample had four strands of scrim which were attached to the material surface. In the tensile load application direction, the scrim was attached only at the intersection points of the glued-down scrim in the transverse direction. The spacing between strands of scrim in both longitudinal and transverse directions was 0.25 in (0.635 cm). The temperature of the test samples was 72°F (22.2°C).

Materials without Scrim Reinforcement (Basic Material).- Mylar withstands initial load with low elongation up to about 4 percent before yielding is evident. Kapton appears to start elongation as load is applied; the curve shows no fast slope change to indicate yield. The ultimate elongation of Mylar increased from about 30 percent for 0.00025 in (0.000635 cm) material to 112 percent for the 0.002 in (0.00508 cm) material. Kapton ultimate elongation increased from 20 percent for the 0.0003 in (0.000762 cm) thick material to 59 percent for the 0.0002 in (0.00508 cm) material. As would be expected, the load required to yield the basic material increases appreciably with material thickness.

It is shown in reference 7 that molecular orientation can change the mechanical properties of a polymer, such as tested in this investigation, and these properties vary depending on the amount of orientation. Therefore, to determine the maximum ultimate tensile load and elongation, the material should be tested in the longitudinal or so-called machine direction (0°), the transverse direction (90°), and other directions as necessary. The uniaxial tensile data presented are data generated from load application in the longitudinal direction.

Materials with Nomex Scrim Reinforcement.- Both Mylar and Kapton reinforced with Nomex scrim exhibited similar force elongation yield curves with load compared to the basic materials curves. Required load to yield was increased, the yield point increasing to about 6 percent elongation with ultimate yield of the Mylar and scrim at about 21 percent. Kapton reinforced with Nomex scrim exhibited no definite yielding as was the case for the unreinforced material. In figures 5 and 6(d), it can be seen that with the 0.002 in (0.00508 cm) the ultimate load of the basic material is close to the same or is more than the ultimate load for the Nomex reinforced material. During these tests, the scrim would reach its ultimate load first and break without breaking the Kapton. The material sample was considered failed at that point. In all other tests except with the 0.002 in (0.00508 cm), the basic material failed before or at the time of ultimate load in the scrim.

Materials with Kevlar Scrim Reinforcement.- The materials reinforced with Kevlar scrim showed a very small (4 percent) elongation to failure. The low elongation to failure was also shown in reference 2.

In general, uniaxial tests are not a reliable indication of material strength and capability. This is particularly true for composites such as the material used herein. However, the uniaxial test is a simple fast method which is adequate to indicate strength and anisotropy of the material, see reference 2.

Biaxial Tensile Tests

Figures 7 and 8 show the effect of increasing biaxial load on material surface deviations of the various materials described above. Each curve represents the surface deviations corresponding to a specific load condition as a function of measuring probe travel across the test sample, see figure 3(a). Two sets of data are generally presented for each material type; one set without, and one set with several fold points as marked in the figures. The material surface deviations shown by the curves without folds represent perturbations caused by general handling of the material such as was needed to prepare the test samples. The second data set represents the surface deviations of the material handling plus the man-made deviations (folds). The fold points were generated by wrapping the material tightly by hand around different small diameter wires (0.062 in; 0.16 cm), (0.052 in; 0.13 cm), and (0.031 in; 0.079 cm), thus generating surface deviations with a different bend radius. The wire size was chosen to represent probable folds which could be inherent in packaging the material.

Effects of Folds and Bend Radii.- The curves with fold points indicate for most of the thinner materials that there are no discernible surface perturbations even though an attempt was made to create the folds as described above. The bending stiffness of the thin material was not adequate to maintain a fold. As the material thickness was increased, and with the addition of the reinforcing scrim, the material exhibited adequate bending stiffness to maintain a fold. The fold resulted in a surface perturbation which could be reduced in height by the application of a tensile load.

It was expected as the bend radius was increased, the tensile load to reduce the surface perturbations would decrease. This trend did not appear to be the case since the three bend radii used did not appear to have an appreciable effect on the width, height, or tensile load necessary to reduce the surface perturbations (fold height) to near zero.

Effect of Increasing Load on Surface Perturbations.- Maximum biaxial load required to reduce the surface perturbations to near zero was approximately 1 to 6 N/cm for both basic and reinforced materials up to a thickness of 0.001 in (0.00254 cm). The man-made perturbations (folds), even though they are large compared to the perturbations caused by general handling of the material, did not appear to require a larger loading to reduce the perturbation to near zero.

The loading to reduce the surface perturbations to near zero for the 0.002 in (0.00508 cm) material appears to be approximately 15 N/cm which is considerably larger than the loads discussed in the previous paragraph. The thicker material had a larger bending stiffness resulting in a larger load to reduce the height and size of the material surface perturbation.

Some tests were conducted with the 0.002 in (0.00508 cm) basic material during which the load in the Y-direction was increased uniaxially until load waves appeared in the material surface. The load was then applied in the X-direction until the load waves disappeared. This load was found to be approximately 40 percent of the Y-direction load. The initial height of the waves was out of the range of the measuring probe, therefore, wave height decrease as a function of increase load was not obtained.

Effect of Kevlar and Nomex Scrim Reinforcement.- The reinforcing scrim appeared to provide added bending stiffness, resulting in a small increase in the height of the man-made surface perturbations (folds) over those installed in the basic unreinforced material. The added height of the surface perturbation, however, did not require a larger biaxial load to reduce the perturbation to near zero. In some cases, the installation of the reinforcing scrim in a checkerboard design resulted in a pillowing effect in the squares between the scrim. This phenomena can be seen as a ripple effect in some of the data curves in figures 7 and 8. As seen in the figures, most of the ripple effect is reduced to near zero by increasing the biaxial load.

Capacitance Probe Measurements and Possible Applications.- The lateral dimension of the affected region of installing the man-made surface perturbations was in the order of 0.20 in (0.508 cm) which is approximately the sensing diameter of the capacitance probe. As the probe was passed over the affected region, the area of the fold underneath the probe was changing which resulted in an averaged fold height measurement. Therefore, the height variations as measured by the probe do not show peak values, but an average over the changing area. The accuracy of the average measurement is in the order of 0.00508 in (0.002 cm). Probe calibrations under similar area changing conditions indicated the peak values could be as much as three times greater than the measured values. However, the relative average peaks are an adequate measure of the tensile load required to reduce the material surface perturbations to near zero.

Two surface variation criteria from well-documented pioneer work in microwave antenna design, by John Ruze (ref. 8), to be considered in determining the performance of a membrane-type reflecting antenna are: (1) $\lambda/32$ to $\lambda/100$ as maximum surface variation from ideal smooth surface, and (2) $\lambda/3$ as the smallest area of variation of interest. The material surface variation measurements discussed in the previous paragraph meet both requirements for a $\lambda > 1.5$ cm wavelength which corresponds to an antenna operating in the range of less than 20 GHz. Therefore, technical development for reflectors operating in the microwave LSX, and Ku bands used for Earth radiometry and communication, may benefit from the surface measurements reported herein.

CONCLUDING REMARKS

Uniaxial Tests

Maximum elongation for the unreinforced Mylar and Kapton was 112 percent and 59 percent, respectively. For the same thickness, Kapton exhibited a higher ultimate strength compared to Mylar. Material reinforced with Kevlar scrim exhibited a higher ultimate strength compared to material reinforced with Nomex scrim. Material reinforced with Kevlar scrim elongated about 4 percent before ultimate strength was reached.

Biaxial Tests

The bending stiffness of some of the thinner materials was not adequate to hold man-made surface folds.

Bend radii used did not appear to have an appreciable effect on width, height, or tensile load necessary to reduce surface perturbations to near zero.

Tensile loads of 1 to 6 N/cm were needed to reduce surface perturbations to near zero for material thickness up to 0.001 in (0.00254 cm).

Tensile loads of approximately 15 N/cm were needed to reduce surface perturbations to near zero for material thickness of 0.002 in (0.00508 cm). Kevlar and Nomex scrim reinforcement added bending stiffness to the basic material.

Technical development for reflectors operating in the LSX and Ku bands used for Earth radiometry and communications may benefit from present material surface perturbation measurements.

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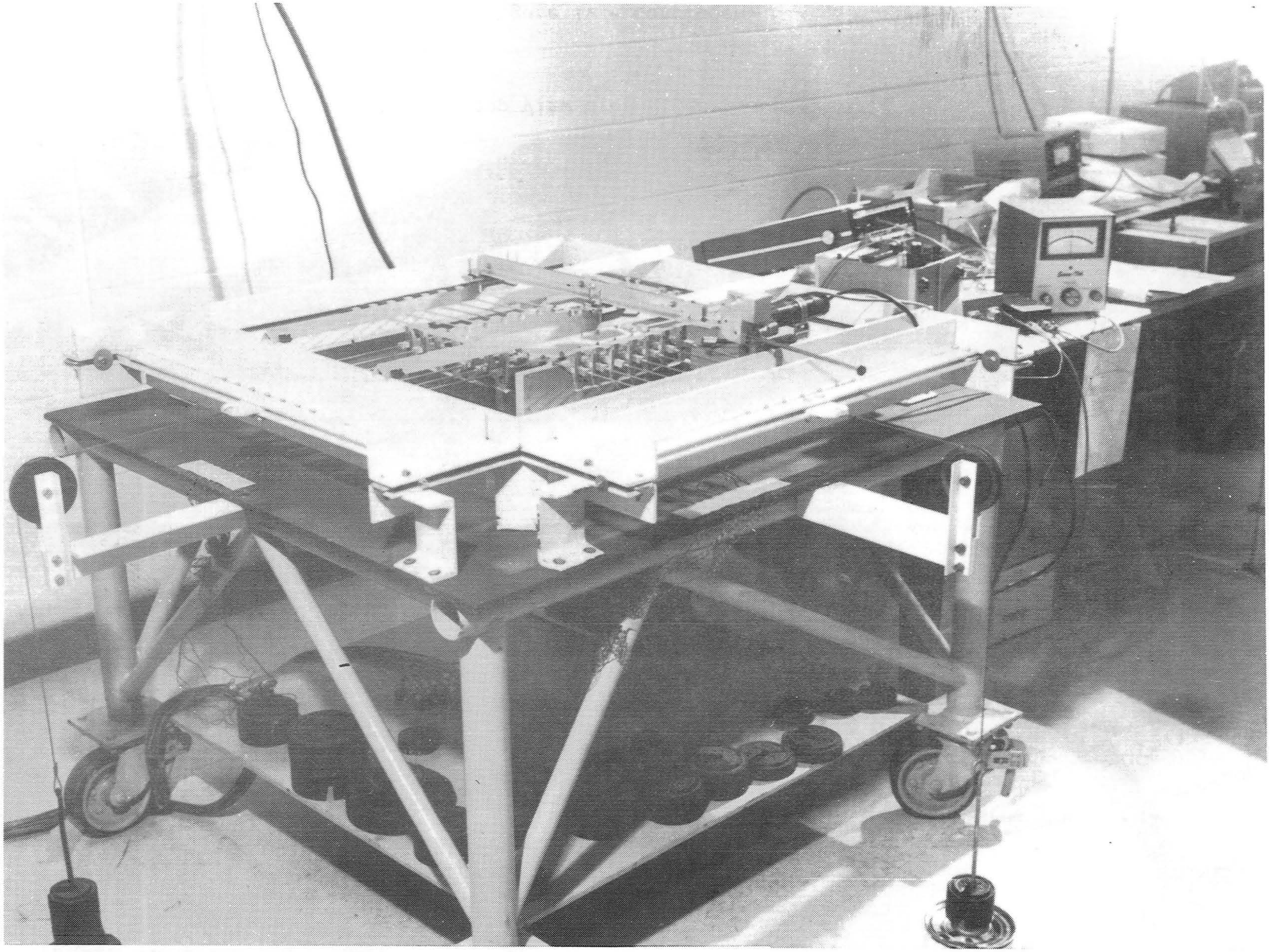
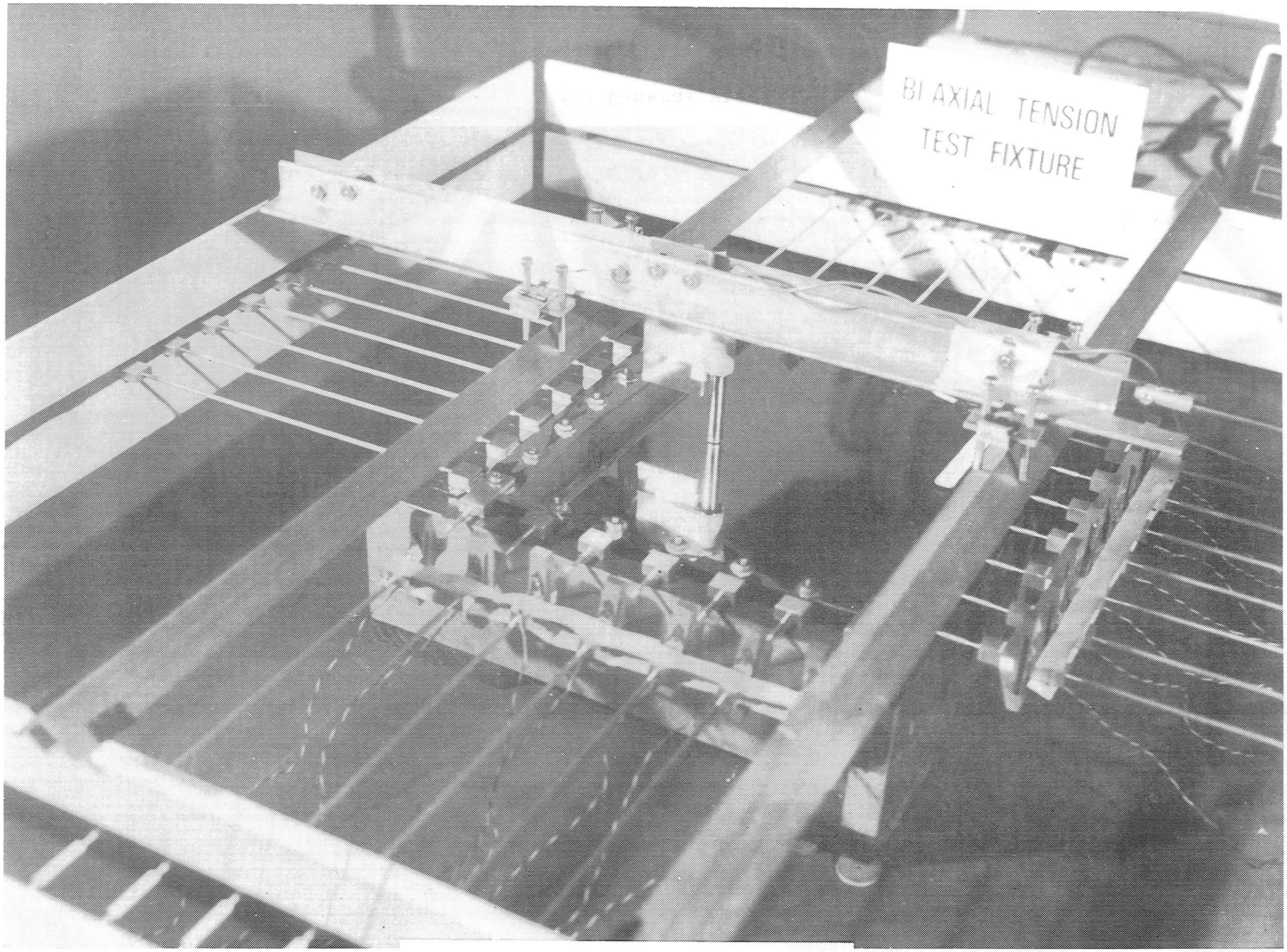
TABLE 1.- MATERIAL CHARACTERISTICS

MATERIAL	FILM THICKNESS MILS	REINFORCING SCRIM	DENIER	WEIGHT		ULTIMATE TENSILE LOAD		MAXIMUM ELONGATION %
				LBS/YD^2	KG/m^2	LBS/IN	KG/CM	
MYLAR	0.25	---	---	0.0171	0.0093	6	1.0715	29.5
	0.50	---	---	0.0265	0.0144	10	1.7858	57.0
	1.00	---	---	0.0574	0.0311	24	4.2859	96.5
	2.00	---	---	0.1272	0.0690	44	7.8576	117.5
	0.25	Kevlar	195	0.019	0.0103	40	7.1432	4.0
	0.50		"	0.0490	0.0265	44	7.8576	4.0
	1.00		"	0.0841	0.0456	47	8.3933	3.5
	2.00		"	0.1527	0.0828	63	11.2506	3.0
	0.25	Nomex	200	0.0322	0.0174	11	1.9644	20.0
	0.50		"	0.0497	0.0269	16	2.8573	22.5
	1.00		"	0.0782	0.0424	23	4.1074	20.5
	2.00		"	0.149	0.0808	41	7.3218	26.5
KAPTON	0.30	---	---	0.0205	0.0111	6	1.0715	20.0
	0.50	---	---	0.0327	0.0177	12	2.1429	25.5
	1.00	---	---	0.0654	0.0354	23	4.1073	58.5
	2.00	---	---	0.1313	0.0712	51	9.1077	59.0
	0.30	Kevlar	195	0.0453	0.0246	41	7.3218	4.0
	0.50		"	0.0588	0.0319	43	7.6790	4.0
	1.00		"	0.0910	0.0493	47	8.3933	4.0
	2.00		"	0.151	0.0819	56	10.000	3.0
	0.30	Nomex	200	0.50	0.0271	13	2.3215	10.5
	0.50		"	0.0677	0.0367	19	3.3931	21.5
	1.00		"	0.110	0.0596	29	5.1788	24.5
	2.00		"	0.1521	0.0825	49	8.7505	22.5



(a) General view.

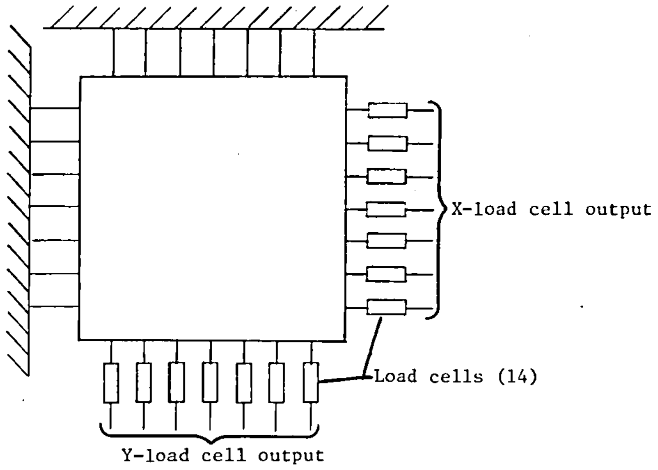
Figure 1. - Photographs of biaxial tension test equipment.

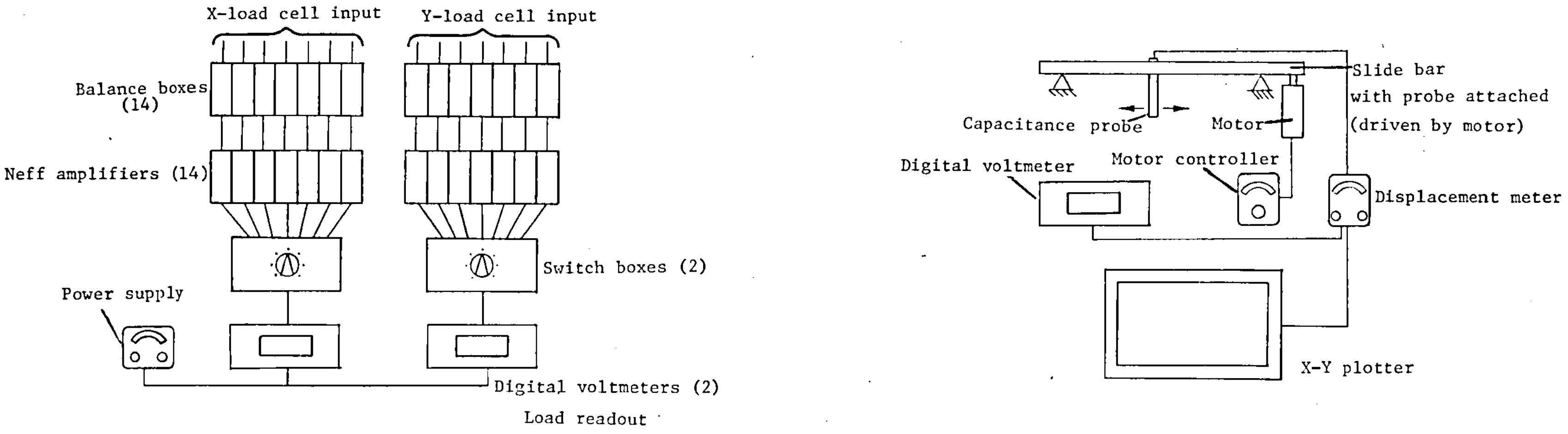


(b) Closeup view around test sample.

Figure 1. - Concluded.

(a) Typical test sample

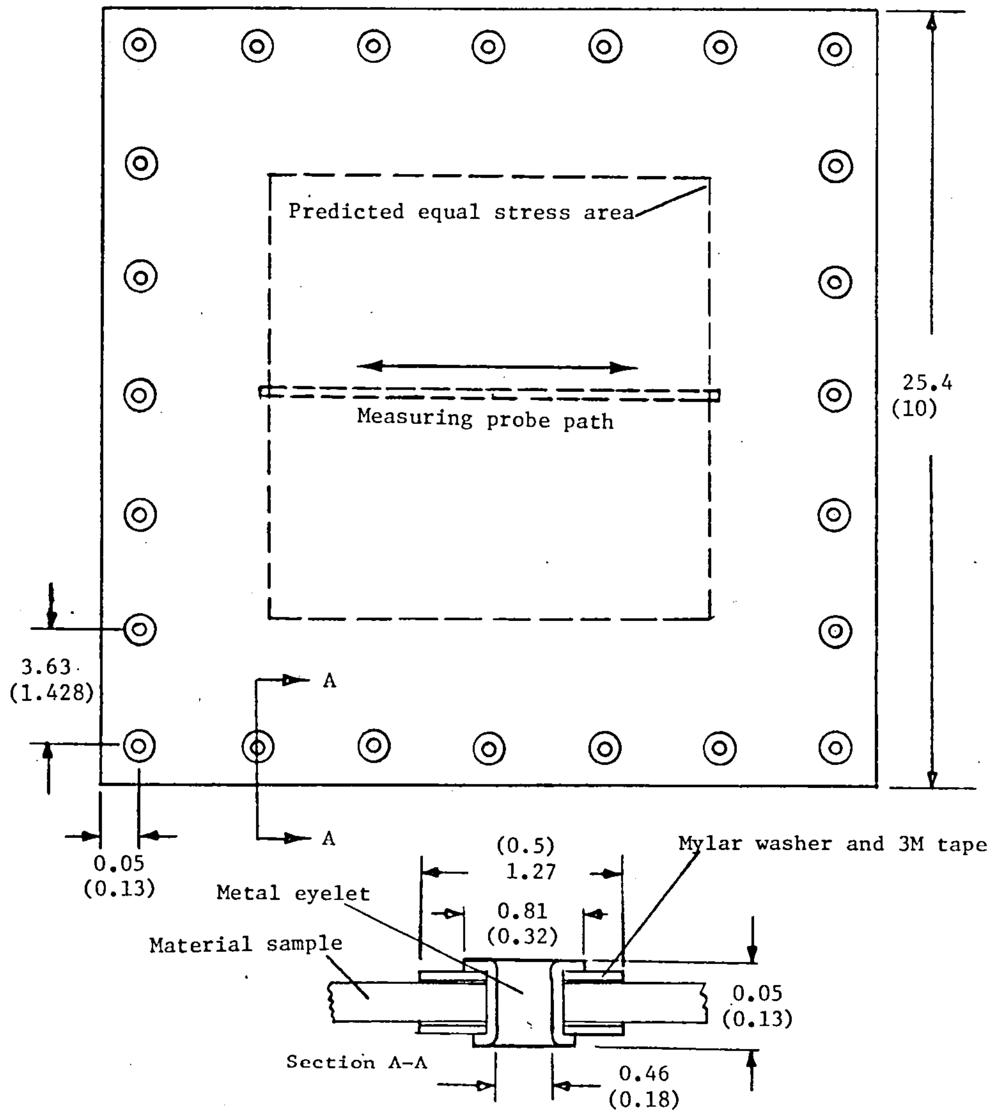



(b) Force measuring system

(c) Material flatness measuring system

Figure 2. - Schematic of biaxial tension test equipment.

(a) Test sample



(b) Typical loading apparatus

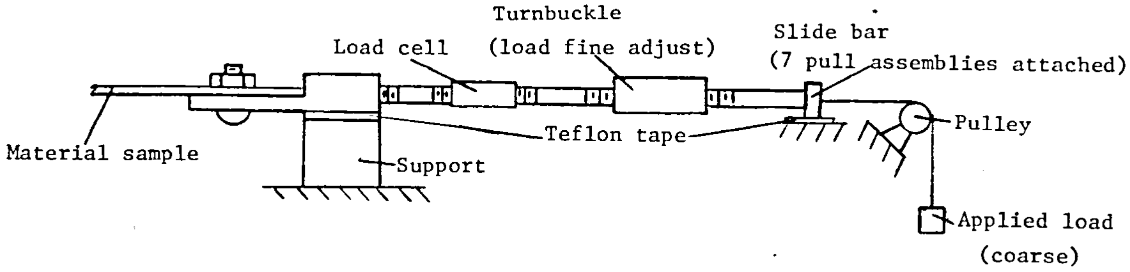
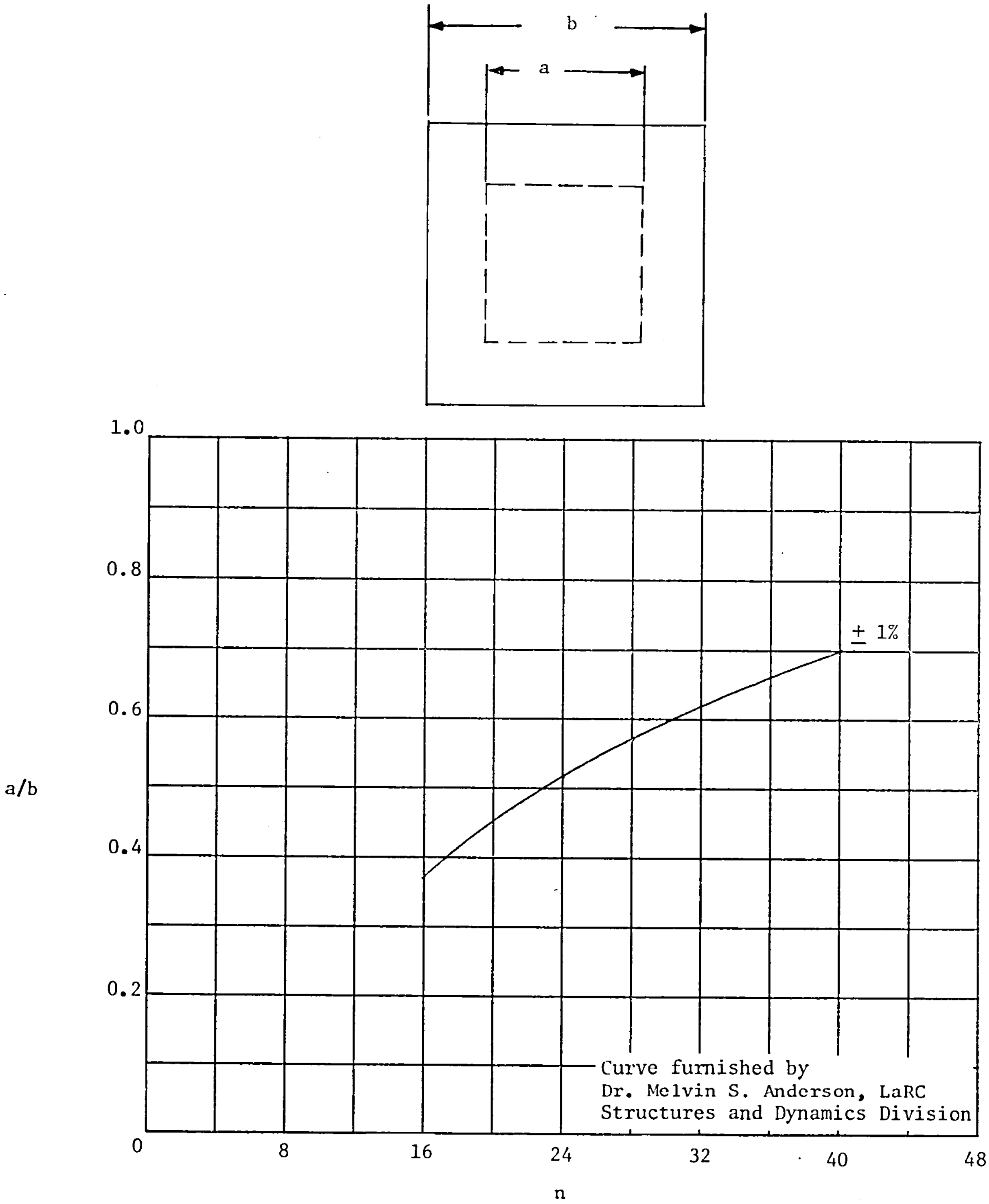


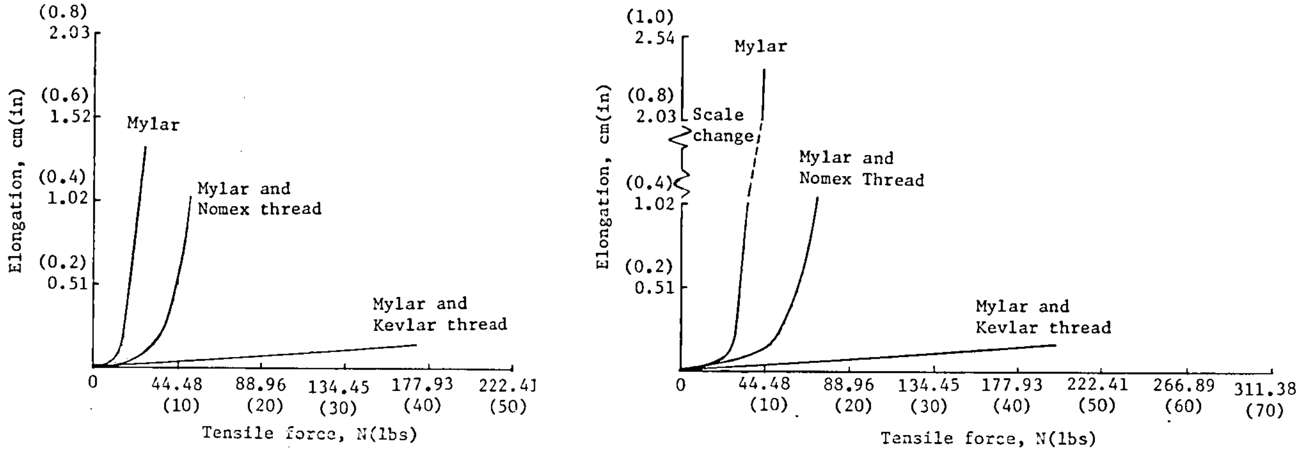
Figure 3. - Typical test sample and loading apparatus. Dimensions are in centimeters with inches in parentheses.



Curve furnished by
Dr. Melvin S. Anderson, LaRC
Structures and Dynamics Division

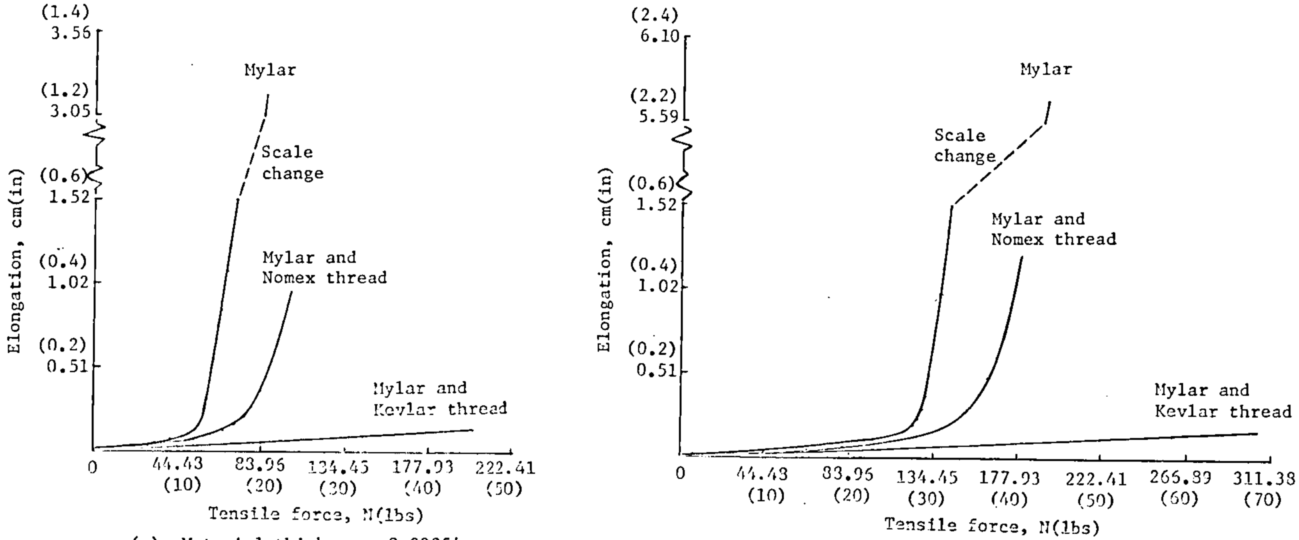
Figure 4. - Fractional region at constant stress versus number of load application points.

NOTE: Upper point of curve represents material ultimate load and elongation



(a) Material thickness, 0.000635 cm. (0.00025 in)

(b) Material thickness, 0.00127 cm. (0.0005 in)

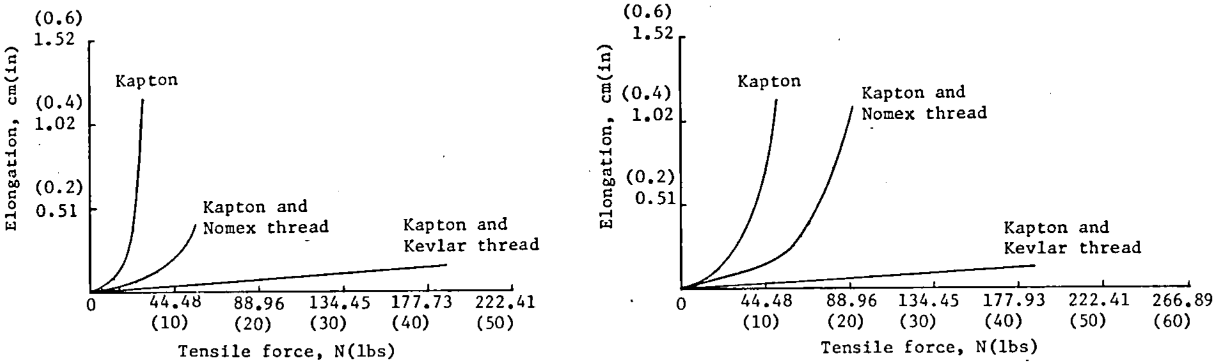


(c) Material thickness, 0.00254 cm. (0.001 in)

(d) Material thickness, 0.00508 cm. (0.002 in)

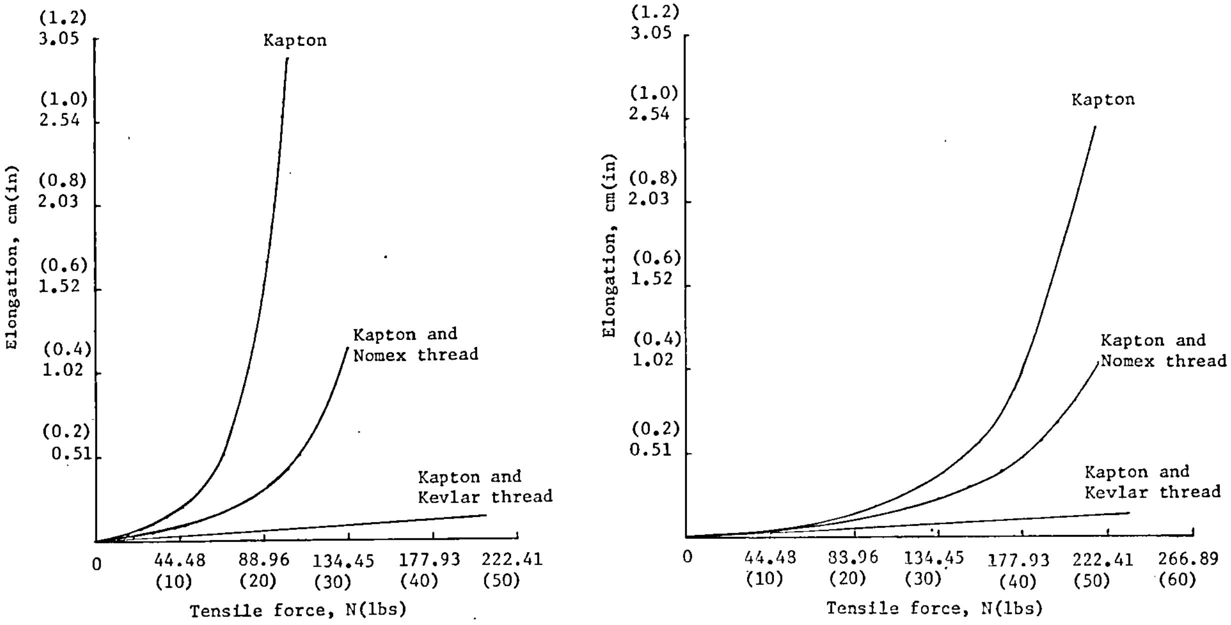
Figure 5. - Effect of increasing uniaxial force on various thicknesses of aluminized Mylar with and without fiber reinforcement. Material width was 2.54 cm (1 in), with four threads per 2.54 cm (1 in).

Note: Upper point of curve represents material ultimate load and elongation



(a) Material thickness, 0.000762 cm.
(0.0003 in)

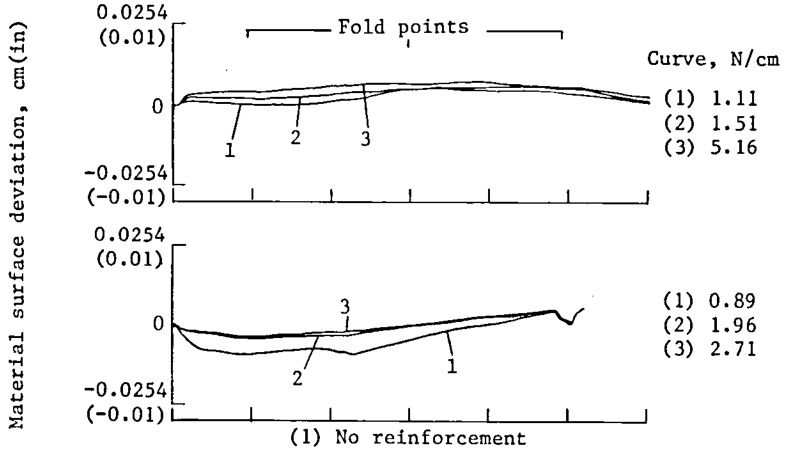
(b) Material thickness, 0.00127 cm.
(0.0005 in)



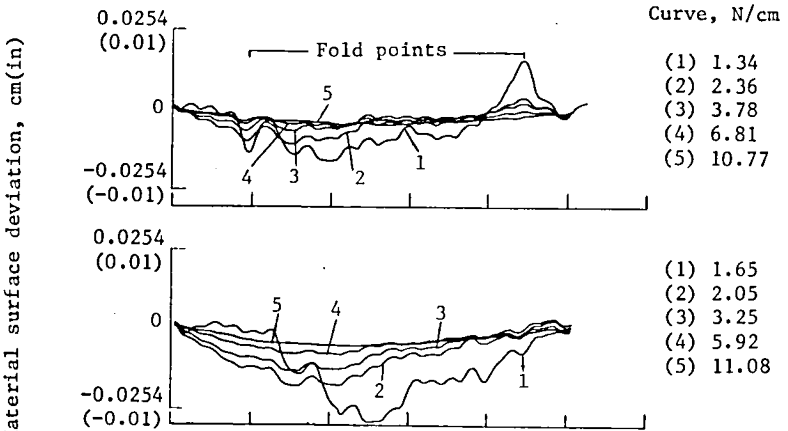
(c) Material thickness, 0.00254 cm.
(0.001 in)

(d) Material thickness, 0.00508 cm.
(0.002 in)

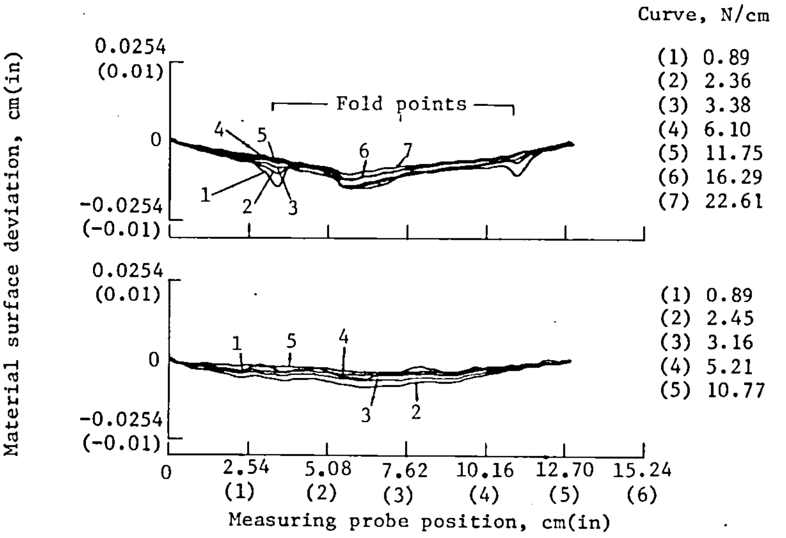
Figure 6. - Effect of increasing uniaxial force on various thicknesses of aluminized Kapton with and without fiber reinforcement. Material width was 2.54 cm (1 in), with four threads per 2.54 cm (1 in).



(1) No reinforcement



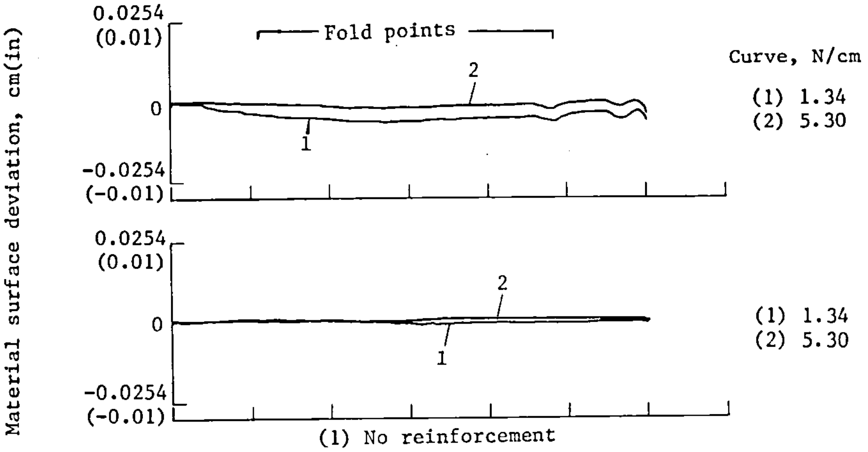
(2) Reinforced with Kevlar thread



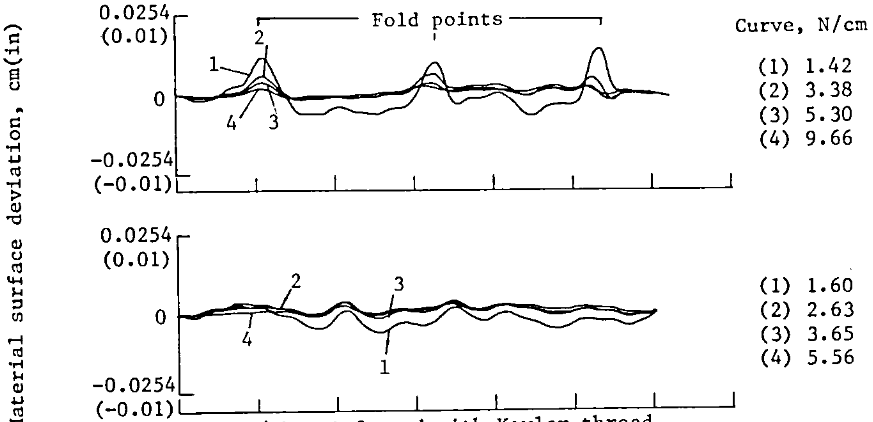
(3) Reinforced with Nomex thread

(a) Material thickness, 0.000635 cm.
(0.00025 in)

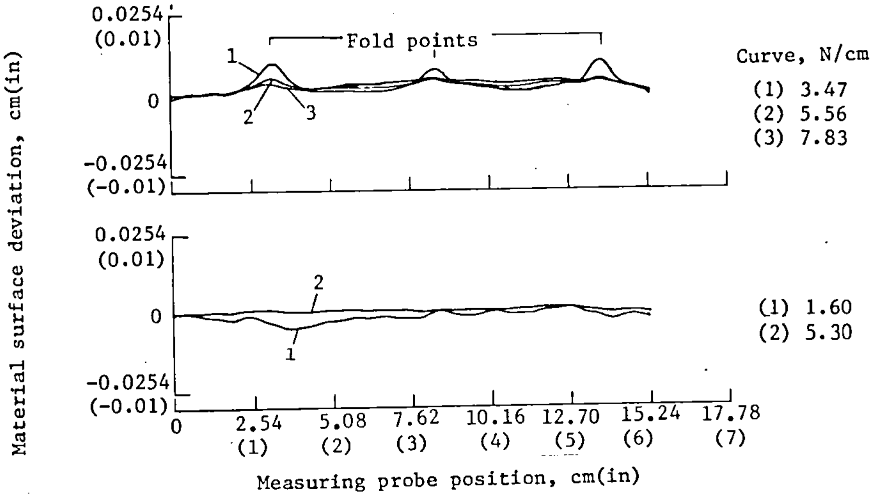
Figure 7. - Effect of increasing biaxial stress on material surface deviation of various thicknesses of aluminized Mylar with and without fiber reinforcement.



(1) No reinforcement



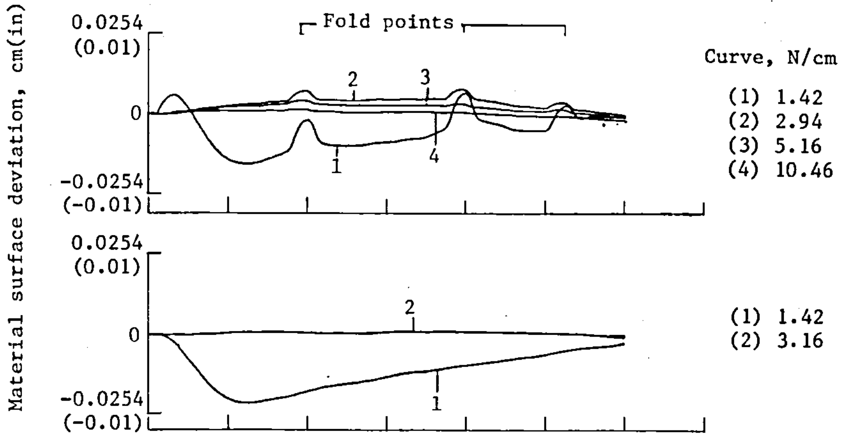
(2) Reinforced with Kevlar thread



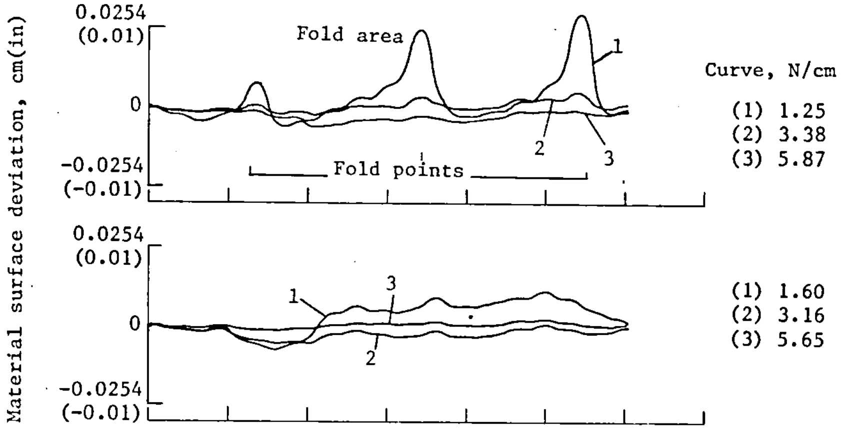
(3) Reinforced with Nomex thread

(b) Material thickness, 0.00127 cm.
(0.0005 in)

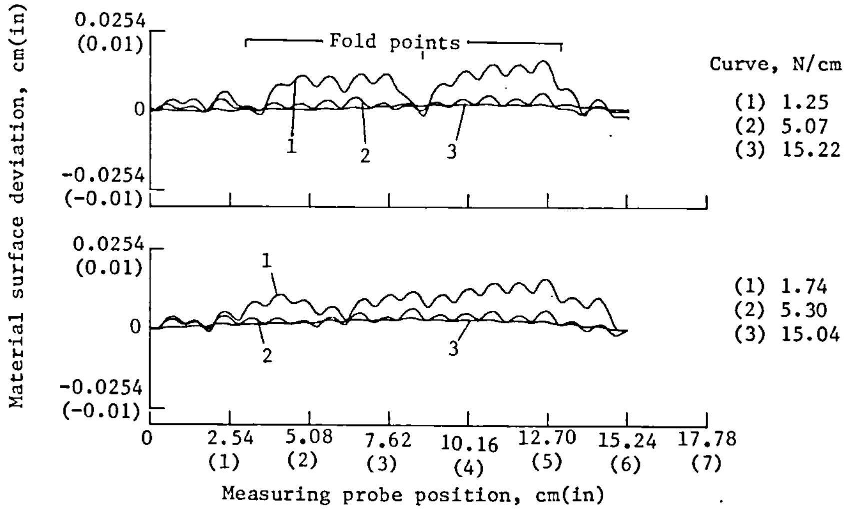
Figure 7. - Continued.



(1) No reinforcement



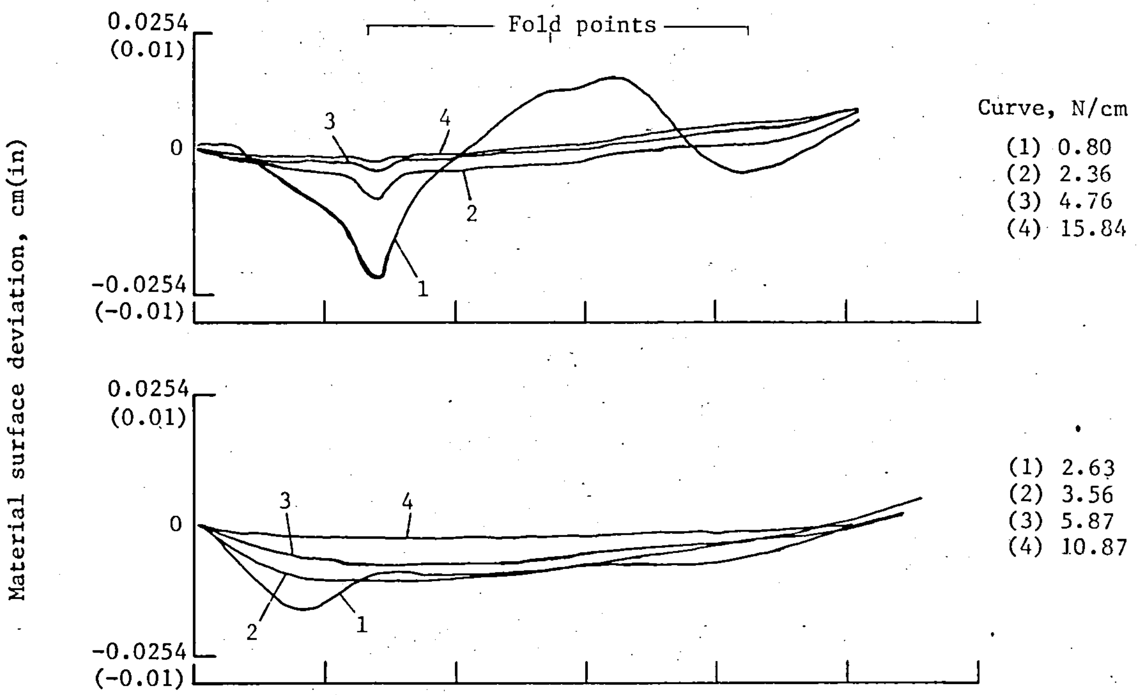
(2) Reinforced with Kevlar thread



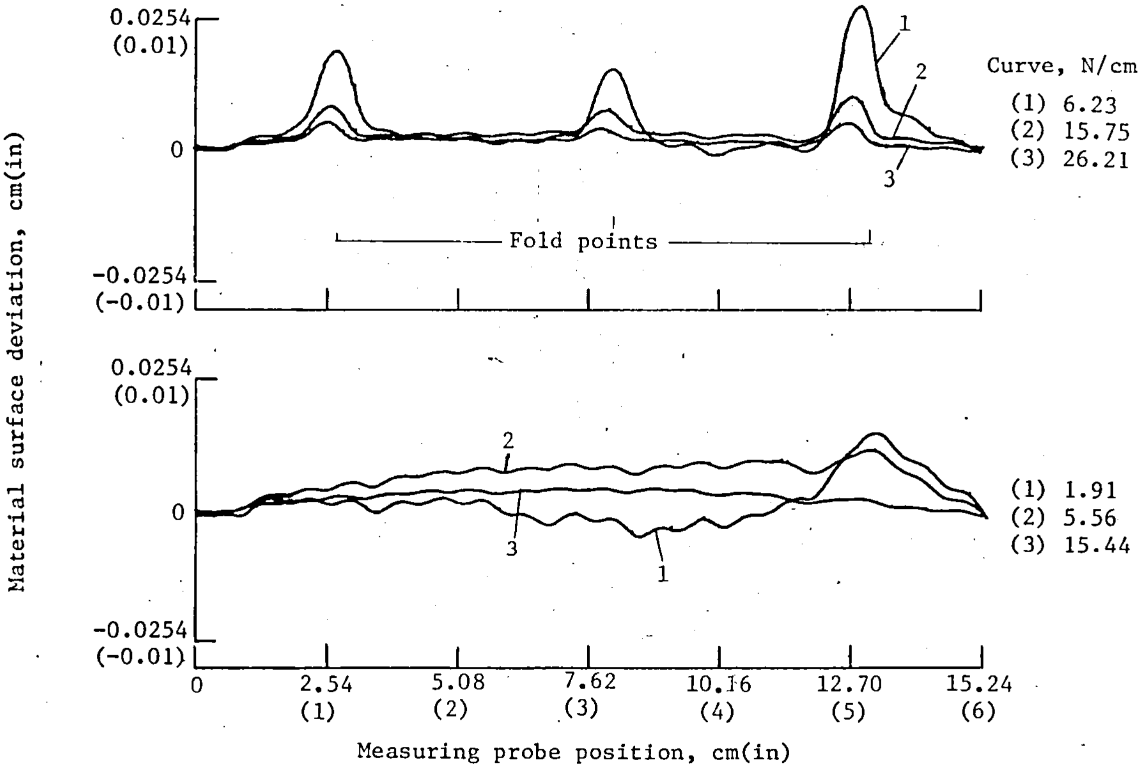
(3) Reinforced with Nomex thread

(c) Material thickness, 0.00254 cm.
(0.001 in)

Figure 7. - Continued.



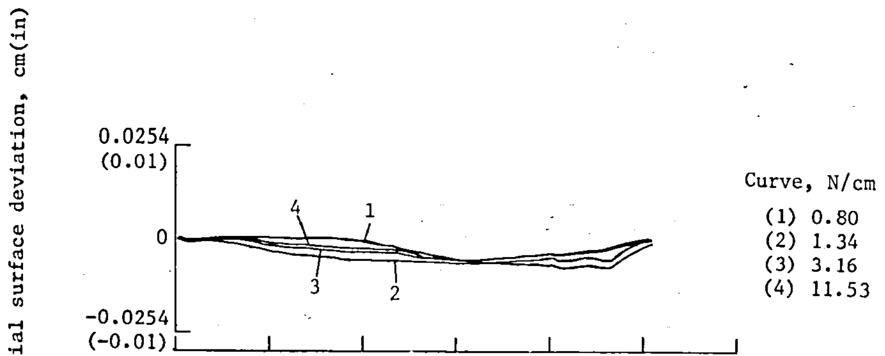
(1) No reinforcement



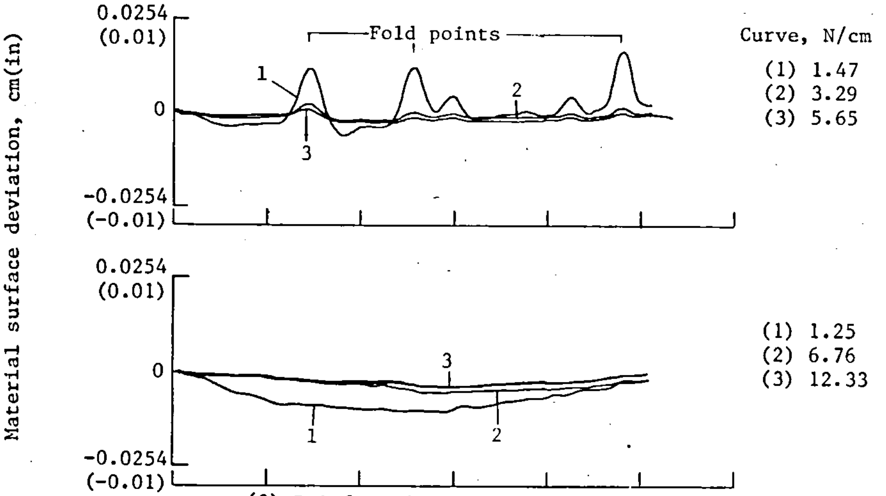
(2) Reinforced with Nomex thread

(d) Material thickness, 0.00508 cm.
(0.002 in)

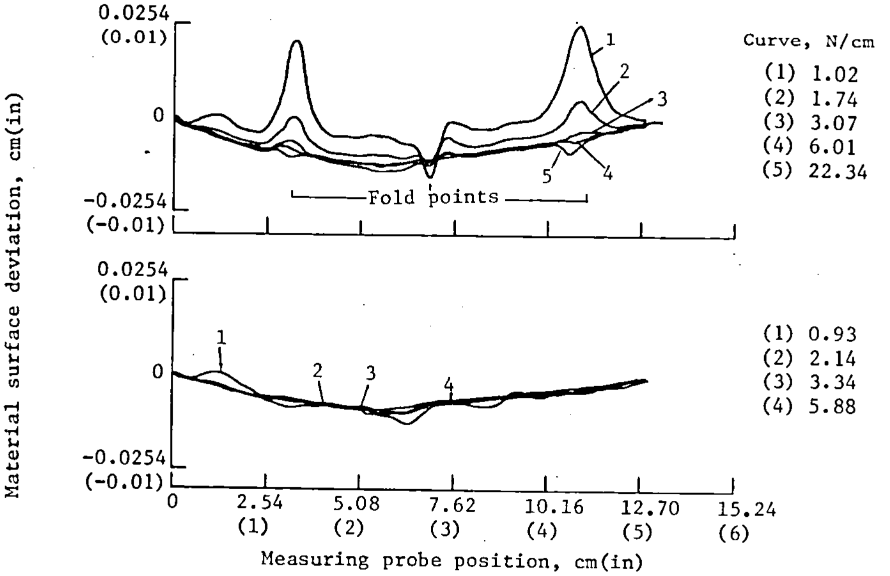
Figure 7. - Concluded.



(1) No reinforcement



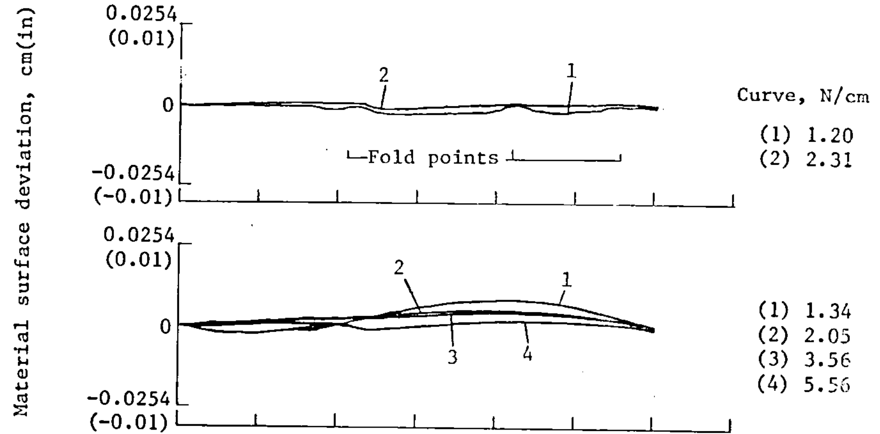
(2) Reinforced with Kevlar thread



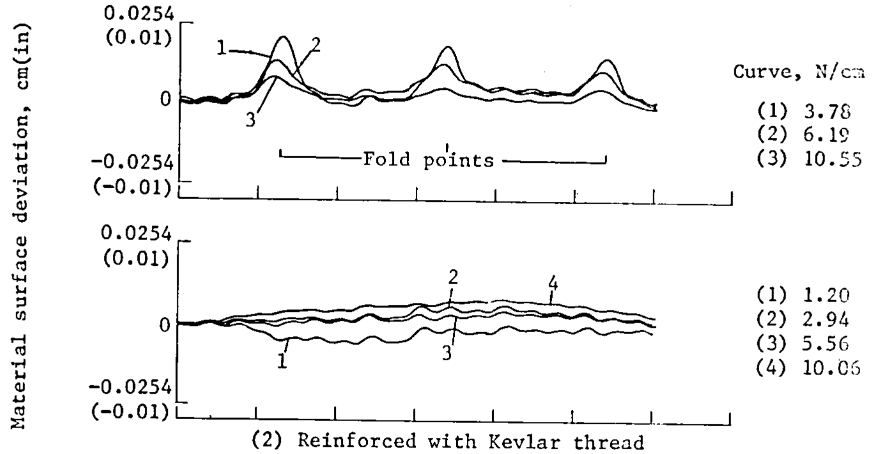
(3) Reinforced with Nomex thread

(a) Material thickness, 0.000762 cm.
(0.0003 in)

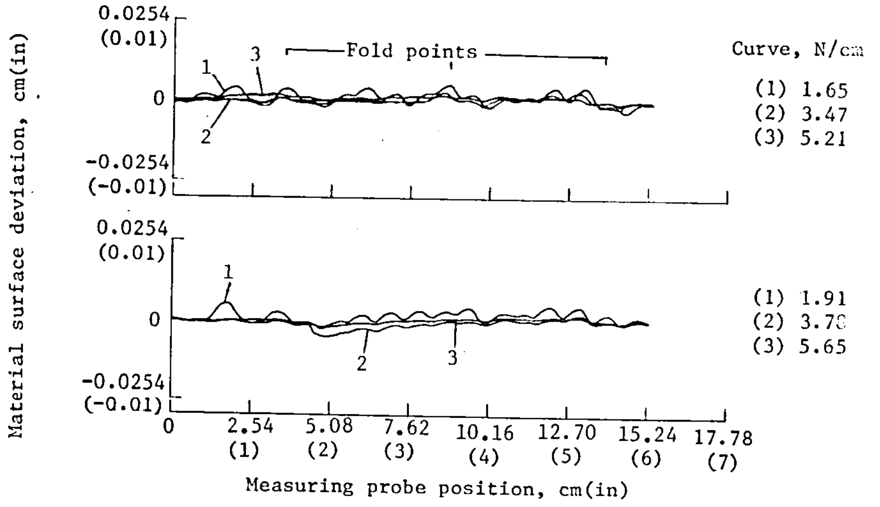
Figure 8. - Effect of increasing biaxial stress on material surface deviation of thicknesses of aluminized Kapton with and without fiber reinforcement.



(1) No reinforcement



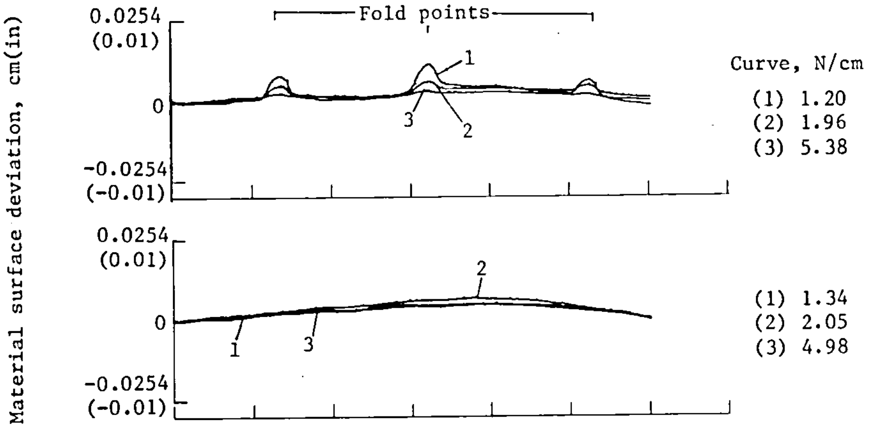
(2) Reinforced with Kevlar thread



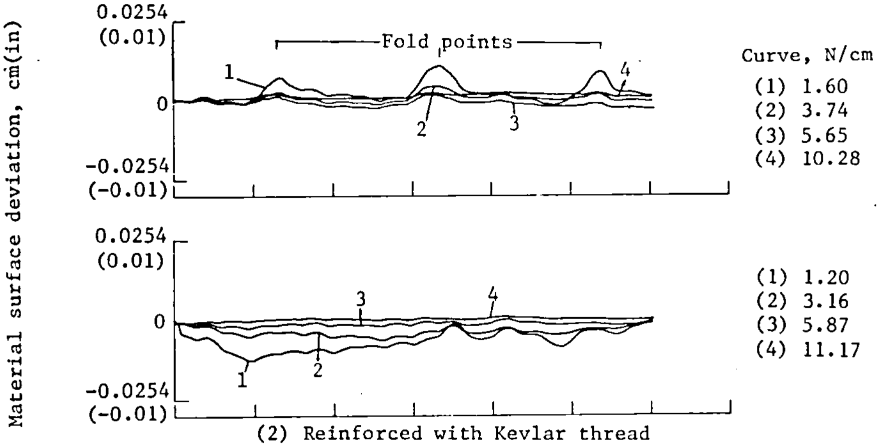
(3) Reinforced with Nomex thread

(b) Material thickness, 0.00127 cm.
(0.0005 in)

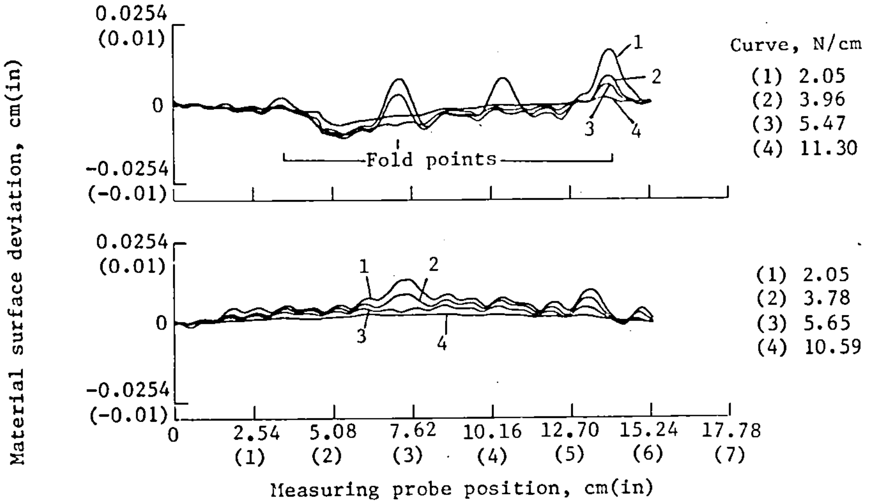
Figure 8. - Continued.



(1) No reinforcement



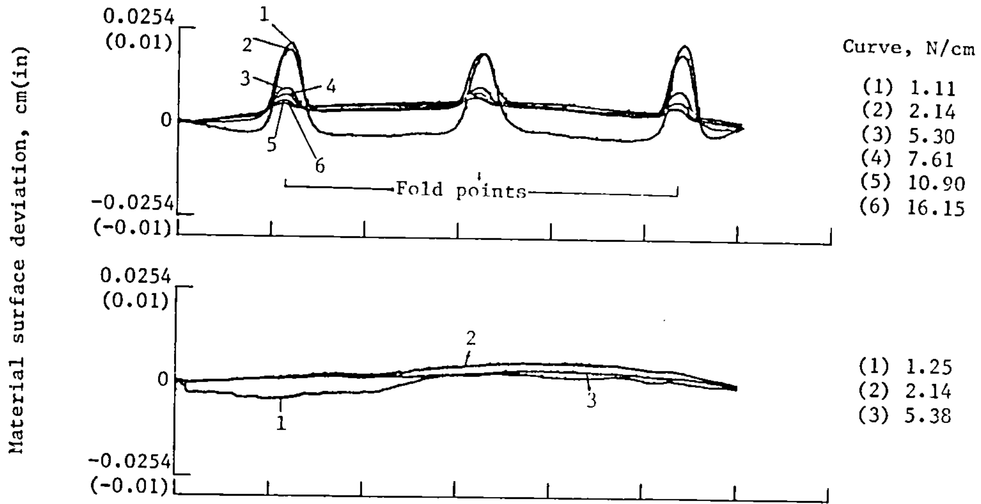
(2) Reinforced with Kevlar thread



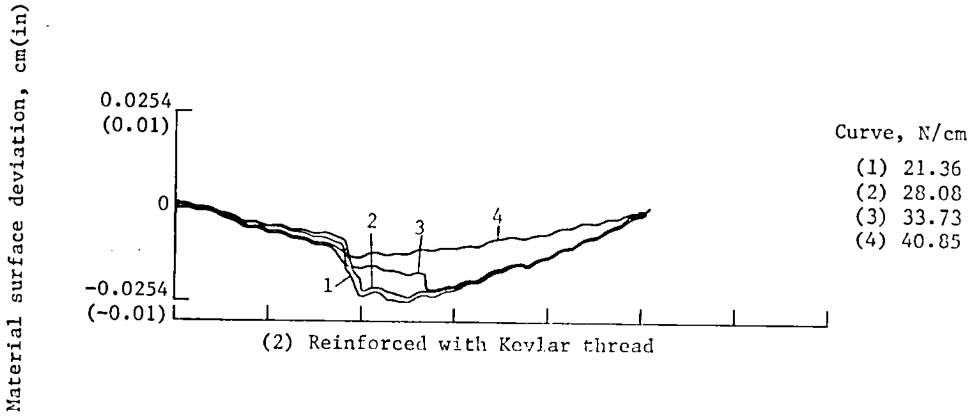
(3) Reinforced with Nomex thread

(c) Material thickness, 0.00254 cm.
(0.001 in)

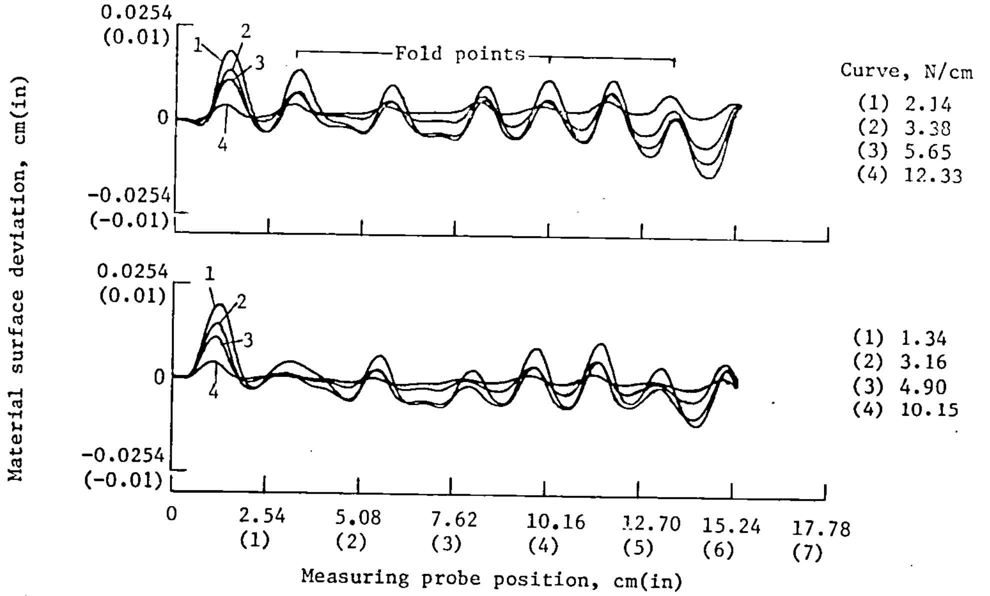
Figure 8. - Continued.



(1) No reinforcement



(2) Reinforced with Kevlar thread



(3) Reinforced with Nomex thread

(d) Material thickness, 0.00508 cm.
(0.002 in)

Figure 8. - Concluded.

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15. Supplementary Notes

16. Abstract

Thin laminated membranes are being considered for various surface applications on future large space structural systems. Some of the thin membranes would be stretched across or between structural members with the requirement that the membrane be maintained within specified limits of smoothness which would be dictated by the particular application such as antenna reflector requirements. The multiaxial tensile force required to maintain the smoothness in the membrane needs to be determined for use in the structure design. Therefore, several types of thicknesses of thin membrane materials have been subjected to varied levels of uniaxial and biaxial tensile loads. During the biaxial tests, deviations of the material surface smoothness were measured by a noncontacting capacitance probe. Basic materials consisted of composites of vacuum deposited aluminum on Mylar and Kapton ranging in thickness from 0.00025 in (0.000635 cm) to 0.002 in (0.00508 cm). Some of the material was reinforced with Kevlar and Nomex scrim. The uniaxial tests determined the material elongation and tensile forces up to ultimate conditions. Biaxial tests indicated that a relatively smooth material surface could be achieved with tensile force of approximately 1 to 15 Newtons per centimeter, depending upon the material thickness and/or reinforcement.

17. Key Words (Suggested by Author(s)) Thin Membrane Polymer Film Material Laminated and Coated Composites Kevlar and Nomex Scrim Reinforcement Uniaxial and Biaxial Testing Non-Contact Gaging	18. Distribution Statement Unclassified - Unlimited Subject Category 24

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