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Extensional, Bending and Twisting Stiffness of Titanium Multi-wall Thermal Protection System (TPS)

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FOREWORD

This is the interim report on work being performed by Rohr Industries in a contract for Design and Fabrication of Titanium Multiwall Thermal Protection System (TPS). This report describes the Task III activities. For Task III, the extensional, bending, and torsional stiffnesses of flat, multiwall sandwich were determined.

This program is administrated by the National Aeronautics Administration Langley Research Center (NASA LaRC). Mr. John Shideler of the Aerothermal Loads Branch, Loads and Aeroelasticity Division, is Technical Monitor for the program.

The following Rohr personnel were the principal contributors to the program during this reporting period: Winn Blair, Program Manager; J. E. Meaney, Structures; and L. A. Wiech, Engineering Laboratory. Overall program responsibility is assigned to the Rohr Aerospace Research and Development Engineering Organization with U. Bockenhauer, Manager.

SUMMARY

This report describes a test program that determined the extensional, bending, and twisting stiffnesses of Titanium Multiwall Thermal Protection System (TPS). The results of the testing are presented in tabular and graphical form. The graphs plot stiffness versus various geometric parameters of the dimpled core. The tests show that unlike honeycomb core, the dimpled core is a significant contributor to the stiffness and strength of the sandwich. Irregularities in the extensional stiffness test data are attributed to foil thickness variations and to difficulty in determining linear values from nonlinear test results.

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1/ INTRODUCTION

Rohr Industries was awarded a contract in January 1979 to design and fabricate titanium Multiwall Thermal Protection Panels for testing by NASA. This contract included Task I, Design Definition, and Task II, Test Model Design and Fabrication. Results of this work are provided in References 1 and 2. Upon completion of these tasks, the basic contract was amended in February 1980 to add a revised Task III, Titanium Multiwall Structural Evaluation.

Task III was a test program for determination of extensional, bending and torsion stiffnesses of various multiwall sandwich configurations. In addition, strength values were determined for these loading modes. The test plan that was followed in performance of the Task is described in Section 2.0. A description of the methods used in fabricating the test specimens is provided in Section 3.0. The test results are presented in graphical and tabular form in Section 4.0 and conclusions are presented in Section 5.0.

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2/ TEST PLAN

The testing performed in this task determined the extensional, bending and torsional stiffness of single layer and double layer multiwall sandwich configurations. The extensional stiffnesses of the individual dimpled sheets were also determined. In addition, this testing considered three variables:

a. Dimpled core foil thickness
b. Dimpled core height
c. Dimpled core orientation

In order to provide all of the required test configurations, a Sandwich Configuration Matrix was established and is presented in Table 1 of this report. The two core foil thicknesses tested were 0.038 mm (0.0015 inch) and 0.076 mm (0.003 inch); the nominal core heights tested were 2.210 mm (0.087 inch) and 4.445 mm (0.175 inch). The two core orientations were 0 Rad (0 degrees) and 0.785 Rad (45 degrees). Notice that the thicknesses of the face sheet and the septum sheet (required in the double layer sandwich configuration) remained constant.

In order to provide multiple test points for a given configuration, three specimens were subjected to each required test.

Table 1

Sandwich Configuration Matrix

Parameters	Single Layer Sandwich						Double Layer Sandwich						One Dimpled Sheet					
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Face Sheet Thickness mm (Inch)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	- -	- -	- -	- -	- -	- -
Septum Thickness mm (Inch)	- -	- -	- -	- -	- -	- -	0 0381 (0 0015)	0 0381 (0 0015)	0 0381 (0 0015)	0 0381 (0 0015)	0 0381 (0 0015)	0 0381 (0 0015)	- -	- -	- -	- -	- -	- -
Core Dimpled Depth mm (Inch)	4 445 (0 175)	4 445 (0 175)	2 21 (0 087)	4 445 (0 175)	4 445 (0 175)	2 209 (0 087)	4 445 (0 175)	4 445 (0.175)	2 21 (0 087)	4 445 (0 175)	4 445 (0 175)	2 21 (0 087)	2 21 (0 087)	2.21 (0 087)	4 445 (0 175)	4 445 (0 175)	4 445 (0 175)	4 445 (0 175)
Core Thickness mm (Inch)	0 0381 (0 0015)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 0381 (0 0015)	0 076 (0 003)	0 0381 (0 0015)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 0381 (0 0015)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 076 (0 003)	0 0381 (0 0015)	0 0381 (0.0015)
Core Orientation Depth Rad (Degrees)	0 (0)	0 (0)	0 (0)	0 785 (45)	0 785 (45)	0 785 (45)	0 (0)	0 (0)	0 (0)	0 785 (45)	0 785 (45)	0 785 (45)	0 (0)	0 785 (45)	0 (0)	0 785 (45)	0 (0)	0 785 (45)

A matrix showing the number of specimens of each sandwich configuration is provided in Table 2. As shown, the total test program required 126 specimens. Their overall dimensions are also included in Table 2.

Table 2. Sandwich Configuration and Number of Specimens

	Single Layer Sandwich						Double Layer Sandwich						One Dimpled Sheet						
Type of Test	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	Total
Beam Flexure (1)	3	3	3	3	3	3	3	3	3	3	3	3	-	-	-	-	-	-	36
Torsion (2)	3	3	3	3	3	3	3	3	3	3	3	3	-	-	-	-	-	-	36
Tension (3)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	54
																			126

(1) Size 76 mm by 305 mm (3 inches by 12 inches)

(2) Size 76 mm by 229 mm (3 inches by 9 inches)

(3) Size 50 mm by 254 mm (2 inches by 10 inches)

3/ TEST SPECIMEN FABRICATION

All test specimens were made of Ti-6Al-4V. The pre-cut panels, 305 mm by 610 mm (12 inches by 24 inches), were formed and Liquid Interface Diffusion (LID) bonded on the tools described in References 1 and 2. The material was fabricated using the same heat and lot as described in References 1 and 2. The thickness range was 0.0305 mm (0.0012 inch) to 0.0406 mm (0.0016 inch) for the septum sheets, and 0.0711 mm (0.0028 inch) to 0.0813 mm (0.0032 inch) for the outside sheets. The single layer and double layer panels were fabricated in accordance with a Rohr Proprietary Process. Figures 1 through 10 show the layout for cutting of the test specimens.

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4/ TEST METHODS AND RESULTS

The strength properties determined during this testing are presented in tabular form, while the stiffness values are presented in graphical form so the various parameters may be easily correlated. Each value presented in the tables and graphs represents an average of three test points.

4.1 EXTENSIONAL STIFFNESS

These specimens consisted of single dimpled sheets, single layer, and double layer multiwall sandwich panels. The overall size of the specimens was 51 mm by 305 mm (2 inches by 12 inches), but they were cut into standard tensile type specimens with a test area width of 25 mm (1 inch). The ends of the specimens were clamped and loaded with an Instron test machine as shown in Figures 11 and 12. A solid metal filler was inserted into the ends of some of the double layer sandwich specimens so that they could be loaded without crushing the ends. The results of testing these specimens did not differ from those obtained testing identical specimens that were held in the test fixture by crushing the ends.

The dimpled sheets were generally not LID plated or exposed to the LID bonding temperature cycle. However, two specimens (M and N) were LID plated and exposed to the LID bonding temperature cycle prior to testing. The test results did not show any significant differences in the stiffness values but did show a reduction in strength of about 17 percent.

The external stiffness values, E, were calculated from the stress equation:

$$\sigma = \frac{P}{\bar{t}W} = E\varepsilon$$

where
σ = stress
P = applied load
$\bar{t}$ = preformed thickness
W = width
ε = strain

Tables 3 and 4 show ultimate and yield strength values in addition to percent elongation and stiffness values. The strength values of the 0.0381 mm (0.0015 inch) dimpled sheets shown in Table 3 (Specimens Q and R) are low because of tearing of the specimens. This can be attributed to the severe forming during specimen fabrication.

The dimpled sheet results are displayed in Figures 13 and 14. These graphs show that the dimpled sheets have significantly less stiffness than the basic flat sheets. They also show that at the greater dimple depths, the core is stiffer in the 0 Rad (0-degree) than in the 0.785 Rad (45-degree) orientation. Figure 13 shows that as the dimple depth is increased, the stiffness is decreased. Figure 14 shows that the stiffness is increased almost two times as the core foil thickness is doubled. It is proposed that bending deflection of the dimple walls causes this relationship.

Figures 15, 16, 17 and 18 are the same type of plots as those of Figures 13 and 14 except they are for single layer and double layer sandwiches. In these figures, it must be remembered that the stiffness is based on stress values which include the thicknesses of the core foil. Therefore, the larger the percentage of core in the cross-sectional depth, the lower the overall extensional stiffness will be. This

Table 3. Axial Strength and Extensional Stiffness of Dimpled Core Sheet

Specimen[1] Configuration	F_{ty}[4] MPa (ksi)	F_{tu}[4] MPa (ksi)	e% Elong.[4]	E[4] Mpa x 10^3 (psi x 10^6)
M	495.06 (71.8)	889.46 (129.0)	4.1	51.02 (7.4)
M[2]	420.60 (61.0)	733.63 (106.4)	2.5	48.95 (7.1)
N[2]	717.77 (104.1)	859.12 (124.6)	4.4	49.64 (7.2)
O	314.41 (45.6)	638.48 (92.6)	5.1	39.99 (5.8)
P	297.7 (43.1)	709.50 (102.9)	8.4	26.20 (3.8)
Q	N/A	181.34 (26.3)	0.2[3]	22.06 (3.2)
R	N/A	253.05 (36.7)	2.6	8.27 (1.2)

(1) See Table 1 for definition of core configuration.

(2) These specimens have been LID plated and run through LID thermal cycle. All others are as received sheet after forming.

(3) All specimens failed outside of 2-inch gage marks.

(4) These values are averages of 3 to 5 separate test points.

N/A--Not available.

Table 4. Axial Strength and Extensional Stiffness of Multiwall Sandwich

Specimen(1) Configuration	F_{ty}(2) MPa (ksi)	F_{tu}(2) MPa (ksi)	e% Elong.(2)	E(2) MPa x 10^3 (psi x 10^6)
A	N/A	797.75 (115.7)	4.3	125.48 (18.2)
B	715.70 (103.8)	775.69 (112.5)	3.2	107.56 (15.6)
C	766.03 (111.1)	841.88 (122.1)	2.6	117.90 (17.1)
D	617.79 (89.6)	758.45 (110.0)	4.1	95.84 (13.9)
E	715.01 (103.7)	794.99 (115.3)	6.5	105.50 (15.3)
F	671.57 (97.4)	892.90 (129.5)	6.6	108.94 (15.8)
G	N/A	664.68 (96.4)	6.1	111.70 (16.2)
H	N/A	695.02 (100.8)	5.3	95.84 (13.9)
I	663.30 (96.2)	768.79 (111.5)	4.0	95.15 (13.8)
J	542.64 (78.7)	675.02 (97.9)	9.7	73.78 (10.7)
K	N/A	584.01 (84.7)	11.2	102.73 (14.9)
L	606.76 (88.0)	816.37 (118.4)	6.5	79.98 (11.6)

(1) See Table 1 for definition of sandwich configuration.

(2) These values are averages of 3 separate test points.

N/A - Not available.

explains why the stiffness appears to decrease as the core foil thickness increases. Also to be noted is that the core is stiffer in the 0 Rad (0-degree) than in 0.785 Rad (45-degree) orientation as in the single dimpled sheet.

The single layer sandwich contains a dimpled sheet which, as shown in Table 3, has significantly less stiffness than a flat sheet. Therefore, the stiffness of a single layer sandwich would be expected to be significantly less than for a basic flat sheet. However, there are three stiffness test values shown in Table 4 that exceed the accepted value (110×10^3 MPa (16×10^6 psi)) of Ti-6Al-4V sheet material. These specimens are A, C and G, and their test values are plotted in Figures 15, 16 and 18. There are two basic reasons for these anomalous results. Both reasons are explained below and must be taken into account when considering the overall accuracy of all test values.

The first reason is that thickness tolerance on foil type gages can be a significant factor. For example, a quarter of a mil on 0.003 inch thick foil (the maximum tolerance encountered with these test specimens) is an eight percent increase or decrease. Even measuring and detecting these small differences is difficult. While this magnitude cannot alone account for the high measured stiffness, it can be a contributing factor.

The second reason involves the technique for measuring the stiffness value. The specimen has a Linear Variable Differential Transformer (LVDT) attached to it to measure strain. The load versus strain values are plotted automatically by the Instron test machine. The scale and the shape of these curves are the basic considerations for determining the accuracy of the stiffness values. Figure 19 shows a typical curve of load versus strain. These curves do not have the classic shape, one of initial straight line portion, but rather, have two or three lines with different slopes. It is suspected that this nonlinear behavior is due to local bending of the dimple walls and a non-uniform stress distribution in the dimpled sheets. Regardless of the cause, however, the selection of the slope (or stiffness value) becomes a matter of judgment on the part of the investigator as illustrated in Figure 19. As previously mentioned, these factors must be taken into account when considering the overall accuracy of all test values.

4.2 BENDING STIFFNESS

These specimens consisted of single layer and double layer sandwich panels which were 75 mm (3 inches) wide by 305 mm (12 inches) long. These specimens were four point loaded in flexure as shown in Figure 20. The inner span length was 152 mm (6 inches) and the outer span was 254 mm (10 inches). As shown, a dial indicator was positioned at the center of the beam. Deflections were recorded during incremental loading. The linear portions of these recorded deflections (before face sheet buckling occurs) were used to calculate bending stiffnesses. These values and the ultimate moment values are tabulated in Table 5. It should be noted that the ultimate failure load ranged from approximately two to five times as much as the maximum load in the linear deflection range.

The maximum linear load can be used as an allowable for design limit loads. This approach provides a large factor of safety for design ultimate loads and also provides a structure that is free from buckling when subjected to limit loading. However, this approach may result in relatively heavier designs. A lighter design will result if the face sheets are allowed to buckle at limit load and if the associated reduction in factor of safety for design ultimate is acceptable.

The bending stiffness values, EI, were calculated from the beam deflection equation $\Delta = \frac{Pa}{24EI}(3L^2-4a^2)$, where terms are defined in Figure 20. These values are plotted on Figures 21, 22, 23 and 24. These figures present the data in the same manner as in the extensional stiffness section. Figures 21 and 23 show that as the core dimple depth is doubled (this is effectively doubling the sandwich height), the

Table 5. Bending Strengths of Multiwall Sandwich

Sandwich[(1)] Configuration	Overall[(2)] Sandwich Ht. mm (Inch)	Proportional[(2)] Moment N.m/0.0762 m (In-Lbs/3 In.)	Ult. Moment[(2)] N.m/0.0762 m (In-Lbs/3 In.)
A	3.556 (0.140)	0.226 (2.0)	0.542 (4.8)
B	3.785 (0.149)	0.339 (3.0)	1.390 (12.3)
C	1.854 (0.073)	0.113 (1.0)	0.475 (4.2)
D	3.912 (0.154)	0.226 (2.0)	0.870 (7.7)
E	3.454 (0.136)	0.158 (1.4)	0.350 (3.1)
F	1.880 (0.074)	0.068 (0.6)	0.373 (3.3)
G	7.493 (0.295)	0.678 (6.0)	1.740 (15.4)
H	7.950 (0.313)	0.904 (8.0)	4.994 (44.2)
I	3.759 (0.148)	0.339 (3.0)	1.560 (13.8)
J	7.976 (0.314)	0.678 (6.0)	2.937 (26.0)
K	7.315 (0.288)	0.452 (4.0)	1.118 (9.9)
L	3.937 (0.155)	0.339 (3.0)	1.277 (11.3)

(1) See Table 1 for definition of sandwich configurations.

(2) These values are averages of 3 separate test points.

stiffness is increased about four times. This is consistent with standard beam theory since height values are squared in the calculation of the moment of inertia of a sandwich structure. All four figures show that, as in the extensional testing, the 45-degree core orientation direction is less stiff than the 0-degree direction. Figures 22 and 24 show that the core foil thickness does have a significant influence on the stiffness of a given panel. This fact plus the core orientation influence indicate that the dimpled core has a significant influence on the bending strength of this type of structure.

4.3 TORSIONAL STIFFNESS

These specimens consisted of single layer and double layer sandwich panels that were 76 mm (3 inches) wide by 229 mm (9 inches) long. One end of these specimens was restrained against rotation and translation and the other end was restrained against translation by a bearing, but was rotated by an off-center dead loading system. This is shown in Figure 25. Note that a lever arm extends from each side of the loaded end of the specimen. Dial indicators are at the tips of the lever arm. As in the bending tests, deflections were recorded during incremental loading. The linear portion of these recorded deflections was used to calculate the torsional stiffnesses. Failure loads were not attainable since the deflection capabilities of the specimens exceeded those that could be handled by the test rig. However, the maximum torque values in the linear deflection range are tablulated in Table 6. The torsional stiffness values, JG, were calculated from the formula

$$JG = \frac{TL}{\Theta}$$

where T = torque value

L = length of specimen

Θ = angle of twist

These values are plotted on Figures 26, 27, 28 and 29. These figures present the data in the same manner as presented in the extensional and bending stiffness sections. Figures 26 and 28 show that a doubling of

Table 6. Torsional Strength of Multiwall Sandwich

Sandwich[1] Configuration	Overall[2] Sandwich Ht. mm (Inch)	Maximum Proportional[3] Torque N.m/0.0762m (In-Lbs/3 In)
A	3.708 (0.146)	0.36 (3.2)
B	4.039 (0.159)	0.36 (3.2)
C	2.032 (0.080)	0.20 (1.8)
D	3.759 (0.148)	0.59 (5.2)
E	3.656 (0.144)	0.45 (4.0)
F	1.956 (0.077)	0.25 (2.2)
G	7.341 (0.289)	0.70 (6.2)
H	7.950 (0.313)	0.97 (8.6)
I	3.861 (0.152)	0.45 (4.0)
J	8.001 (0.315)	1.58 (14.0)
K	7.366 (0.290)	0.81 (7.2)
L	3.912 (0.154)	0.56 (5.0)

(1) See Table 1 for definition of sandwich configuration.

(2) These heights are averages of 3 values.

(3) These values are averages of 3 test points and are the maximum values in the linear deflection range. Note that ultimate torque values were not determined.

the dimpled depth causes approximately a quadrupling of the stiffness. This is consistent with basic torsion theory, which states that in multicell torque boxes:

$$J = \frac{4A^2}{\Sigma \frac{ds}{t}}$$

where J = polar moment of inertia of cross section

A = cross sectional area of torque cell

ds = distance around torque cell

t = thickness of torque cell wall

When analytically treating the multiwall specimens as a series of triangles and applying this equation, an approximate quadrupling is achieved when the height of the triangle is doubled.

An inconsistency, however, arises with this equation when examining Figures 27 and 29. The test data shows that a doubling of the core foil thickness causes an approximate quadrupling of the stiffness. The previous equation would predict only about a doubling of the stiffness. Also, this data shows that 0.785 Rad (45 degrees) core orientation has a very slight advantage over the 0 degree direction, which is opposite to that found in the bending and extensional tests.

5/ CONCLUSIONS

The test specimen variables included the following dimpled core properties:

a. Dimple depth
b. Core foil thickness
c. Core orientation

All of these had an influence on the stiffness and strength values measured. Consequently, these tests showed that, unlike honeycomb core, dimpled core is a significant contributor to the extensional, bending and torsional stiffnesses as well as to the overall strength of a sandwich structure.

5.1 EXTENSIONAL STIFFNESS OF DIMPLED SHEET

All core variables produced values significantly less than that for a flat sheet. Average values ranged from 8.3×10^3 to 51.0×10^3 MPa (1.2×10^6 to 7.4×10^6 psi). The most significant core variable was the foil thickness.

5.2 EXTENSIONAL STIFFNESS OF MULTIWALL SANDWICH

The core variables had less effect on the results of these tests on single and double layer sandwich specimens. The range of average values was 73.8×10^3 to 125.5×10^3 MPa (10.7×10^6 to 18.2×10^6 psi). There were three configurations that produced values even greater than 110×10^3 MPa (16.0×10^6) psi (the accepted stiffness value of Ti-6Al-4V). These irregularities are attributed to the foil thickness variations and to difficulty in determining the extensional stiffness for this type of structure. The judgment of the investigator was often required to obtain linear values from nonlinear test results. This difficulty must be considered when evaluating the accuracy of the data.

5.3 BENDING STIFFNESS OF MULTIWALL SANDWICH

All core variables had a significant influence on these values. This indicates that the dimpled core contributes to the overall bending strength and stiffness of the multiwall sandwich. This is in contrast to the honeycomb core which is normally considered to be a noncontributor to the moment of inertia of a sandwich structure.

5.4 TORSIONAL STIFFNESS OF MULTIWALL SANDWICH

The core orientation did not have a significant influence on the results of these tests. However, a doubling of either the core foil thickness or core height caused a quadrupling of the torsional stiffness value. The increase in torsional stiffness due to core foil thickness is greater than would be predicted analytically.

6/ REFERENCES

1. Winford Blair, John E. Meaney, Jr., and Herman A. Rosenthal, "Design and Fabrication of Titanium Multi-Wall Thermal Protection System (TPS) Test Panels," NASA CR 159241, February 1980.

2. Winford Blair, J. E. Meaney, Jr., and H. A. Rosenthal, "Fabrication of Titanium Multi-Wall Thermal Protection System (TPS) Test Panel Arrays," NASA CR 159383, December 1980.

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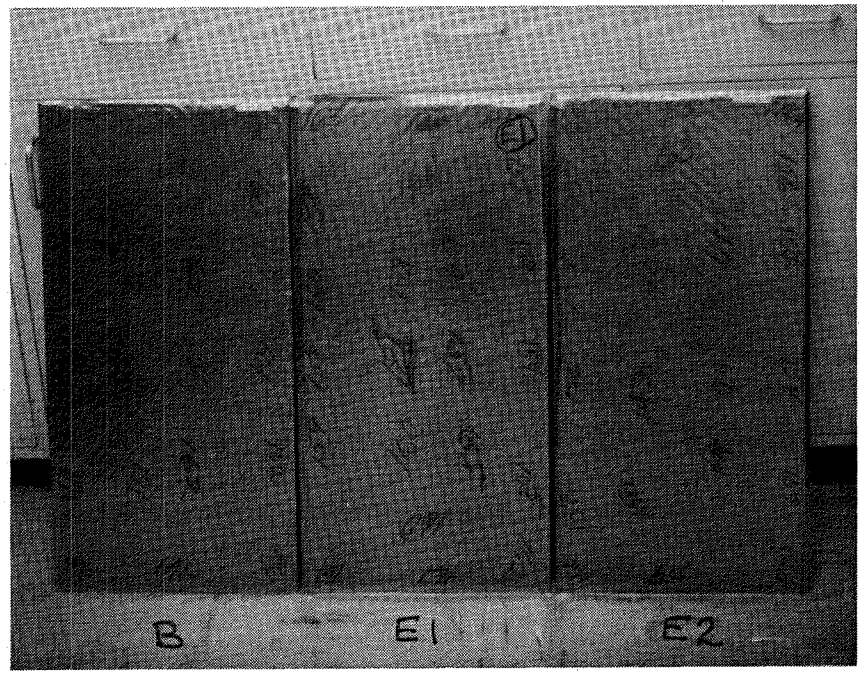

Figure 1. Panels B, E1, and E2 Showing Overall Panel Thickness

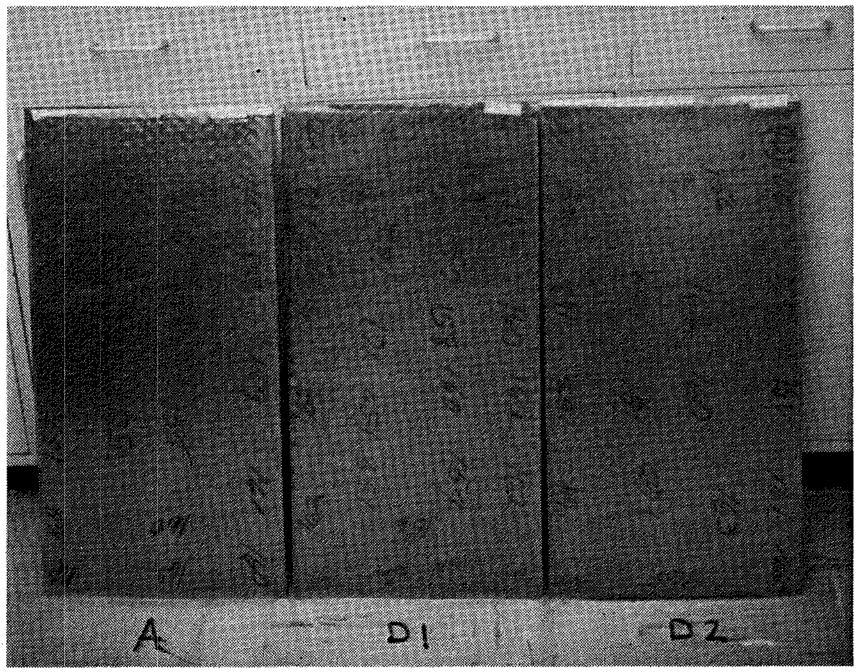

Figure 2. Panels A, D1, and D2 Showing Overall Panel Thickness

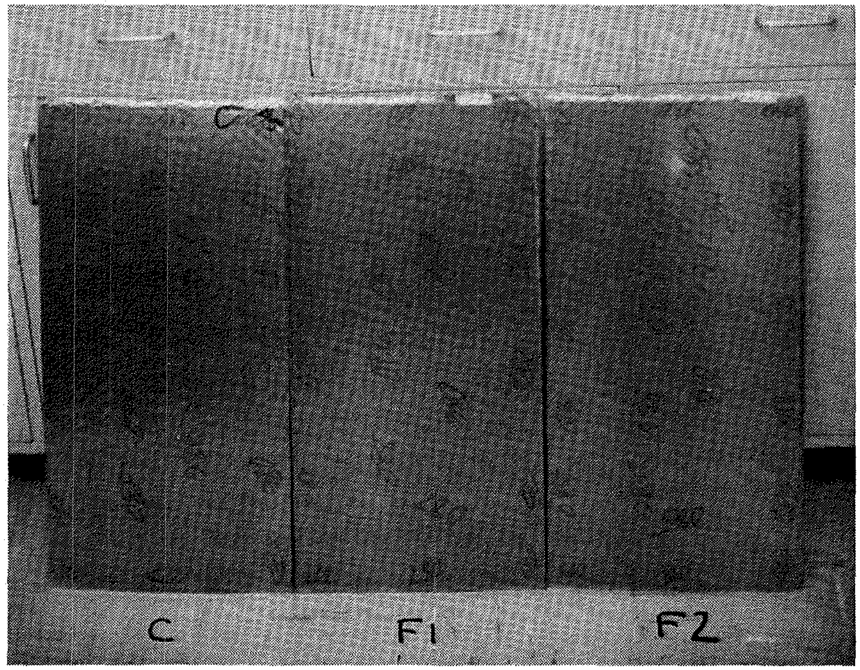

Figure 3. Panels C, F1, and F2 Showing Overall Panel Thickness

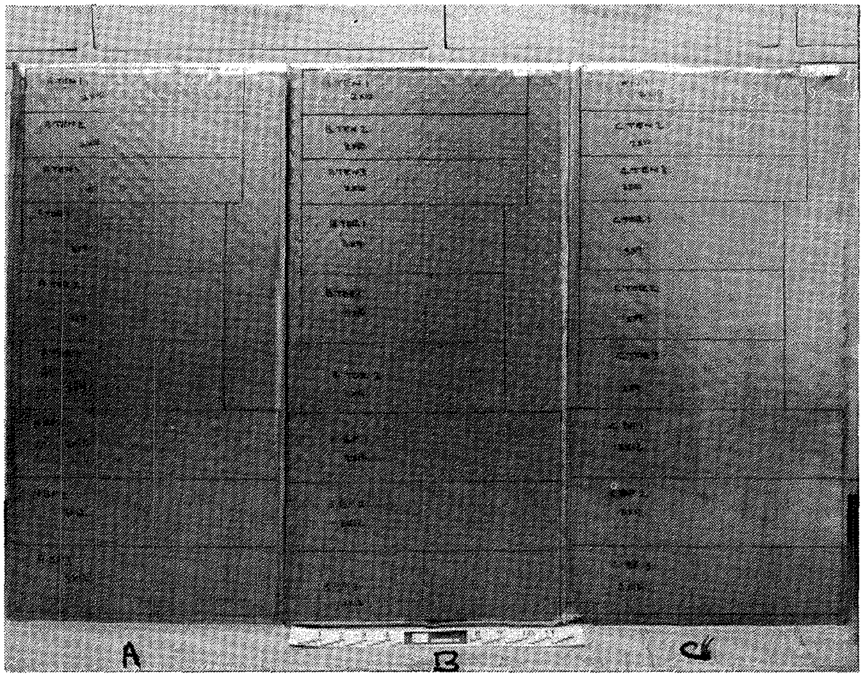

Figure 4. Panels Showing Specimen Layout

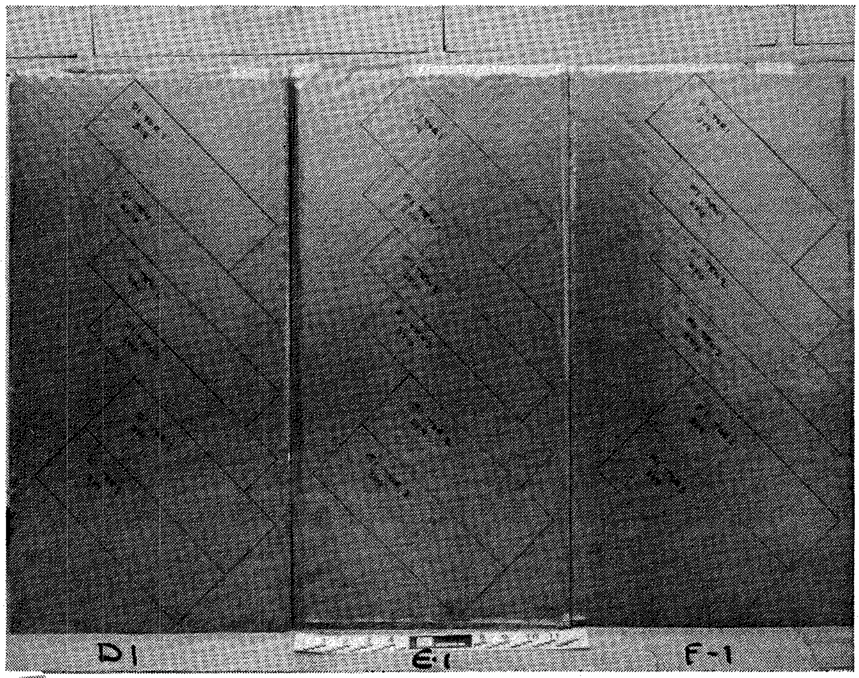

Figure 5. Panels Showing Specimen Layout

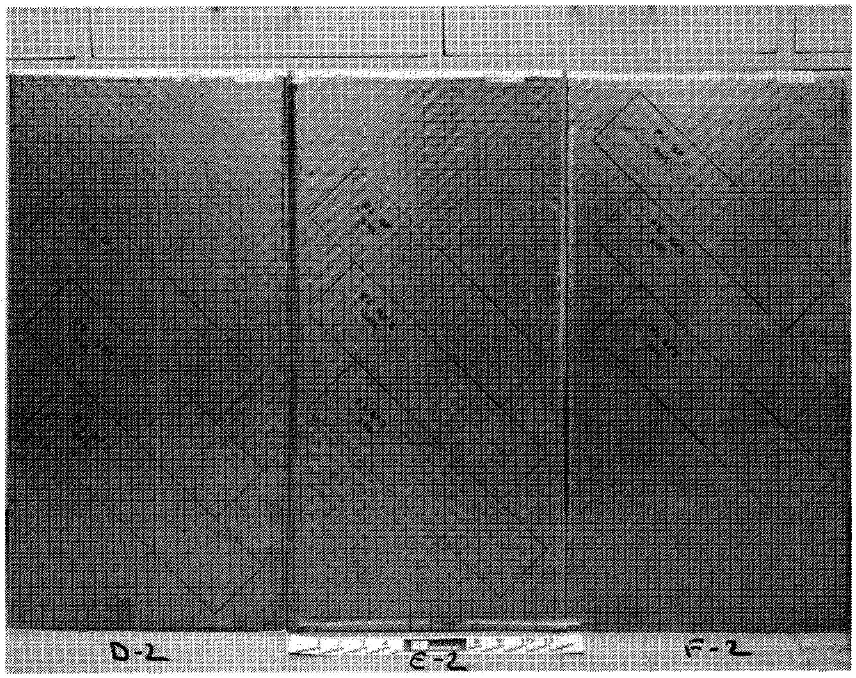

Figure 6. Panels Showing Specimen Layout

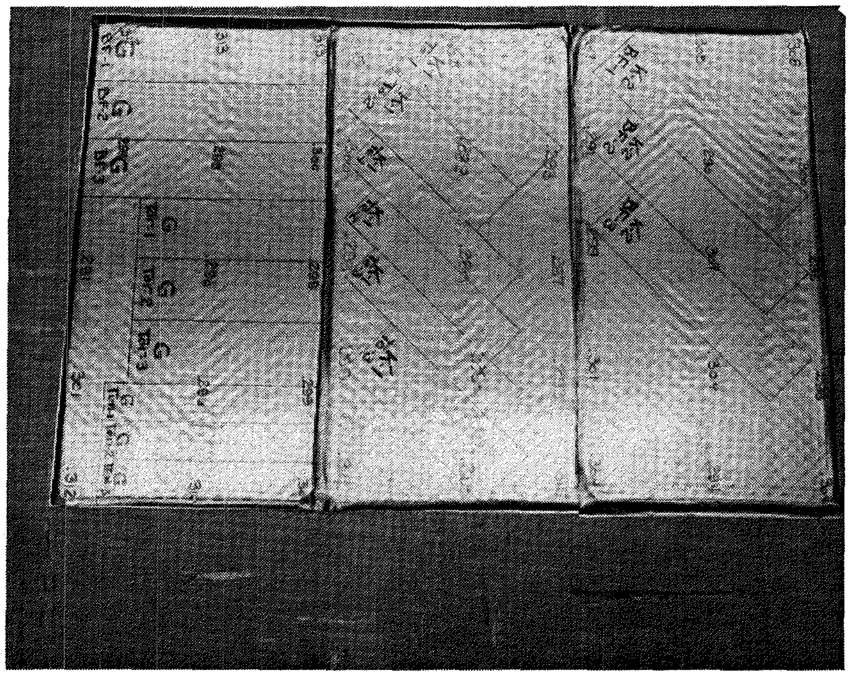

Figure 7. Panels G, K1, and K2 Showing Thickness and Specimen Layout

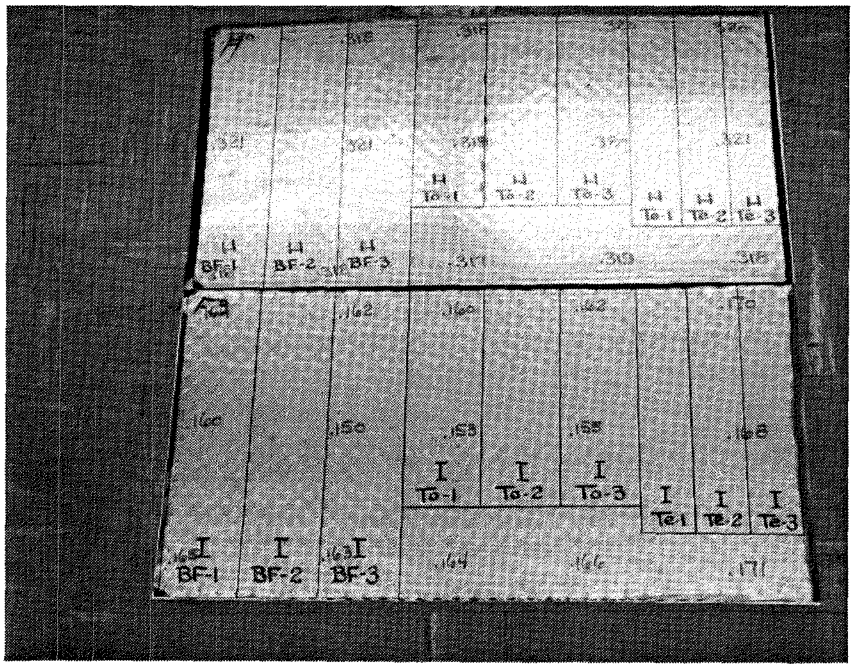

Figure 8. Panels H and I Showing Thickness and Specimen Layout

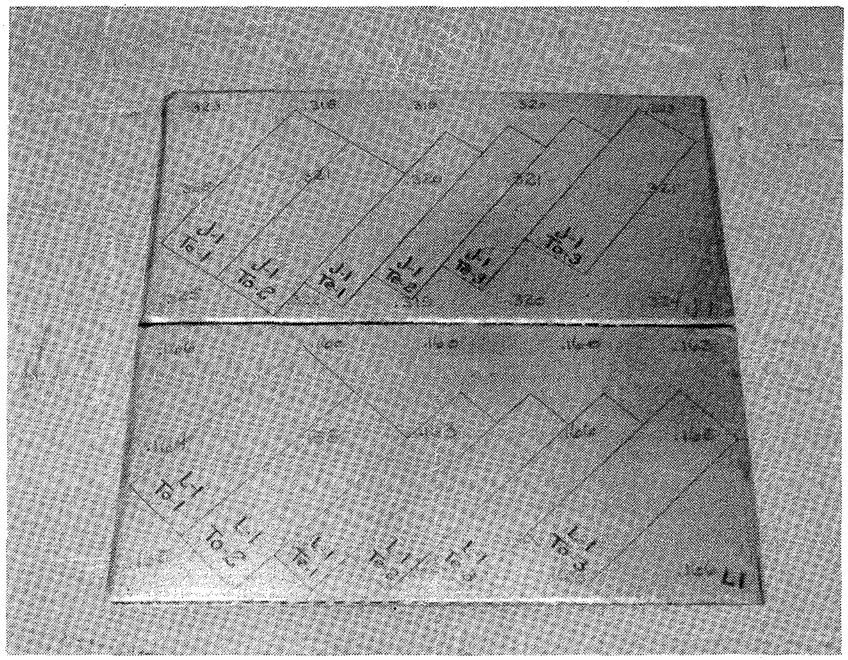

Figure 9. Panels J1 and L1 Showing Thickness and Specimen Layout

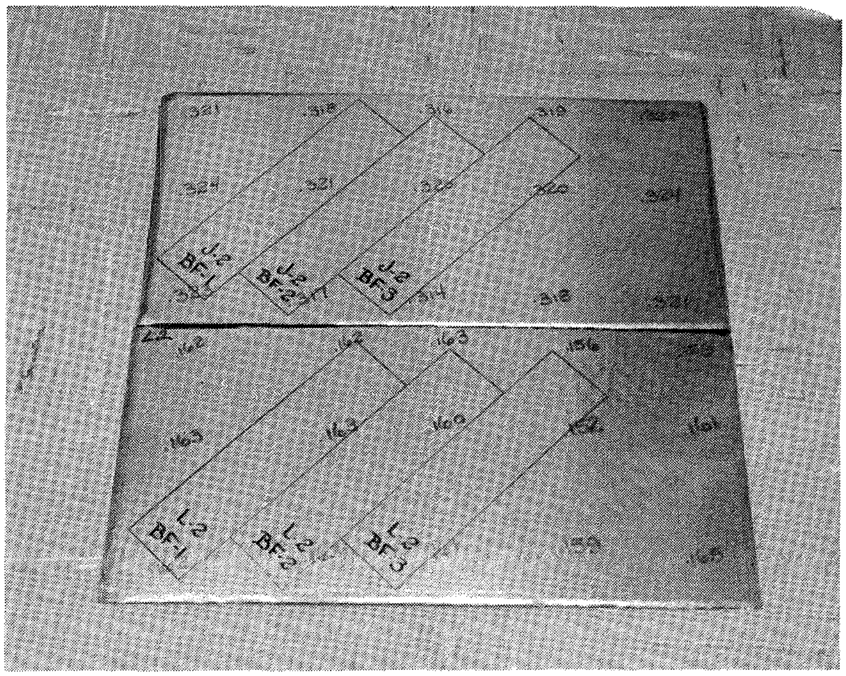

Figure 10. Panels J2 and L2 Showing Thickness and Specimen Layout

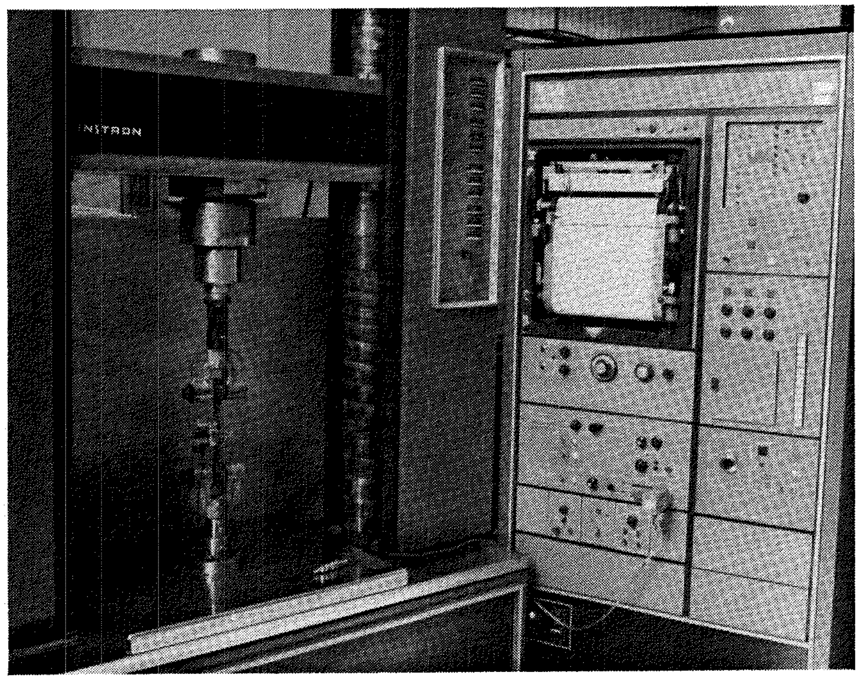

Figure 11. Tensile Test Set-up Showing Instron Tester

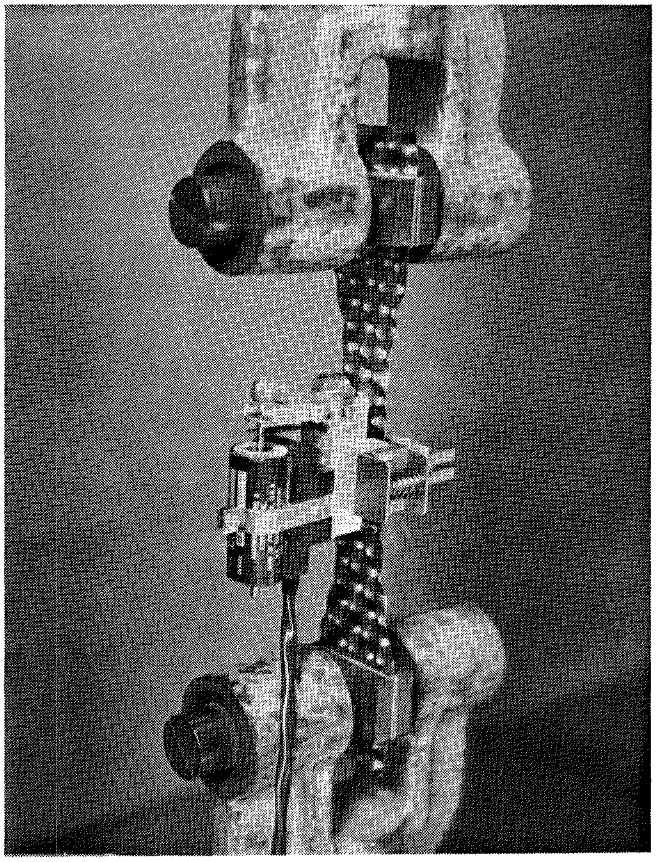

Figure 12. Close-up of Dimple Sheet Tensile Test

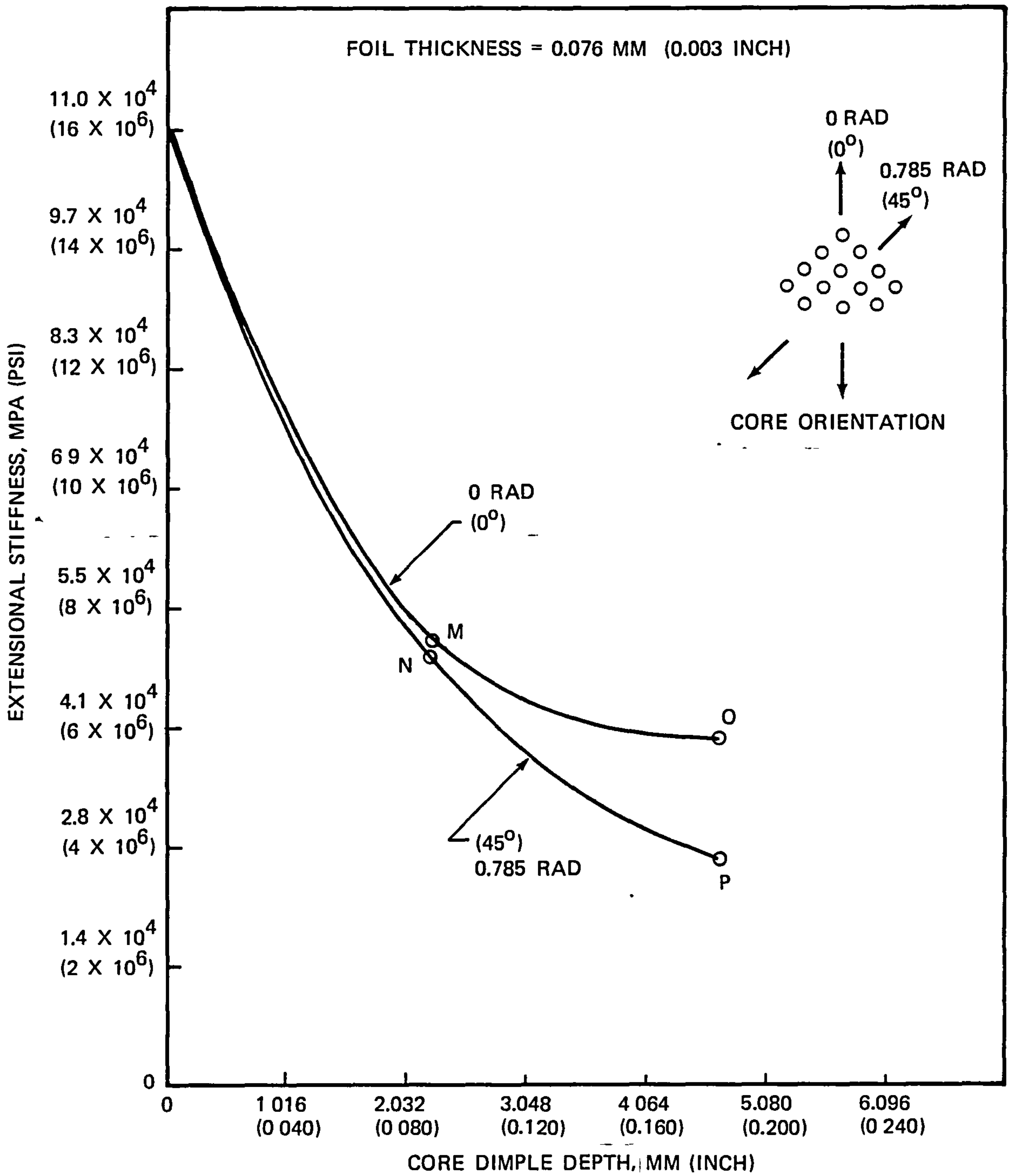

Figure 13. Dimpled Sheet - Effect of Dimpled Depth and Orientation of Dimples

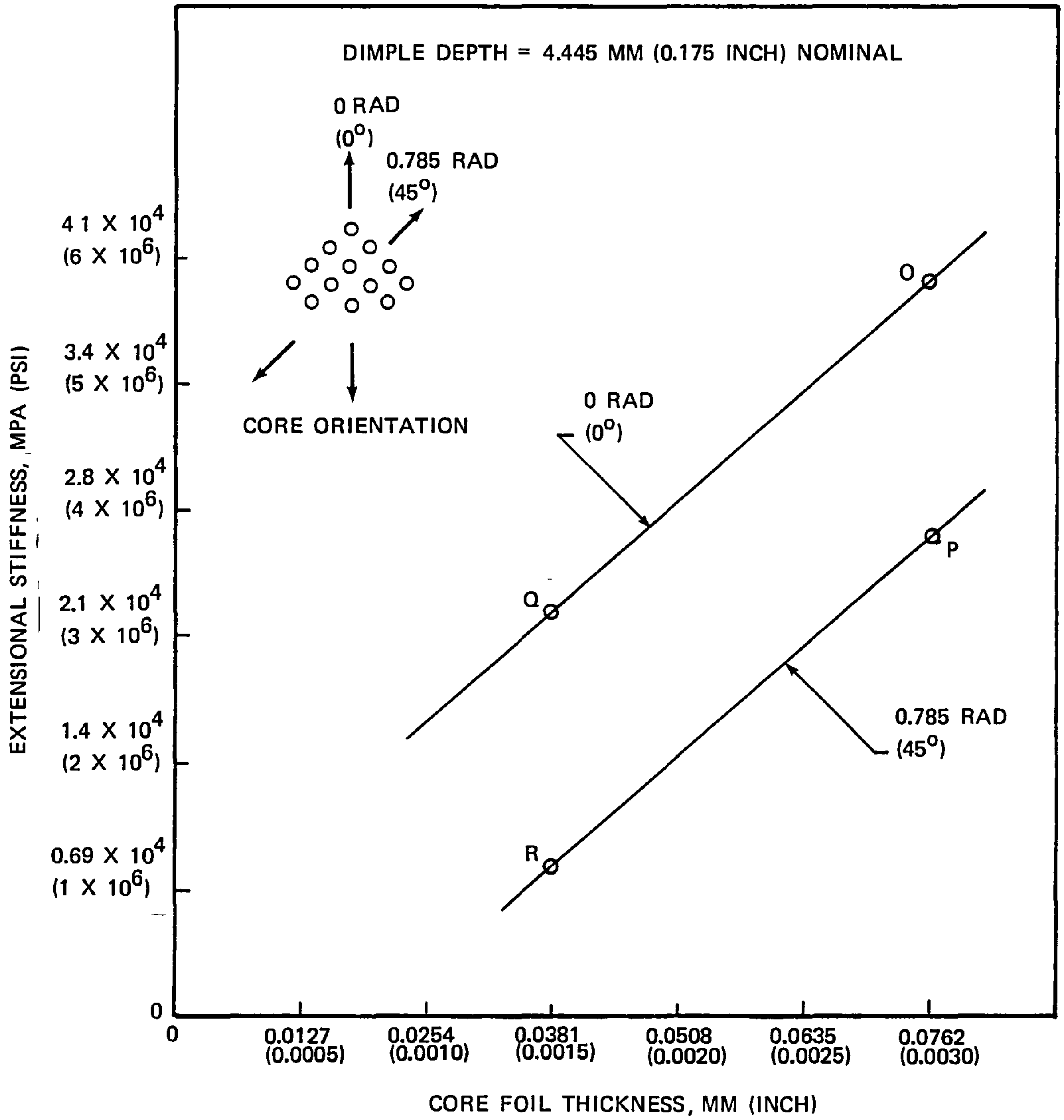

Figure 14. Dimpled Sheet - Effect of Foil Thickness and Orientation of Dimples

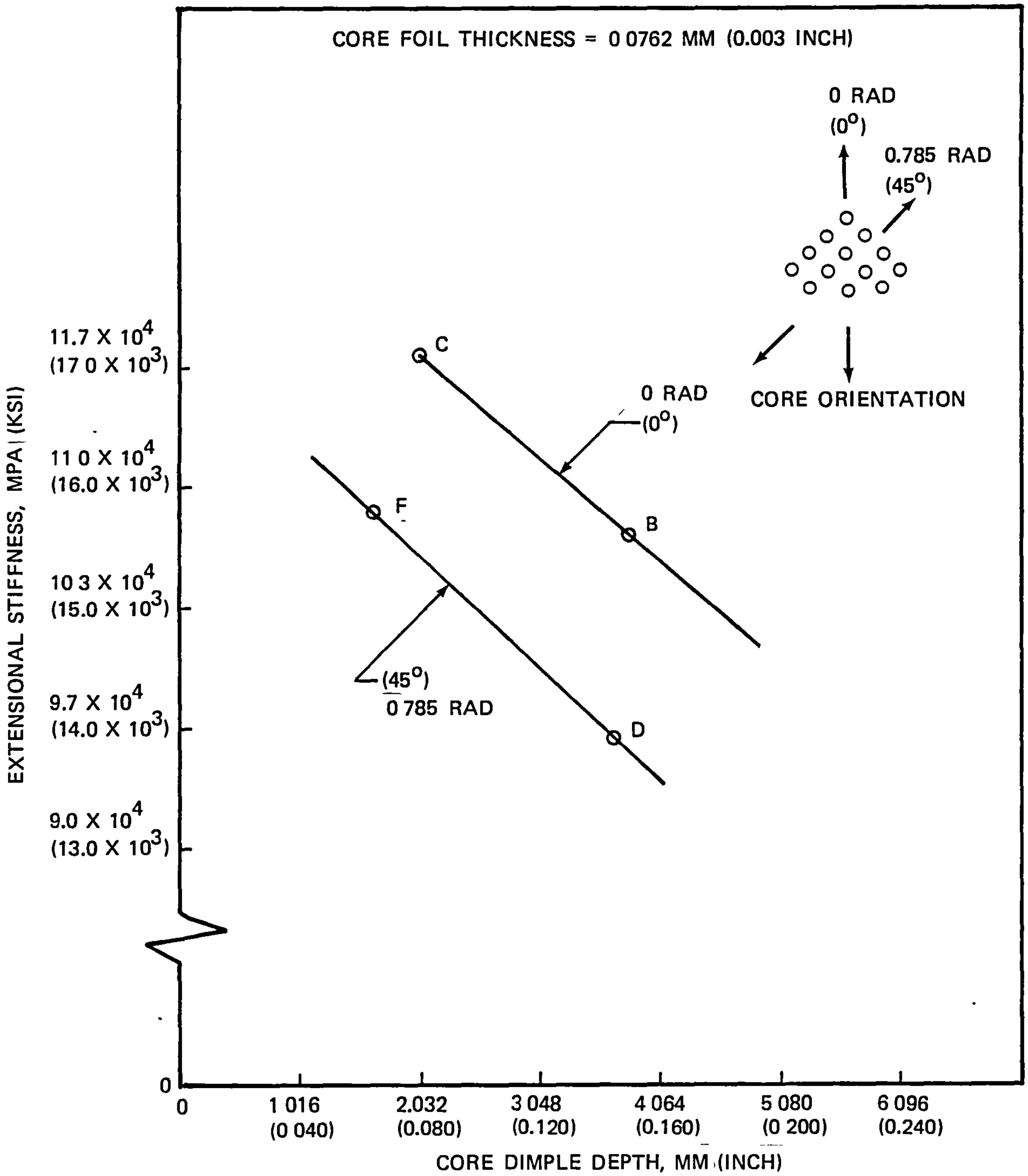

Figure 15. Extensional Stiffness - Single Layer Stiffness Versus Dimple Depth

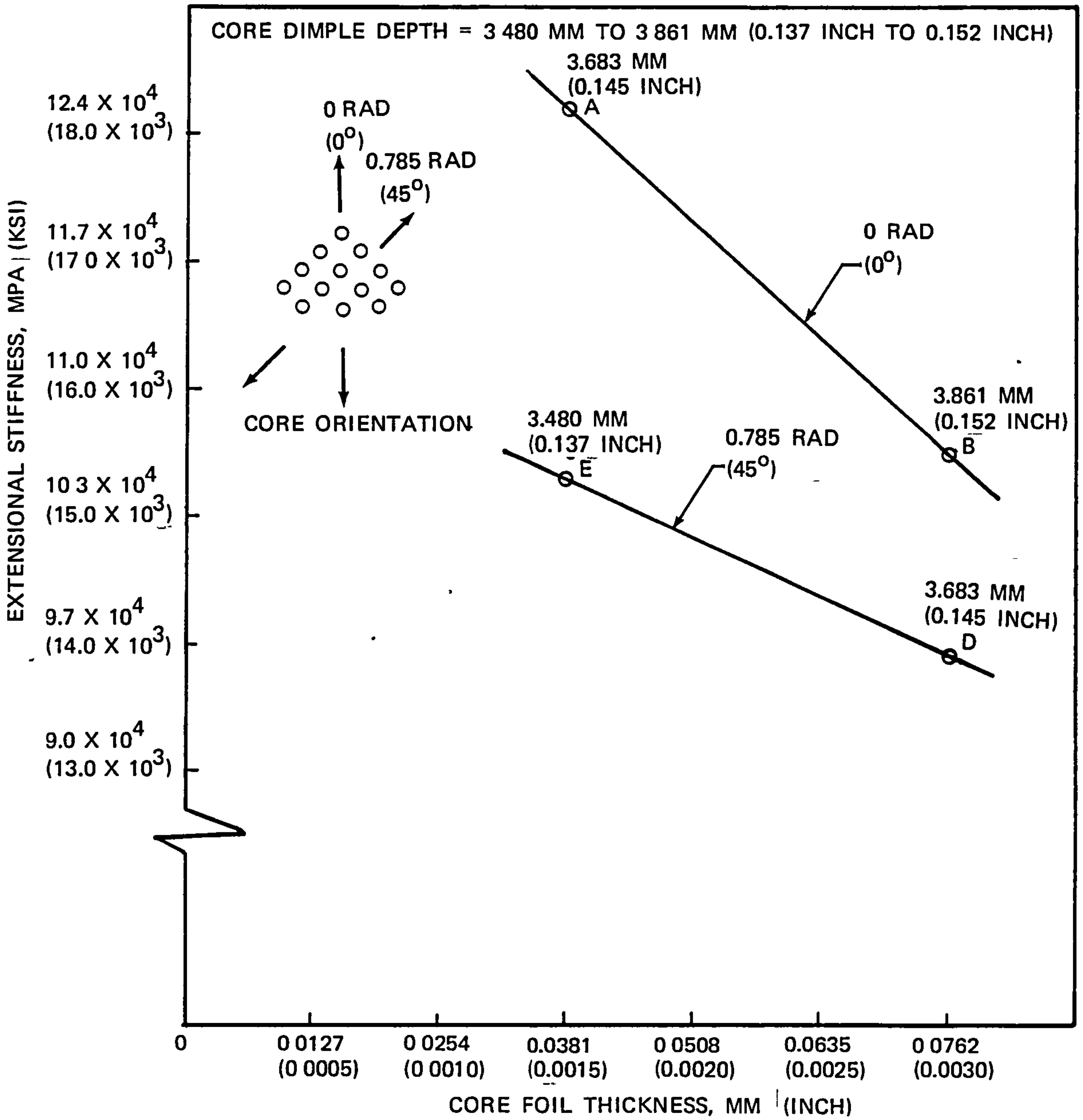

Figure 16. Extensional Stiffness - Single Layer Stiffness Versus Core Foil Thickness

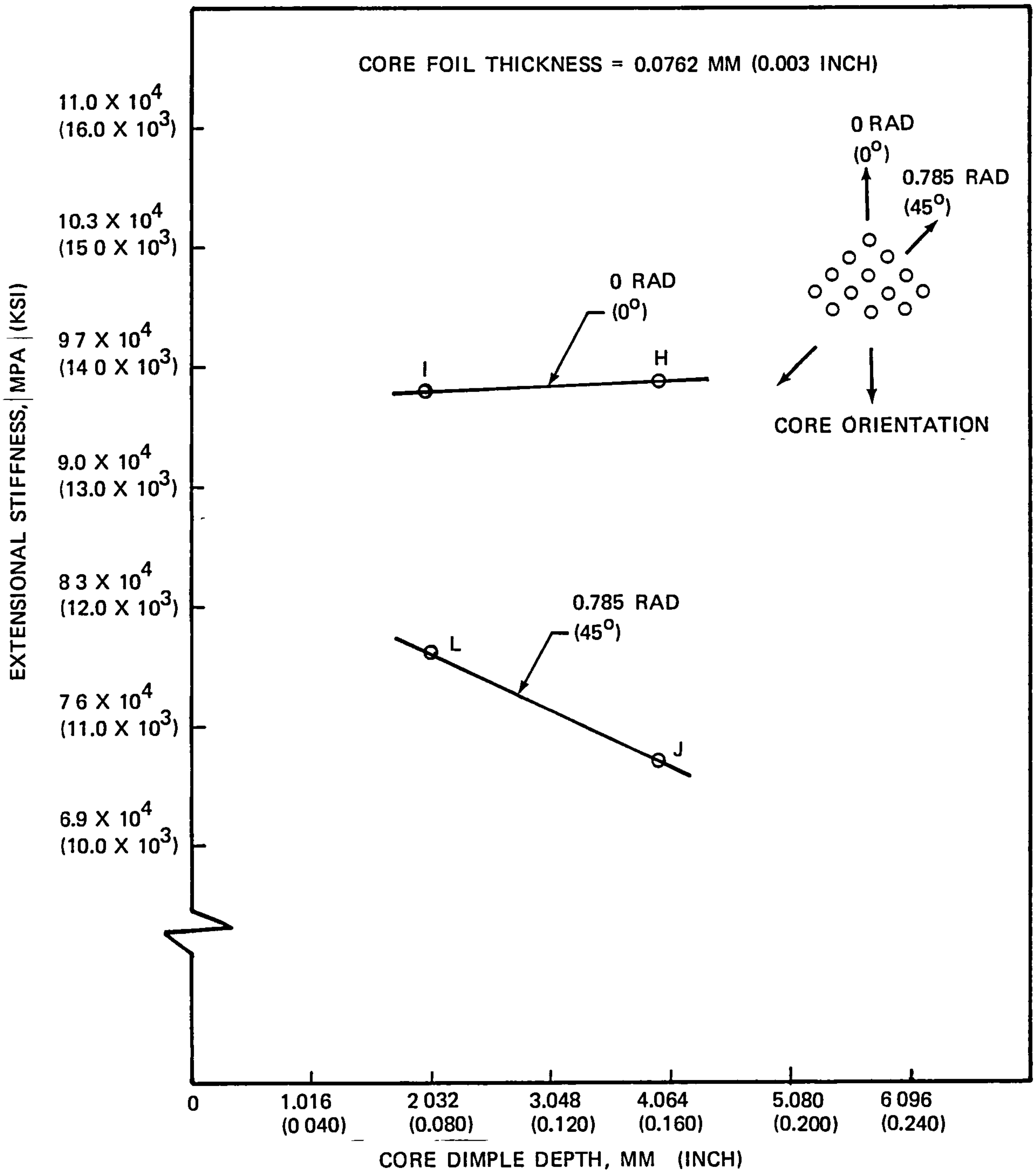

Figure 17. Extensional Stiffness - Double Layer Stiffness Versus Dimple Depth

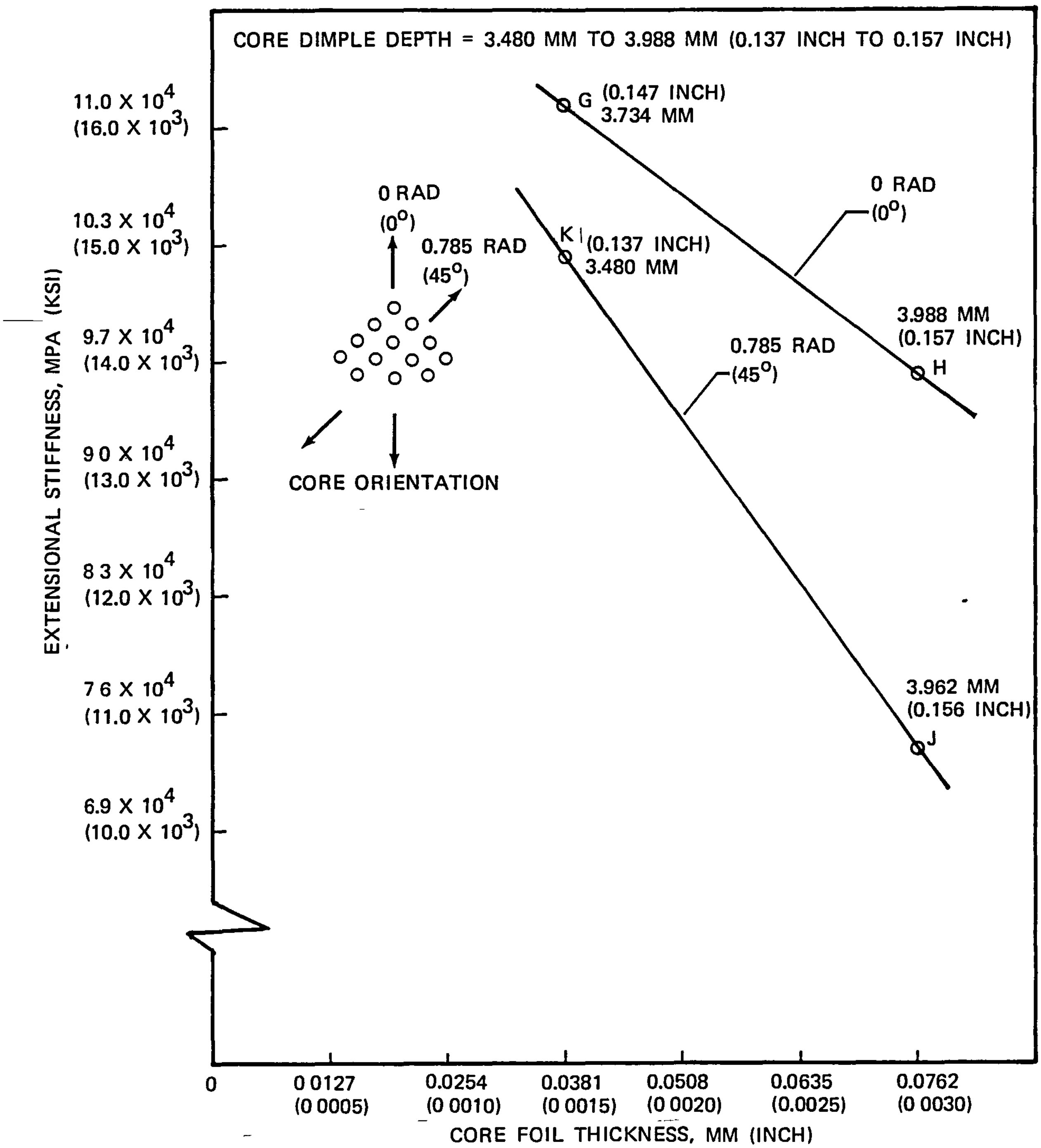

Figure 18. Extensional Stiffness - Double Layer Stiffness Versus Core Foil Thickness

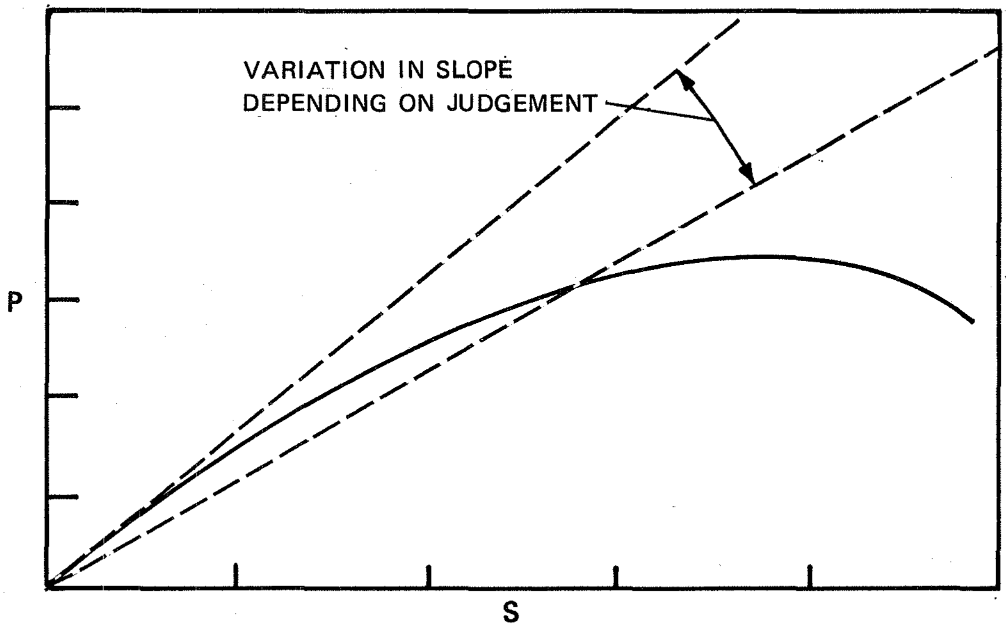

Figure 19. Load Versus Strain, Extensional Stiffness Test Data

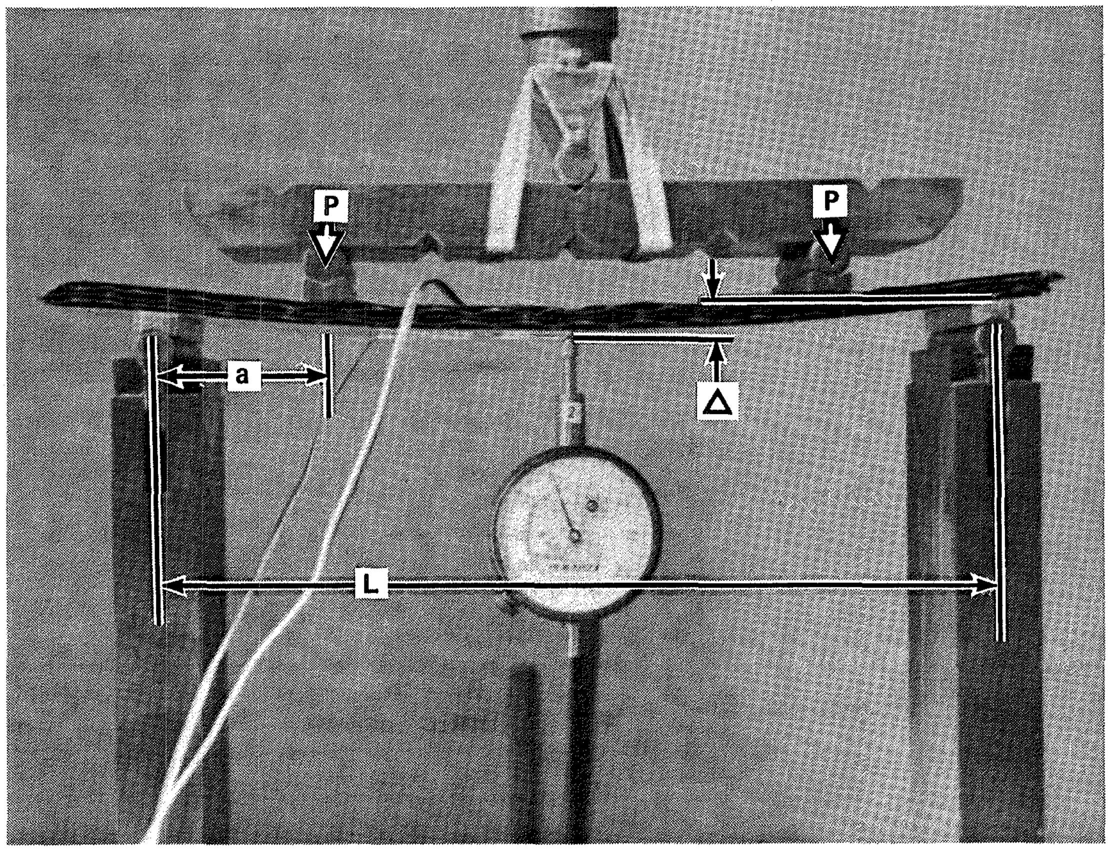

Figure 20. Beam Flexure Test Set-up

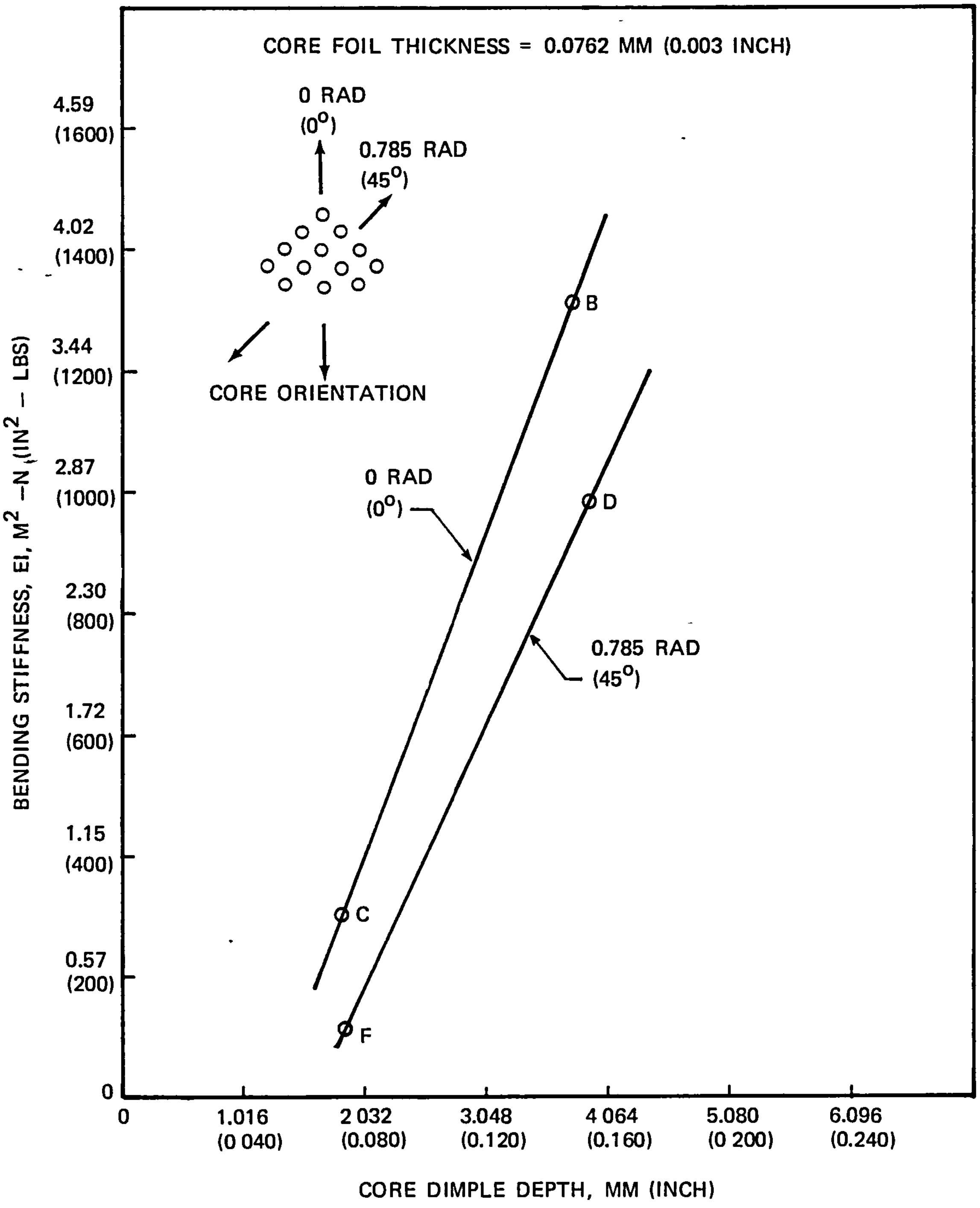

Figure 21. Bending Test - Single Layer EI Bending Stiffness Versus Core Dimple Depth

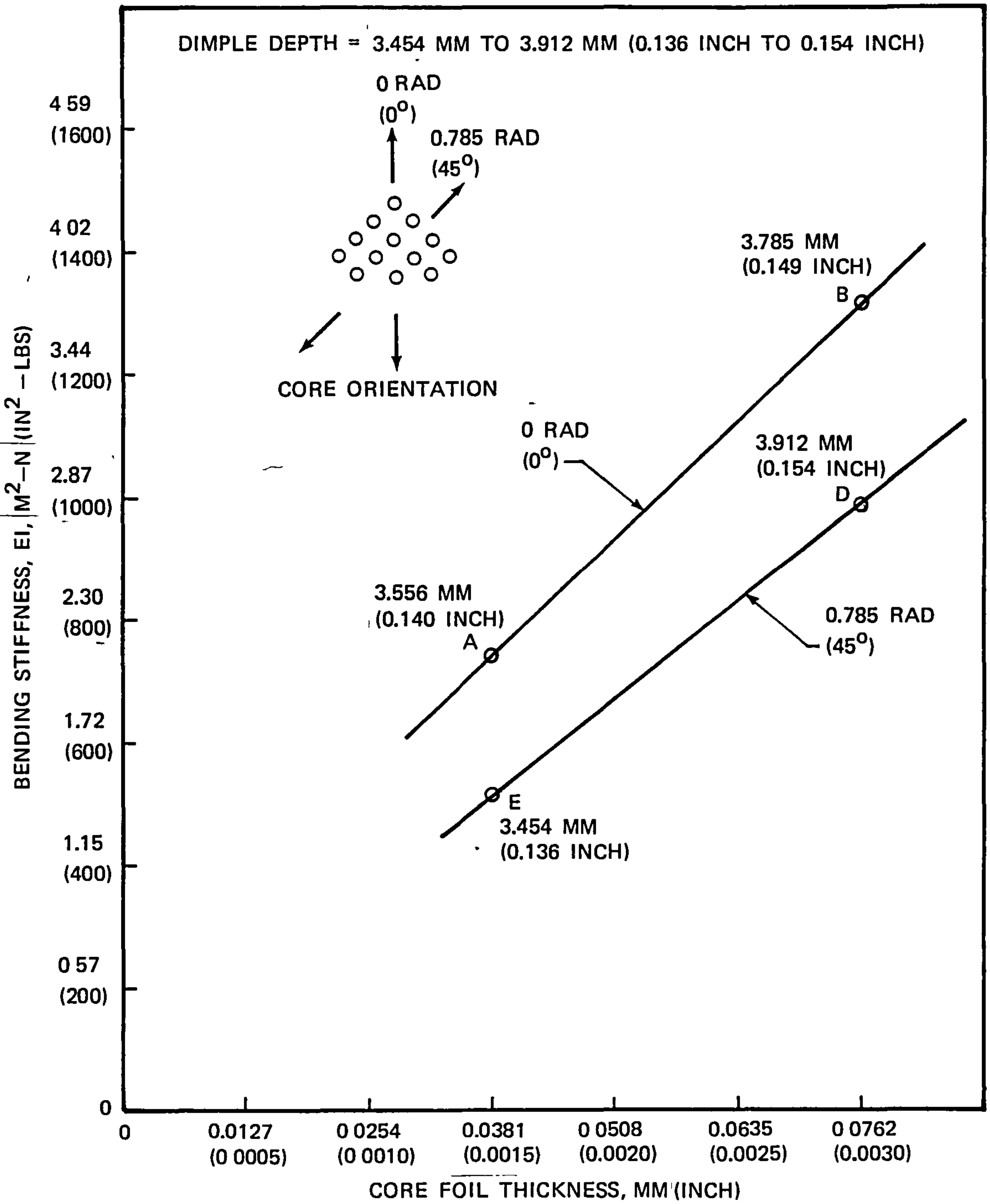

Figure 22. Bending Test - Single Layer EI Bending Stiffness Versus Core Foil Thickness

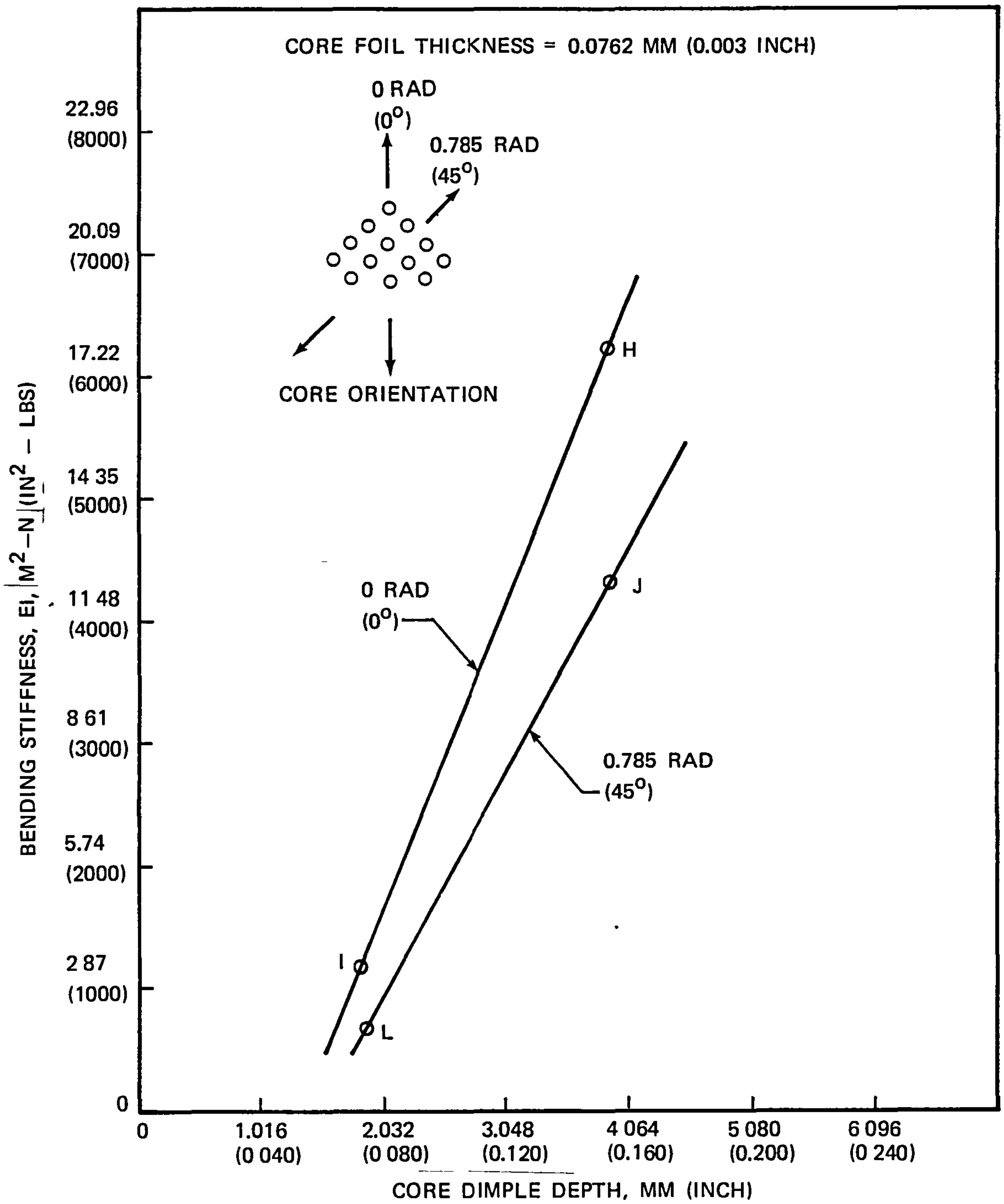

Figure 23. Bending Test - Double Layer EI Bending Stiffness Versus Core Dimple Depth

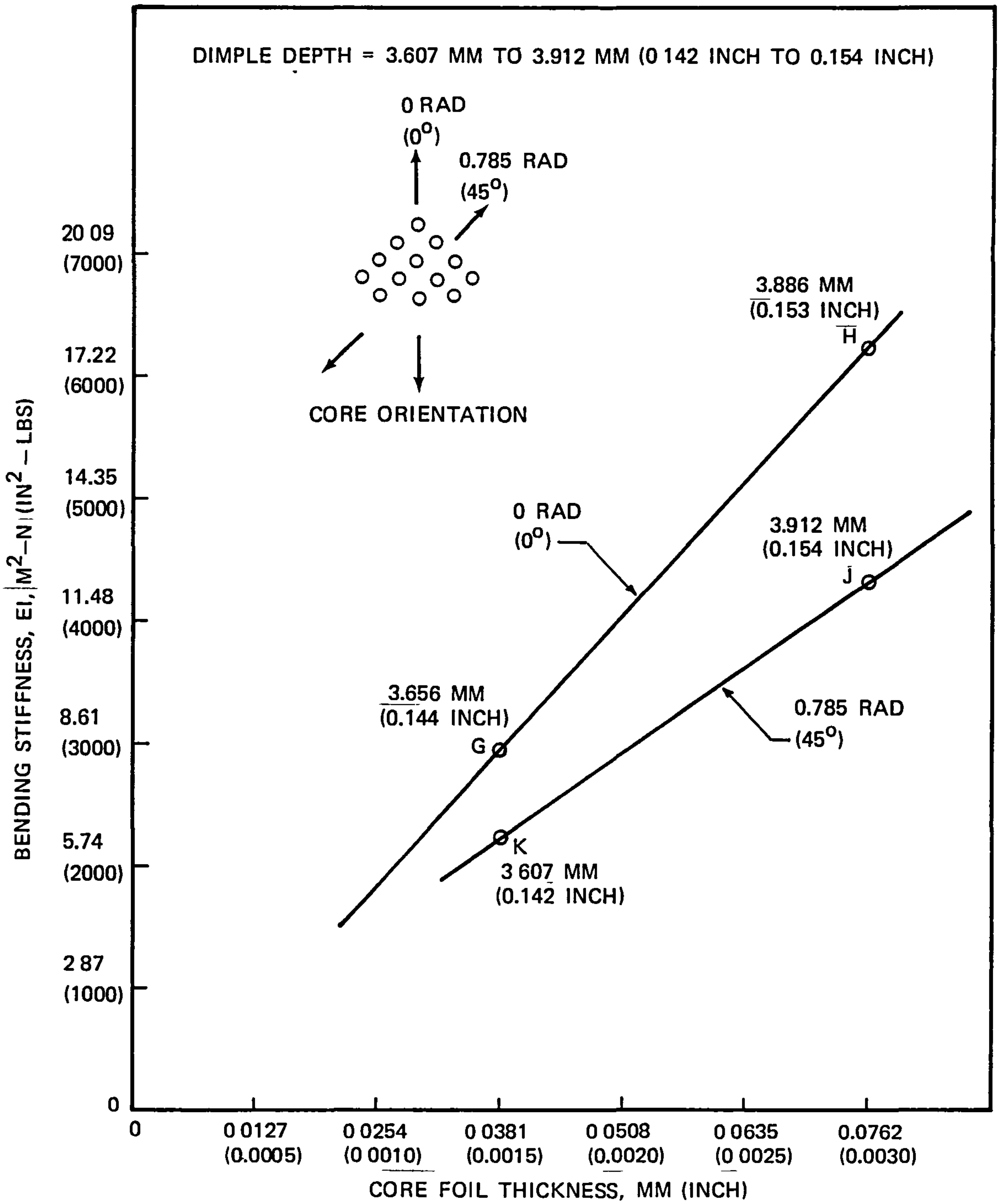

Figure 24. Bending Test - Double Layer EI Bending Stiffness Versus Core Foil Thickness

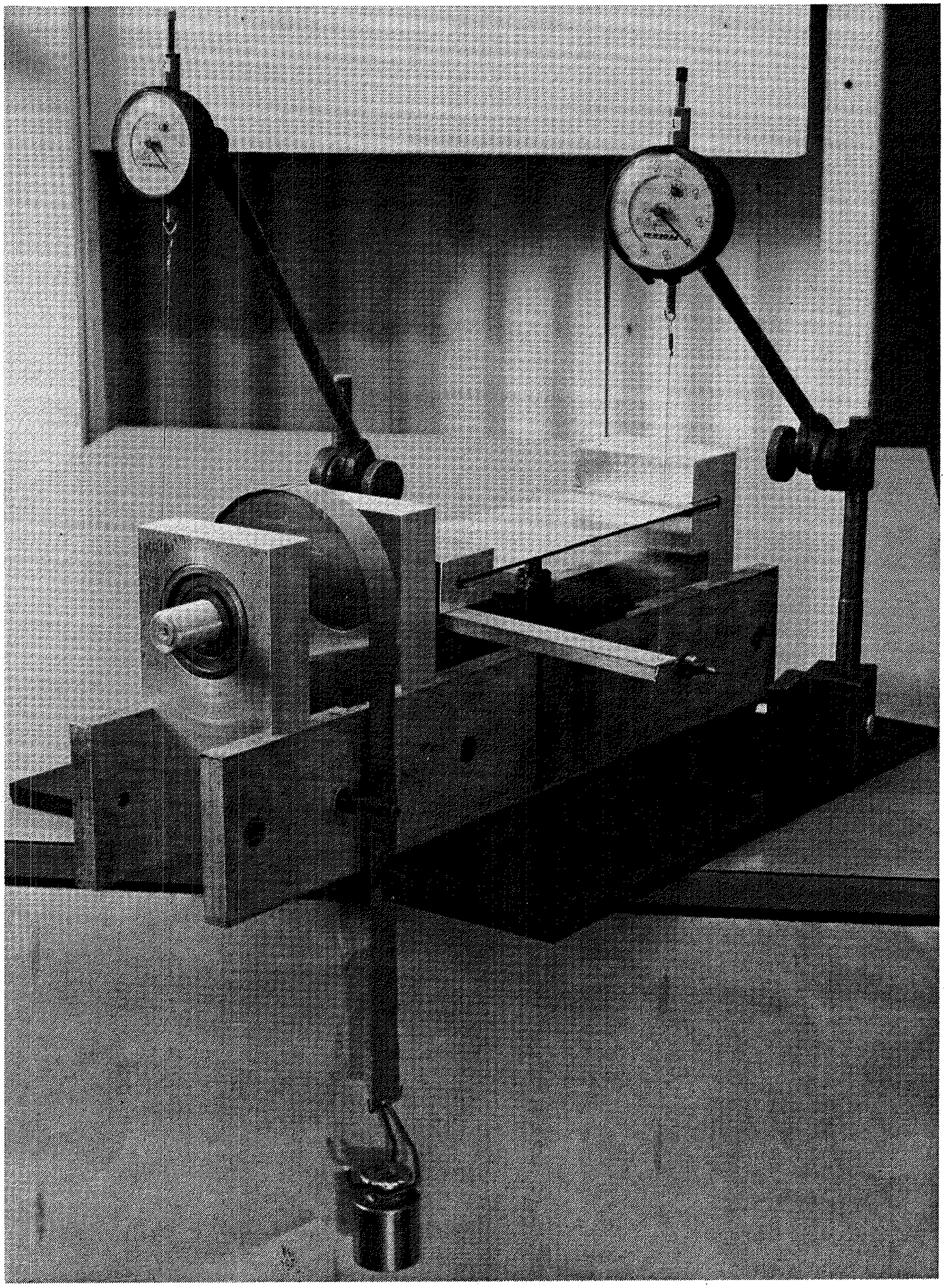

Figure 25. Torsional Stiffness Test Set-up

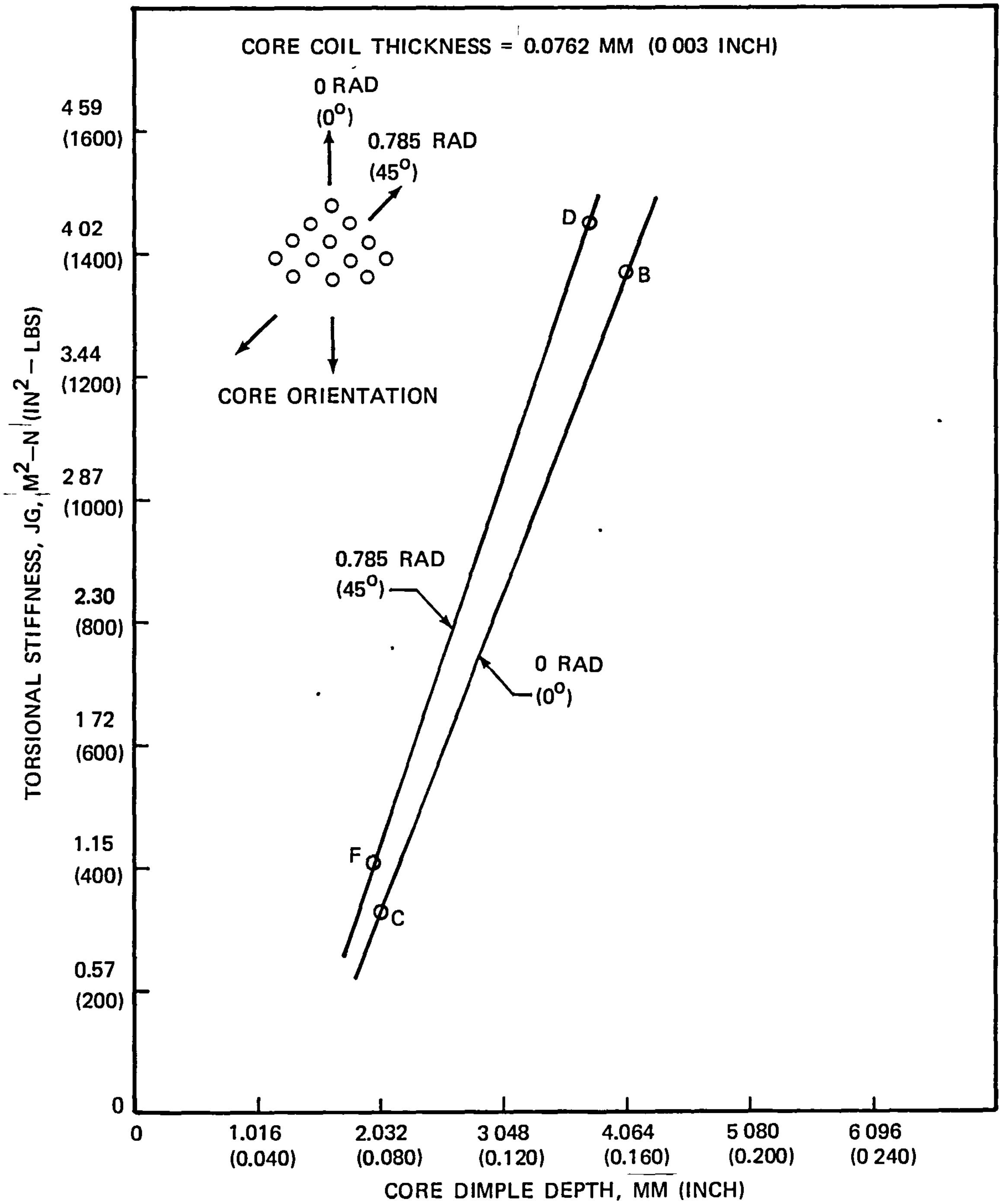

Figure 26. Torsion Test - Single Layer JG Torsional Stiffness Versus Core Dimple Depth

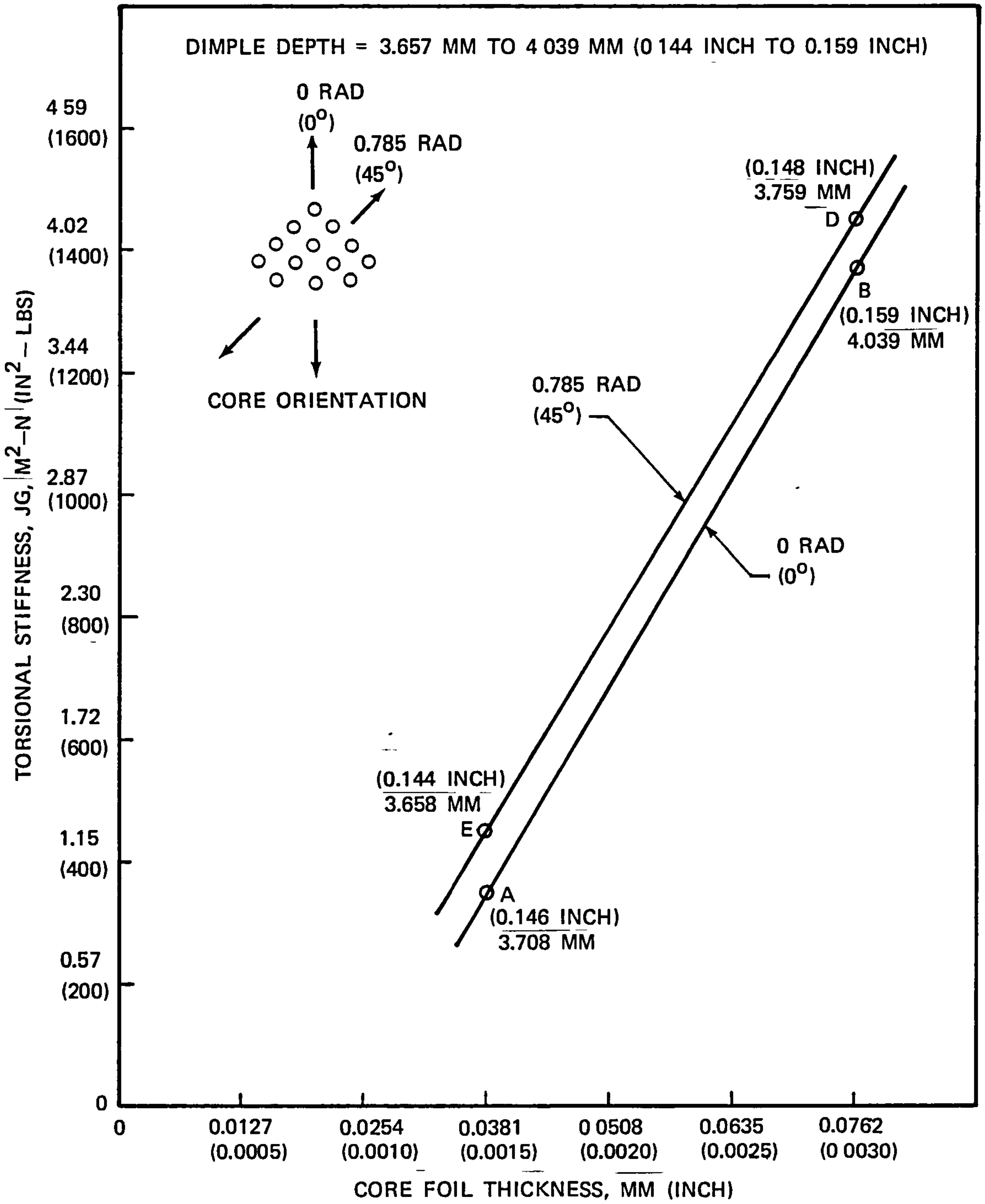

Figure 27. Torsion Test - Single Layer JG Torsional Stiffness Versus Core Foil Thickness

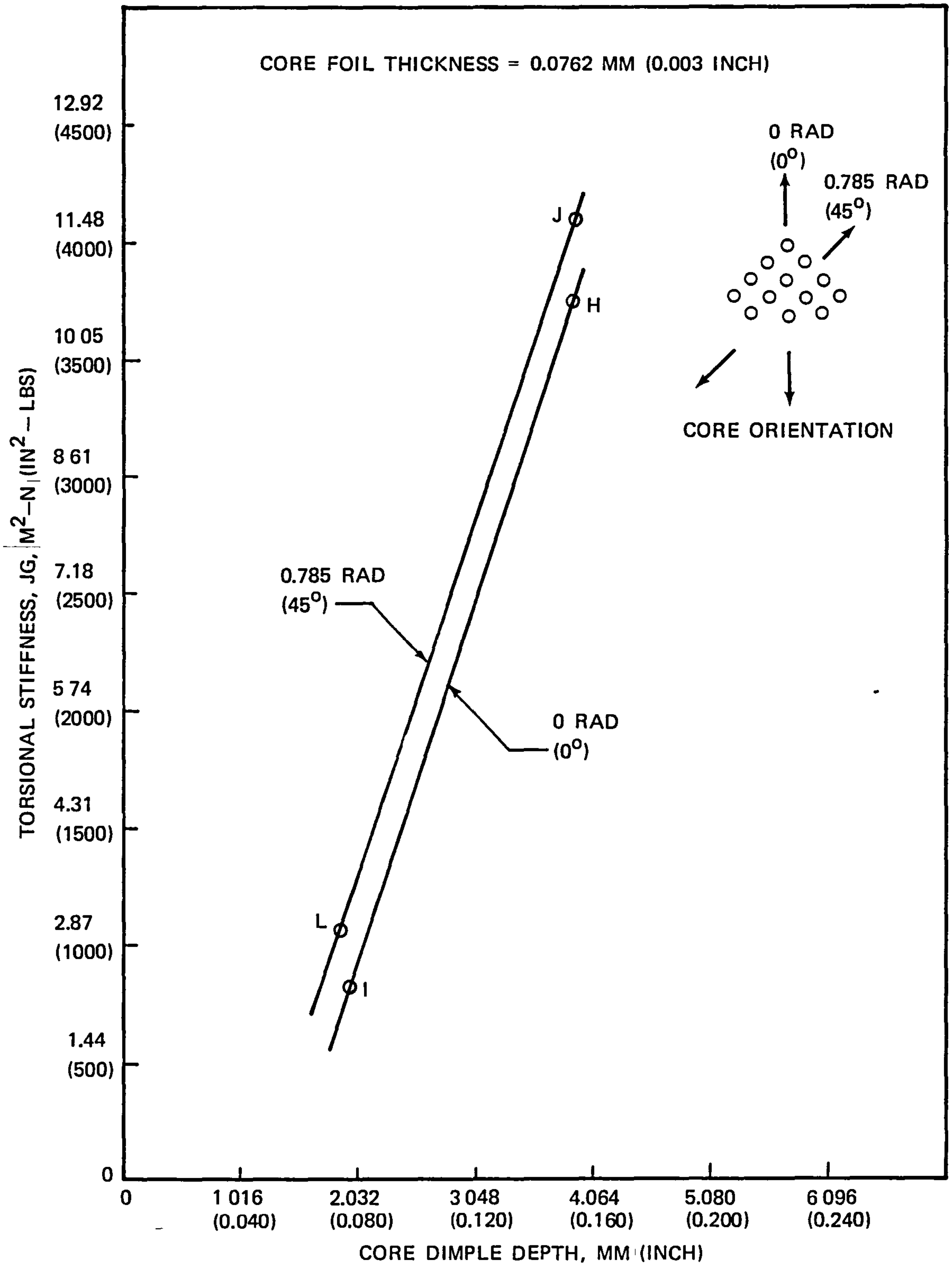

Figure 28. Torsion Test - Double Layer JG Torsional Stiffness Versus Core Dimple Depth

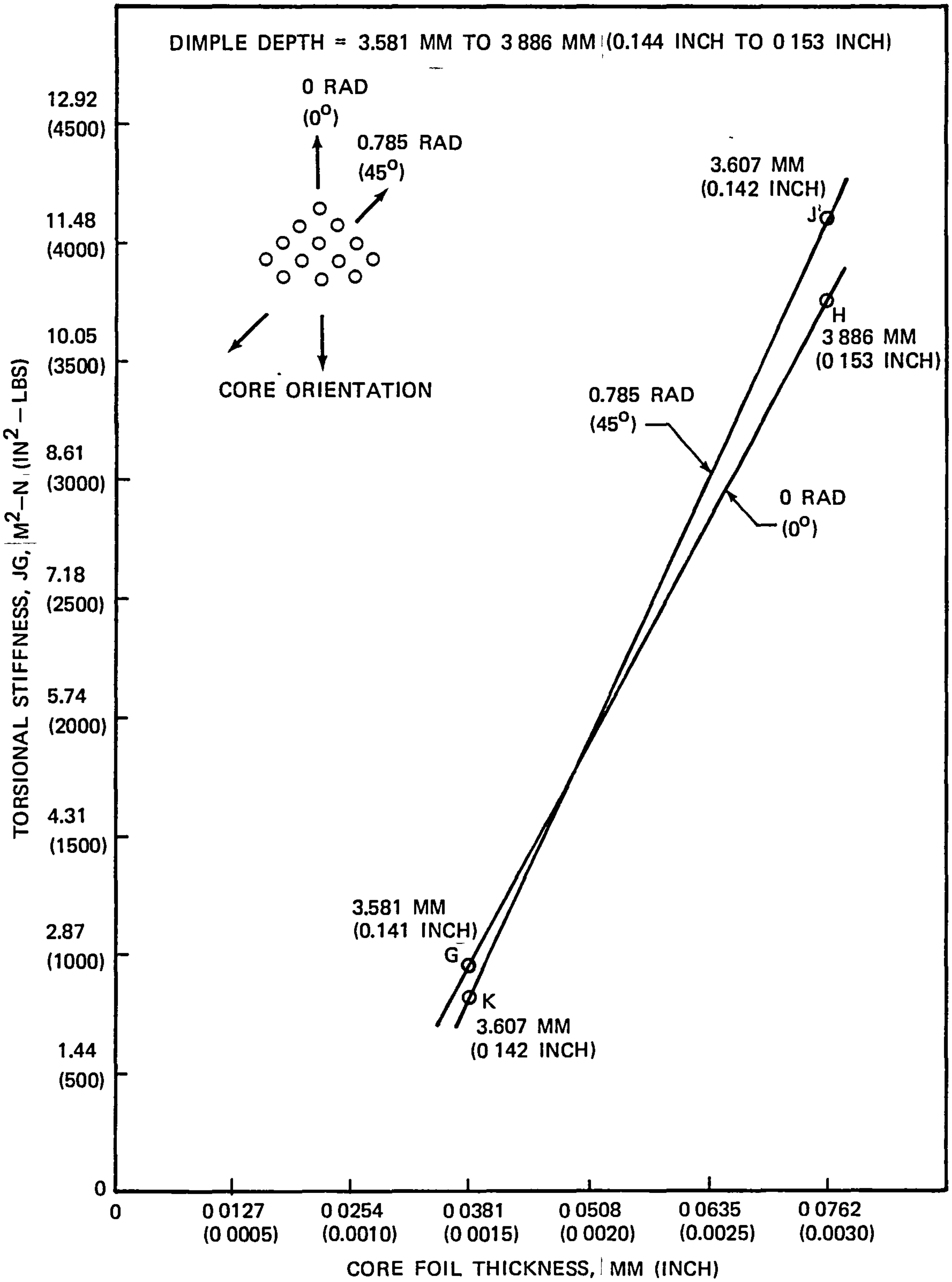

Figure 29. Torsion Test - Double Layer JG Torsional Stiffness Versus Core Foil Thickness

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15. Supplementary Notes

Langley Technical Monitor: John Shideler
Interim Report

16. Abstract

A test program was conducted which determined the extensional, bending and torsional stiffness of various titanium multiwall sandwich configurations. The test methods and results are described.

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