NASA Technical Paper 3512

Buckling of Composite Beams (CDDF Final Report—Project No. 91–20)

P. Thompson
Marshall Space Flight Center • MSFC, Alabama

National Aeronautics and Space Administration
Marshall Space Flight Center • MSFC, Alabama 35812

October 1994

ACKNOWLEDGMENTS

Thanks to Steve Franklin and Ed Kirch of Martin-Marietta, and USBI and Boeing personnel whose contributions to the manufacturing of the research components were invaluable.

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LIST OF SYMBOLS

b	beam width, inches
h	beam height, inches
t_w	web thickness, inches
t_f	flange thickness, inches
P	load applied, lb
E	modulus of elasticity, lb/in^2
d	deflection, inches
ϕ	angle of twist, degrees
Θ	ply orientation angle, degrees
m,n	laminate stacking sequence number

TECHNICAL PAPER

BUCKLING OF COMPOSITE BEAMS

INTRODUCTION

Torsion/bending coupling is an interesting, inherent phenomenon occurring in open-section structural elements subjected to bending and/or combined axial/bending loads. The benefits of using open-section beams are many: stackability, weight savings, and dual functions (e.g., serving as load carriers as well as conduits). Likewise, composites offer advantages over their metallic counterparts; primarily, their higher strength-to-weight ratios and lower coefficients of thermal expansion (CTE) are favorable. This type beam is used extensively in the aircraft industry in the fuselage support structure and wing supports, and has present and potential future use in aerospace applications; namely tankage stiffeners, intertank stiffeners, and as primary load carriers in truss work. However, in each of the aforementioned applications the layups are symmetric in nature. By understanding the bending/torsion effects indigenous to open-section beams one can make use of the tailorability of composites (to achieve desired optimum material properties) without compromise to the design (e.g., no added plies to accomplish symmetry).

Antisymmetric layups lend themselves well to thin-walled structural members. With an average ply thickness of 0.005 in, a beam of wall thickness less than 0.040 in (8 plies) is difficult to manufacture using a symmetric laminate layup.

Even an open-section beam made of an isotropic material has an inherent tendency to bend and twist if the transverse load is applied anywhere other than along the plane of the shear center. A transverse load applied to such open sections undergoes pure bending only when the load is applied at points along the shear center located outside the section.[1] As Valsov illustrates, an open section not loaded at points along its shear center will twist and bend as in figure 1(b). Figure 1(a) shows the same open-section beam with no load applied. In the case with loading at the shear center, notice that pure bending results, as in figure 1(c).

As in symmetrically laminated structural elements, unsymmetrically laminated elements can have many different resultant properties depending on the chosen material system, ply orientations, and layup sequence.[2] Add these factors to the bending/twisting coupling inherent to an open section loaded transversely and one can easily surmise the difficulties that might be associated with designing using unsymmetric, open-section structural elements.

Characterization of the relationship between angle of twist and ply orientation is one of the objectives of this paper. This is being done based strictly on test results, with results of the analytical aspect to be presented in a later paper. Also examined and presented here are the results of testing involving shear center location, load application relative to shear center, and the resulting angle of twist on open-section beams. Curves depicting these parameters and the various interrelationships are contained in this paper.

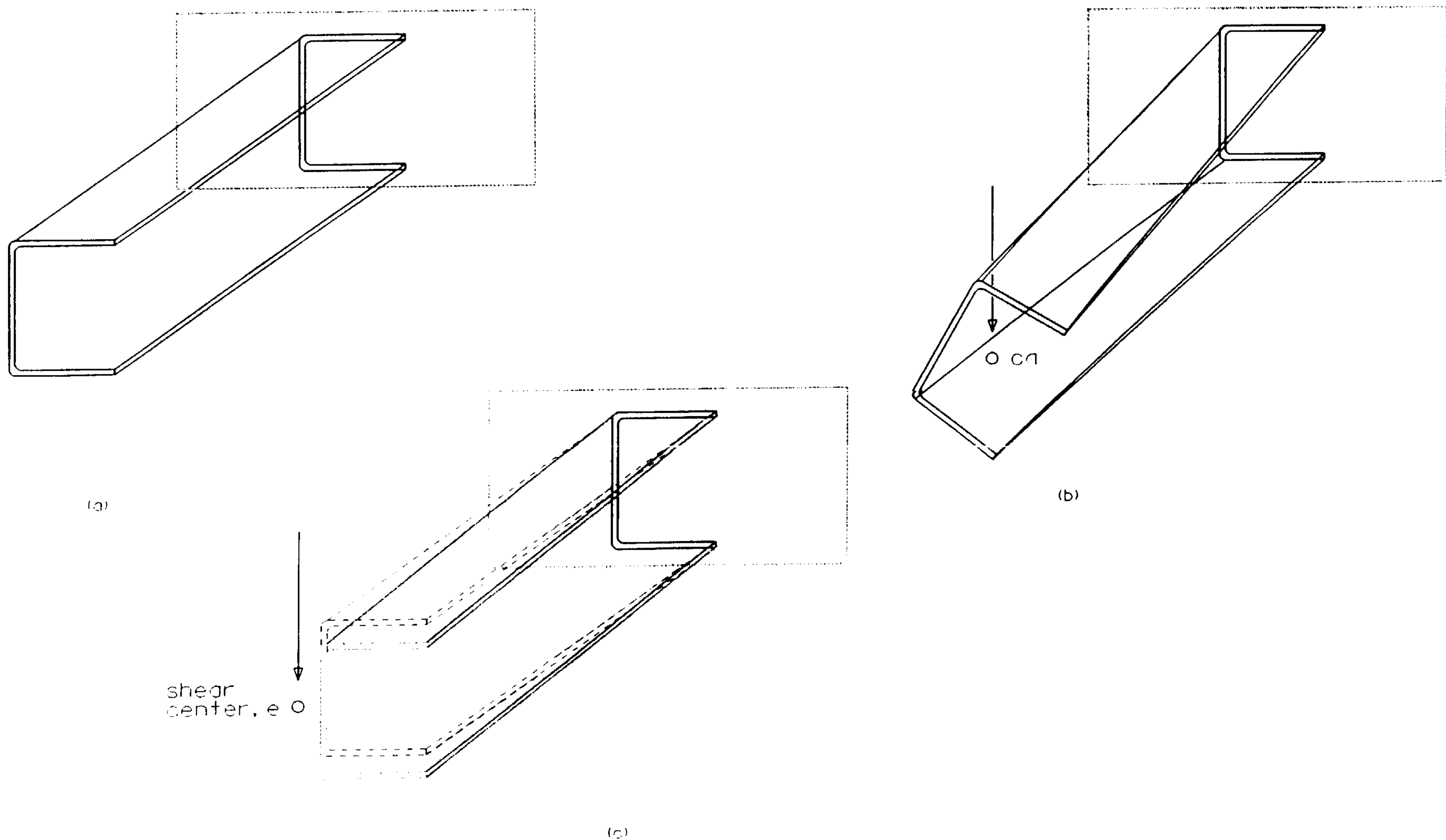


Figure 1. Open-section beam.

APPROACH

To reach the first objective (characterization of the relationship between the angle of twist and ply orientation), the effects of distortions due to CTE must be included. This produces an amount of pretwist in the beam apart from the twisting that is to occur due to the load not being applied at the actual shear center. Examination of the various laminate layups will reveal a general relationship between the ply orientation and angle of twist.

Open-section beams of various ply orientations were manufactured and tested to determine what effect ply orientation and laminate layup have on the shear center location, i.e., can the shear center in open-section structural elements be shifted toward its geometric center? As illustrated in figure 2, the geometric center and theoretical shear center differ. Yet this moving of the shear center can possibly be observed by comparing the various twist and deflections in each beam tested as a specified load is applied at designated positions along the horizontal plane of the shear center (fig. 2). Recalling that no twist (pure bending only) will occur when transverse loads are applied at the shear center, one can better define the location of the "true" shear center. This "true" position, since it is observed after the curing process (hence, CTE mismatches are already accounted for), reflects the dependency of shear center on laminate layup. No attempts were made to quantify this preload twist; however, measurements were taken prior to testing the beams to analyze trends.

Open-section beams (C-channels) of the layup $[0/\Theta]_m$ are referred to as Form 1. The laminates referred to as Form 2 are of $([0/\Theta]_n,[0/\Theta]_n)$ construction.

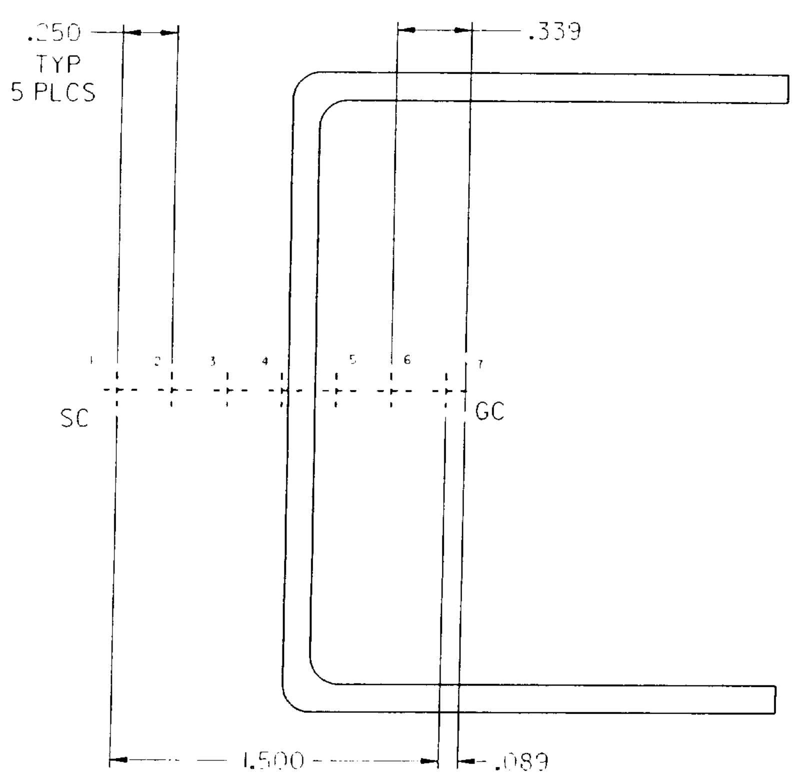
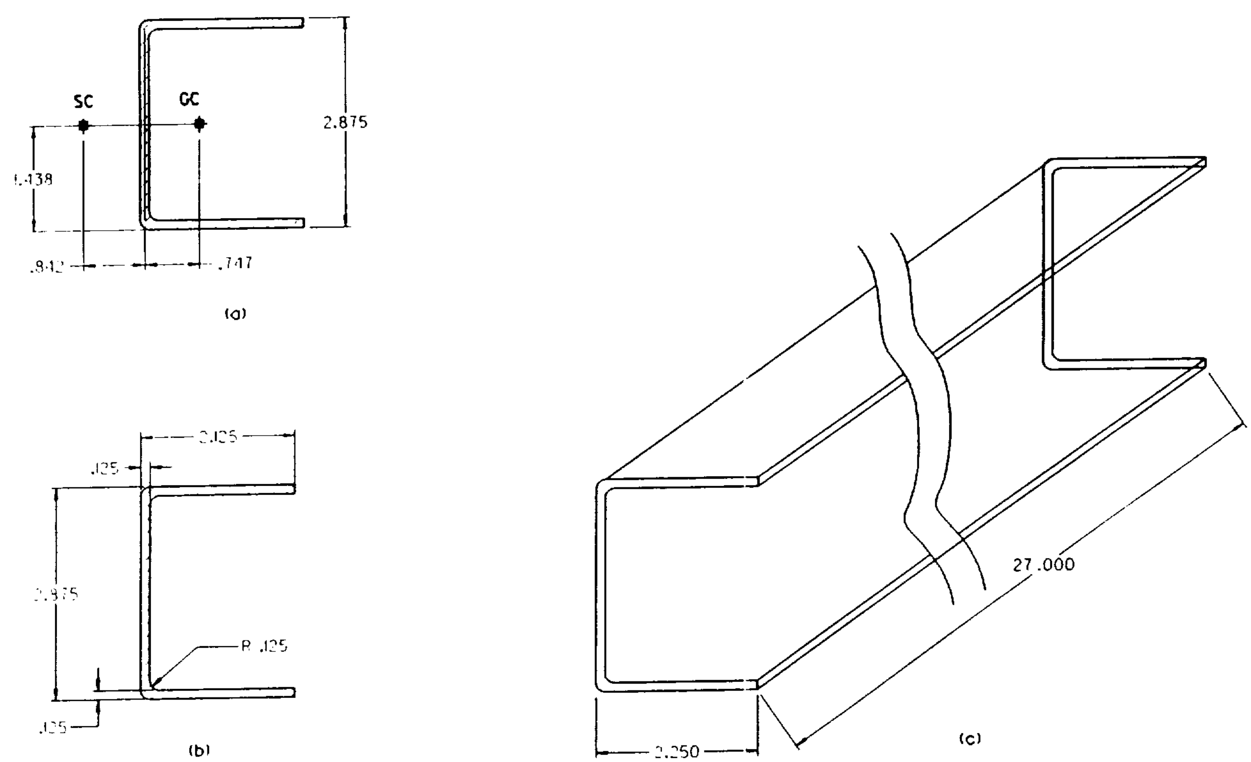


Figure 2. Load application points.

MANUFACTURING METHODS AND TESTING

As previously stated, the beams were fabricated using the hand layup and hot-drape forming techniques. Hand layup involved cutting 3-in wide strips of the unidirectional tape to the correct lengths and wrapping the tape at proper angles across the tool (in this case a solid aluminum square tube served as the tool) layer by layer. Intermediate vacuum bagging was performed to ensure adequate compaction prior to the autoclave cure of the part. Hot-drape forming was a new procedure used to take advantage of the multiaxis tape laying machine. Using this technique panels (approximately 18-in wide by 72-in long) were tape layed by machine. This provided repeatability of the part, provided adequate compaction (tape head is pressure sensitive, i.e., constant pressure as tape is layed in place), and reduced time of manufacturing. After the panels were cut to a strip 9 by 72 in, they were "draped" over the same tool used previously, bagged, and placed in the hot-drape forming "oven" under controlled temperatures (see the photographs in the appendix). This allowed the material's resin to flow enough so that the panel would take the shape of the tool.

After the part was formed (regardless of method), it was vacuum bagged for autoclave cure using standard procedures. The resulting channels were then removed from the tool and cut and machined to dimensions suitable for testing. Figure 3 shows the geometry of the finished beam prior to instrumentation for testing.



C-CHANNEL CROSS-SECTION

C-CHANNEL COMPOSITE BEAM

Figure 3. C-channel beams.

The testing included applying load at several locations along the horizontal plane of the shear and geometric centers. After the beam was instrumented and the load cells calibrated, load was applied in 15 to 20 lb increments until a total of 130 lb was being applied. Beginning at the theoretical shear center, this procedure was repeated (at 0.25-in increments) until the final measurements at the geometric center (fig. 2). During the test procedure, the deflections and strains were recorded with the addition of load at each of the incremental points.

EFFECT OF FIBER ORIENTATION OF FLANGE DEFLECTION

Graphs 1 through 6 of section I of the appendix show deflections in the upper and lower flanges for samples of various layups of the C-channels. Also, charts 1 through 6 show a complete set of deflection data for the $[(0/75)]_{12}$ case. The beams were instrumented as shown in figure 4. An interesting occurrence in the beams, discovered through observation of the test results, is that the deflections decreased as the load application point is moved away from the center of gravity. This fact becomes more important in the following section when angle of twist is discussed. As expected, the deflection represented by D9 on the charts is smallest; this measurement is taken at a point on the beam's web. The top flange deflected the most in all cases examined.

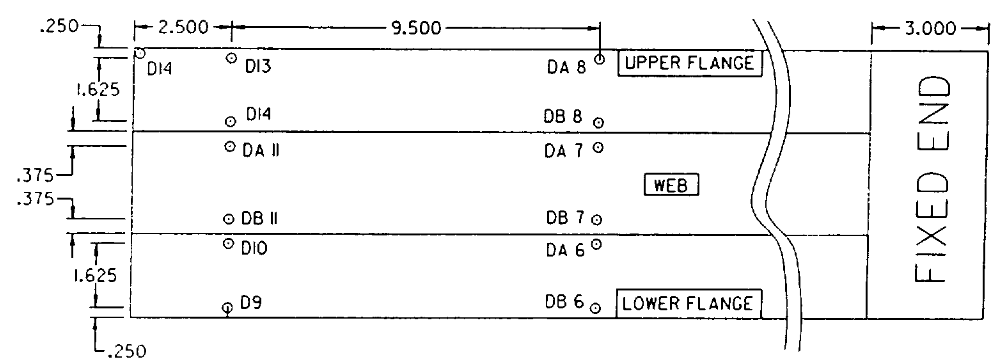


Figure 4. Deflection gauge locations for composite beam load tests.

Another observation was that for beams having the same ply angle, the beams of Form 1 deflected at least twice (100 percent) as much as those of Form 2 when the load was applied near the shear center, and almost 80 percent more when loaded at the geometric center. Additionally, by examining the deflection data at the 0.25-in increments, more interesting facts were revealed. For example, in the case where the cross ply angle is ±75°, it is noted that the deflection in the web and flanges decrease (for the maximum load case) as one moves toward the calculated shear center located 1.44 in from the geometric center. Yet, as will be discussed later, the deflections approach zero in the web even more by moving further than 1.44 in from the shear center. This serves as an indicator that the true shear center is further than 1.44 in away from the centroid. Therefore, one would opt for the laminate layup of Form 2 in situations in which low deflections are desired.

Two materials systems were used: AS4/3501-6 and IM7/8552. Figures 5 through 8 show deflections measured at the geometric centers and shear centers for a [0/75]12 beam of each material. Due to material properties, the IM7/8552 beams deflected more than the AS4/3501-6 beams. Another point of interest from the data gathered is that the further away from the geometric center that the load is applied, the greater the difference in the deflection amounts. The explanation of this could also form the basis for more research work.

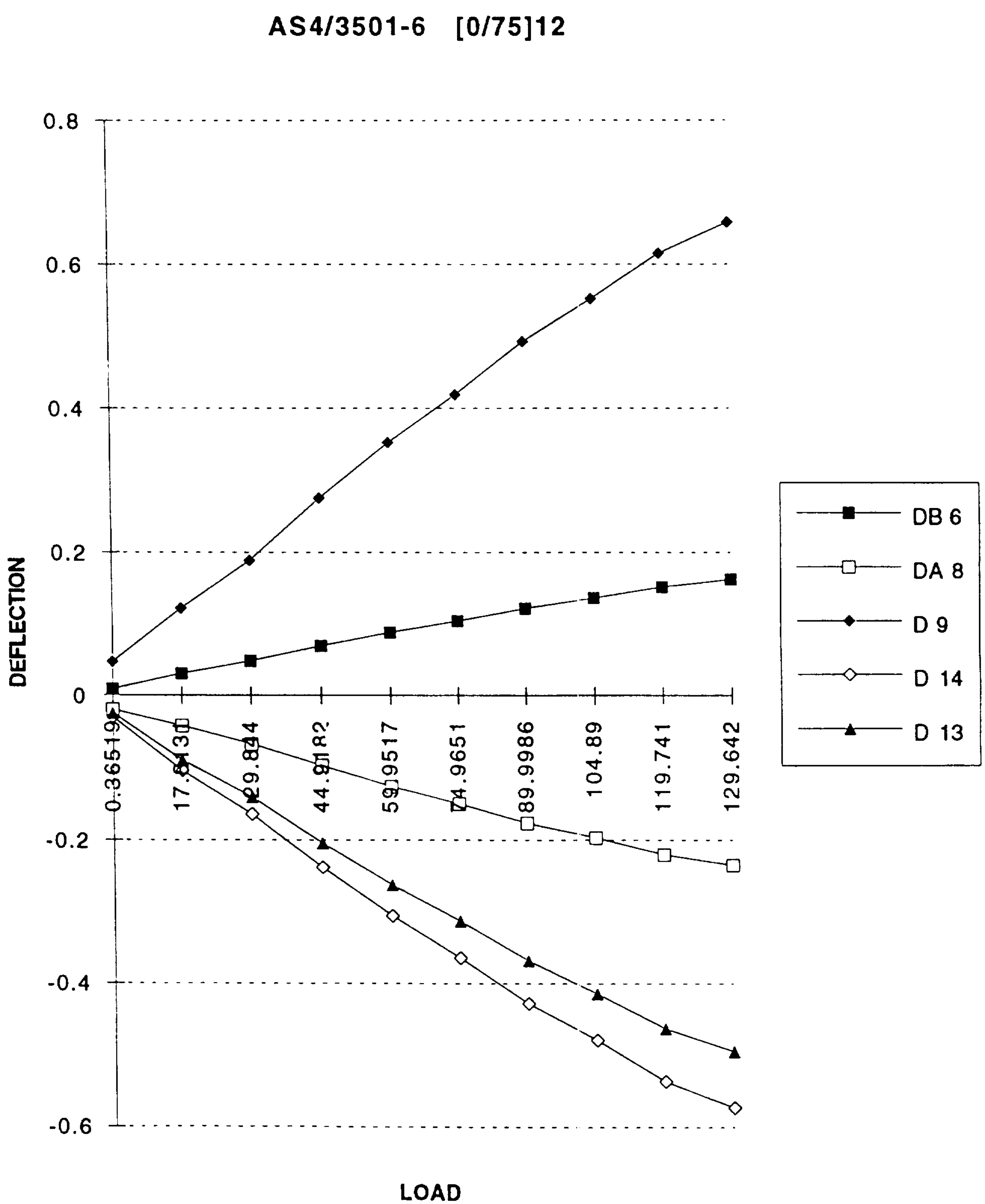


Figure 5. Deflections for C-channel loaded at geometric center (AS4/3501-6).

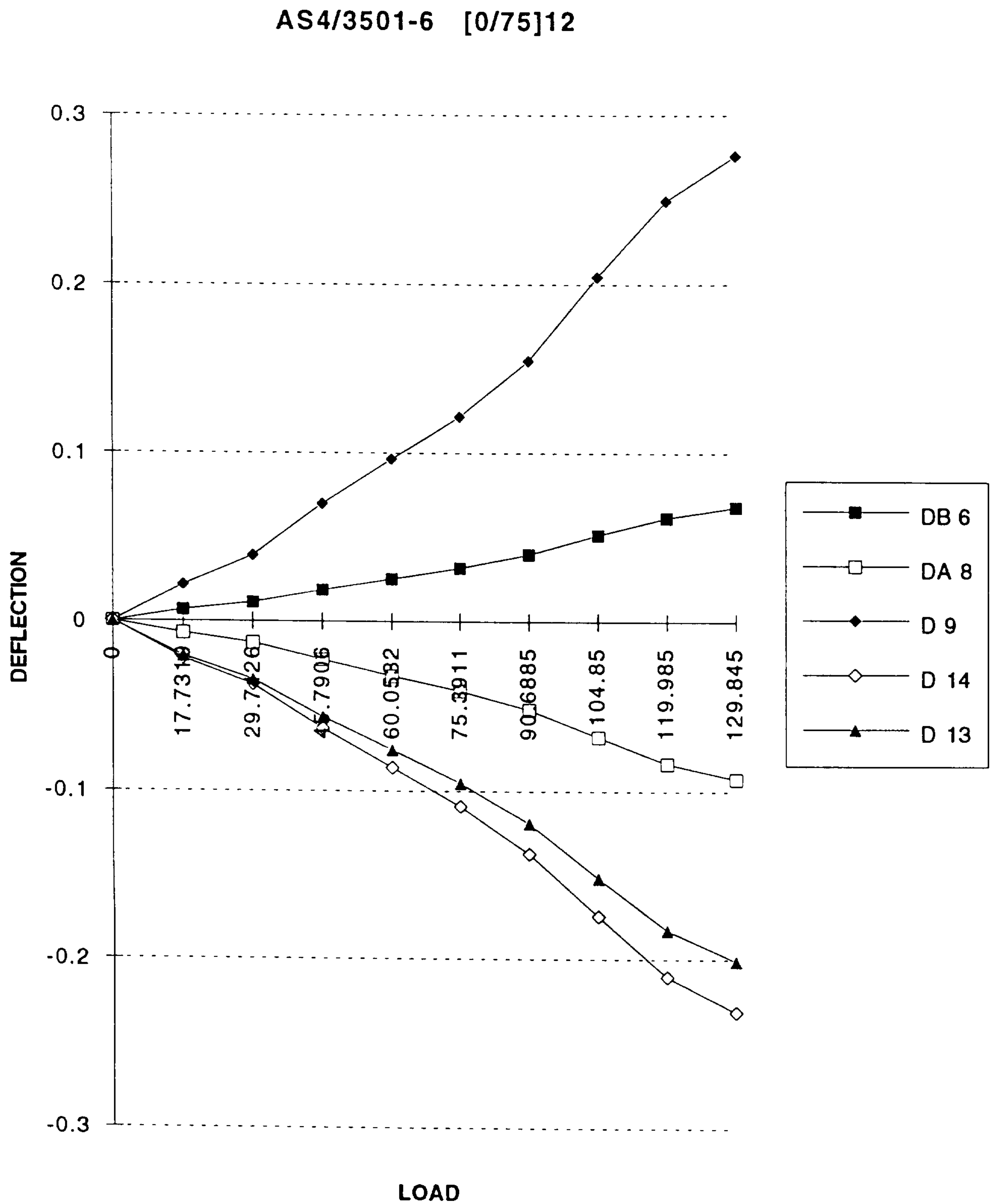


Figure 6. Deflections for C-channel loaded at theoretical shear center (AS4/3501-6).

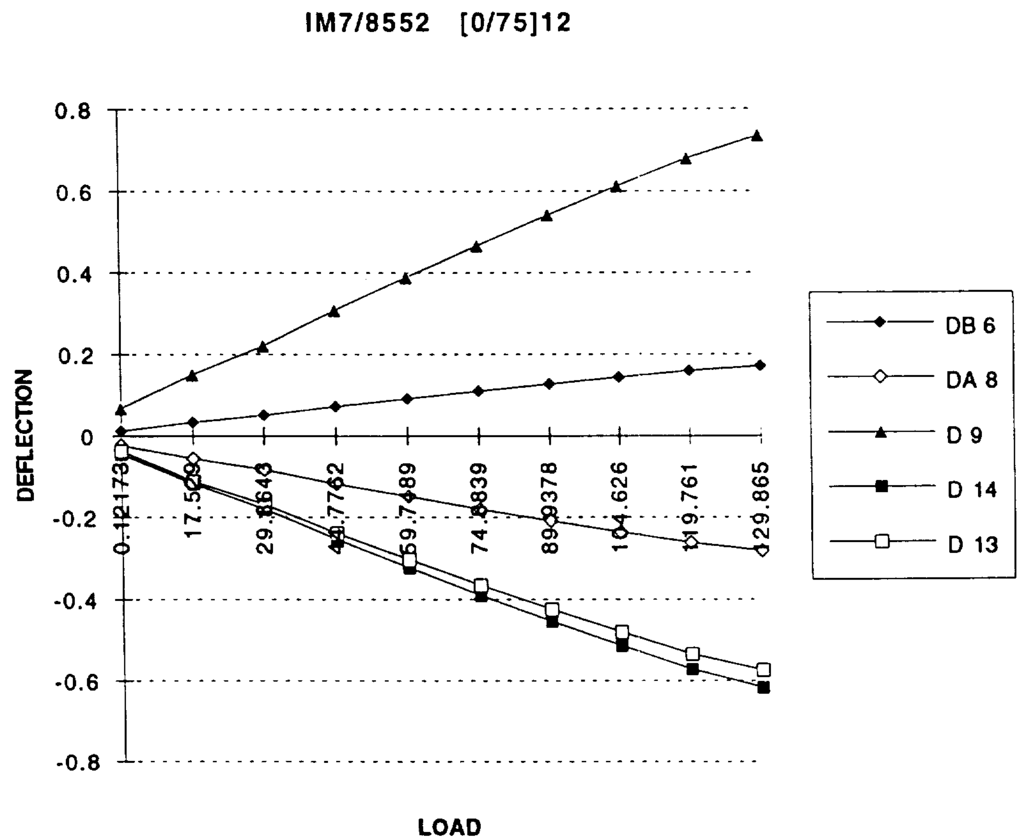


Figure 7. Deflections for C-channel loaded at geometric center (IM7/8552).

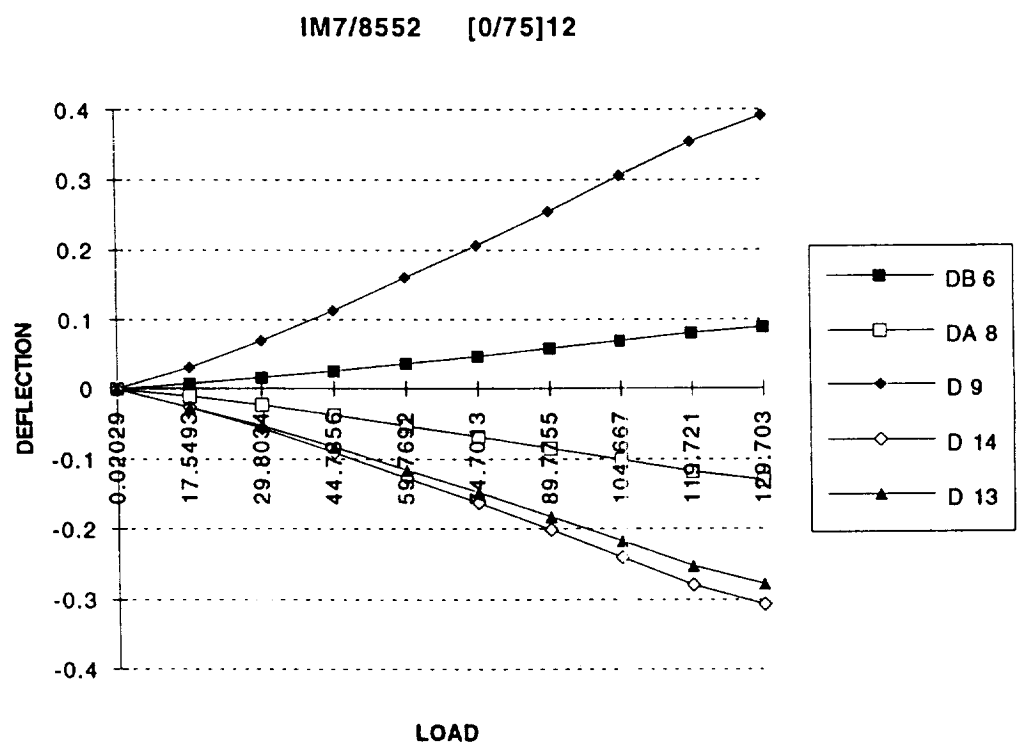


Figure 8. Deflections for C-channel loaded at theoretical shear center (IM7/8552).

EFFECT OF FIBER ORIENTATION OF SHEAR CENTER LOCATION

For this research effort, the theoretical shear center for the given cross section is easily determined by the formula:

$$e = bht/4I \ .$$

After this shear center is known, one would expect that a transverse load applied through this point would produce only bending, and that the same load applied through the beam's geometric center produces both bending and torsion coupling. Yet, due to the layup of these open-section members (no midplane symmetry) the true shear center does not follow this equation. The research work showed that for some of the laminate layups the true shear center actually lies between the geometric center and theoretical shear center, and could, in some cases, lie beyond the calculated shear center. As the angle increased, the amount of twist observed and measured when the beam was loaded at this "predicted" shear center increased also. As the load application point was shifted toward the center of gravity (c.g.), the trend was for more twisting to occur. However, for most of the cases tested, this increase did not occur until after the load application point had been shifted more than 0.25 in from the shear center in the direction of the c.g. This would indicate that the true shear center is actually between the predicted shear center and a 0.25 in toward the c.g. Yet, for those beams of Form 1 with a cross-ply angle greater than 45°, the "true" shear center was outside the theoretical value, i.e., more than 1.44 in from the geometric center.

Figure 9 shows the angle of twist for various layups as calculated by the formulas[3]

$$e = d_1/2L \quad \text{and} \quad e = d_2/2L \ ,$$

$$\phi = d_1/(h/2) \quad \text{and} \quad \phi = d_2/(b/2) \ ,$$

where

h = height of web

b = width of flange

d_1 = web deflection

d_2 = flange deflection.

For presentation purposes, beams made with only the 15°, 45°, and 75° cross-ply angles of Form 1 are shown. Measured strains and deflections for the 30° and 60° cases fell between the extremes of the charts shown. Charts 1 through 6 in section II of the appendix contain the strain data as measured for the $[(0/15)]_{12}$ beam.

Graphically, one can see from figure 10 that the angle of twist does increase with an increase in the cross-ply laminate angle, regardless of the overall layup (Form 1 or Form 2). The range in angle of twist as measured is between –18° and 55° for Form 1, while its range was –25° to 75° for Form 2 beams.

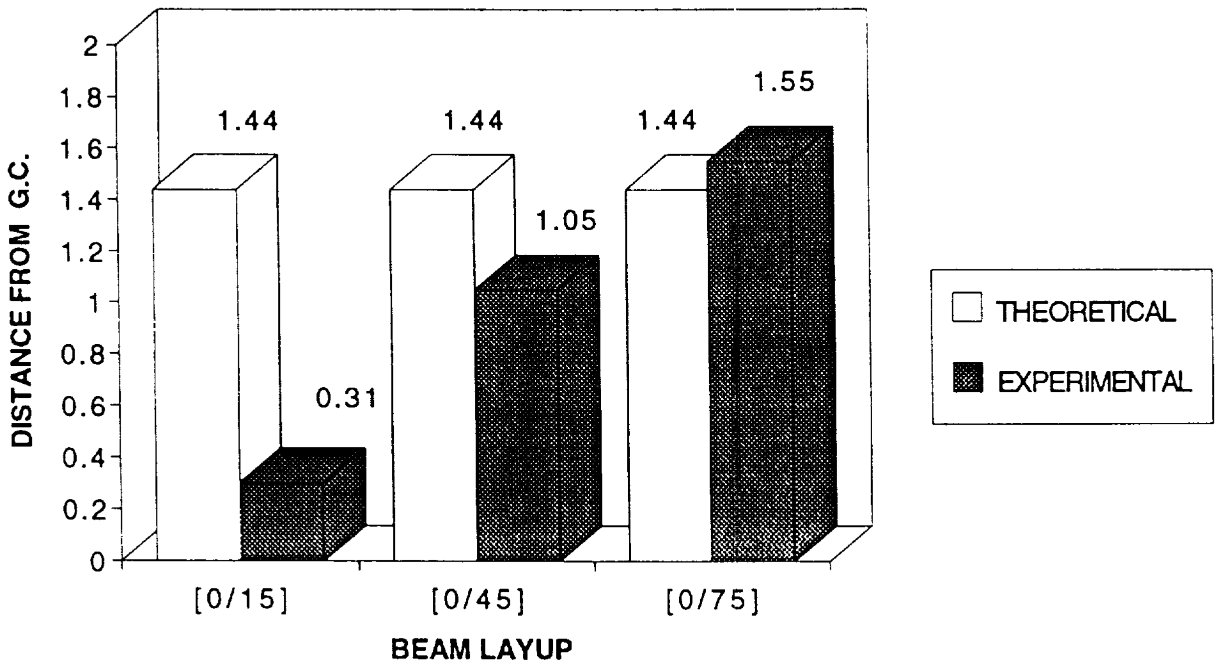


Figure 9. Theoretical versus measured shear center comparison.

What these equations and formulas do not show, however, is the postcure inward canting of the beams as shown in figure 7. No quantitative assessment of the amount of this cant is presented here. Nevertheless, it should be pointed out that this phenomena occurred in all the beams. Interestingly, the beams containing 45° plies of Form 1 canted outward (i.e., pulled away from the tool after curing) and twisted along the length of the beam by more than 90°. CTE's, as well as interlaminar shear stress and strains during the curing process, would have to be closely examined. The explanation of this occurrence could provide the basis for additional research work.

Test data were also used to gain insight on the location of the beam's "true" shear center (i.e., no twist when transverse load applied) as a function of laminate layup. Due to the beams' geometry, they are expected to twist as well as bend, and all the beams tested experienced this. However, the focus here was to attempt to categorize the amount of twist that could be expected from a given layup. In analyzing the test results, several interesting trends were noticed and are reported here.

First, the beams of the Form 1 construction had higher degrees of rotation (angles of twist) than those of Form 2 for any given cross-ply lamina. Remembering that the Form 1 beams have cross plies only in the positive direction, whereas the Form 2 beams have both positive and negative plies, it is obvious that, upon completion of the appropriate stiffness matrices, this in itself is not abnormal.

Figure 10 reveals another trend. By calculations using the given geometry of the beams, one can find that the theoretical shear center is located 1.44 in to the left of the geometric center as shown in figure 3. By observing the charts, one can see that none of the plotted beams show an experimental shear center that matches its theoretical value. All the beams were of the same overall geometry and the results shown on the charts were based on a 130-lb transverse load placed on the beams.

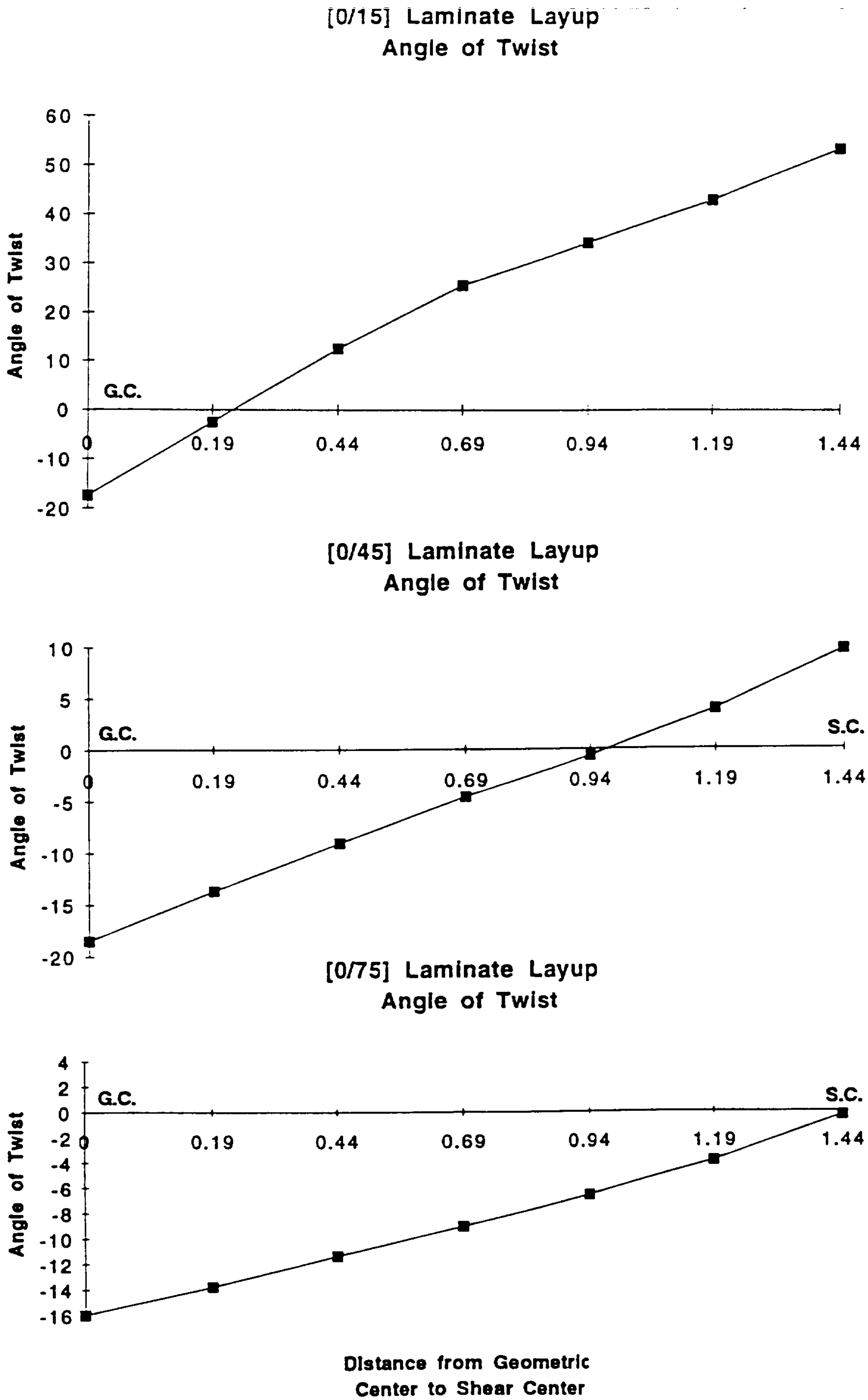


Figure 10. Angle of twist versus load application points for Form 1 beam (AS4/3501-6).

The $[0/75]_{12}$ layup most closely approached the theoretical value and had the highest angle of twist, while the $[0/15]_{12}$ layup had the lowest angle of twist. This tendency, particularly the least twist in the $[0/15]_{12}$ members, was not expected. It would appear intuitively that since the tendency to rotate in these beams would not be offset by the almost horizontal plies of the 15° laminates they would have the higher twist angle. Similarly, these same beams had true shear centers located more than 1 inch from the theoretical value.

All beams had some small amount of twist before loading due to CTE differences between the plies during the cure process. This pretwist was most noticeable in the $[0/45]_{12}$ beams which rotated more than 90° along the length of the beam. Pretwist due to CTE mismatches is not addressed here, but it is worthy of future consideration, as is controlling the various parameters comprising the cure cycle (e.g., cure pressure, tooling materials, cure temperature profiles). This pretwist, however, does not significantly alter the trends reported here since the loads were applied at the calculated theoretical shear center and additional twisting occurred, again verifying the shifting of the "true" shear center. Figures 11(a) and (b) shows the angle of twist for Form 1 beams when Θ is equal to 15, 45, and 75, respectively, and only a minimal load is applied ($P < 5$ lb).

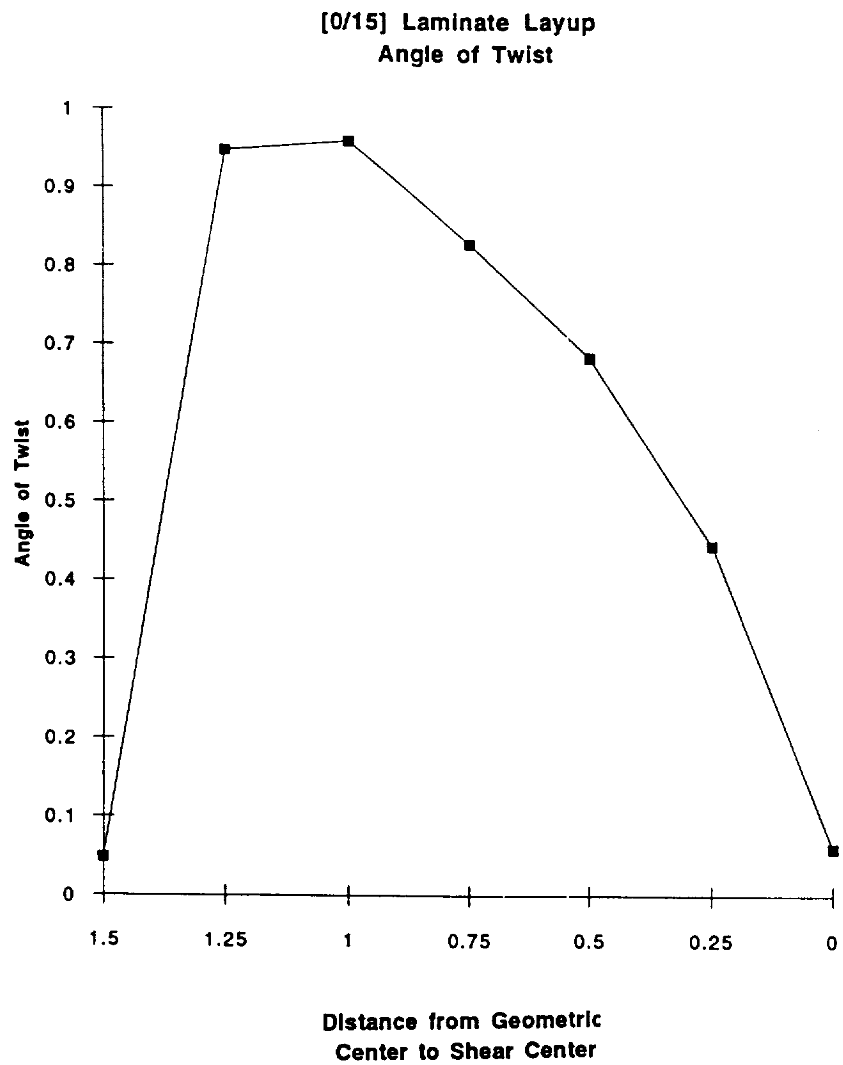


Figure 11(a). Angle of twist versus load application points for Form 1 beam with minimal load applied, $P \leq 5.0$ lb (AS4/3501-6).

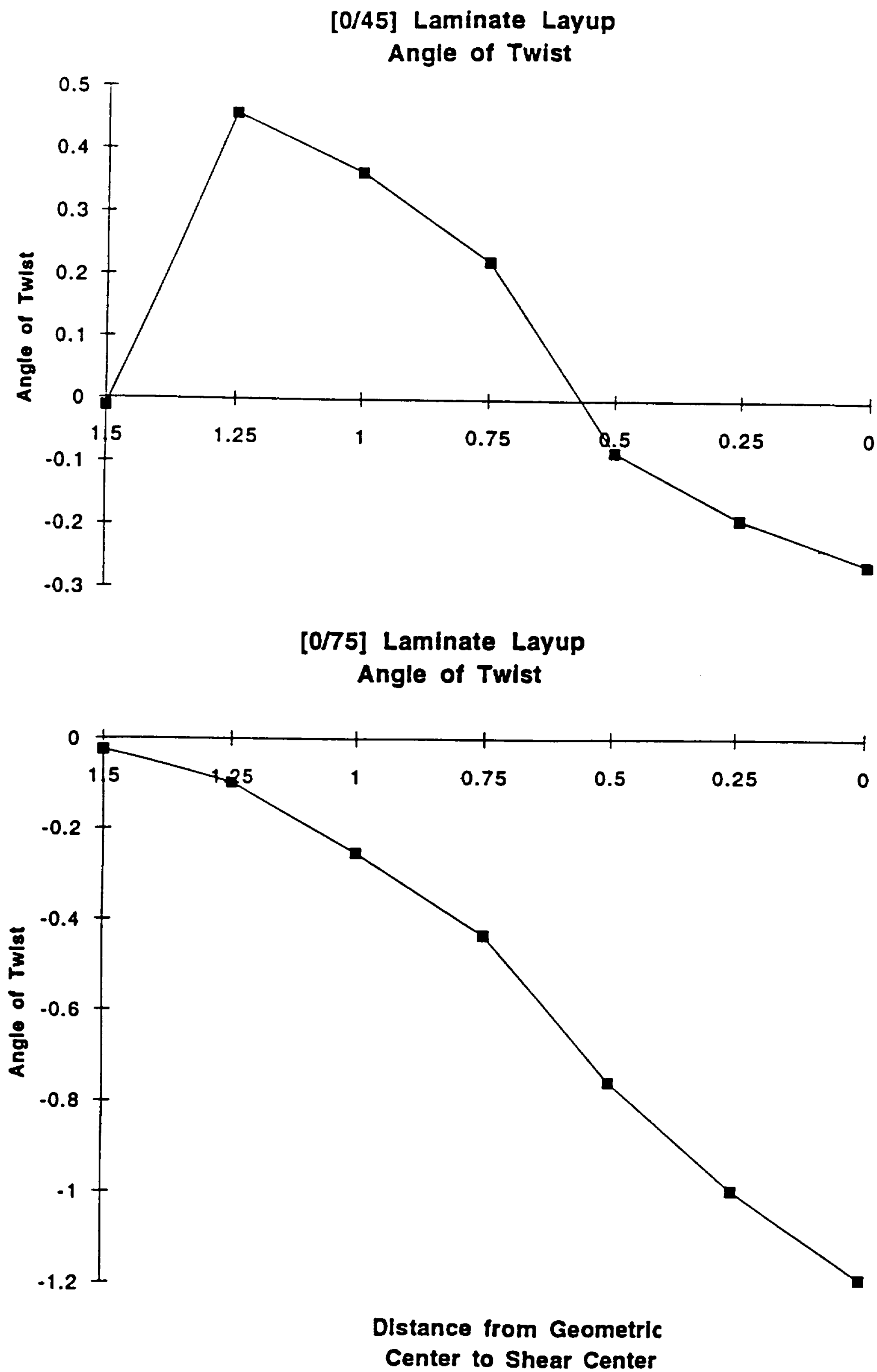


Figure 11(b). Angle of twist versus load application points for Form 1 beam with minimal load applied, $P \leq 5.0$ lb (AS4/3501-6).

Assuming plate theory, it can be shown that in-plane stress resultants for laminated structures are not only functions of midplane strains but can be functions of curvatures and twists. Additionally, the in-plane forces can cause deformations that can cause curvatures or twisting deformations.[4] Plate theory does not directly apply to beams as presented in the above cases. As Vinson points out, the above analytical procedures are valid only if no coupling exists, i.e., the D_{16} and D_{26} terms of the stiffness matrix are zero.[5] The equations were used in this paper only to produce a relative number that would allow numerical comparisons to be made. More complex analysis that considers not only the nonzero cases for $D16$ and $D26$ but also hygrothermal effects would need to be developed to more accurately assess the true values for the amount of twist produced due to laminate angle orientation.

Even though plate theory may not be directly applicable to beam theory, one can use it to gather trend data. This is an attempt to categorize the behavior of the laminates rather than assign a quantitative value for the angle of twist. Regardless of the number assigned to this angle, the observed trends would still be valid. The analysis method used to arrive at this value does not influence the direction or importance of the trend.

CONCLUSIONS

The magnitude of information gathered through tests performed on open-section unsymmetric beams was tremendous. All data gathered were not discussed in this paper; however, subsequent writings will explore other areas worthy of further investigation in an attempt to more accurately categorize the behavior of such beams. Major findings reported here deal with the primary objective regarding shear center location and manipulation, as well as angle of twist and warpage in these structural members.

One important revelation is that the angles of twist and associated warpage in open-section beams is higher for antisymmetric beams of the $[0/\phi]m$ laminate layup. Some amount of bending/stretching is expected in any antisymmetric layup due to the fact that the components of the $[B]$ coupling matrix, which relates stress couples to midsurface planes and stress resultants to curvatures, are not all zero if the structure is not symmetric about its midplane. Likewise, unless the $D16$ and $D26$ terms of the stiffness matrix $[D]$, which relates the stress couples to curvatures, are zero, bending/twisting will occur.[6] No attempt is made to measure the magnitude of hygrothermal effects on twist in the beam, even though there could be as many as three different CTE's depending on cross-ply angle and orientation, all which play a role in the warping of the beams.[7]

The major fact borne out here is that laminate layup does control shear center location. As evidenced by charts presented earlier, the same geometric shape can yield "true" shear centers that differ by more than an inch depending on laminate layup. The location of the "true" shear center for the type beam investigated here depends on several factors. Cross-ply angle sequence is important (Form 1 or Form 2) in that other unsymmetrical layups using the same angle would yield different shear center locations. Yet not to be overlooked are factors such as cure cycle and laminate materials.

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3. Vinson, J.R., and Serakowski, R.L.: "The Behavior of Structures Composed of Composite Materials." Martinus Nijhoff Publisher, 1986, pp. 101–103.

4. Ibid., p. 54.

5. Ibid., p. 82.

6. Ibid., p. 56.

7. Ibid. p. 41.

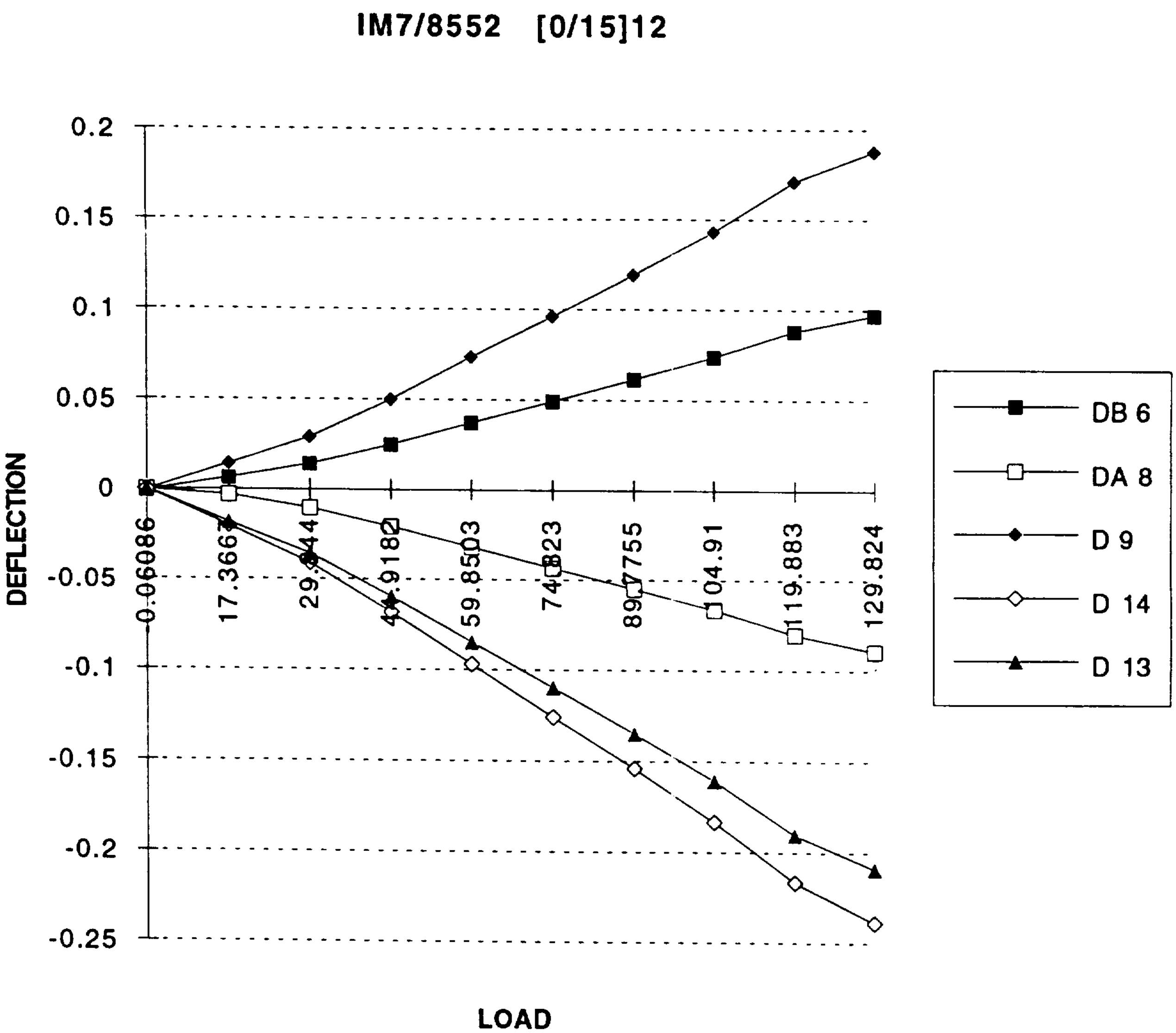
APPENDIX

Contents

SECTION I

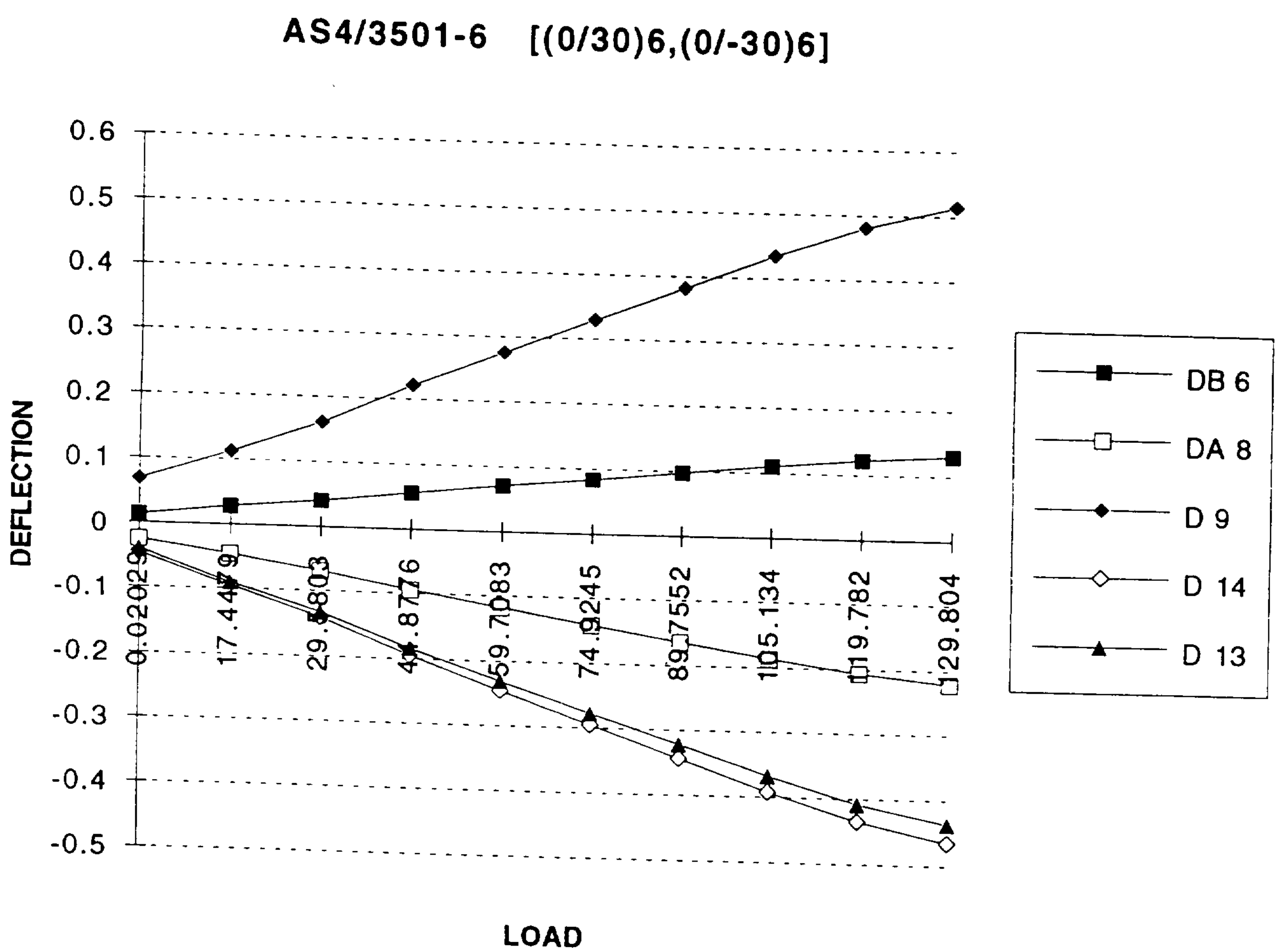
Deflection Graphs and Data

IM7/8552 1.5 IN GC GRAPH



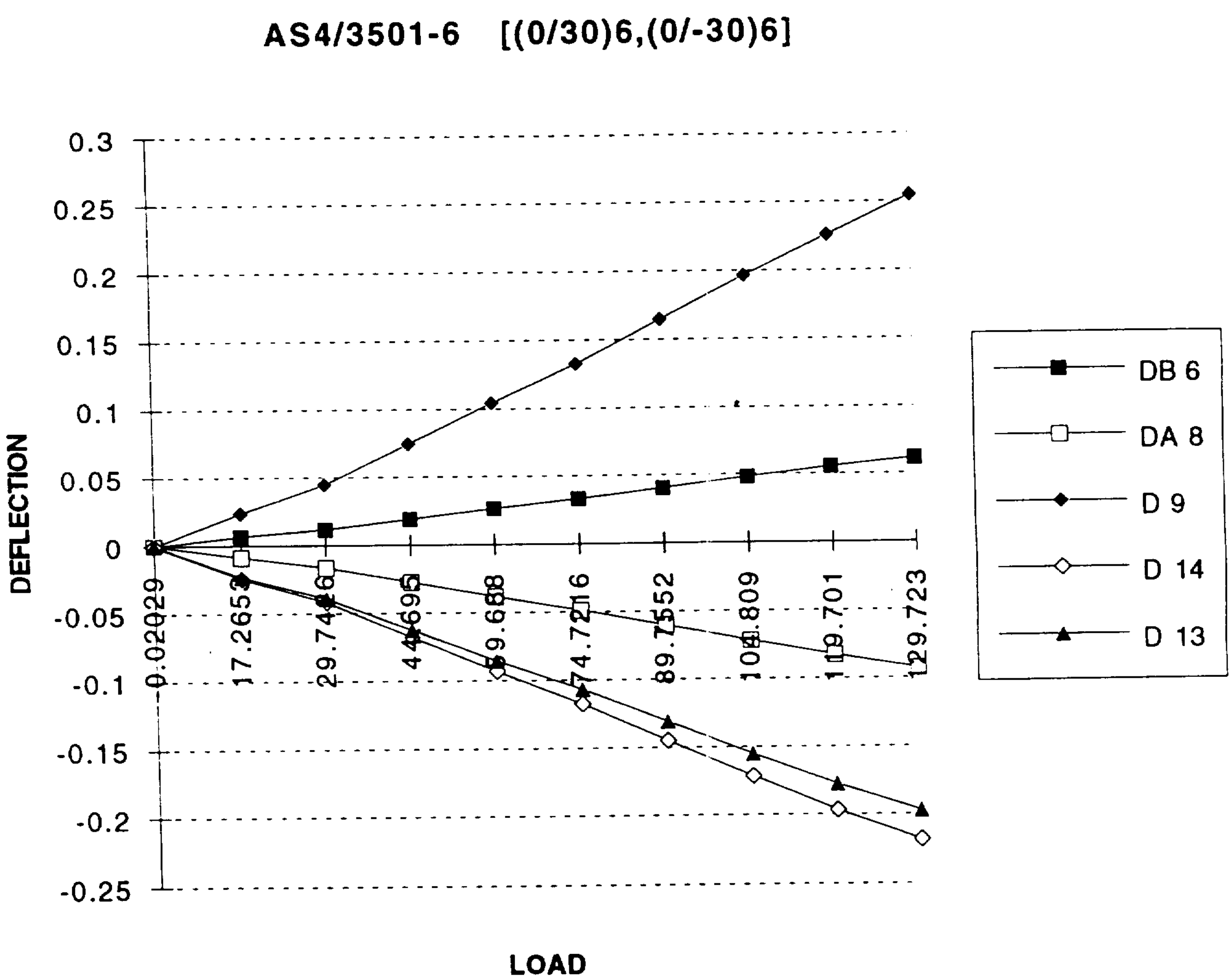
Graph 1

R13 GRAPH 0.0INCG



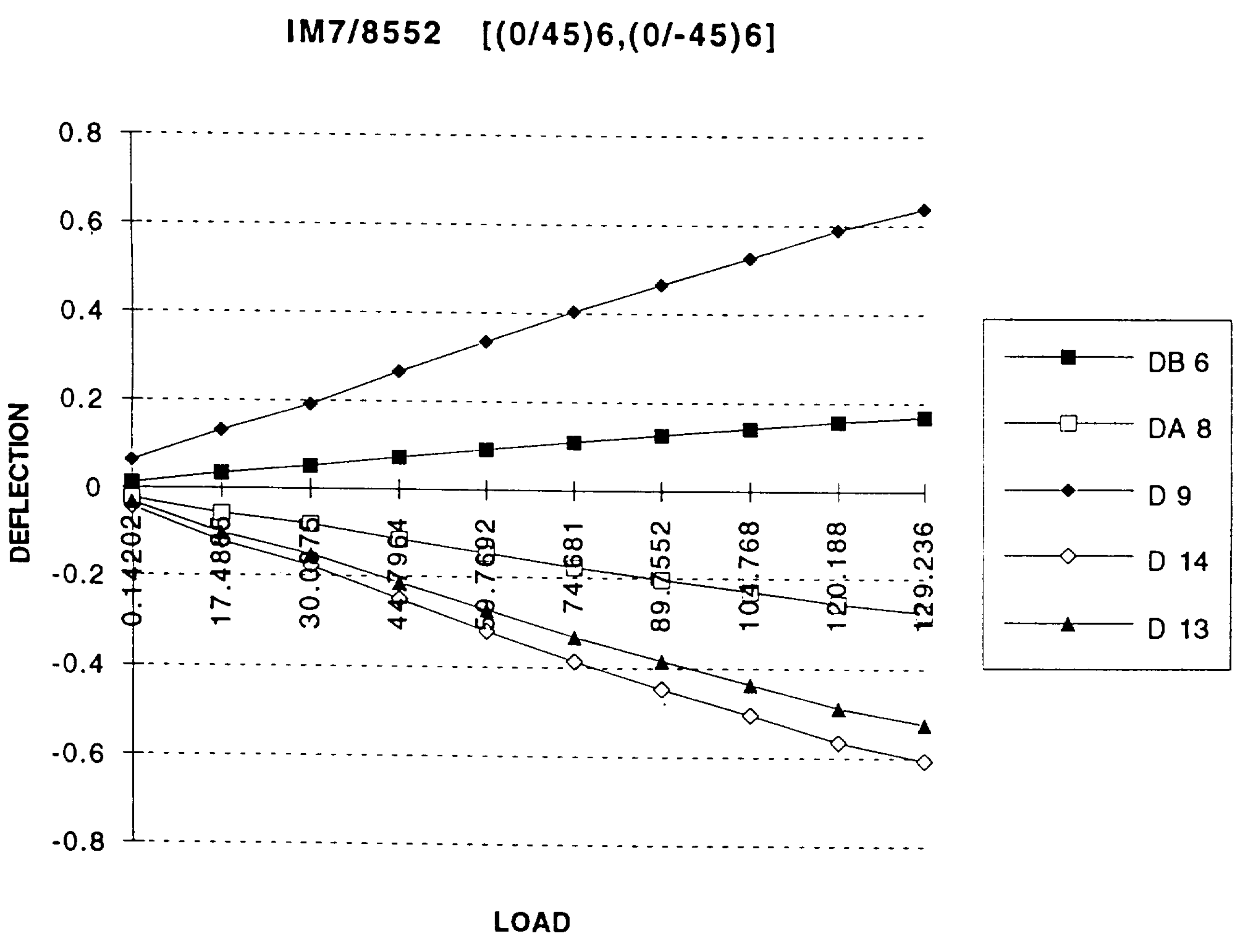
Graph 2

R13 GRAPH 1.5IN



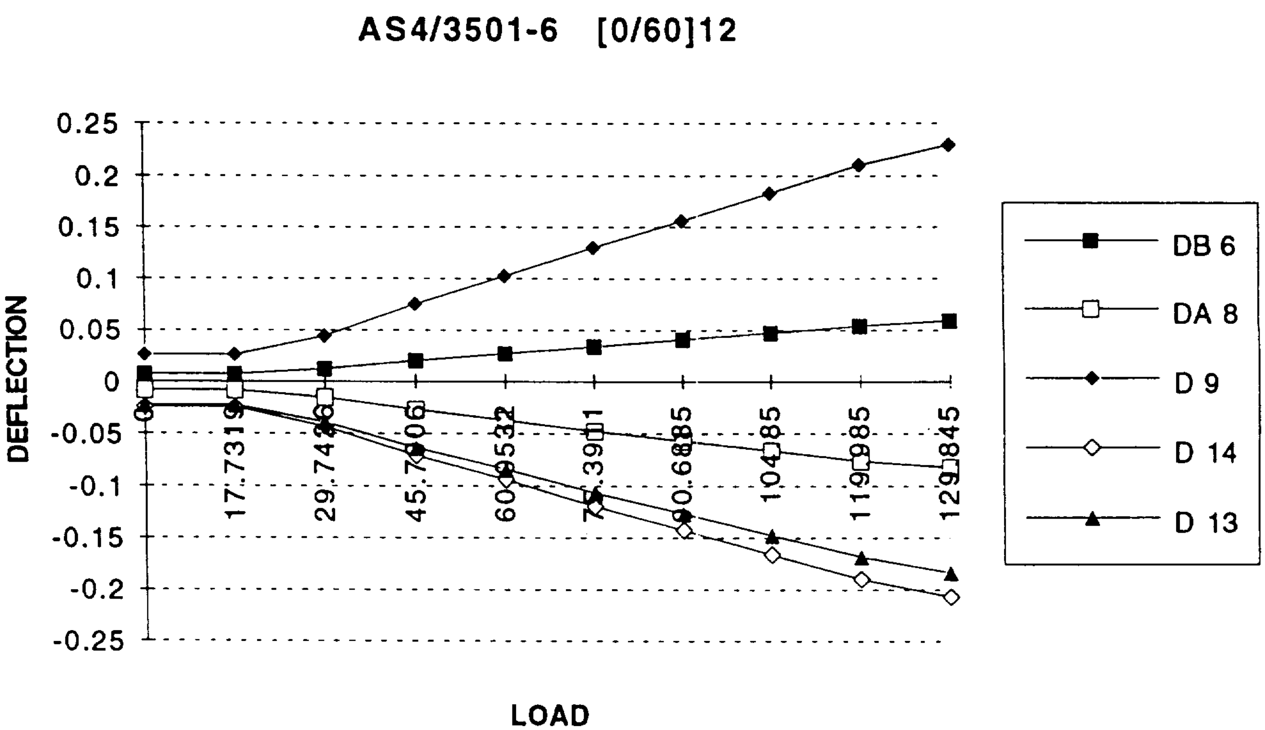
Graph 3

R11 GRAPH 0.0IN



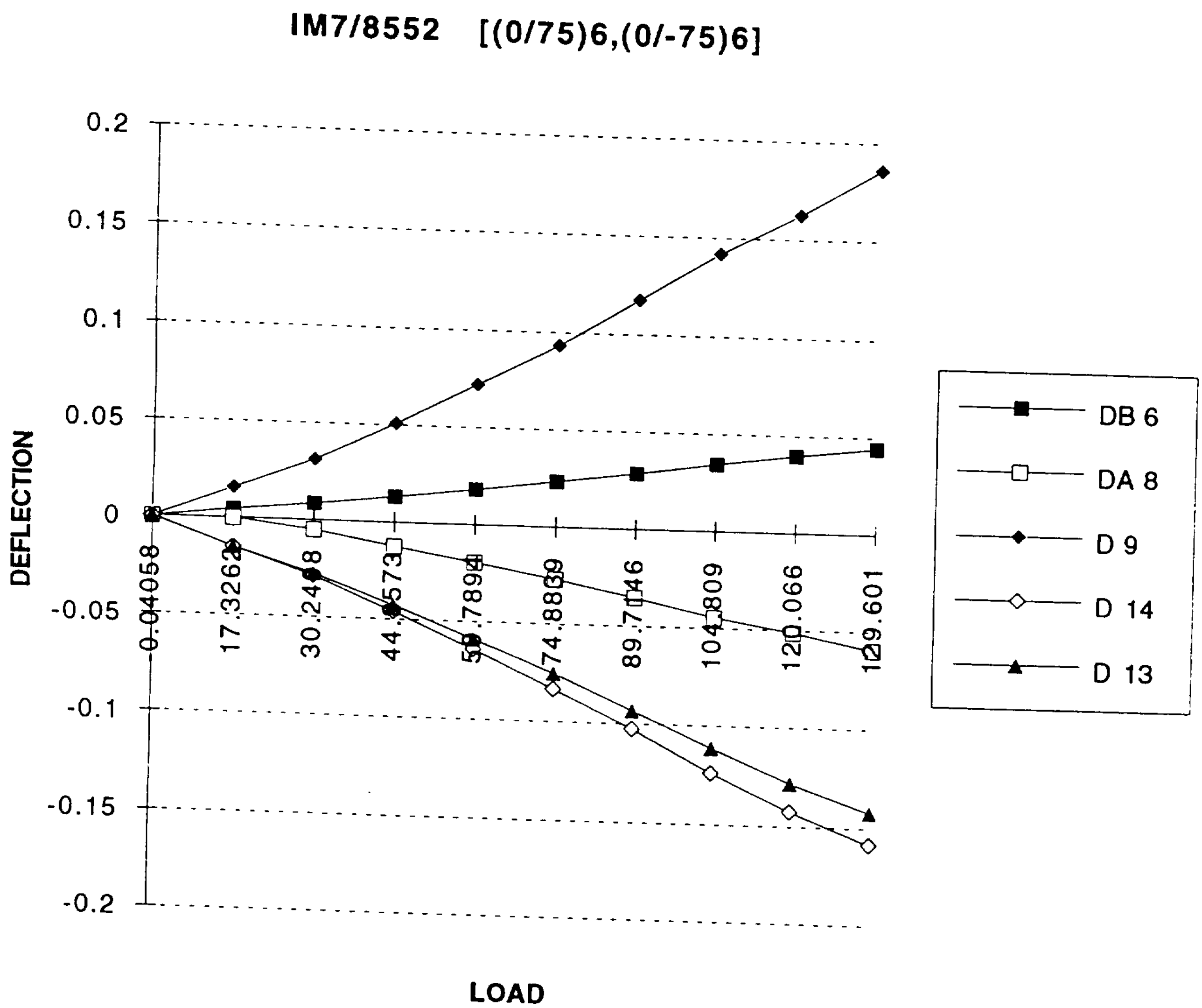
Graph 4

AS4/3501-6 1.5 IN GC GRAPH



Graph 5

R15 GRAPH 1.5IN



Graph 6

PT CDDF COMPBEAM S/N 20 RUN 19					
			" L 1"	" DB 8"	" DB 7"
SCAN"DELTA MINUTES			" LBS "	" INCH "	" INCH "
10 0.075000			0	-0.00003	-0.00029
17 0.816650			17.73192	-0.00438	0.00036
25 1.366633			29.74255	-0.00987	0.0004
33 1.816633			45.79056	-0.01885	0.00129
41 2.149950			60.05319	-0.02773	0.00212
49 2.574950			75.39111	-0.03662	0.00287
57 3.116600			90.68845	-0.04752	0.00423
65 3.591583			104.84964	-0.06319	0.00425
73 4.108250			119.98465	-0.07913	0.00521
81 4.524900			129.84473	-0.0887	0.00526
89 5.033217			0.30432	-0.01173	-0.00067
97 5.891533			17.79279	-0.01073	0.001
105 6.341533			30.0063	-0.0179	0.00218
113 6.733183			45.24277	-0.02924	0.00377
121 7.258167			59.87059	-0.04203	0.00552
129 7.624833			76.02005	-0.05608	0.00776
137 8.166483			90.20151	-0.06726	0.00881
145 8.616467			105.01193	-0.08014	0.00987
153 9.091467			120.26868	-0.09277	0.01083
161 9.483117			131.2243	-0.1036	0.01133
169 10.049783			0.36519	-0.013	-0.00065
177 10.516433			17.83336	-0.01542	0.00246
185 11.008083			30.14832	-0.02274	0.00406
194 11.449750			44.99931	-0.03615	0.00654
201 12.033067			60.19521	-0.04989	0.00894
210 12.499717			75.26938	-0.06231	0.01102
226 13.274700			104.68732	-0.08884	0.01536
235 13.716367			120.83676	-0.10312	0.01685
241 14.316350			130.65625	-0.11419	0.01751
250 15.049667			0.3449	-0.01225	-0.00115
257 15.549650			17.79279	-0.01579	0.0033
265 16.024650			30.10774	-0.02581	0.00568
273 16.441300			45.03989	-0.04019	0.00939
282 16.899633			60.49953	-0.0544	0.01218
290 17.507950			74.98535	-0.06911	0.01525
298 17.949600			89.75519	-0.08329	0.01814
305 18.357933			104.76846	-0.0974	0.02026
314 18.824583			119.98465	-0.1124	0.02229
321 19.141250			130.16931	-0.12092	0.02262
330 20.066217			0.30432	-0.01279	-0.00089
331 20.524550			17.73192	-0.01868	0.00485
346 21.041200			29.88457	-0.02853	0.00717

Chart 1

354 21.591200		44.95874	-0.04423	0.01114
362 22.074517		59.83002	-0.05784	0.01467
375 22.557833		74.98535	-0.07449	0.01823
385 23.066167		89.91748	-0.08921	0.02145
393 23.624483		105.05252	-0.10437	0.02332
402 24.066133		119.74121	-0.11879	0.02575
410 24.507800		129.92584	-0.12942	0.02698
418 25.649433		0.36519	-0.01371	-0.00098
434 26.507750		29.80342	-0.03241	0.00968
442 27.082733		44.8573	-0.0484	0.01453
451 27.724400		59.87059	-0.06498	0.01849
458 28.366050		74.92447	-0.08143	0.02207
467 28.974367		90.20151	-0.09703	0.02549
475 29.582683		105.09308	-0.11432	0.02889
482 30.216000		119.9035	-0.13006	0.03171
490 30.741000		129.96643	-0.1412	0.03495
498 31.432650		0.36519	-0.01459	-0.00074
505 32.090967		17.81307	-0.02229	0.00681
513 32.607617		29.84399	-0.0364	0.0119
522 33.374267		44.91815	-0.05346	0.01703
529 33.957600		59.95174	-0.07144	0.02253
537 34.532583		74.96506	-0.08766	0.02635
546 35.082567		89.99863	-0.10573	0.03084
554 35.590883		104.8902	-0.12126	0.03331
562 36.140883		119.74121	-0.13889	0.03703
570 36.882517		129.64185	-0.15148	0.03842

Chart 2

DEFLECTIONS

" DB 6"	" DB 11"	" DA 8"	" DA 7"	" DA 6"	" DA 11"
" INCH "	" INCH "	" INCH "	" INCH "	" INCH "	" INCH "
-0.00008	-0.00028	0.00002	-0.00007	-0.00013	-0.00011
0.00689	0.00122	-0.00676	-0.00012	0.00738	-0.00185
0.01142	0.00235	-0.01257	-0.0001	0.01311	-0.00243
0.01897	0.00485	-0.02238	-0.00013	0.0219	-0.00366
0.02542	0.00687	-0.03193	-0.0001	0.03001	-0.00408
0.032	0.00922	-0.04071	-0.0001	0.03854	-0.00299
0.04023	0.01242	-0.05194	0.00023	0.04998	-0.00101
0.05155	0.01261	-0.06814	0.00021	0.06578	-0.00221
0.06194	0.01492	-0.08356	0.00074	0.08113	-0.00144
0.06822	0.01539	-0.09245	0.00178	0.09037	-0.00052
0.00293	-0.00024	-0.00846	0.00251	0.00613	0.00183
0.01259	0.00471	-0.01544	-0.00086	0.01282	-0.00677
0.02014	0.00776	-0.02517	-0.00291	0.02049	-0.01112
0.03057	0.01134	-0.03949	-0.00499	0.03173	-0.01602
0.04172	0.01609	-0.05513	-0.00694	0.04436	-0.01989
0.05328	0.02047	-0.07346	-0.0091	0.05826	-0.02378
0.06227	0.02348	-0.08434	-0.00918	0.06948	-0.02494
0.07276	0.0264	-0.09908	-0.00912	0.08208	-0.02735
0.0822	0.02885	-0.11244	-0.00915	0.09475	-0.0283
0.08972	0.03035	-0.1235	-0.00913	0.1048	-0.02879
0.00467	-0.00019	-0.01266	0.00094	0.00769	-0.00075
0.01742	0.00748	-0.02275	-0.00477	0.01684	-0.01262
0.02667	0.01186	-0.03478	-0.0077	0.02543	-0.01983
0.03942	0.0175	-0.05317	-0.01115	0.03819	-0.02789
0.0523	0.02334	-0.07193	-0.01473	0.05214	-0.03498
0.06431	0.02847	-0.08856	-0.01703	0.06474	-0.04068
0.08708	0.0375	-0.12059	-0.02045	0.09039	-0.04911
0.09849	0.04099	-0.13644	-0.02094	0.10423	-0.05255
0.10644	0.04282	-0.14795	-0.02152	0.11454	-0.05421
0.00472	-0.00118	-0.00739	0.00041	0.00725	-0.00207
0.02034	0.00951	-0.02621	-0.00742	0.018	-0.01834
0.03194	0.01501	-0.0426	-0.01212	0.02843	-0.02845
0.04688	0.02268	-0.0639	-0.01726	0.04202	-0.03935
0.06128	0.02969	-0.08454	-0.02155	0.05667	-0.04858
0.0753	0.03703	-0.10441	-0.02565	0.0715	-0.05701
0.08813	0.04273	-0.12268	-0.02879	0.08517	-0.06404
0.09994	0.04649	-0.14017	-0.03011	0.09889	-0.06905
0.11233	0.05162	-0.15803	-0.03212	0.11291	-0.0747
0.1192	0.05294	-0.16737	-0.0326	0.12128	-0.07713
0.00636	-0.00061	-0.01483	-0.00319	0.00732	-0.00628
0.02466	0.01266	-0.03508	-0.01277	0.021	-0.02544
0.03681	0.01859	-0.04956	-0.01652	0.03074	-0.03668

Chart 3

DEFLECTIONS

0.0534	0.02828	-0.07406	-0.02301	0.04627	-0.05064
0.06856	0.036	-0.09511	-0.02776	0.06035	-0.06191
0.08386	0.04339	-0.1169	-0.03252	0.07567	-0.07231
0.09771	0.04979	-0.13726	-0.03662	0.09026	-0.08143
0.11087	0.05435	-0.15655	-0.03936	0.10458	-0.08909
0.12367	0.05915	-0.17523	-0.04177	0.11877	-0.09608
0.1322	0.06174	-0.18744	-0.0436	0.12886	-0.10008
0.0077	-0.00042	-0.01831	-0.00466	0.00925	-0.00789
0.04277	0.02292	-0.05831	-0.02104	0.03473	-0.04557
0.06108	0.03369	-0.08503	-0.02899	0.05048	-0.06288
0.07845	0.04273	-0.10936	-0.03582	0.06626	-0.07735
0.09453	0.05106	-0.13374	-0.04128	0.08195	-0.09089
0.10966	0.05807	-0.15614	-0.04623	0.09757	-0.10199
0.12502	0.0647	-0.17883	-0.05067	0.11326	-0.11321
0.13873	0.06955	-0.19874	-0.05447	0.12833	-0.1214
0.1478	0.07346	-0.21218	-0.05794	0.13882	-0.12655
0.00887	-0.00024	-0.01974	-0.00745	0.01071	-0.00983
0.03099	0.01671	-0.04203	-0.01713	0.02415	-0.03679
0.0482	0.02786	-0.06691	-0.02613	0.03777	-0.05518
0.06921	0.04009	-0.09724	-0.03566	0.05498	-0.07661
0.08806	0.05073	-0.1255	-0.04435	0.07197	-0.0941
0.10458	0.05882	-0.14938	-0.05059	0.08733	-0.10939
0.12177	0.06743	-0.17597	-0.05695	0.10409	-0.12397
0.13643	0.07284	-0.19669	-0.06141	0.11908	-0.13583
0.15214	0.08	-0.22037	-0.06686	0.13516	-0.14749
0.1625	0.08263	-0.2352	-0.06897	0.14649	-0.15392

Chart 4

" D 9"	" D 14"	" D 13"	" D 12"	" D 10"
" INCH "	" INCH "	" INCH "	" INCH "	" INCH "
0	0.00019	-0.00005	-0.0001	-0.00005
0.02193	-0.02177	-0.02025	-0.01786	0.01736
0.03925	-0.03713	-0.03398	-0.03048	0.0297
0.06991	-0.06337	-0.05634	-0.04965	0.04894
0.0965	-0.0863	-0.07592	-0.06687	0.06615
0.12187	-0.10924	-0.09535	-0.08512	0.08411
0.15467	-0.13743	-0.11916	-0.10826	0.10769
0.20454	-0.17455	-0.15203	-0.13966	0.13842
0.24951	-0.21051	-0.18245	-0.16916	0.16842
0.2761	-0.23112	-0.20069	-0.18804	0.18711
0.01683	-0.0105	-0.00926	-0.01037	0.0113
0.0441	-0.03985	-0.03671	-0.02891	0.02994
0.07564	-0.06628	-0.05922	-0.04598	0.04563
0.11741	-0.10205	-0.08964	-0.07025	0.06951
0.16219	-0.14015	-0.12208	-0.09671	0.09595
0.21594	-0.18077	-0.15587	-0.12469	0.12353
0.24825	-0.21012	-0.18245	-0.14842	0.14706
0.29114	-0.24589	-0.21345	-0.17464	0.17315
0.32937	-0.27835	-0.24186	-0.20066	0.19856
0.36158	-0.30362	-0.26384	-0.22082	0.21859
0.02634	-0.01711	-0.01473	-0.01375	0.01475
0.06472	-0.05695	-0.0512	-0.03713	0.03779
0.10242	-0.08883	-0.07856	-0.05645	0.05668
0.15292	-0.13237	-0.11556	-0.08385	0.08391
0.20794	-0.17689	-0.15385	-0.11315	0.11277
0.25601	-0.21829	-0.18888	-0.14093	0.13951
0.34955	-0.29682	-0.25664	-0.19558	0.19274
0.39564	-0.33511	-0.29014	-0.22454	0.22086
0.42786	-0.36193	-0.31384	-0.24538	0.24148
0.01596	-0.01283	-0.0132	-0.01247	0.0147
0.07748	-0.06784	-0.0596	-0.0407	0.04168
0.12318	-0.10691	-0.09348	-0.06364	0.06379
0.1831	-0.15822	-0.13729	-0.09432	0.09348
0.24262	-0.20818	-0.18	-0.12577	0.12367
0.29958	-0.25639	-0.22142	-0.15703	0.15406
0.35169	-0.30051	-0.25962	-0.18658	0.18223
0.40224	-0.3425	-0.29522	-0.21534	0.20981
0.45405	-0.38565	-0.33285	-0.24577	0.23871
0.48142	-0.40781	-0.35329	-0.26348	0.25608
0.03508	-0.02294	-0.01795	-0.01355	0.01529
0.10251	-0.08339	-0.0716	-0.04603	0.04622
0.1439	-0.12363	-0.10711	-0.06966	0.06941

Chart 5

DEFLECTIONS

0.21143	-0.18174	-0.15702	-0.10366	0.10197
0.2727	-0.23423	-0.20169	-0.13541	0.13265
0.33374	-0.28749	-0.2481	-0.16887	0.16398
0.39244	-0.3355	-0.28975	-0.20086	0.19353
0.44707	-0.38176	-0.33016	-0.23217	0.22332
0.4983	-0.42725	-0.36893	-0.26279	0.25253
0.53478	-0.4564	-0.39466	-0.28432	0.27325
0.04303	-0.02682	-0.02159	-0.01649	0.02146
0.16815	-0.14481	-0.12477	-0.07861	0.0815
0.24253	-0.20857	-0.17957	-0.11491	0.11534
0.31579	-0.26902	-0.23121	-0.15042	0.14829
0.38245	-0.32695	-0.2815	-0.18579	0.18085
0.44319	-0.38021	-0.32805	-0.21994	0.21267
0.50587	-0.43502	-0.37565	-0.25506	0.24463
0.56137	-0.48323	-0.41759	-0.28803	0.27512
0.59999	-0.51549	-0.44562	-0.31112	0.29633
0.04691	-0.03013	-0.02438	-0.01903	0.02314
0.12163	-0.10438	-0.08955	-0.05523	0.05772
0.18916	-0.16406	-0.14085	-0.08654	0.08761
0.27474	-0.2385	-0.20443	-0.12699	0.12422
0.35256	-0.30615	-0.26288	-0.16574	0.15954
0.41932	-0.36466	-0.31365	-0.20125	0.19165
0.49267	-0.42841	-0.36778	-0.23951	0.22589
0.55244	-0.47934	-0.41376	-0.27346	0.25608
0.61571	-0.53649	-0.46309	-0.31063	0.28923
0.65918	-0.57264	-0.49457	-0.33578	0.31212

Chart 6

SECTION II

Test Strain Data

" 1T1009"	" 1T1010"	" 1T1011"	" 1T1012"	" 1T1013"	" 2T1009"
" MST "	" MST "	" MST "	" MST "	" MST "	" MST "
0	-0.26075	-1.04522	-1.04236	-1.04527	-1.03109
-1.82052	-7.04018	-15.15401	-3.90876	-12.02065	16.75423
-0.26009	-8.3439	-21.4245	-3.38757	-15.15646	27.32236
1.0403	-11.47288	-31.87544	0.2607	-13.58858	41.75674
2.08057	-14.60185	-40.49747	0.2607	-17.24705	53.35596
2.86079	-17.99157	-47.02927	0	-17.76966	56.44922
1.56043	-22.16352	-56.95758	-0.26048	-20.64416	66.24393
1.0403	-26.07473	-65.3183	-1.82403	-26.13184	72.9458
1.0403	-30.50742	-71.58899	-2.08472	-27.43847	76.55438
0.78021	-31.81113	-74.72424	-3.12688	-28.74505	76.03903
2.08057	1.56446	-1.56783	2.34521	3.1358	0.77301
-1.56044	-5.73647	-29.00151	6.77516	-2.09054	42.01483
-4.68134	-9.90842	-41.80379	5.47231	-13.58858	64.18216
-5.46156	-14.60185	-57.2189	8.3387	-17.50835	86.86484
-5.72161	-18.25231	-70.80508	11.72628	-18.81492	108.00107
-5.20148	-22.42426	-82.56235	14.59268	-21.16682	125.52875
-5.9817	-25.0317	-93.79721	17.45908	-21.95078	140.9942
-8.32235	-29.98594	-106.07709	18.76192	-25.60925	155.94434
-8.84251	-34.41862	-116.00543	20.32547	-26.6545	167.80121
-9.62273	-37.54759	-121.49219	21.62833	-25.60925	173.98737
1.0403	1.04297	-3.13545	2.8664	4.96503	2.31984
-4.68134	-5.99721	-35.7946	8.59919	-4.70374	56.96455
-7.54213	-10.16916	-53.56104	9.64156	-14.89515	86.34909
-8.06229	-16.16631	-74.72424	16.6772	-15.41781	120.37329
-12.22346	-21.12055	-95.88724	21.36784	-19.33758	155.42859
-13.52382	-25.81399	-110.51862	25.01591	-21.95078	176.56488
-16.6447	-30.76817	-126.71747	28.14279	-25.87054	200.79437
-19.24542	-35.98308	-138.99731	30.7487	-28.74505	219.35309
-22.88646	-41.4588	-151.7998	33.09392	-30.83558	234.30322
-23.92676	-44.06628	-161.20551	33.87558	-29.529	244.61328
-8.58243	-3.91121	-6.532	-6.25397	-3.91977	-4.63969
-15.08426	-13.03739	-48.33557	-0.52118	-15.94042	63.66641
-18.98537	-18.51305	-71.3277	5.21162	-22.73473	100.78387
-21.84616	-25.0317	-97.45505	13.02914	-24.56393	146.14923
-24.4469	-29.98594	-120.18567	20.84666	-27.69978	186.87531
-27.82787	-34.94011	-141.08752	27.8823	-29.00634	220.89954
-28.86815	-39.89429	-154.41241	34.13628	-28.48374	244.61328
-31.72896	-43.8055	-170.35016	37.26315	-32.9261	268.84277
-35.63007	-50.32413	-185.24268	41.43262	-36.58456	291.01013
-39.01102	-53.71387	-195.43231	43.77783	-36.84592	305.44458
-16.90477	-8.60464	-12.54118	-15.63483	-9.40746	-6.95953
-23.40663	-18.25231	-61.92175	-0.78167	-17.76966	80.67871
-26.78757	-23.98873	-88.0491	5.47231	-26.91581	127.07516
-30.42859	-29.98594	-118.35675	15.63504	-29.79031	178.62701

Chart 1

STRAINS

-35.36998	-36.50456	-144.74542	25.27639	-29.79031	226.57031
-39.53116	-41.4588	-167.4762	33.6151	-31.09689	264.71887
-42.65205	-47.71671	-187.85547	41.43262	-35.278	301.83594
-46.033	-52.93167	-207.45105	48.72894	-37.36853	337.40662
-50.19417	-58.66803	-222.86597	53.41937	-39.19777	361.63611
-53.31505	-62.05774	-233.31689	54.46175	-41.2883	376.07043
-23.40663	-14.60185	-18.55057	-20.06478	-11.49805	-7.73294
-30.42859	-23.20649	-71.58899	-6.51446	-27.43847	90.98877
-34.32968	-28.42142	-105.55447	6.25397	-29.79031	152.33575
-39.53116	-35.46159	-141.34888	20.58596	-32.4035	218.83734
-43.69232	-41.198	-170.87274	33.09392	-31.88085	273.48242
-50.45424	-48.23819	-200.13538	44.03831	-35.278	328.12756
-54.61543	-53.45316	-221.82074	52.11632	-37.62984	366.7915
-57.73631	-59.45032	-240.37134	60.9762	-37.89119	400.29993
-62.41762	-64.66528	-259.70532	68.79373	-39.98172	435.87061
-64.75827	-67.27274	-270.67896	74.00534	-39.72043	455.46045
-24.70699	-15.12334	-19.07297	-21.10714	-11.49805	-8.50595
-32.76926	-24.77096	-82.56235	-1.82403	-27.17712	111.60968
-37.45058	-30.50742	-120.18567	12.76844	-29.79031	183.78204
-40.57146	-37.02606	-160.16052	32.31224	-28.48374	261.62561
-45.77293	-41.71954	-195.17102	48.46826	-30.05161	331.22046
-49.67403	-47.71671	-221.55988	63.06093	-30.05161	386.38098
-55.13557	-53.19235	-247.16443	74.26584	-30.05161	436.38635
-59.81688	-57.88586	-269.89502	85.47092	-32.4035	479.17419
-65.79855	-63.10074	-290.27466	93.80963	-33.44876	518.354
-68.91946	-66.49045	-304.38306	100.06342	-34.23273	543.61426

Chart 2

" 2T1010"	" 2T1011"	" 2T1012"	" 2T1013"	" 3T1009"	" 3T1010"
" MST "	" MST "	" MST "	" MST "	" MST "	" MST "
-1.54683	1.02696	-4.36252	-3.36532	0	-2.58828
4.64089	-18.99861	-4.10595	-6.18445	19.06746	10.87062
6.18772	-33.11916	-2.82282	-5.15372	29.77654	18.37659
6.96113	-50.3205	21.29935	10.82273	43.09766	25.6237
8.76603	-70.08929	29.76782	18.29559	54.85156	32.09435
-1.54683	-91.91193	44.65173	29.89143	57.72469	28.98846
-0.25767	-112.7077	52.09363	37.36429	68.95618	36.49443
-5.15623	-133.24664	53.12021	39.94116	76.53094	39.60033
-16.24252	-156.09631	68.51733	51.53697	80.18777	38.04738
-23.97706	-172.01404	72.87985	57.9791	80.18777	34.94148
1.03149	-4.10786	7.95514	6.44213	0.5224	0
37.64165	-14.89074	35.41347	17.00719	43.09766	33.64729
55.68907	-24.64677	27.97146	5.66906	66.34427	53.31808
73.99417	-37.22691	45.16496	13.14192	90.37445	72.47113
86.3692	-51.0907	64.66806	23.19164	111.27023	86.96536
96.16632	-67.26517	80.83499	33.7567	130.07648	100.16541
102.61172	-84.20984	100.85132	45.09483	144.44244	109.74203
110.34668	-101.41116	109.57635	50.24855	162.46509	121.64798
113.18265	-119.38281	126.76984	61.84436	174.74127	128.37738
112.92459	-132.73322	144.47662	73.95554	180.48773	131.4834
9.0237	-1.28373	19.24643	13.14192	2.08962	5.69417
63.16554	-8.47239	35.41347	12.11118	59.8143	53.83569
91.0101	-16.43124	39.77599	6.69979	89.32965	78.94177
************	-24.64677	73.90631	22.1609	123.02423	105.85956
154.1756	-35.17299	95.97556	31.17983	159.33069	134.33044
170.16046	-48.52333	117.53159	41.22957	181.27124	151.15405
190.78577	-62.64388	135.75159	49.73318	207.39105	171.86005
202.64551	-78.56158	149.86566	56.94836	226.98096	186.09552
212.95837	-94.73605	166.54584	66.22501	243.95874	198.26038
220.17712	-106.03247	189.64154	80.65536	255.19037	206.80157
11.08628	-2.05393	5.64565	5.92673	-1.30601	10.09415
80.43954	-5.39149	31.82075	4.896	68.95618	67.29459
119.62805	-9.24258	48.75768	6.95747	108.13589	100.68311
166.55103	-14.89074	87.50708	21.90318	153.06201	138.73047
207.28638	-22.8496	114.96542	32.21062	194.33118	173.15424
240.80286	-32.60562	141.65375	42.51802	230.63776	202.1427
258.84998	-45.18578	173.47461	58.23677	253.10077	220.00171
281.53821	-59.30632	188.61511	64.16351	279.22058	241.48419
301.13245	-74.45383	203.49908	72.15176	304.29553	260.89612
312.99219	-83.69641	219.92273	81.6861	319.70618	273.8374
17.53167	-1.79716	3.59262	4.63833	-2.87323	13.97661
110.862	2.05383	47.98778	11.85346	87.24002	90.07126
161.91016	0.7702	64.41138	9.53432	134.77814	130.44806
218.63031	-3.33756	102.90433	22.1609	188.5849	176.00128

Chart 3

STRAINS

269.16284	-8.21562	148.58252	40.71422	236.38403	217.15454
309.38232	-16.43124	182.71295	55.14456	276.60852	250.28412
348.05542	-25.1603	201.44617	57.9791	315.52698	283.67273
385.1814	-34.65955	227.62128	69.57492	352.09473	315.76709
409.41614	-49.03687	248.15076	78.07852	377.95337	336.99084
422.82263	-59.04955	258.41565	83.74759	393.62512	349.67334
21.39915	-0.7702	11.80442	10.56506	-1.82841	18.11774
************	7.18866	40.54578	0.77306	99.25513	107.15375
205.22382	10.26945	80.32175	11.59579	164.03229	162.28357
279.47559	12.06662	127.79642	26.54151	229.85406	221.29578
338.77368	8.47229	178.09381	45.61021	285.75049	267.88452
402.71301	5.13473	210.68433	55.40224	342.4303	318.09644
447.05774	-2.56736	240.45215	64.93658	383.96094	355.10852
481.60535	-12.58015	275.60925	81.17075	418.17773	384.09692
523.8877	-22.59293	295.11218	86.32443	456.05139	420.8501
547.09155	-30.03825	314.61511	94.82803	477.20837	441.03857
23.71939	1.28363	8.9816	7.9882	-1.82841	22.25896
165.00385	15.91771	54.40323	3.34987	121.457	132.25989
249.56854	22.8496	96.74545	13.65726	193.54767	196.44855
338.77368	27.72755	161.41351	34.52977	272.95166	266.3313
422.30725	28.24109	206.06512	47.41402	343.99756	331.29663
486.24622	25.67373	251.48676	62.35973	399.89392	381.24988
547.60693	21.82263	287.92676	75.75934	452.65576	432.49731
598.65503	14.37721	320.51746	86.32443	497.58191	472.87402
645.57812	5.64816	348.74548	96.11646	539.89575	511.18018
676.51636	-0.51353	367.22217	102.81628	565.49316	535.76855

Chart 4

" 3T1011"	" 3T1012"	" 3T1013"	" L 1"
" MST "	" MST "	" MST "	" LBS "
-0.26059	-4.42657	-1.30672	0.24346
16.15704	-17.70631	0.2613	17.67105
31.79279	-24.73676	2.35215	29.844
56.54953	-16.92516	9.66988	44.89787
78.70032	-20.0498	13.59006	59.58656
111.53552	-15.36283	18.81716	74.62012
133.68622	-21.35174	23.26015	89.75516
158.18231	-30.46528	26.3962	104.56558
191.53876	-26.29908	31.3618	119.78174
213.42889	-27.60102	34.49806	129.56073
10.16325	2.0831	5.74971	0.3449
0	5.20774	8.36316	17.69135
-3.90896	-13.54012	7.57904	30.00631
0.26059	-13.54012	10.71531	44.71529
10.42384	-11.71741	15.4196	59.7083
22.41132	-9.89471	20.12389	74.64041
38.82895	-5.46812	25.08948	89.71457
50.81644	-11.45702	29.00965	104.84961
68.27643	-9.37393	33.71394	119.78174
85.47583	0	37.63412	129.76361
8.07852	11.45703	8.36316	0.3449
-20.84776	0.78116	8.36316	17.71163
-34.65938	-11.45702	8.10186	29.92515
-38.82893	-2.0831	13.85157	44.8573
-47.68922	-1.04155	16.46502	59.58656
-41.69554	2.34348	21.69192	74.66071
-41.69554	1.82271	24.82818	89.75516
-34.91998	-0.26039	28.22574	104.76846
-24.23555	1.04155	32.14592	119.94406
-14.07221	10.93625	36.06609	130.33167
4.95133	0.26039	4.18168	0.3449
-41.17436	-8.33238	3.39757	17.73192
-63.58566	-11.71741	4.44299	29.98602
-81.04565	-1.56232	9.40858	44.79643
-96.94211	0.26039	14.11287	59.85031
-106.32358	4.94735	17.77174	74.76215
-101.89343	17.18554	25.08948	89.55228
-104.49936	13.27974	27.96423	104.68729
-104.75995	10.67587	31.10049	119.86292
-101.63284	14.0609	33.97525	129.96649
-1.82413	-3.90581	1.56803	0.3449
-65.67041	-2.34348	4.18168	17.71163
-98.50565	-9.11354	3.65887	30.10775
-128.4743	-1.82271	8.36316	44.69499

Chart 5

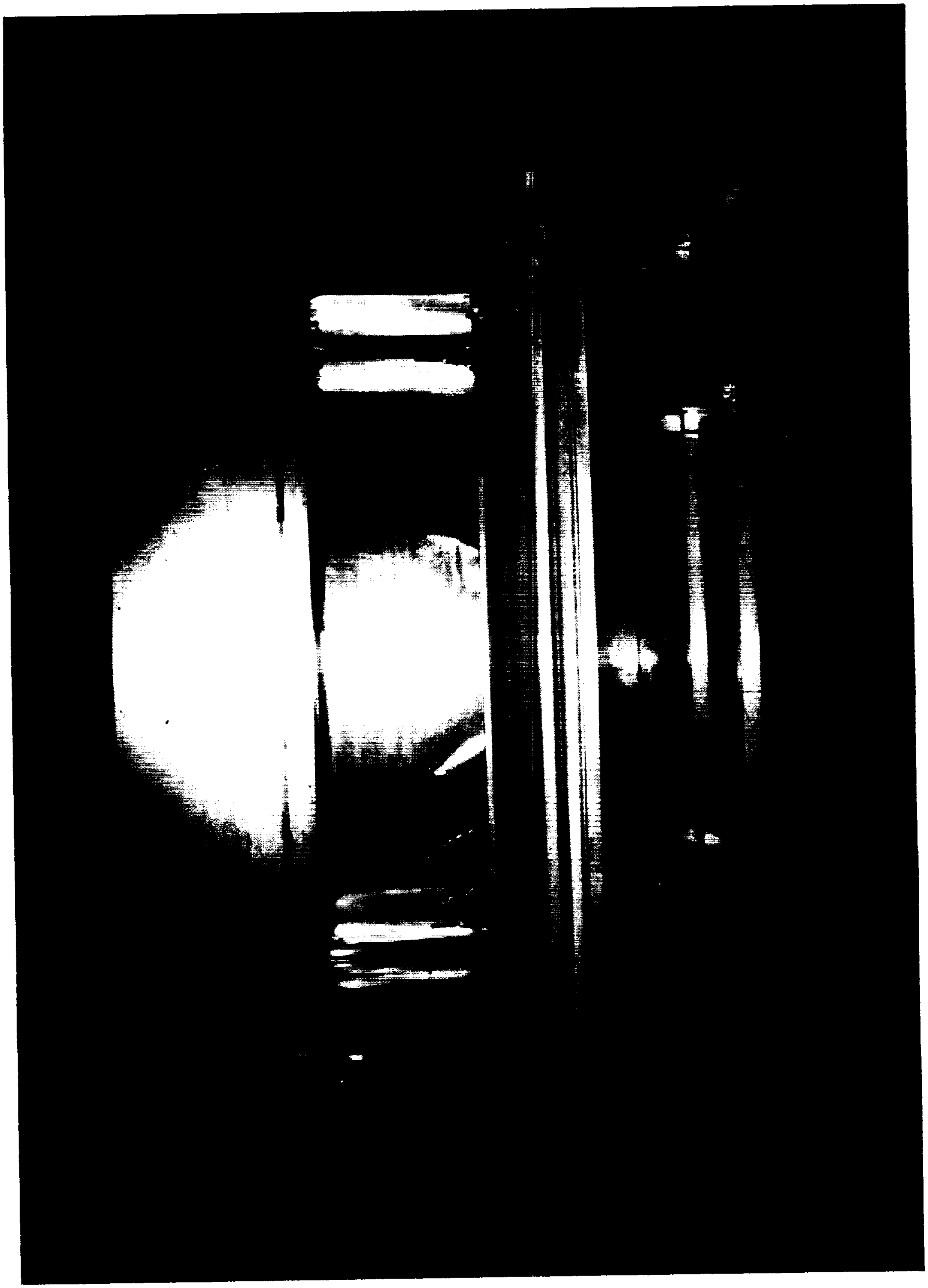
STRAINS

-149.5827	13.80051	14.37418	59.80974
-163.65491	22.91415	19.07847	74.51868
-182.93903	18.48758	22.21473	89.71457
-196.49011	20.83106	26.91901	104.60614
-200.39911	22.39338	30.31638	119.70059
-200.65961	21.61222	32.14592	129.64185
-4.16955	1.56232	1.56803	0.36519
-90.68774	-13.54012	0	17.73192
-135.77106	-5.9889	2.87496	29.844
-178.76953	4.68697	8.10186	44.69499
-209.5199	22.39338	14.63548	59.99232
-247.04596	23.69531	16.98763	74.86359
-266.85132	28.64267	21.95322	89.59286
-277.01465	39.83931	27.18032	104.84961
-297.08069	38.0166	30.8392	119.66003
-303.33484	42.18279	34.23676	129.8042
-5.7331	-0.52077	0.52281	0.30432
-114.66269	-7.81161	1.04542	17.79279
-171.47284	-2.0831	3.92017	29.78313
-226.4588	19.52912	10.97661	45.18192
-276.49353	27.60112	15.9422	59.74887
-311.67395	40.09969	22.21473	75.02591
-346.07275	48.43207	26.1349	89.75516
-370.82959	54.94174	31.3618	104.64673
-394.80444	57.806	34.75937	119.49771
-408.87671	60.14949	37.89563	130.29108

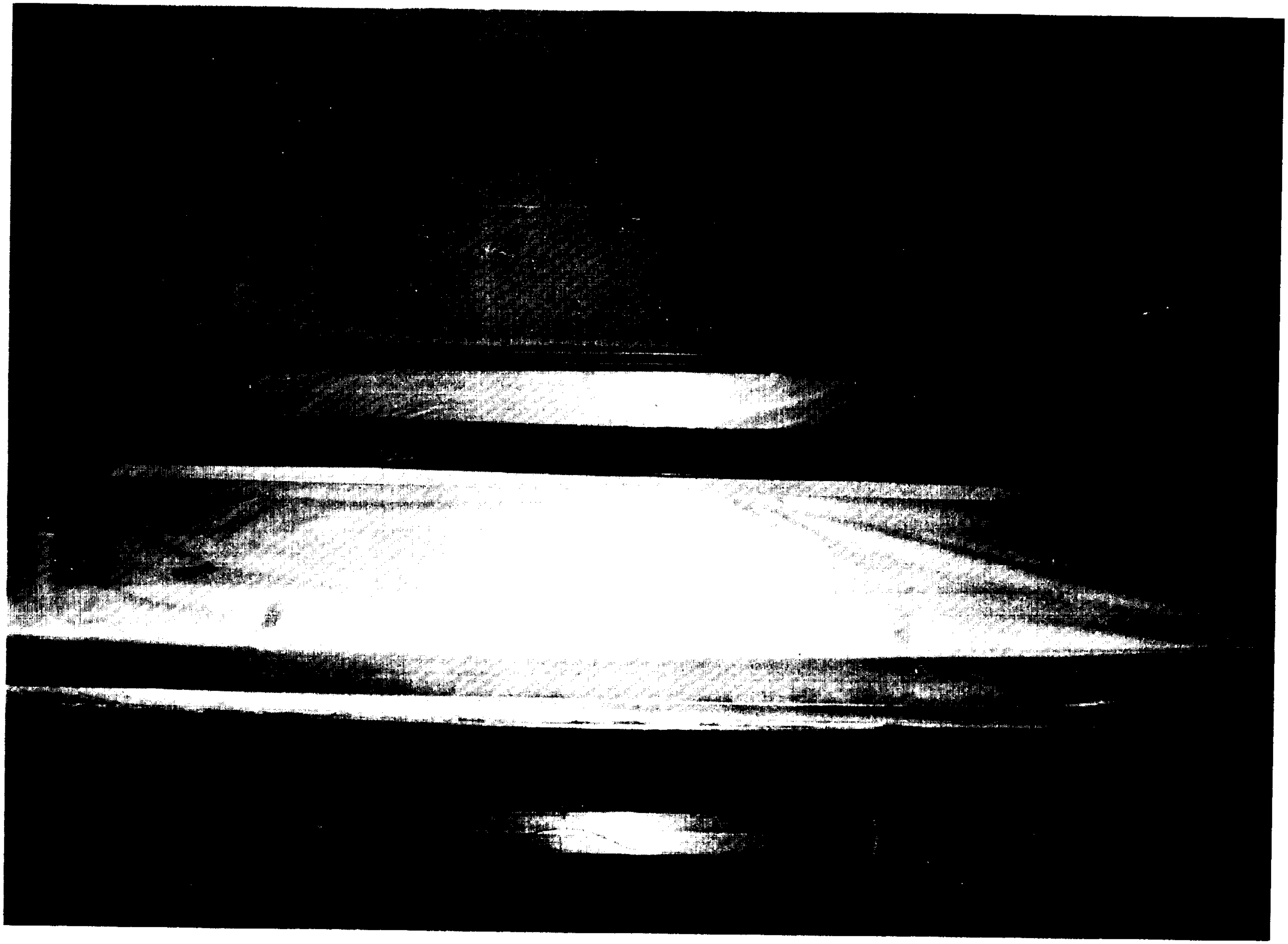
Chart 6

SECTION III

Manufacturing and Testing Photographs



Hot-drape forming "oven."



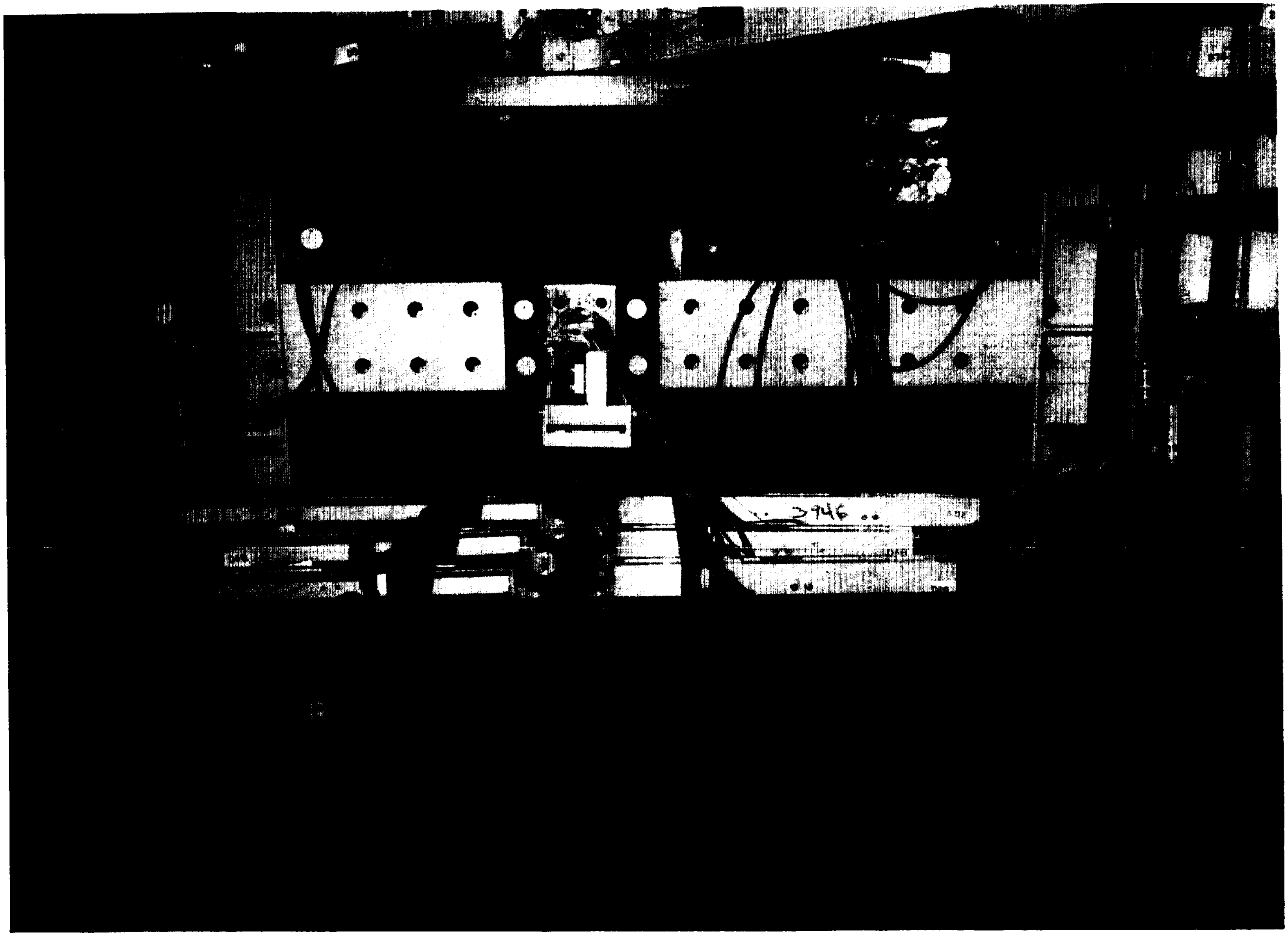
Laminate placed on tool ready for hot-drape forming.

C-channel upon removal from tool after autoclave cure.
Notice warpage of beam along its length.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

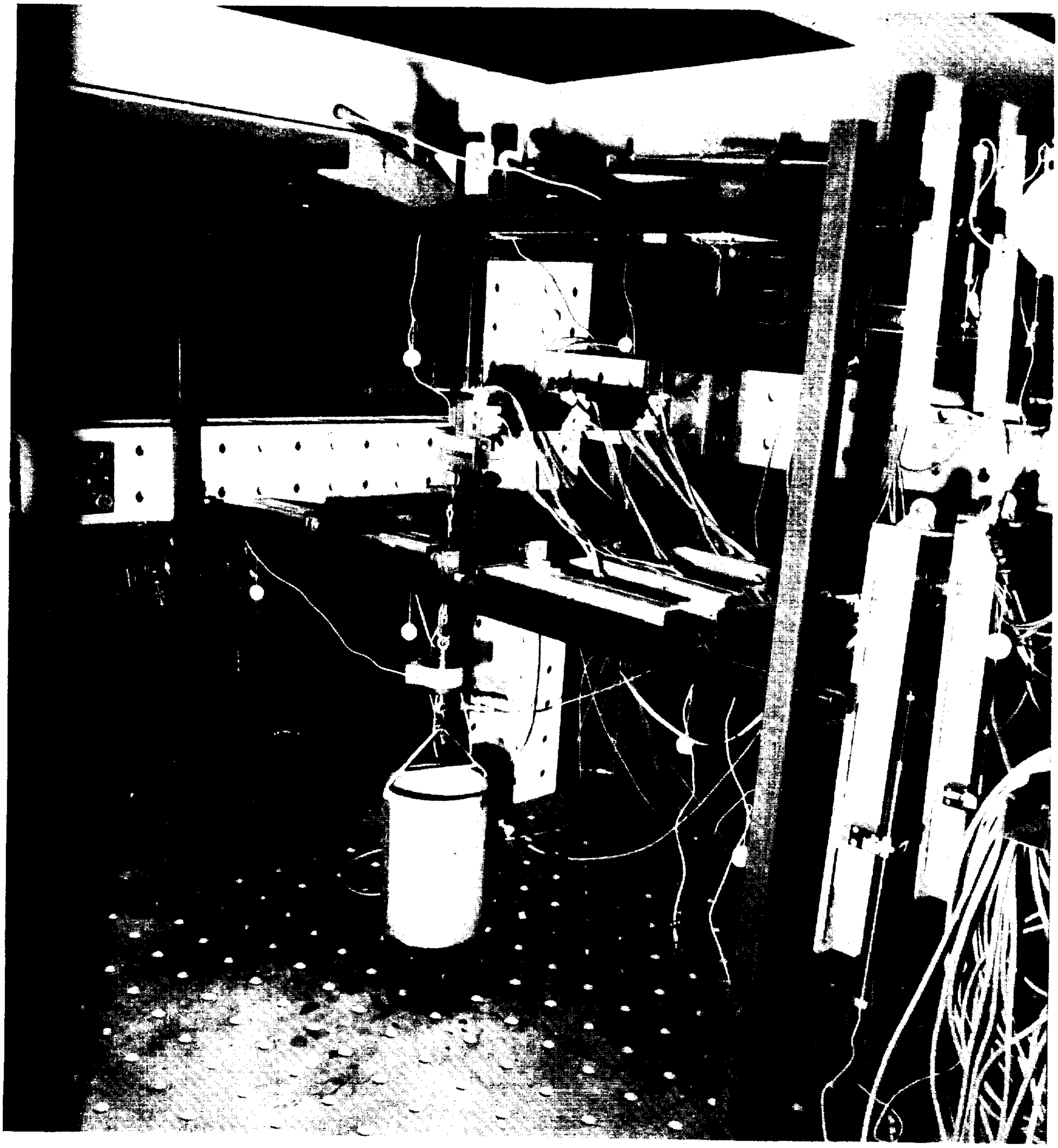
Fully instrumented beam C-channel prior to testing.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



Front view of test configuration. Slide block allows load application point to be changed.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



C-channel with load being applied. No rotation has occurred at this point of the test.

Test being performed on L-angle. Beam has started to rotate.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1994

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
Buckling of Composite Beams
(CDDF Final Report – Project #91-20)

5. FUNDING NUMBERS

6. AUTHOR(S)
P. Thompson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M-765

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3512

11. SUPPLEMENTARY NOTES
Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Subject Category: 24
Unclassified-Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Presented in this report are the results of an investigation of the twisting/warping deformations occurring in open-section composite beams. A series of C and L channels were manufactured using both hand layup and the innovative "hot-drape forming" techniques. A transverse tip load was applied at the free end of the cantilevered open-section beams. The test setup allowed the tip load to be applied at various locations along the plane of and at the beam's shear center. Charts are included in this report depicting various angles of ply layups, loads applied, and load application points.

A major verification resulting from this study is that the shear center of an open section composite beam can be altered, if not completely controlled, through laminate layup. Also, it was observed that the choice of the material system does not have an effect on the amount of deformation, as expected, and the material affects the location of an unsymmetric open section composite beam's true shear center. The results from this study have provided a foundation for further investigation into the apparent shifting of the shear center location in open-section composite beams.

14. SUBJECT TERMS
antisymmetric laminate layup, hot-drape forming, torsion/bending coupling, composite beams

15. NUMBER OF PAGES
54

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited