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EXTENDED TORSIONAL TESTS OF AN INTERLOCKED BI-STEM SATELLITE BOOM

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16. Abstract

This report examines the effect of continued oscillations of a 1.27-cm interlocked bi-stem satellite boom. The test setup oscillated a boom continuously between set torque limits and periodically recorded its hysteresis characteristics. Results showed that repeated oscillations affected torsional characteristics and that torsional rigidity changed as a function of the number of cycles oscillated within certain torque limits. Torsional characteristic changes caused by repeated oscillations were retained.

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FOREWORD

This document makes use of international metric units according to the Systeme International d'Unites (SI). In certain cases, utility requires the retention of other systems of units in addition to the SI units. The conventional units stated in parentheses following the computed SI equivalents are the basis of the measurements and calculations reported.

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EXTENDED TORSIONAL TESTS OF AN INTERLOCKED BI-STEM SATELLITE BOOM

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INTRODUCTION

A 1.27-cm interlocked bi-stem satellite boom had been subjected to a number of static and dynamic torsional tests in previous work by the author (Reference 1). In those tests the boom was rotated a minimum number of times in both clockwise (CW) and counterclockwise (CCW) directions prior to making torsional measurements. To determine the effect of continued oscillations, a device was developed (Reference 1) that instruments the plotting of angular deflection versus torque. This electromechanical device can subject a boom to any desired number of ocsillations, recording each oscillation, and permitting instrumented hysteresis plots to be recorded periodically on an x-y plotter. This report deals with results obtained from subjecting a particular boom to extended tests.

TEST SETUP

The deployer mechanism for a 1.27-cm, tabbed, interlocked bi-stem boom was secured to a ceiling beam in a high-bay area. The boom was deployed 5.867 m (231 in) and the free (tip) end was clamped to the angular deflection mechanism as shown in Figure 1. (When both ends of a boom are secured in this manner, the boom is referred to as being clamped-clamped.) The torque limits of 0.0106 N·m (1.5 oz·in) were set by the electronic controls of the deflection device, controlling the angular deflection of the boom in both the CW and CCW directions. Thus, a nominal torque of 0.0106 N·m in either direction would cause the deflection device to reverse direction. Using torque forces as controlling limits did not limit the number of degrees the boom had to be rotated to reach these limits. This configuration allowed changes in angular deflection to be observed while holding the torque limits constant.

DESCRIPTION OF TESTS

Initial Test Runs

The torsional measuring device was started up and the boom was oscillated in both directions between the 0.0106 N·m (1.5 oz·in) limits initially set. A hysteresis plot was made of the first complete cycle; additional plots were made periodically up to 150,000 cycles (Figures 2 and 3).

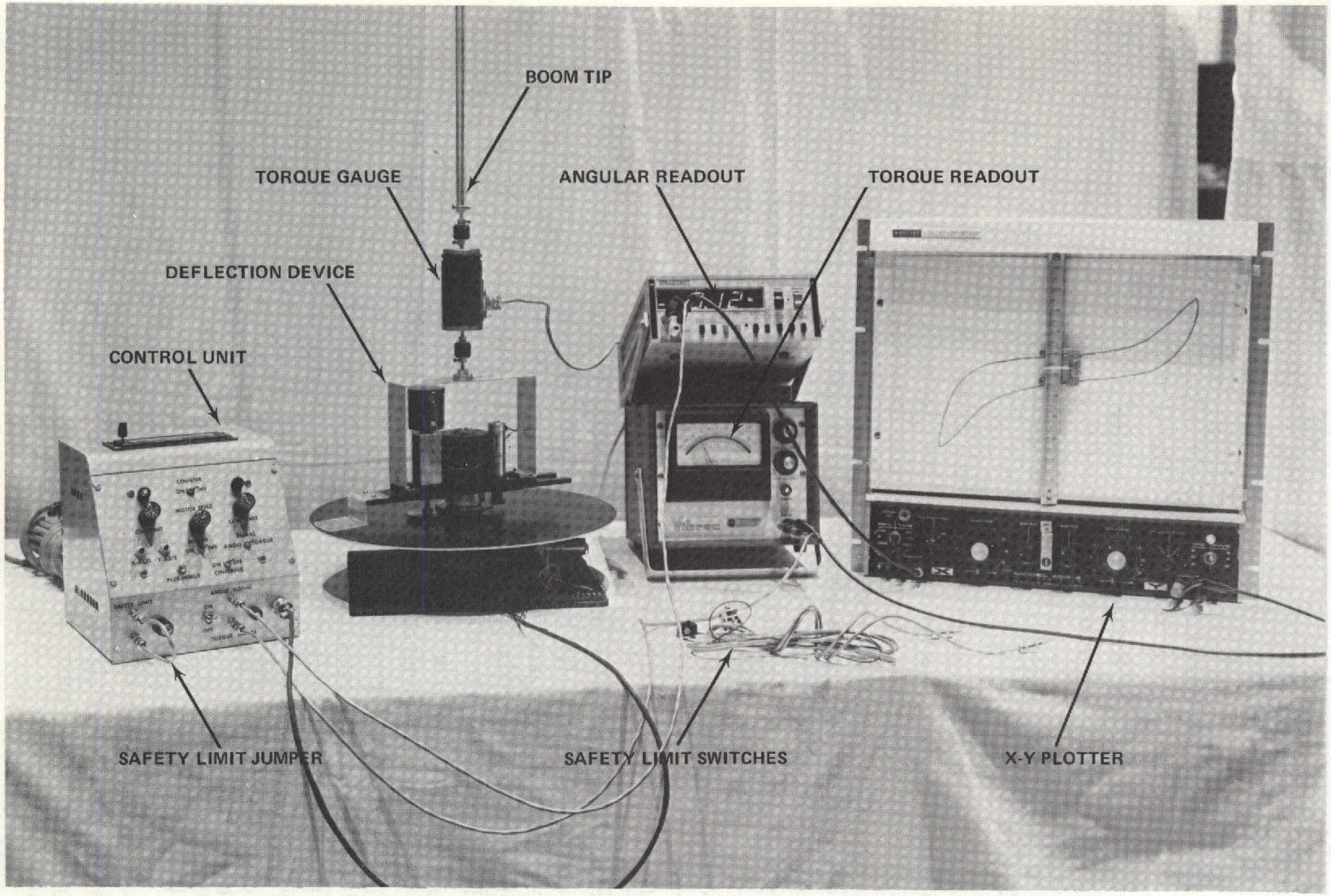
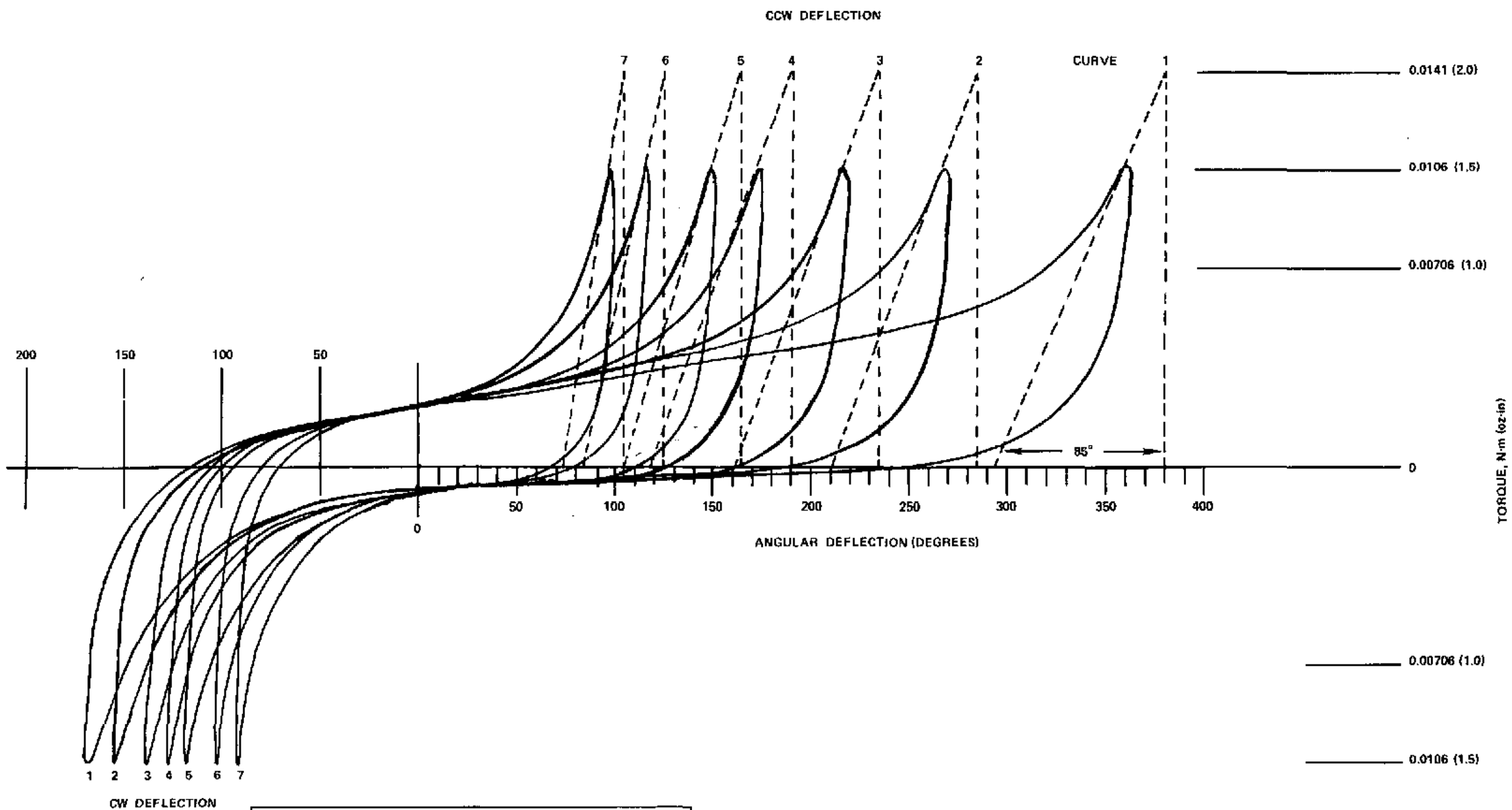


Figure 1. Instrumented hysteresis plotting unit.



TYPICAL TIP SPRING RATES S
AND TORSIONAL RIGIDITY C CALCULATIONS
USING CURVE NO. 1

$$S = \frac{\text{TORQUE (N·m)}}{\text{Deg}} = \frac{0.0141}{85} = 1.658 \times 10^{-4}\ \text{N·m/Deg}$$

$$C = 1.658 \times 10^{-4}\ \text{N·m/Deg} \times 5.867 \times 57.3 = 0.0557\ \text{N·m}^2$$

NOTE: SEE TABLE 1 FOR SUMMARY OF S AND C VALUES.

Figure 2. Hysteresis curve samples 1 through 7 of initial tests.

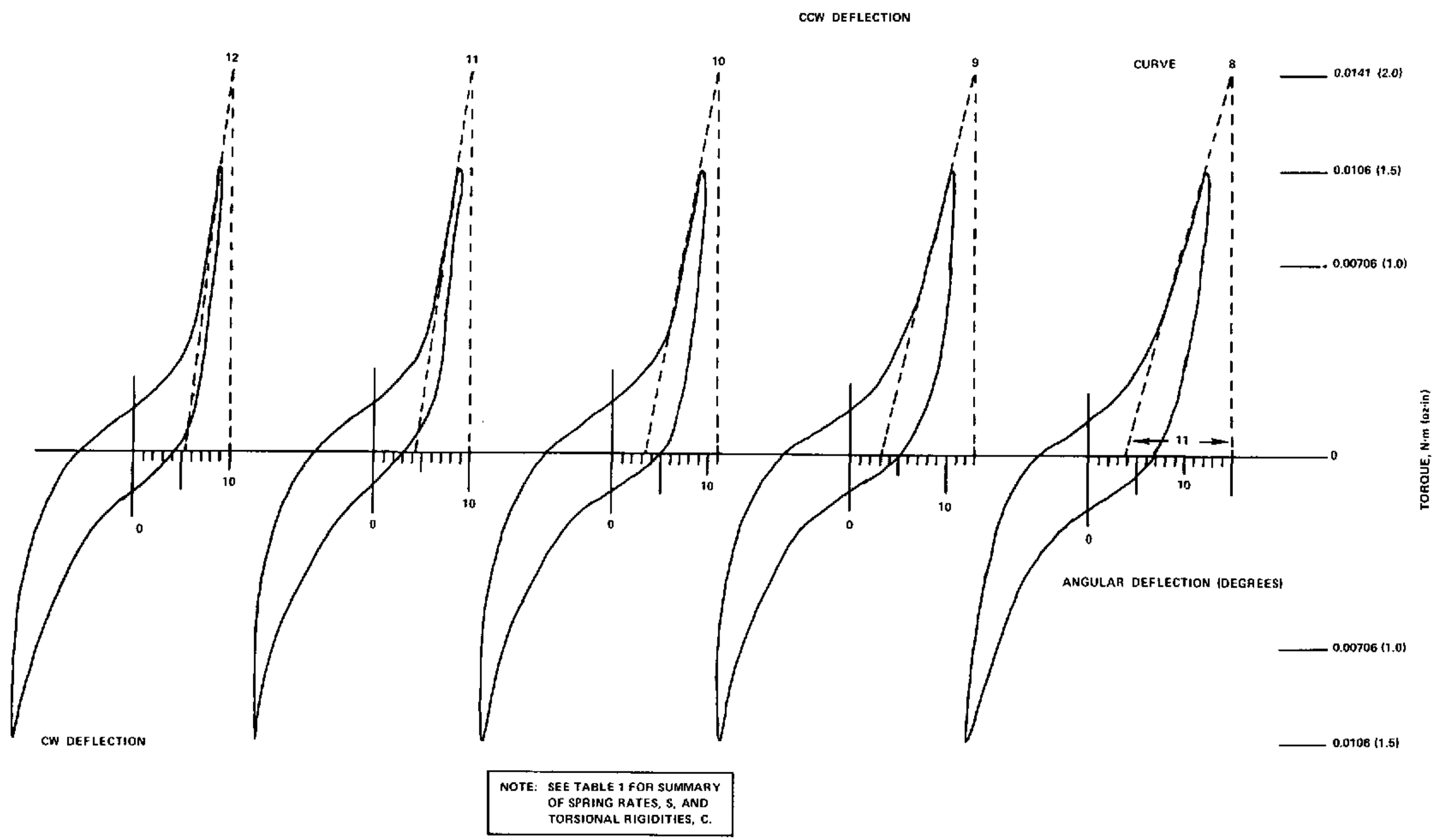


Figure 3. Hysteresis curve samples 8 through 12 of initial tests.

It can be seen from these plots that the "dead space" of the boom decreased somewhat logarithmically. The dead space has been defined (Reference 1) to be the distance a boom can be rotated in either direction without exhibiting an angular change upon being released. In the case of a boom having interlocking tabs, the dead space is defined as the angle through which the boom may be deflected without encountering resistance of the engaging tabs.

The initial test cycle (Figure 2) shows that the boom had to be rotated approximately 360° in the CCW direction and 170° in the CW direction before the set limits of 0.0106 N·m were reached. It should be noted here that the boom originally had some degree of offset in the CW direction prior to testing. Thus, the boom would originally have to rotate more in the CCW direction (opposing the offset) than in the CW direction (with the offset) to reach a point in angular deflection where the tabs would begin to lock up. The result is the larger deflection in the CCW direction shown by the hysteresis plots.

The initial offset, which appears to be independent of the manufactured pretwist, may indicate that this particular section of boom had been given a large deflection in the CCW direction prior to testing.

Continued cycling of the boom between the torque limits indicated that the dead space zone steadily decreased until, at the end of 20,000 cycles (Figure 2, curve 7), the dead space was approximately 50° in each direction. Hysteresis plots shown on Figure 2 illustrate this gradual decrease in the dead space of the boom. Also, the torque limits of 0.0106 N·m were reached after deflecting the boom approximately 100° in either direction, indicating an increase in boom-tip spring rate (stiffness per degree of rotation).

The boom was then disconnected from the deflection device, unclamped, and retracted by the deployer.

The same boom section was redeployed and clamped to the deflection device. The boom was again cycled between the 0.0106 N·m limits, and a hysteresis plot (Figure 4) was made of the initial cycle. The plot, indicating a dead space of approximately 50° in each direction, showed that the boom did not return to the dead space limits exhibited originally by Figure 2 (curve 1), but retained the dead space limits developed after 20,000 cycles. In addition, the total angular deflections remained approximately 100° in each direction and the tip spring rate remained the same. Apparently, extended cycling caused a working-in of the boom by polishing the tabs so that they seated themselves more readily upon deflection from null in either direction.

The boom was retracted and redeployed several times; hysteresis plots made each time showed a dead space of approximately 50° in each direction. Thus, it appears that once a boom section of this design has been subjected to oscillations, it will retain the hysteresis characteristics resulting from these oscillations, provided the boom is subjected to no greater force than the original torque limits.

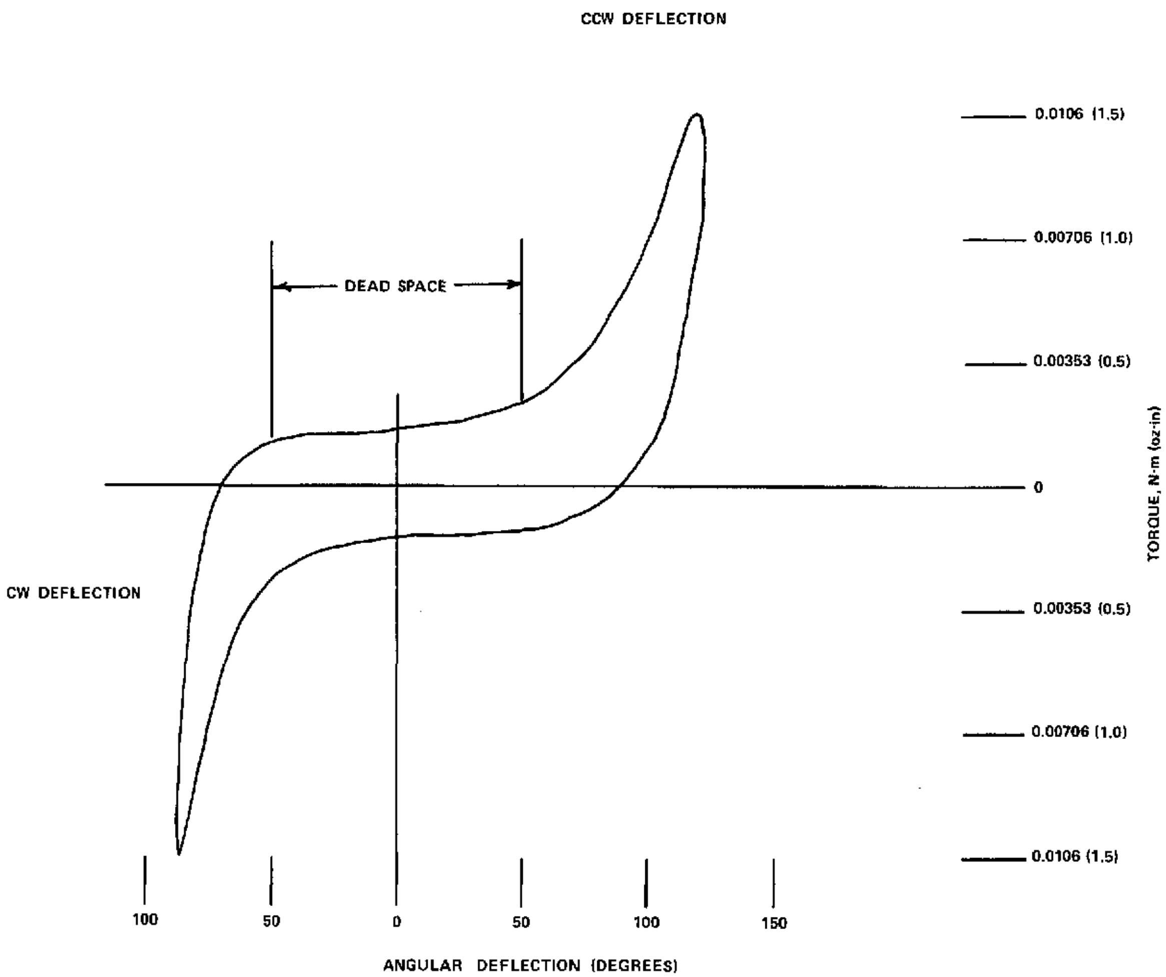


Figure 4. Hysteresis plot after reclamping and redeploying.

First Large CCW Deflection Test

Following the preceding tests, the boom was rotated to 540° in the CCW direction and reconnected to the instrumented deflection device; a hysteresis plot was made of the initial cycle (Figure 5). Since the boom had not been deflected in the CW direction, the plot showed as expected that the CW dead space remained in the worked-in condition. However, the CCW dead space increased considerably due to the large deflection in that direction. The large CCW deflection also lowered the CCW tip spring rate.

Additional plots were made after 2000 and 20,000 cycles of oscillation within the 0.0106 N·m limits. Figure 6 indicates that the boom again returned to the worked-in condition of 50° of dead space in each direction and showed increased tip spring rate after 20,000 cycles.

Second Large CCW Deflection Test

The boom was deflected again in the CCW direction for 360°. A hysteresis plot made of the first cycle (Figure 7) shows that the CCW dead zone had increased. The boom was removed from the deflection device after the first cycle, retracted, and extended without unclamping the free end. A hysteresis plot was made (Figure 8) showing no significant change from Figure 7. The boom was again removed from the deflection device, unclamped, retracted, and extended. After again securing the boom to the deflection device, a hysteresis plot (Figure 9) was made, which again showed little change.

The results of these tests determined that this boom, as manufactured, has a dead space of approximately 250° in the CCW direction and 100° in the CW direction. However, the dead space is appreciably reduced by continued oscillations of the boom.

To determine the minimum dead space that could be obtained by continued cycling, the boom was oscillated for 150,000 cycles using the 0.0106 N·m limits. It was found that no appreciable change in the dead space, which was approaching zero, occurred after 60,000 cycles. However, from the hysteresis plots (Figures 2 and 3), the torsional rigidity of the boom continued to rise.

Increased Torque Limits

All test conditions remained the same as they were in the initial tests, with one exception: Torque limits of 0.0353 N·m (5 oz·in) were set by the control unit. Thus, it would take this torque in either the CW or CCW direction to cause the deflection device to reverse direction.

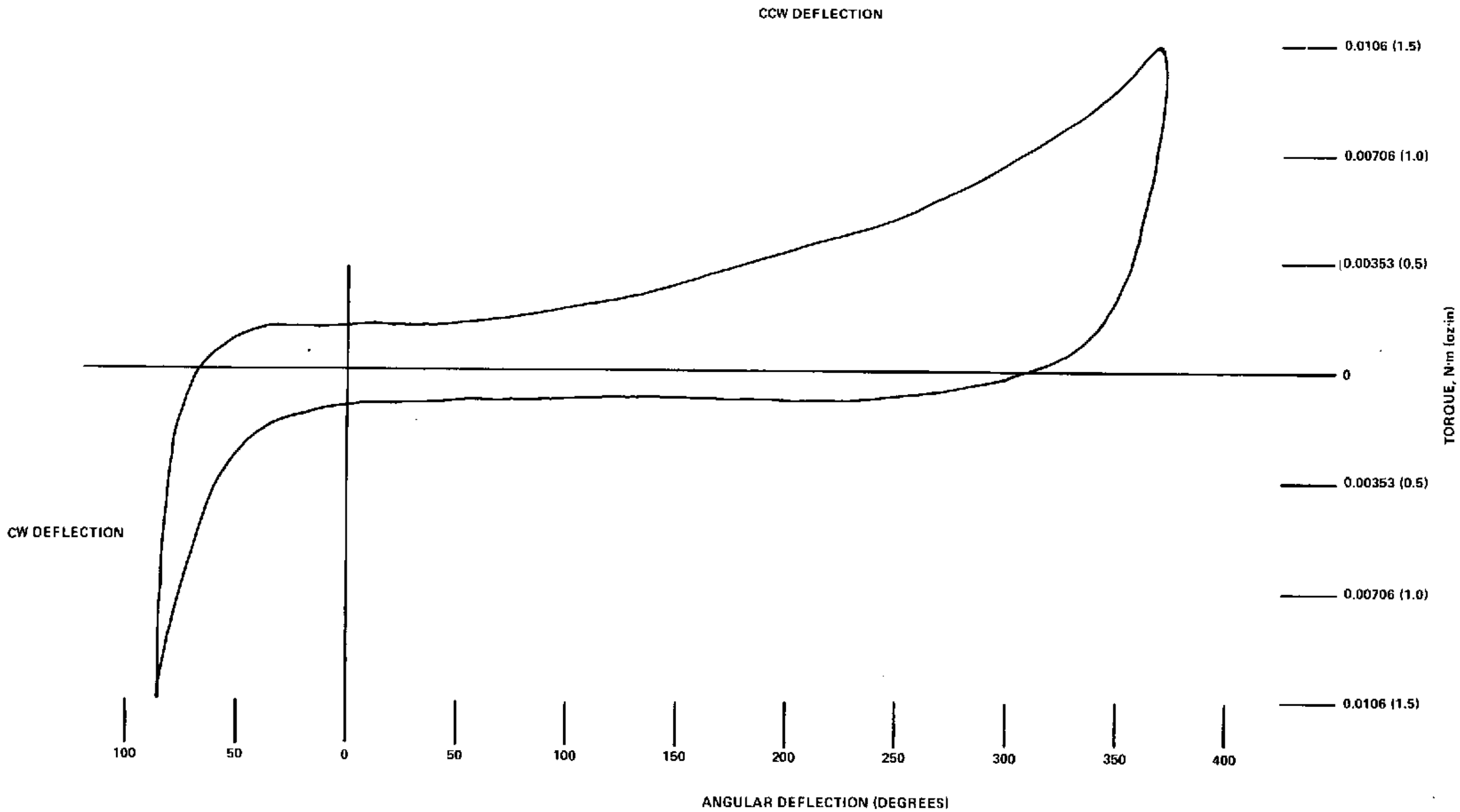


Figure 5. Hysteresis plot after 540° CCW deflection.

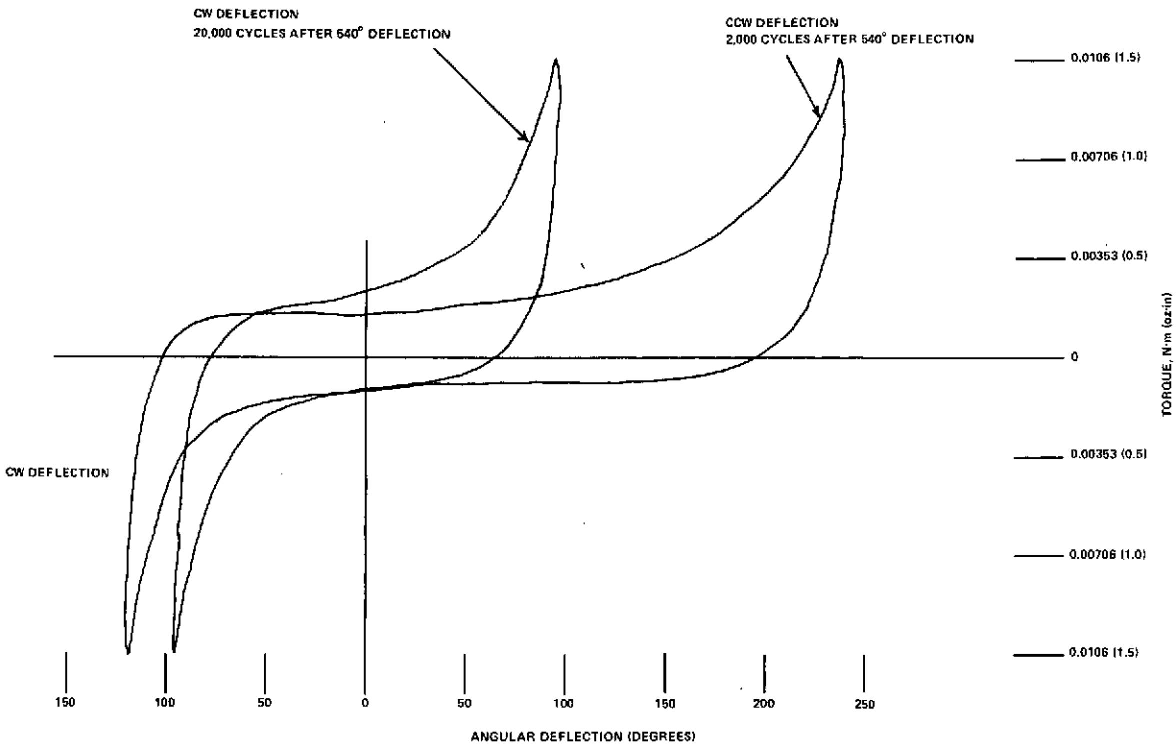


Figure 6. Hysteresis plots after cycling boom following 540° CCW deflection.

0.0353 N·m Limits

The torque-measuring device was started up and the boom was oscillated in both directions between the torque limits. A hysteresis plot was made of the first complete cycle; then additional plots were made periodically up to 85,000 cycles (Figure 10). It can be seen from these plots that the dead space decreased in the same manner as it did during the 0.0106 N·m limit test. However, it should be noted that a dead space limit of less than 10° in either direction was reached after 1250 cycles.

The boom was then oscillated continuously until 150,000 total cycles had been reached. It can be seen from Figure 10 that a comparatively small change in dead space took place between the 1250th cycle and the 85,000th cycle. Thus, it appears that increasing the torque limits caused the boom to approach its worked-in condition with fewer oscillations than were necessary when using the 0.0106 N·m limits.

0.1059 and 0.1412 N·m Limits

The torque limits were next increased to 0.1059 N·m (15 oz·in) and the boom section was oscillated between these limits. Inspection of the boom after a few cycles indicated that this applied torque had caused the sharp edges of the tabs to bite into the thin metal of the boom wall.

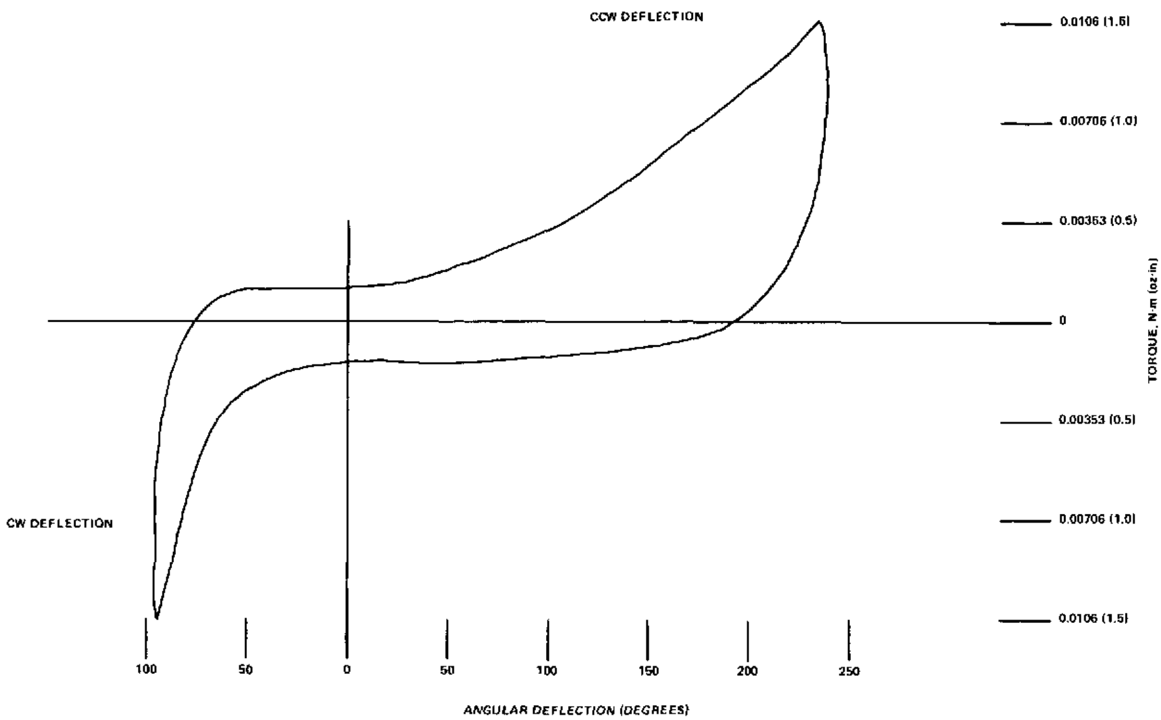


Figure 7. Hysteresis plot after 360° CCW deflection.

Increasing the torque limits to 0.1412 N·m (20 oz·in) caused the boom section to buckle and to be permanently damaged. Figure 11 shows hysteresis plots for torque limits of 0.0353, 0.1059, and 0.1412 N·m, respectively.

It appeared from these tests that the maximum torque this boom could be subjected to without being permanently damaged is approximately 0.1059 N·m.

Effects on Torsional Rigidity

The rigidity of the boom (in N·m^2) was determined by plotting the applied torque at the tip versus the angular tip rotation. The tip spring rates were found from the slope of these plots. The torsional rigidity, C, of the boom was then found by multiplying the tip spring rate by the length of the boom section and converting N·m/° into N·m^2/rad. First, define

$$S_r = \text{tip spring rate (N·m/°)}$$

$$l = \text{length of boom (m)}$$

Then

$$C = 57.3\, S_r l \text{ N·m}^2$$

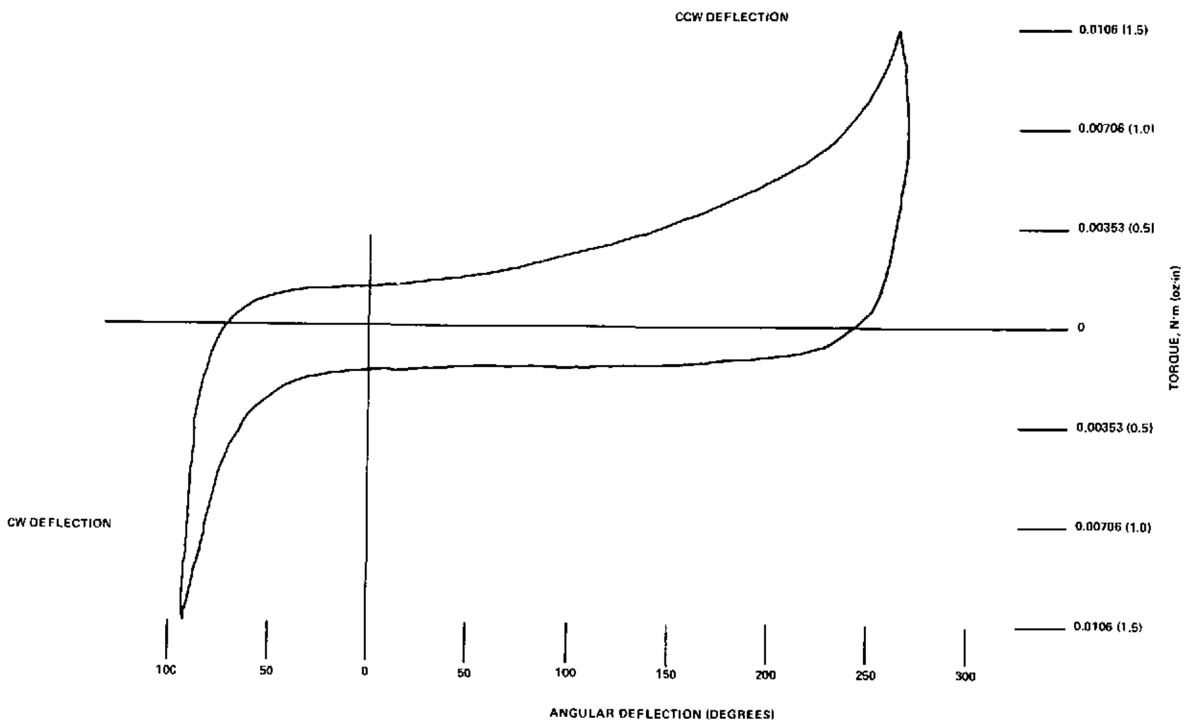


Figure 8. Hysteresis plot as in Figure 7, plus retraction and redeployment without unclamping.

From the slope of the hysteresis plot (Figure 11) at a nominal 0.1059 N·m the tip spring rate, S, would initially be calculated as

$$S_r = \frac{0.1059 \text{ N·m}}{100°} = 0.1059 \times 10^{-2} \text{ N·m/°}$$

with a torsional rigidity, C, of

$$C = 0.1059 \times 10^{-2} \times 5.867 \text{ m} \times 57.3 = 0.35 \text{ N·m}^2$$

However, these tests have shown that the maximum torsional rigidity was attained by permitting the boom to oscillate approximately 200,000 cycles, using torque limits of either 0.0106 N·m or 0.0353 N·m. At this point, the torsional rigidity was estimated at 1.29 N·m^2 by extension of the graph (Figure 12).

The graph of torsional rigidity versus number of cycles of oscillation shown on Figure 12 indicates (by graphical extension of the curves) that the maximum torsional rigidity would be reached in the vicinity of 200,000 cycles, whether the 0.0106 N·m or 0.0353 N·m limits were used. It can also be seen from these curves, that curve B (0.0353 N·m limit) indicates that the boom attains greater torsional rigidities with fewer cycles of oscillation than does curve A (0.0106 N·m limit). However, the difference in number of cycles of oscillation required to reach a particular torsional rigidity gradually lessens until, at the 200,000th cycle, the two curves converge.

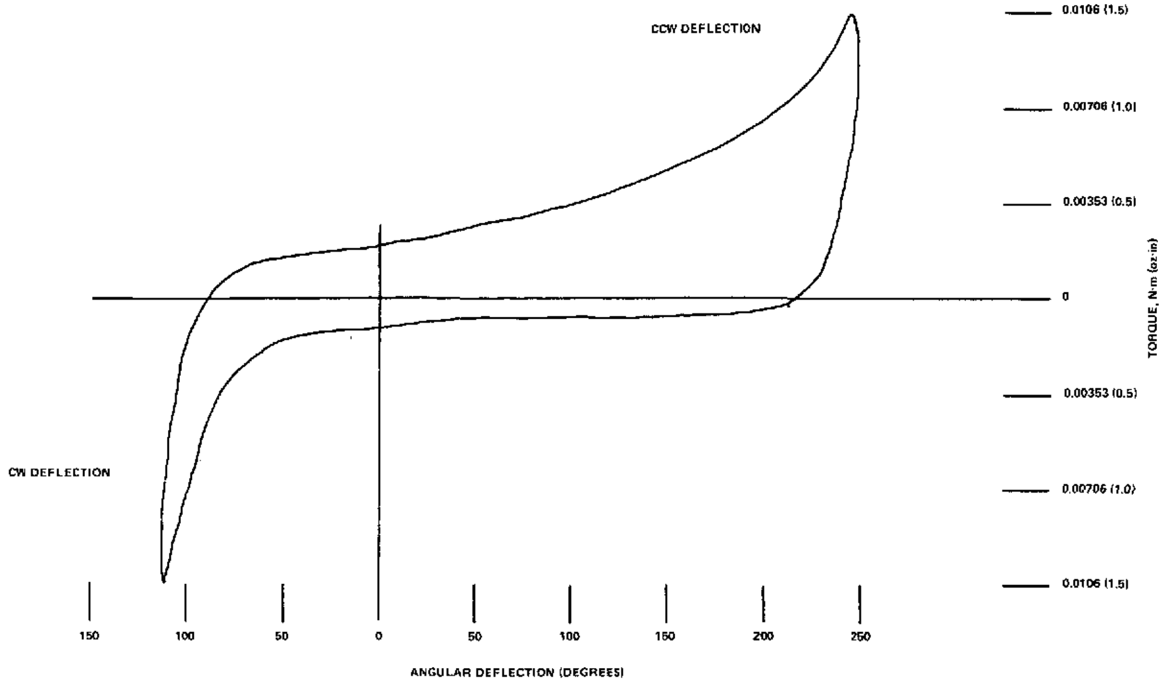


Figure 9. Hysteresis plot as in Figure 8, plus unclamping, retraction, redeployment, and reclamping.

It may be surmised that at this point the tabs have been completely worked-in. Apparently it is not necessary to use torque limits greater than 0.0106 N·m if it is planned to oscillate the boom until the tabs are completely seated. Torque limits less than this value were not investigated.

Calculations showing a comparison of the maximum torsional rigidity of this boom with that of a closed solid-walled tube of the same dimensions are of interest.

Using the maximum estimated torsional rigidity of 1.29 $N{\cdot}m^2$ obtained by projecting the curves of Figure 12 and the theoretical torsional rigidity equation $C = 2\pi t r^3 G$ (Reference 2) for a closed, thin-walled tube, an effective shear modulus for this boom would be

$$G = \frac{1.29\ N{\cdot}m^2 \times 10^{-8}\ m^4}{6.28(.005)(0.635)^3} = 1.6047 \times 10^{10}\ N/m^2$$

where

t = thickness of boom wall (cm)
r = radius of boom (cm)
C = torsional rigidity ($N{\cdot}m^2$)

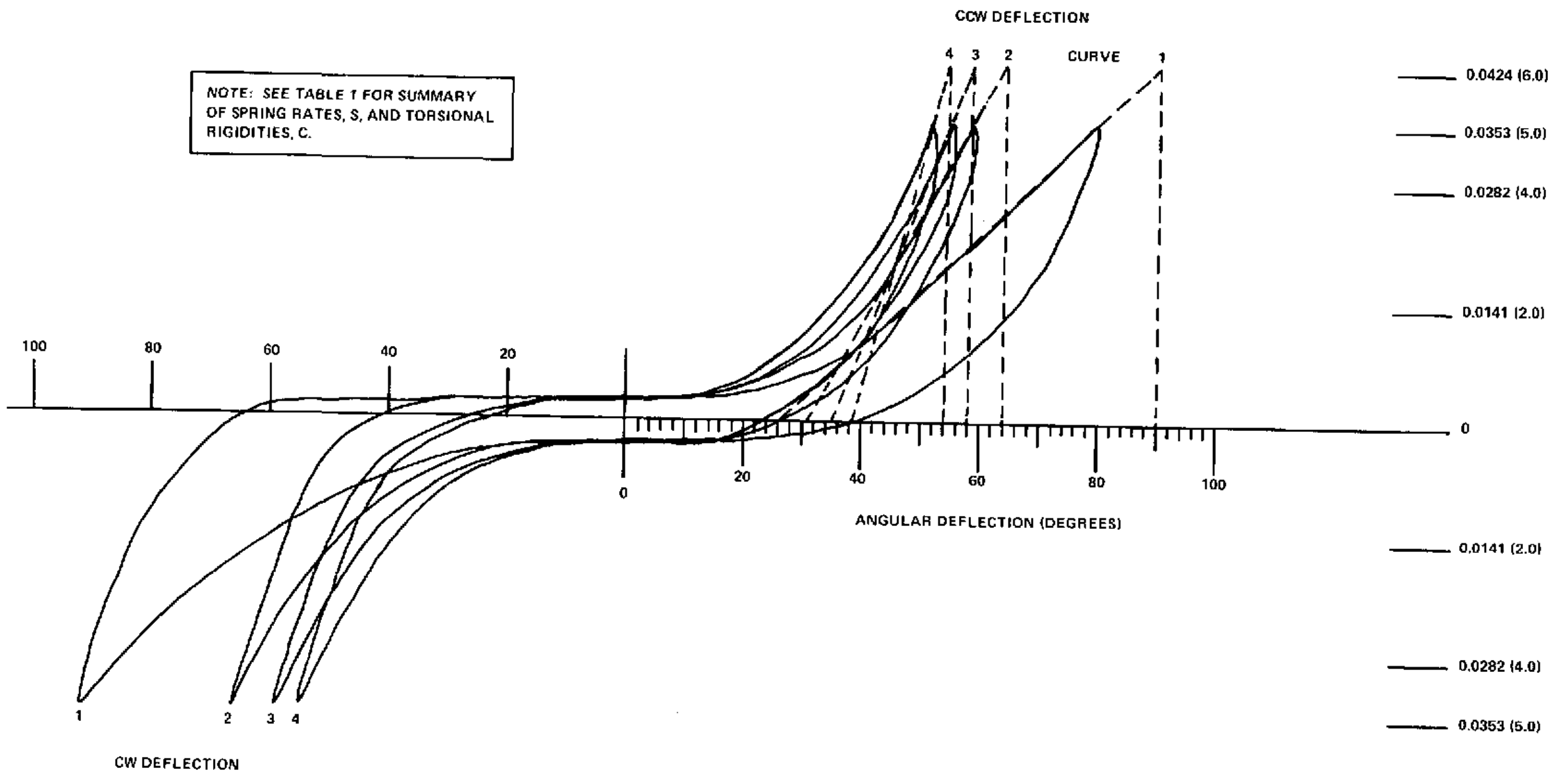


Figure 10. Hysteresis plots for 0.0353 N·m torque limits, initial test.

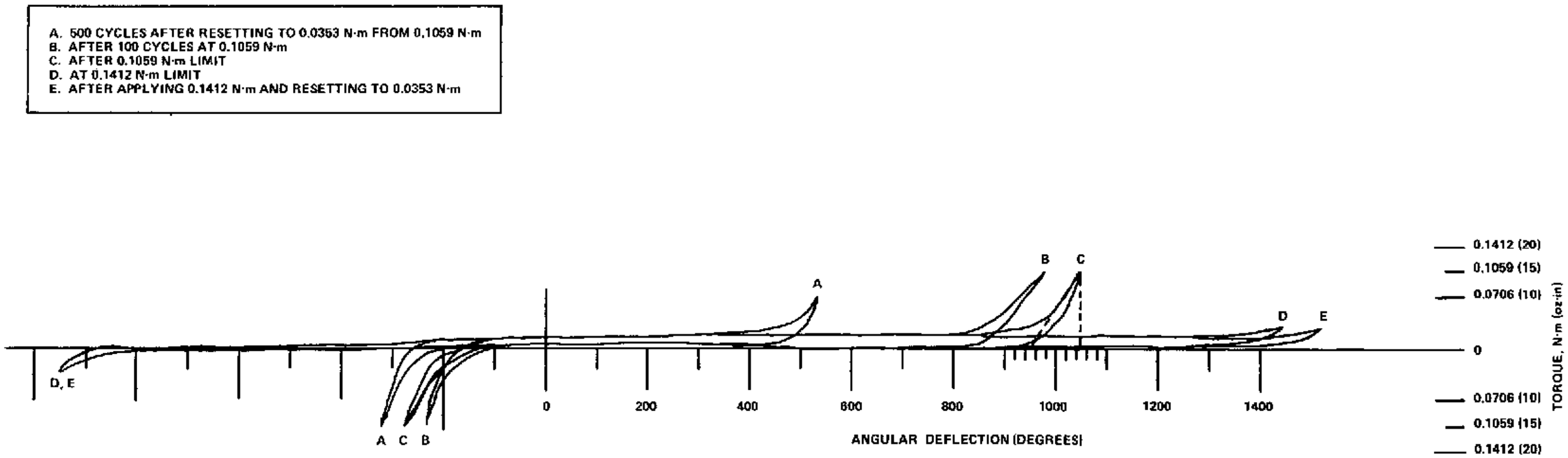


Figure 11. Hysteresis plots for torque limits of 0.0353, 0.1059, and 0.1412 N·m.

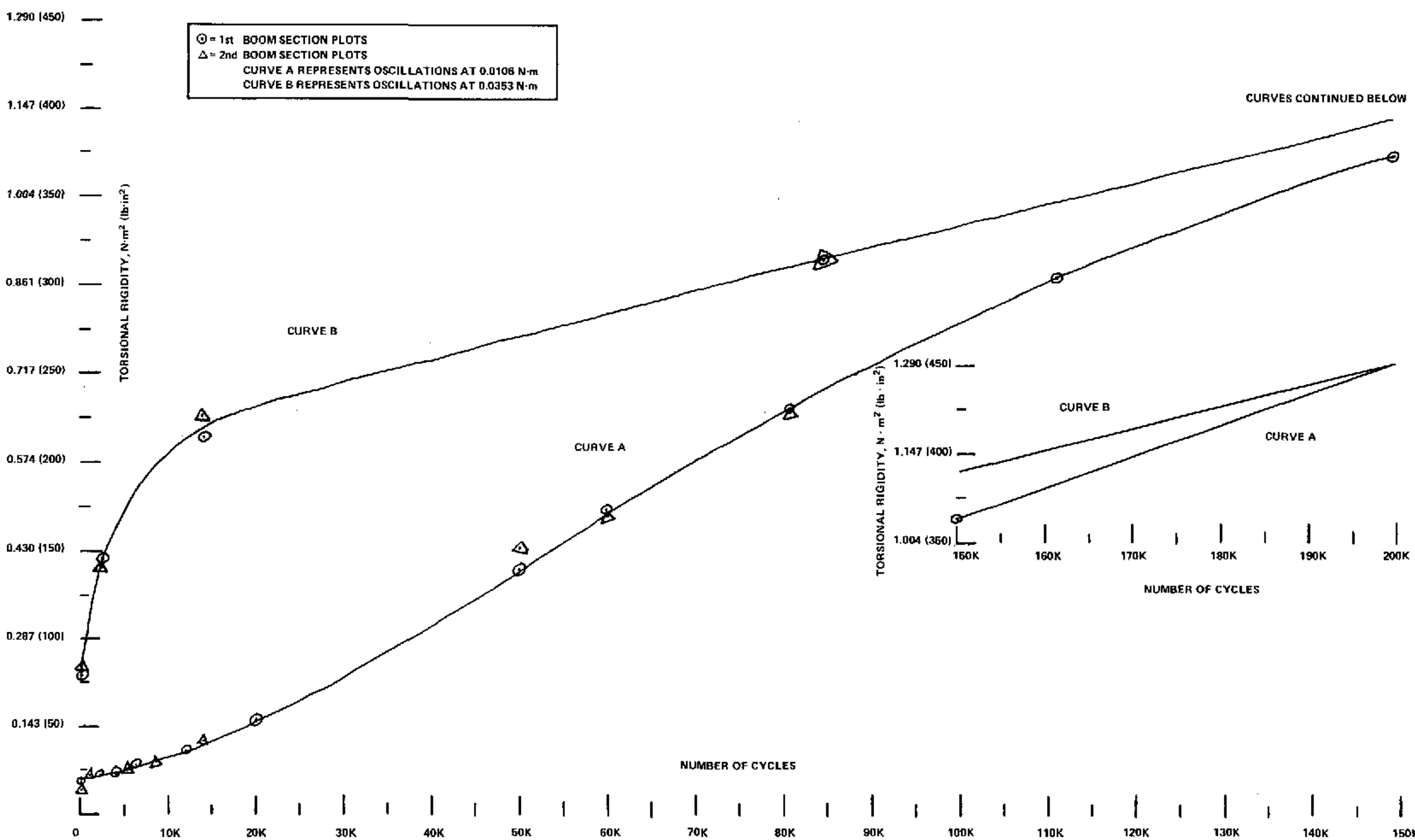


Figure 12. Torsional rigidity versus number of cycles of oscillation.

A thin-walled tube (without tabs) having the same dimensions would have a theoretical torsional rigidity of

$$
\begin{aligned}
C &= 2\pi t r^3 G \\
&= 6.28(.005\ \mathrm{cm})(0.635\ \mathrm{cm})^3\ (4.137 \times 10^{10}\ \mathrm{N/m^2}) \\
&= 3.32\ \mathrm{N \cdot m^2}
\end{aligned}
$$

where the shear modulus G is 4.137×10^{10} $\mathrm{N/m^2}$ (Reference 2).

Thus it appears that the torsional rigidity of this boom is less than that of a solid-walled tube by a factor of approximately 2.6, or

$$\frac{3.32\ \mathrm{N \cdot m^2}}{1.29\ \mathrm{N \cdot m^2}} \cong 2.6$$

Tests of New Section of Boom

The section of boom subjected to the initial tests was cut off and a new 5.867-m section was deployed. This section of boom was connected to the deflection device as shown in Figure 1. Nominal torque limits of 0.0106 N·m were set by the controls and this section of boom was oscillated 150,000 cycles between these set limits. Figures 13 and 14 show the hysteresis plots made at the initial and subsequent cycles.

The initial cycle (Figure 13) shows an angular deflection of approximately 200° in each direction. Comparing this result with the initial cycle of the first section tested, it was found that the angular deflections of each boom section differed prior to reaching the torque limits. Tip spring rates and resulting torsional rigidities of the two boom sections differed somewhat until the 12,000th cycle of oscillation was reached. However, it can be seen from study of Figures 13 and 14 that the torsional characteristics of both sections of boom appear to be the same from the 12,000th cycle on.

Figure 15 shows hysteresis plots made periodically while cycling the boom between 0.0353 N·m limits. These plots, as anticipated, are similar to those made while cycling the first section of boom at 0.0353 N·m (Figure 10).

Comparison of Tests on Each Boom Section

A comparison was made of torsional rigidities of the two boom sections after they had been subjected to the same number of cycles of oscillation between the same set limits. Figures 2, 3, 13, and 14 give hysteresis plots of each section of boom when oscillated between 0.0106 N·m limits; whereas Figures 10 and 15 give plots of each section when oscillated between 0.0353 N·m limits.

Slopes of the plots made at each significant cycle are shown by dotted lines. The tip spring rates and torsional rigidities were determined from these slopes. The results of these calculations are shown in Table 1 for various numbers of cycles that boom sections were oscillated.

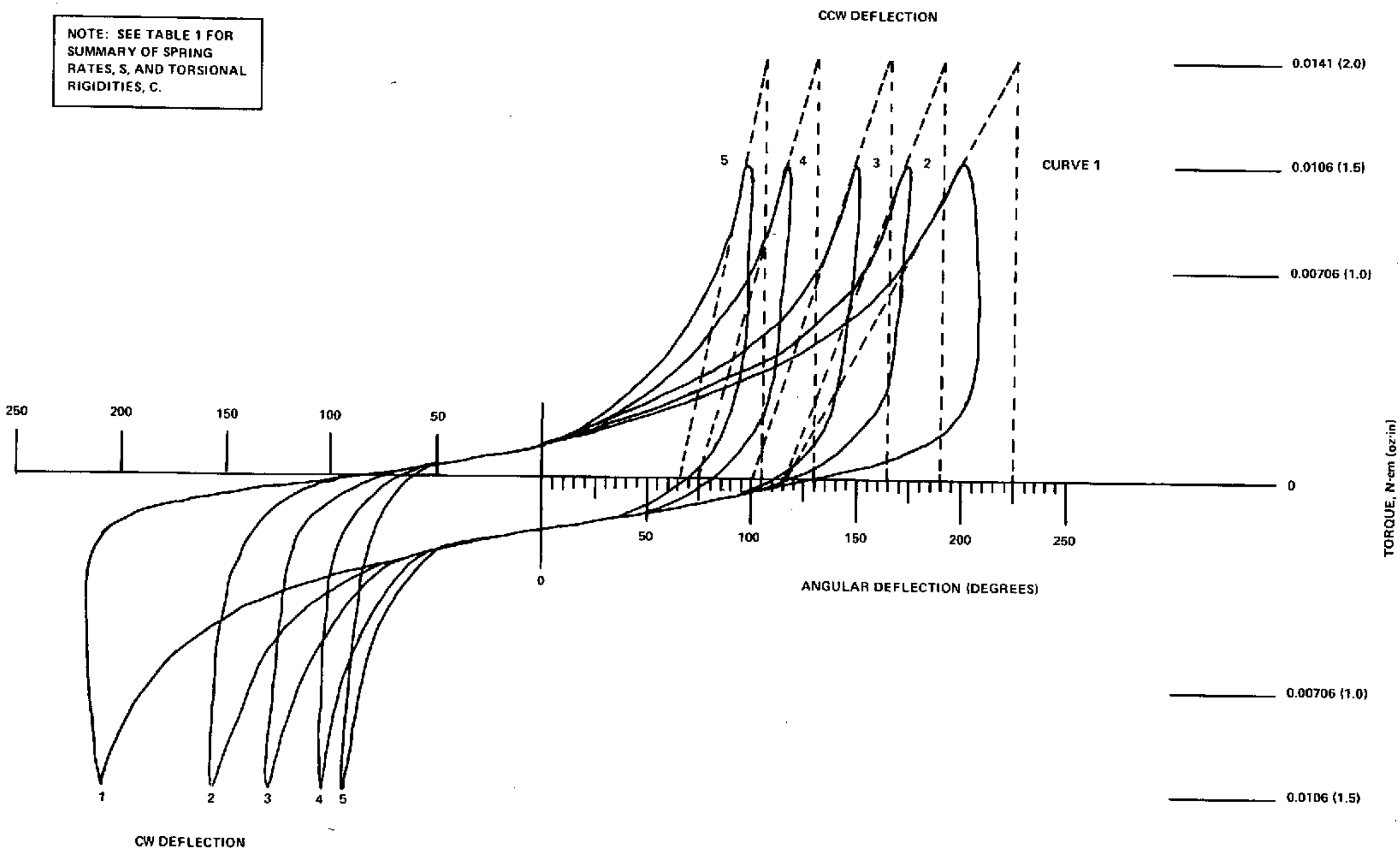
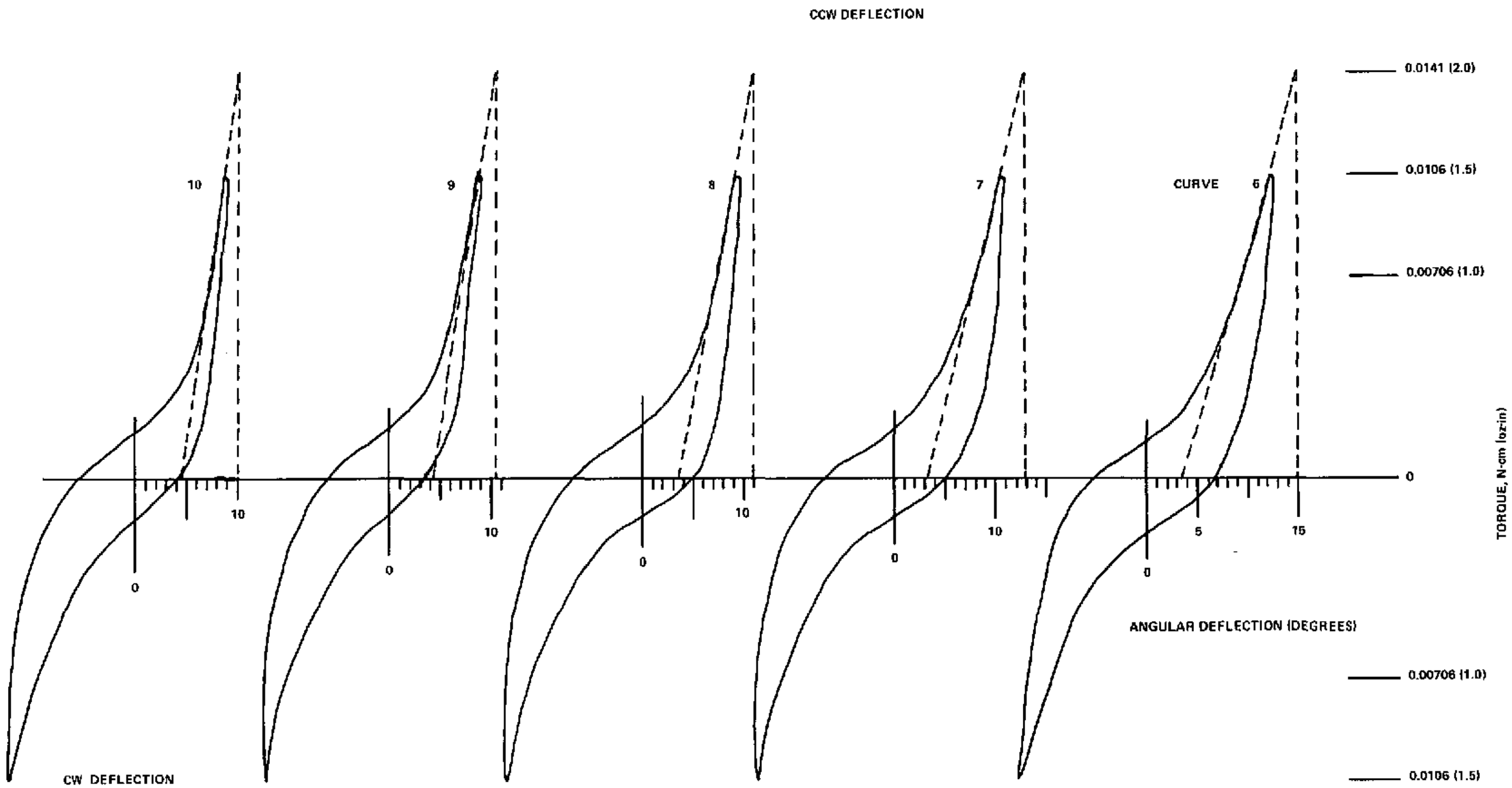


Figure 13. Hysteresis curve samples 1 through 5 on second section of boom.



NOTE: SEE TABLE 1 FOR SUMMARY OF SPRING RATES, S, AND TORSIONAL RIGIDITIES, C.

Figure 14. Hysteresis curve samples 6 through 10 on second section of boom.

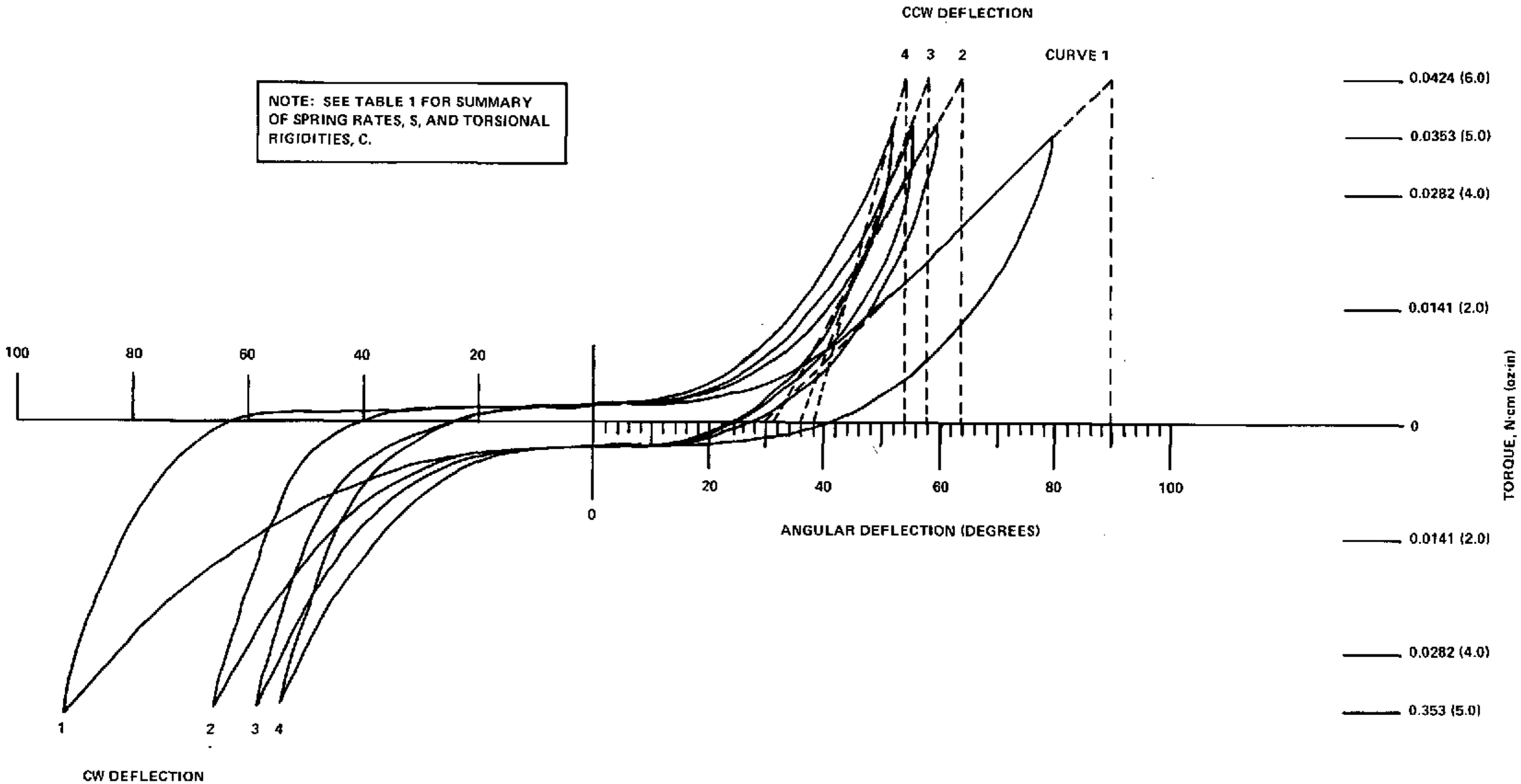


Figure 15. Hysteresis plots for 0.0353 N·m torque limits, second section of boom.

Table 1
Calculated Values of Tip Spring Rate, S, and Torsional Rigidity, C.
(Values of S are in N·m/deg; C is in N·m^2)

Torque Limits of 0.0106 N·m				
Data of Figures 2 and 3			Data of Figures 13 and 14	
First Boom Section		Curve No.	Second Boom Section	Curve No.
Cycles	1	1	1	1
S	1.658×10^{-4}		1.278×10^{-4}	
C	0.0557		0.0429	
Cycles	1000	2	1200	2
S	1.878×10^{-4}		2.012×10^{-4}	
C	0.06313		0.0676	
Cycles	2000	3		
S	1.906×10^{-4}		—	
C	0.0641			
Cycles	4000	4		
S	2.012×10^{-4}		—	
C	0.0676			
Cycles	6000	5	6000	3
S	2.330×10^{-4}		2.168×10^{-4}	
C	0.0783		0.07287	
Cycles	—		8500	4
S			2.563×10^{-4}	
C	—		0.08616	
Cycles	12,000	6	14,000	5
S	3.531×10^{-4}		3.714×10^{-4}	
C	0.1187		0.1248	
Cycles	20,000	7		
S	4.554×10^{-4}		—	
C	0.1531			
Cycles	50,000	8	50,000	6
S	1.228×10^{-3}		1.228×10^{-3}	
C	0.4130		0.4130	
Cycles	60,000	9	60,000	7
S	1.455×10^{-3}		1.440×10^{-3}	
C	0.4890		0.4843	

Table 1 (cont.)

Torque Limits of 0.0106 N·m				
Data of Figures 2 and 3			Data of Figures 13 and 14	
First Boom Section		Curve No.	Second Boom Section	Curve No.
Cycles	81,000	10	81,000	8
S	1.935×10^{-3}		1.878×10^{-3}	
C	0.6504		0.6314	
Cycles	111,500	11	111,500	9
S	2.570×10^{-3}		2.570×10^{-3}	
C	0.8641		0.8641	
Cycles	150,000	12	150,000	10
S	3.142×10^{-3}		3.142×10^{-3}	
C	1.056		1.056	
Torque Limits of 0.0353 N·m				
Data of Figure 10			Data of Figure 15	
First Boom Section		Curve No.	Second Boom Section	Curve No.
Cycles	1	1	1	1
S	6.616×10^{-4}		7.0612×10^{-4}	
C	0.222		0.2374	
Cycles	1,250	2	1,250	2
S	1.278×10^{-3}		1.207×10^{-3}	
C	0.4296		0.4059	
Cycles	14,000	3	14,000	3
S	1.843×10^{-3}		1.921×10^{-3}	
C	0.6195		0.6456	
Cycles	85,000	4	85,000	4
S	2.648×10^{-3}		2.647×10^{-3}	
C	0.8902		0.8902	

OBSERVATIONS

- As the interlocked, tabbed bi-stem booms are oscillated, their dead spaces decrease and their torsional rigidities increase.
- All booms tested in this report consistently retain the torsional rigidity developed through oscillations even after retraction and redeployment.
- The torsional rigidity of the boom sections tested appears to be a function of cycle number and applied torque level. For example, a torsional rigidity of 0.717 N·m^2 was reached after oscillating a boom section 90,000 times with an applied torque of 0.0106 N·m (Figure 12). However, the same torsional rigidity was reached after oscillating a similar section of boom only 30,000 times with an applied torque of 0.0353 N·m.
- A stable value of torsional rigidity cannot be established until the boom has been subjected to many cycles of torsional oscillation. Before reaching a fixed torsional rigidity value for a particular boom, rigidity is a strong function of the number of cycles of oscillation and applied torque.

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Greenbelt, Maryland December 8, 1972
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