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TECHNICAL NOTE 2821

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By J. W. Clark and R. L. Moore

Aluminum Company of America

Washington
November 1952

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TORSION TESTS OF ALUMINUM-ALLOY STIFFENED CIRCULAR CYLINDERS

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SUMMARY

Results are presented for the second series of torsion tests on aluminum-alloy stiffened circular cylinders, the first series having been reported in NACA ARR 4E31. The cylinders were similar in construction except that the wall thickness was 0.020 inch for the first series and 0.032 inch for the second series.

The significant observations from both series of tests are summarized and some comparisons are made with more recent theoretical work. In general, the mean observed shear-buckling strengths of the curved sheet panels agreed well with those indicated by the theoretical solution of NACA TN's 1344 and 1348. An empirical equation is presented showing the relation observed between average compressive stresses in the longitudinal stiffeners and torques in the tension-field range. Some analysis of longitudinal-stiffener failures is also included.

INTRODUCTION

A study of the strength characteristics of aluminum-alloy 24S-T3 stiffened circular cylinders loaded in torsion was begun at Aluminum Research Laboratories during World War II. These tests were conducted in two series. The results of the first series of tests, made on cylinders 30 inches in diameter and having a nominal wall thickness of 0.020 inch, were reported in 1944 (reference 1). The results of the second series, made on cylinders similar in construction to those of the first group except that the wall thickness was nominally 0.032 inch, are given herein. The present report summarizes the significant observations made from both series of tests and includes some comparisons with more recent theoretical work (references 2, 3, and 4).

The object of this investigation was to obtain information on the shear-buckling resistance and tension-field behavior of aluminum-alloy stiffened circular cylinders loaded in torsion.

This work was done by the Aluminum Company of America and has been made available to the National Advisory Committee for Aeronautics for publication because of its general interest.

Specimens

The specimens for these tests were circular cylinders, formed of 0.032- by 36- by 96-inch 24S-T3 sheet. The mean diameter was 30.08 inches and the over-all length, 36 inches. Figure 1 gives the essential structural details. The ring stiffeners were made of 1/2- by 1/2-inch 24S-T4 square bars, shaped cold to approximate size in forming rolls. After forming, the rings were spliced and machined to obtain the required diameter. The longitudinal stiffeners were formed of 0.032-inch 24S-T3 sheet. Figure 1 shows the nominal dimensions. One of these stiffeners was used at the longitudinal seam of all specimens in order to prevent the waviness which might otherwise occur in a long thin lap joint having a large number of closely spaced rivets. The end bulkhead rings were made from 3/8-inch-thick steel plates.

Twelve cylinders were tested. Four of the specimens had no longitudinal stiffeners except for the one at the lap joint in the sheet. Four other specimens were fitted with eight equally spaced longitudinal stiffeners and four were fitted with sixteen equally spaced longitudinal stiffeners. The four cylinders of each group incorporated six different spacings of ring stiffeners so that a total of eighteen different sizes of curved sheet panels were studied. The stiffener spacings, the average measured sheet thicknesses, and the specimen number designations are shown in table I and also in the sketches in figures 17, 18, and 19. Photographs of the specimens, taken after failure, are shown in figures 2 to 13.

PROCEDURE

Method of Loading

Figures 14 and 15 show the loading fixture in which the torsion tests were made. This equipment consisted of two similar structural steel frames having a depth of 3 feet and 6 inches at the center and an effective lever arm of 12 feet and 1/8 inch. One frame was held against rotation by anchoring it to the floor by means of bolts used in floor inserts; the other was rotated by means of loading screws so arranged as to pull in opposite directions at the ends. Spherically seated nuts were provided at each end of both loading screws to accommodate the rotation of the frame.

The forces at the ends of the movable frame were determined by means of an aluminum-alloy dynamometer link having a capacity of 5000 pounds. This force, applied in opposite directions at the ends of the loading frame, provided a maximum torque capacity of about 60,000 foot-pounds. Calibration of the dynamometer indicated a linear relation between load and deflection throughout the entire working range (0.236-in. deflection for 5000-lb load). Deflections were estimated by means of a dial indicator to the nearest 0.0001 inch, corresponding to a torque of about 25 foot-pounds.

The application of torque required two operators, one at each of the loading screws. Since the center of rotation was not fixed, it was necessary to provide some means of keeping the two ends of the specimen in the same relative position, otherwise some transverse bending as well as torque might have been applied. Figure 16 shows the bar which was mounted on the longitudinal axis of the specimen to serve as a reference for maintaining the proper position relative to the floor. By keeping a dial indicator at the rotating end in a position where it could be viewed by one loading-screw operator during the application of torque, it was possible to keep the vertical position of the center of rotation constant within 0.001 or 0.002 inch. Readings were taken at intervals at the fixed end of the specimen until it was demonstrated that for practical purposes these movements were negligible.

Although torque was applied in increments in all tests, it was generally not practical to attempt to apply definite predetermined values. The zero reading for each case was obtained with the specimen suspended loosely between the loading frames in order to eliminate accidental and unknown clamping torques. After the specimen was bolted in place, the loading arm was rotated until a dynamometer reading approximately equal to that desired was obtained, after which a final adjustment for cylinder position was made.

When buckling torques were being determined, it was necessary to watch the dynamometer deflection readings closely in order to catch the maximum values, since the torques fell off as soon as buckling occurred. It was generally not possible from visual observation to predict when this buckling would occur. In the specimens having ring stiffeners only,[1] an increase in the angle of twist after buckling resulted only in a further decrease in torque. If the angle of twist was returned to zero, however, a torque reading approximately equal to the initial buckling value was obtained when the sheet snapped back to its original curved form. In specimens having 8 or 16 longitudinal stiffeners in addition

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[1]The longitudinal stiffener used at the seam in all specimens was not considered effective in increasing shear-buckling resistance.

to ring stiffeners, this sudden buckling action and subsequent falling off of the torque occurred repeatedly until all panels were buckled.

All of the specimens with longitudinal stiffeners, except cylinders 11 and 12, were loaded more than once, the first loading being carried only far enough to cause buckling of the least stable panels. This load generally did not cause buckling of all panels, even for the cylinders whose panels were all of the same size. Critical loads for the stiffer panels were determined in subsequent loadings. The cylinders having 8 or 16 longitudinal stiffeners were finally loaded to ultimate failure, or, as was the case with specimen 12, until the load capacity of the testing apparatus was reached.

Measurements

In addition to visual observations of the behavior of the cylinders and the determination of buckling and ultimate torques, measurements were made of over-all twist and of strains in the sheet and longitudinal stiffeners.

The twists were determined by means of a 10-inch level bar, used in the manner indicated in figure 16. This instrument, equipped with a 45-second bubble and a micrometer screw graduated in 0.001-inch intervals, was sensitive to changes in slope of about 1 part in 50,000. The reference bars for these measurements, which also served to support the reference used for maintaining vertical position, were located on the inside face of the end bulkheads. The effective length of specimen was assumed to be $35\frac{5}{8}$ inches, or the distance between bulkhead centers.

Strains in the sheet were measured by means of Baldwin-Southwark SR-4 type R-1 wire-resistance strain rosettes. Measurements of average compressive strain in the longitudinal stiffeners were made by means of a 10-inch Whittemore strain gage.

Results and Discussion

Torque-twist curves for the various specimens are plotted in figures 17, 18, and 19. Although in some cases different portions of these curves were determined from different loading cycles, the torque-twist relationships obtained in the final loading did not appear to be materially affected by the previous loadings.

The torque-twist curves in figures 18 and 19 for the cylinders with more than one longitudinal stiffener indicate four distinct stages in

the behavior of the cylinders: (1) The range of shear-resistant action before buckling, in which the relation between torque and twist is linear; (2) the buckling range, where there is a marked decrease in torsional stiffness until the sheet is stretched to the point where it is capable of transmitting shear by diagonal tension; (3) the tension-field range in which the shear is carried principally by tension in the sheet and an approximately linear relation between torque and twist is again obtained; and (4) ultimate failure, which, for these cylinders, occurred by collapse of the longitudinal stiffeners.

Action before Buckling

The straight-line portions of the torque-twist curves before buckling show good agreement with calculated values, also shown in figures 17, 18, and 19, based on the formula

$$\theta = \frac{48TL}{\pi D^3 Gt} \tag{1}$$

where

θ over-all twist, radians

T torque, foot-pounds

L length, inches $\left(35\frac{5}{8}\right)$

D mean diameter, inches (30.08)

G modulus of elasticity in shear, psi (4,000,000)

t sheet thickness, inches

In cases where strains were measured in the sheet the corresponding stresses, based on a modulus of elasticity of 10,600,000 psi and a Poisson's ratio of 1/3, showed good agreement with the calculated average shear stresses determined by the following formula

$$\tau = \frac{24T}{\pi D^2 t} \tag{2}$$

where τ is average shear stress in pounds per square inch.

Buckling of Curved Panels

The torque-twist curves in figures 17, 18, and 19 show that fairly well defined ranges of buckling action were obtained in most cases. Since buckling did not occur simultaneously in all panels of the same dimensions, the buckling torque for each size of panel was taken to be the average of the torques for the individual panels. After the first buckling, some panels became unstable subsequently at lower values of torque. The critical torque for these panels was assumed to be the highest torque which they withstood without buckling.

The values of mean buckling torque and the corresponding calculated shear stresses for the various panel proportions are listed in table I. Also shown in the table are values obtained from the critical-shear-stress curves of Batdorf, Stein, and Schildcrout (references 2 and 3). In applying the theoretical solution, the panel dimensions were considered to be measured from the center lines of the stiffeners, and the edges were assumed to be hinged. With the exception of the smallest panel (6 by 5.9 in.) the theoretical buckling stresses are all within 10 percent of measured values. The calculated critical stress for the smallest panel was about 17 percent less than the measured value.

The agreement between theoretical and mean observed shear-buckling stresses is also shown in figure 20, in which the experimental values were adjusted as indicated to correspond to a nominal thickness of 0.032 inch. A similar comparison is shown in figure 21 for the test results on cylinders of 0.020-inch sheet, reported in reference 1. Except for the smallest panels, the agreement is close for these cylinders also.

Tension-Field Action

Shell stresses.- Measurements of strain in the sheet at torques appreciably above the buckling torque were made for only two of the cylinders, 2 and 12. These results followed the same general trend as those reported in reference 1. Maximum midplane tensile stresses in the sheet at the center of the panels, corresponding to torques just below the maximum test values, ranged from 1.9 to 3.4 times the calculated average shear stresses. The corresponding measured compressive stresses ranged from approximately zero to the calculated average shear stress at the buckling torque.

Longitudinal-stiffener stresses.- The measured stresses in the longitudinal stiffeners, plotted in figure 22, are of particular interest because all except two of the stiffened cylinders of this and the previous series failed by collapse of the longitudinal stiffeners. In order to

make comparisons between measured and computed values of longitudinal-stiffener stress, the results from this and the earlier series of tests (reference 1) were replotted in figure 23. Values are not shown in cases where the 10-inch gage length of the Whittemore strain gage extended over more than one size of panel, except for the 9-inch-long central panels of specimens 11 and 12.

The dashed lines in figure 23 represent stiffener stresses computed by the semiempirical method of Kuhn and Griffith (reference 4).[2] It will be noted that the measured stresses are generally higher than the computed values; in several instances the measured values are more than twice as high. These differences probably resulted from the fact that the proportions of the cylinders were different from those used in the tests on which the method in reference 4 was based. The primary difference is that the ratios of area of sheet to area of stiffeners in this investigation were considerably greater than those in the tests reported in reference 4.

The solid lines in figure 23 are values computed by means of an empirical formula which was found to give reasonable agreement with the measured stiffener stresses in these tests as well as those reported in reference 4. In the notation employed in reference 4, this formula is

$$\sigma_{ST} = \frac{ht}{A_{ST}}\left(\tau - \frac{h}{d}\tau_{cr}\right) \tag{3}$$

where

σ_{ST} average stress in longitudinal stiffener, psi

h spacing of longitudinal stiffeners, inches

d spacing of ring stiffeners, inches

A_{ST} cross-sectional area of longitudinal stiffener, square inches

t thickness of sheet, inches

τ average shear stress in sheet, psi

τ_{cr} shear-buckling stress for panels, psi

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[2]The curves computed by this method for cylinders 14, 15, 20, and 21 are merely replotted from reference 4.

The value of the ratio h/d in equation (3) is taken to be 0.8 if the actual ratio exceeds this value.

Figure 24 shows a comparison between the measured stiffener stresses reported in reference 4 and the computed values determined from equation (3), as well as by the method of Kuhn and Griffith (reference 4).

In view of the simplicity of equation (3) and its agreement with the available test results, it is believed that this expression for stiffener stress may have some application in the analysis of tension-field action in curved sheet panels.

Ultimate Torsional Strengths

The maximum torques for the various specimens and the average shear stresses at failure are listed in table II. Also given in the table are values of estimated average compressive stress in the longitudinal stiffeners at failure, obtained by extrapolating the curves of average measured stiffener stress to the maximum torque as shown in figure 22. For cylinders having two sizes of panels, the stress listed in table II is the larger of the two values indicated from the measurements. In each case the larger stress was measured at the central panel. Where all the panels of a cylinder were the same size the average stiffener stress at failure listed in table II is an average of the two values indicated by the measurements.

In the first series of tests (reference 1) it was found that the average stiffener stresses at failure agreed fairly closely with the maximum stresses developed by individual stiffener sections tested separately as flat-end columns, where the length of the separate stiffener sections was equal to the spacing of ring stiffeners on the cylinders.

Figure 25 shows that the maximum stresses developed in the stiffeners on a number of the cylinders in this second series of tests were also in agreement with the column strengths of individual stiffener sections. Where there were significant differences between these values, the stiffener strengths developed on the cylinders were higher.

In view of the agreement between the column strength of individual stiffener sections and the average stiffener stresses at failure of the cylinders, methods of calculating such column strengths are of interest. Figure 25 shows four possible calculated column curves, based on the following assumptions: (a) The stringer fails as an axially loaded flat-end column, free to twist about the shear center, (b) the stringer fails as an axially loaded simply supported column, forced by the sheet to

twist about an axis through the line of attachment between the stiffener and the sheet, (c) the stringer fails as an axially loaded flat-end column, forced by the sheet to twist about an axis through the line of attachment between the stiffener and the sheet, and (d) the stringer fails as an Euler flat-end column by bending about axis x-x as shown in figure 25. Failure in either case (a), (b), or (c) is by lateral torsional buckling and the critical loads may be calculated by the methods given in reference 5. The cross-section properties and dimensions used were the average measured values taken from reference 1 and shown in figure 25. The calculated column-strength curve for case (d) was extended into the plastic stress range by means of the straight-line formula (reference 6). Curves for cases (a), (b), and (c) were extended into the plastic stress range by straight lines drawn from the same intercept on the axis at $L = 0$ to points of tangency on the elastic buckling curves.

The assumptions on which curve (a) is based represent the test conditions for the stiffeners loaded separately as flat-end columns. The curve gives reasonable agreement with those test results. The assumptions for curve (b), which falls very close to curve (a), are probably more nearly representative of the conditions of support for the stiffeners on the cylinders. Five of the nine test values of ultimate stress for stiffeners on the cylinders are within 18 percent of strengths indicated by curve (b). The other four test values were appreciably higher than curve (b).

SUMMARY OF RESULTS

The torsion tests of aluminum-alloy stiffened circular cylinders described in this report comprise the second of two series of such tests, the first series having been reported in NACA ARR 4E31. The following summarization is based on an analysis of both series of tests:

1. In general, the mean observed shear-buckling strengths of the curved sheet panels agreed well with those indicated by the theoretical solution of Batdorf, Stein, and Schildcrout (NACA TN's 1344 and 1348), assuming hinged edges and taking the panel dimensions to be the distances between center lines of stiffeners.

2. The average compressive stresses measured in the longitudinal stiffeners, in the tension-field range, showed reasonably good agreement with those computed by an empirical straight-line relationship.

3. All of the cylinders having a wall thickness of 0.032 inch and 8 or 16 longitudinal stiffeners failed by collapse of these stiffeners

with the exception of cylinder 12, for which the ultimate strength exceeded the capacity of the testing apparatus. Three of the four cylinders having a wall thickness of 0.020 inch, and developing tension-field action, also failed in this manner.

4. In five of nine cases the average longitudinal-stiffener stresses at failure were within 18 percent of compressive strengths calculated for individual stiffeners, assuming that the stiffeners were simply supported at the rings and failed by twisting about the line of attachment between the stiffener and the sheet. In the other four cases the test results were appreciably higher than those computed on the basis indicated.

Aluminum Research Laboratories
Aluminum Company of America
New Kensington, Pa., October 16, 1951

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6. Templin, R. L., Sturm, R. G., Hartmann, E. C., and Holt, M.: Column Strength of Various Aluminum Alloys. Tech. Paper No. 1, Aluminum Res. Lab., Aluminum Co. of Am., 1938.

TABLE I

COMPARISON OF OBSERVED AND COMPUTED SHEAR-BUCKLING

STRESSES FOR 24S-T3 CURVED SHEET PANELS

Specimen	Sheet thickness (in.)	Stiffener spacing (in.)		Mean observed buckling torque (ft-lb)	Corresponding average shear stress (psi)	Theoretical buckling stress[1] (psi)	Ratio of theoretical to observed shear-buckling stresses
		Ring	Longitudinal				
Ring stiffeners only							
1	0.0325	35.6	-----	9,650	2510	2420	0.96
4	.0325	16	-----	14,050	3650	3640	1.00
7	.0325	12	-----	16,550	4300	4190	.97
7	.0325	10	-----	17,200	4470	4550	1.02
10	.0325	9	-----	17,950	4660	4870	1.05
10	.0325	6	-----	21,950	5710	6110	1.07
Eight longitudinal stiffeners							
2	0.032	32	11.81	13,100	3460	3200	0.92
5	.0325	16	11.81	15,900	4130	3970	.96
8	.033	12	11.81	18,200	4660	4730	1.02
8	.033	10	11.81	19,800	5060	5290	1.04
11	.0325	9	11.81	19,850	5160	5370	1.04
11	.0325	6	11.81	23,500	6110	6690	1.09
Sixteen longitudinal stiffeners							
3	0.032	32	5.90	17,900	4720	4700	1.00
6	.033	16	5.90	23,600	6040	5610	.93
9	.0315	12	5.90	21,800	5840	5660	.97
9	.0315	10	5.90	24,650	6600	5950	.90
12	.0325	9	5.90	27,500	7150	6480	.91
12	.0325	6	5.90	36,050	9370	7790	.83

[1]According to references 2 and 3.

TABLE II

TORSIONAL STRENGTHS OF 24S-T3 CYLINDERS HAVING BOTH RING AND LONGITUDINAL STIFFENERS

Specimen	Sheet thickness (in.)	Number of longitudinal stiffeners	Ring-stiffener spacing for central panels (in.)	Maximum torque (ft-lb)	Stresses at maximum torque (psi)	
					Average shear	Average compression in longitudinals
2	0.032	8	32	17,200	4,500	23,000
5	.0325	8	16	27,700	7,200	26,000
8	.033	8	12	34,000	8,700	41,000
11	.0325	8	9	40,000	10,400	36,000
3	.032	16	32	18,800	5,000	(a)
6	.033	16	16	44,200	11,300	17,000
9	.0315	16	12	53,600	14,400	31,500
12	.0325	16	9	[b]57,600	15,000	31,000

[a]Collapse of stiffeners occurred shortly after sheet buckled so that strain readings were not obtained above buckling load.

[b]Specimen did not fail. All other specimens failed by collapse of longitudinal stiffeners.

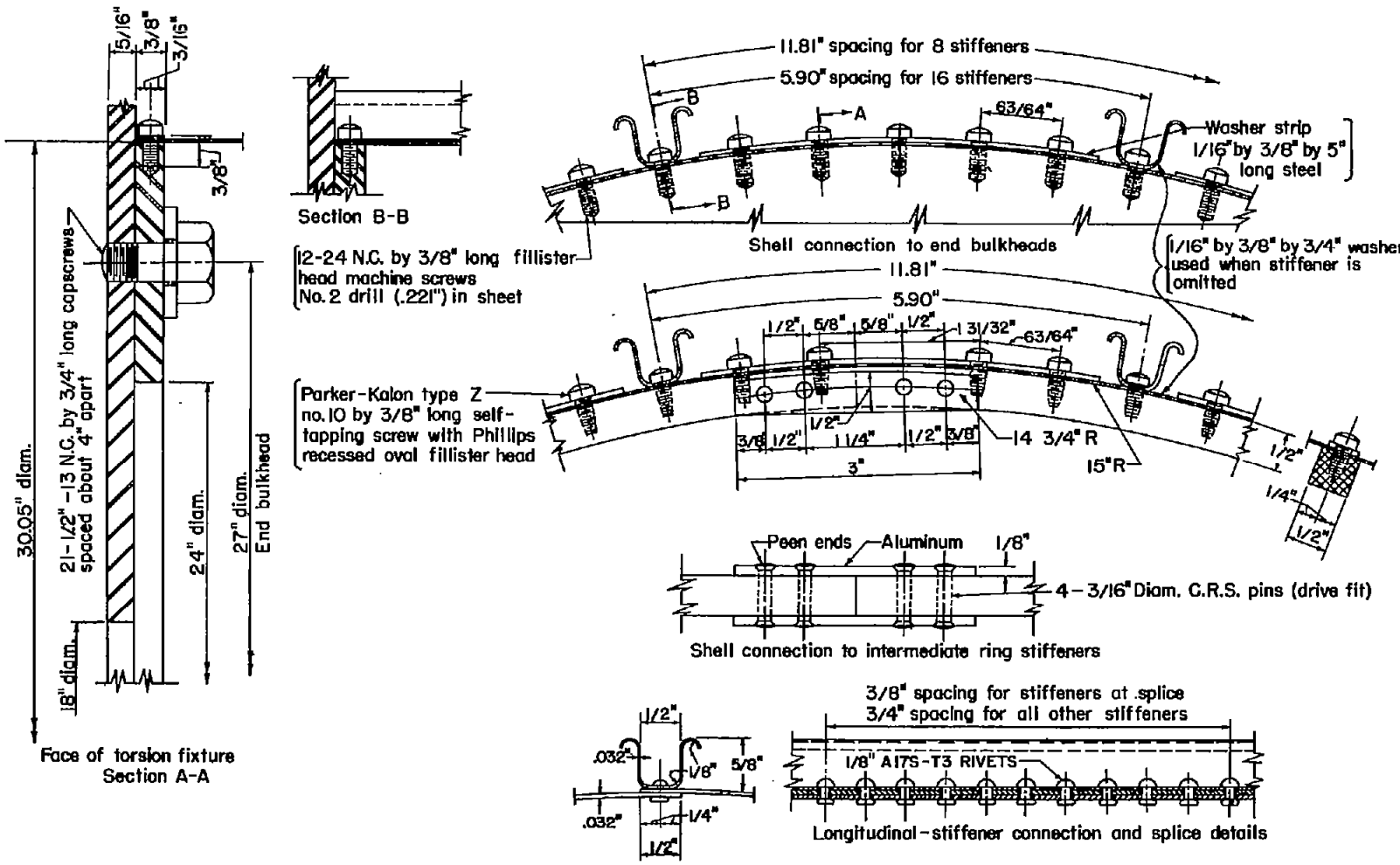


Figure 1.- Details of stiffened circular cylinders for torsion tests.

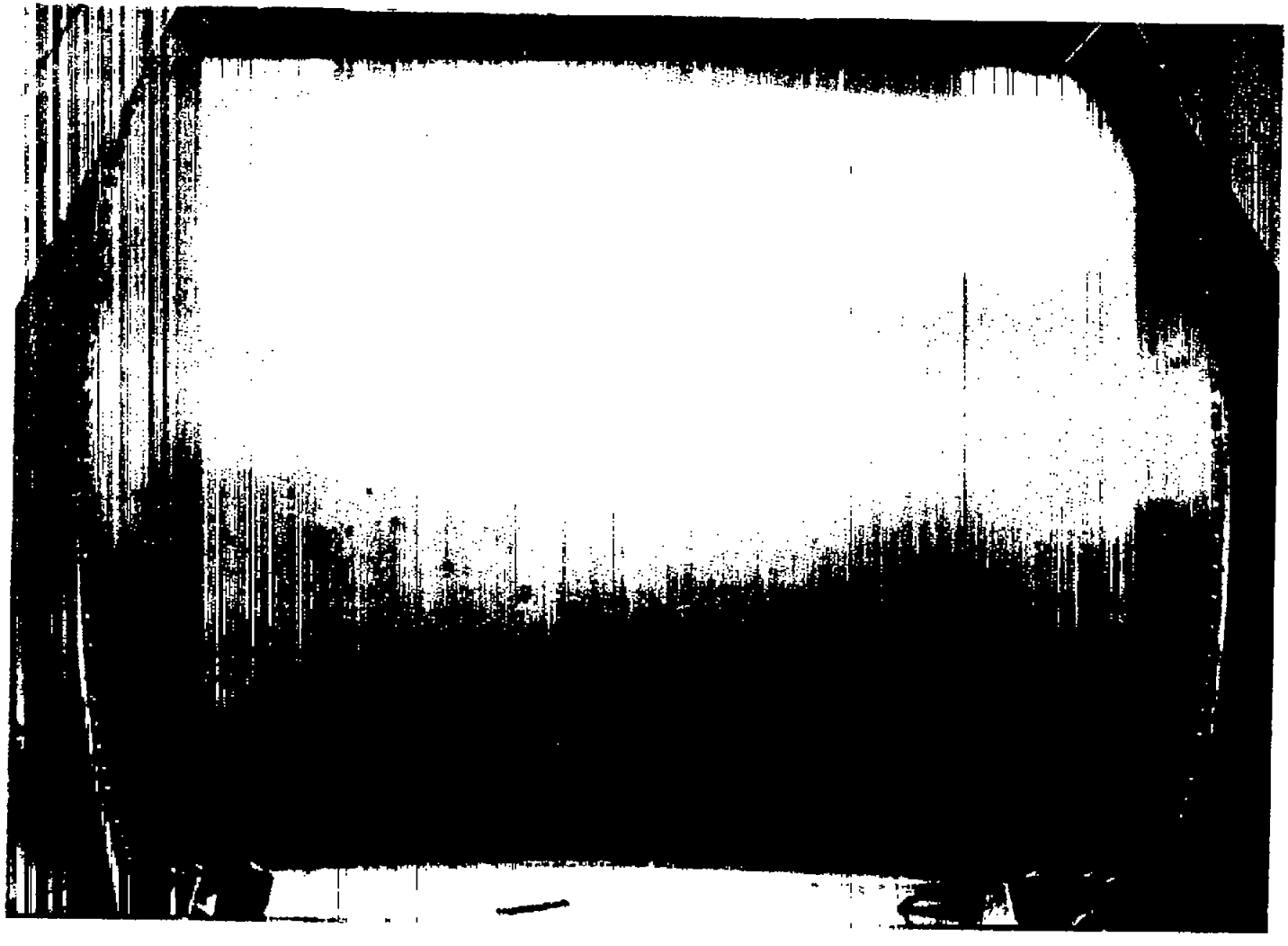


Figure 2.- Specimen 1 after failure.

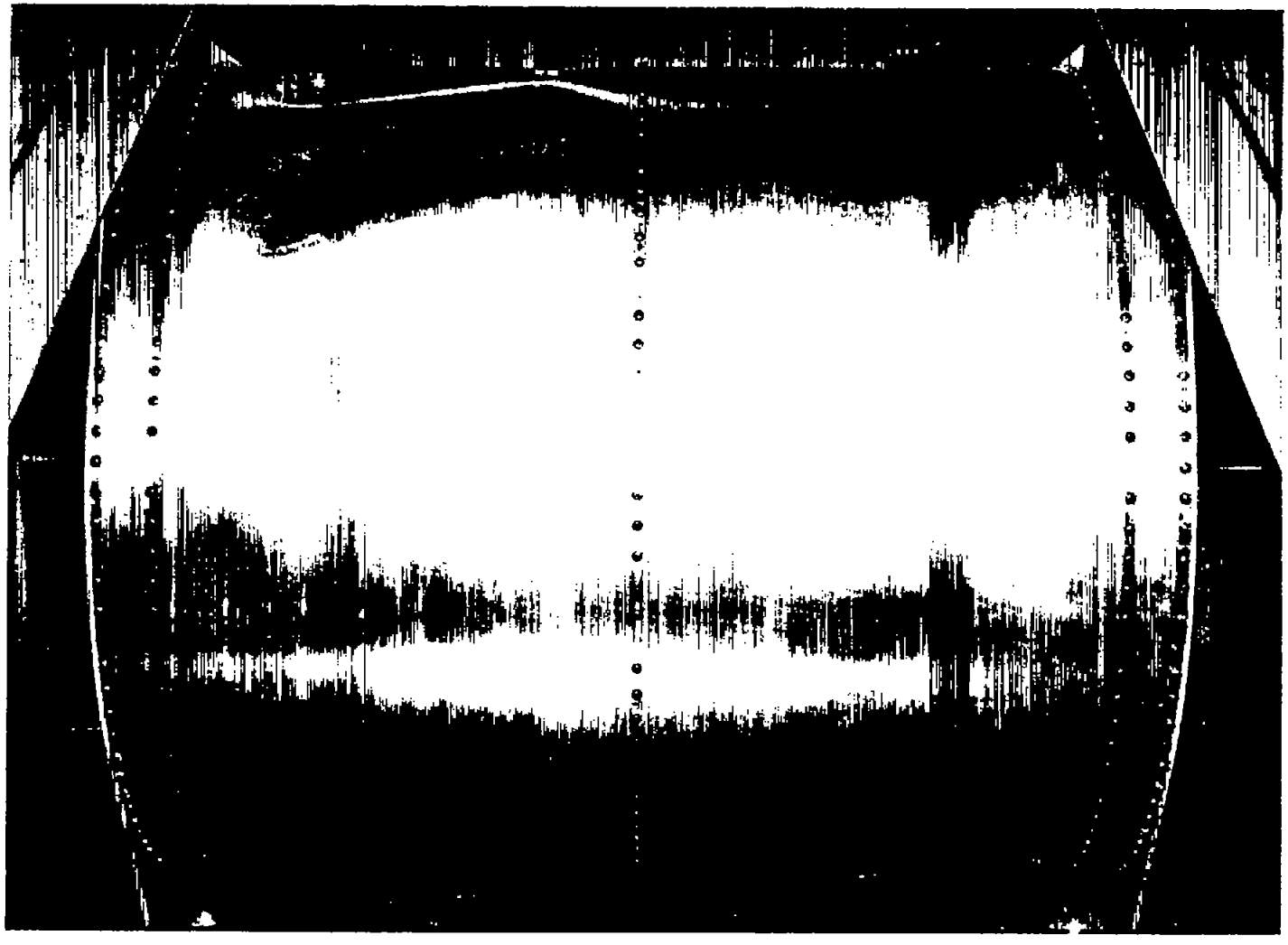


Figure 3.- Specimen 4 after failure.

Figure 4.- Specimen 7 after failure.

Figure 5.- Specimen 10 after failure.

Figure 5.- Specimen 10 after failure.

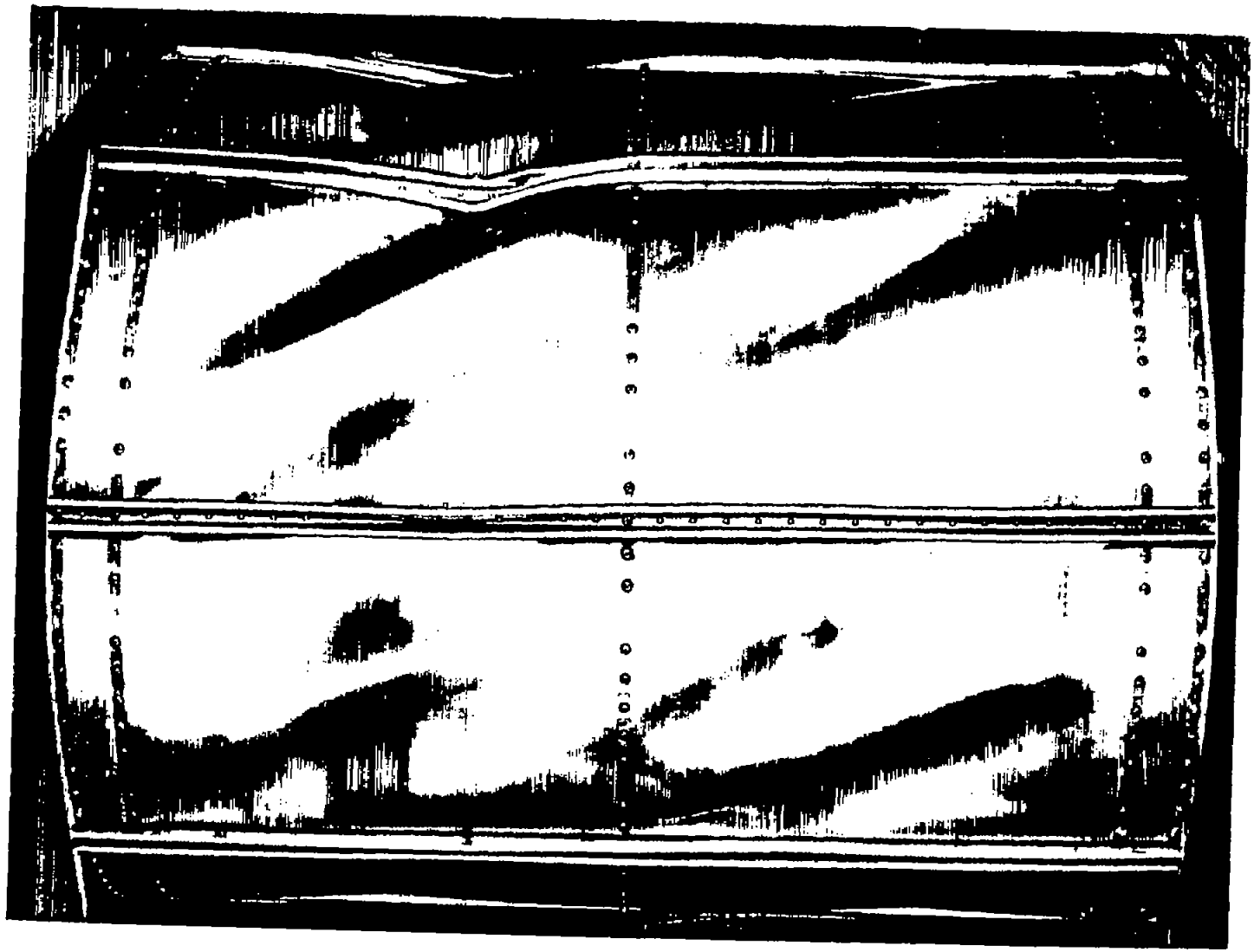


Figure 7.- Specimen 5 after failure.

Figure 8.- Specimen 8 after failure.

Figure 9.- Specimen 11 after failure.

Figure 9.- Specimen 11 after failure.

Figure 11.- Specimen 6 after failure.

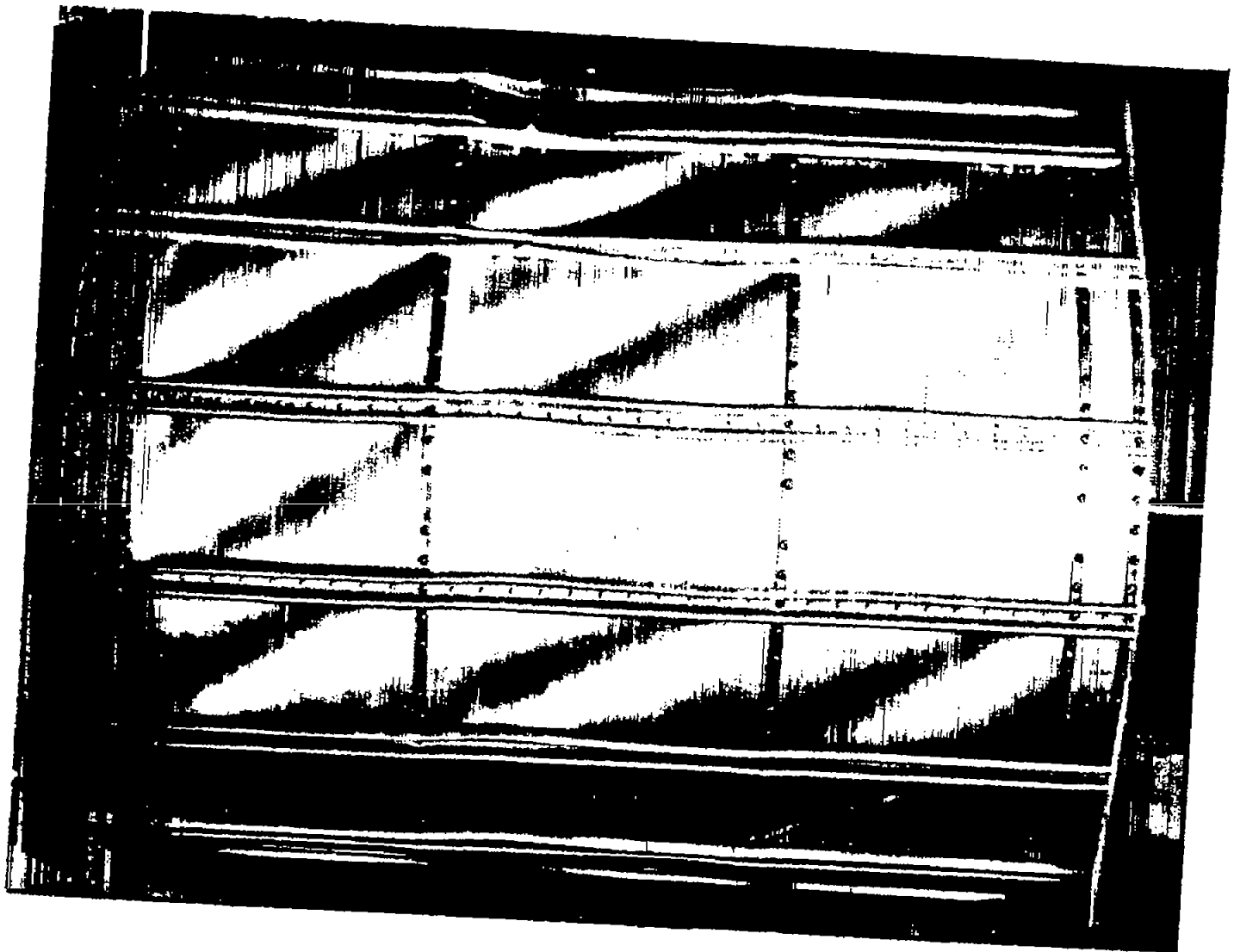


Figure 12.- Specimen 9 after failure.

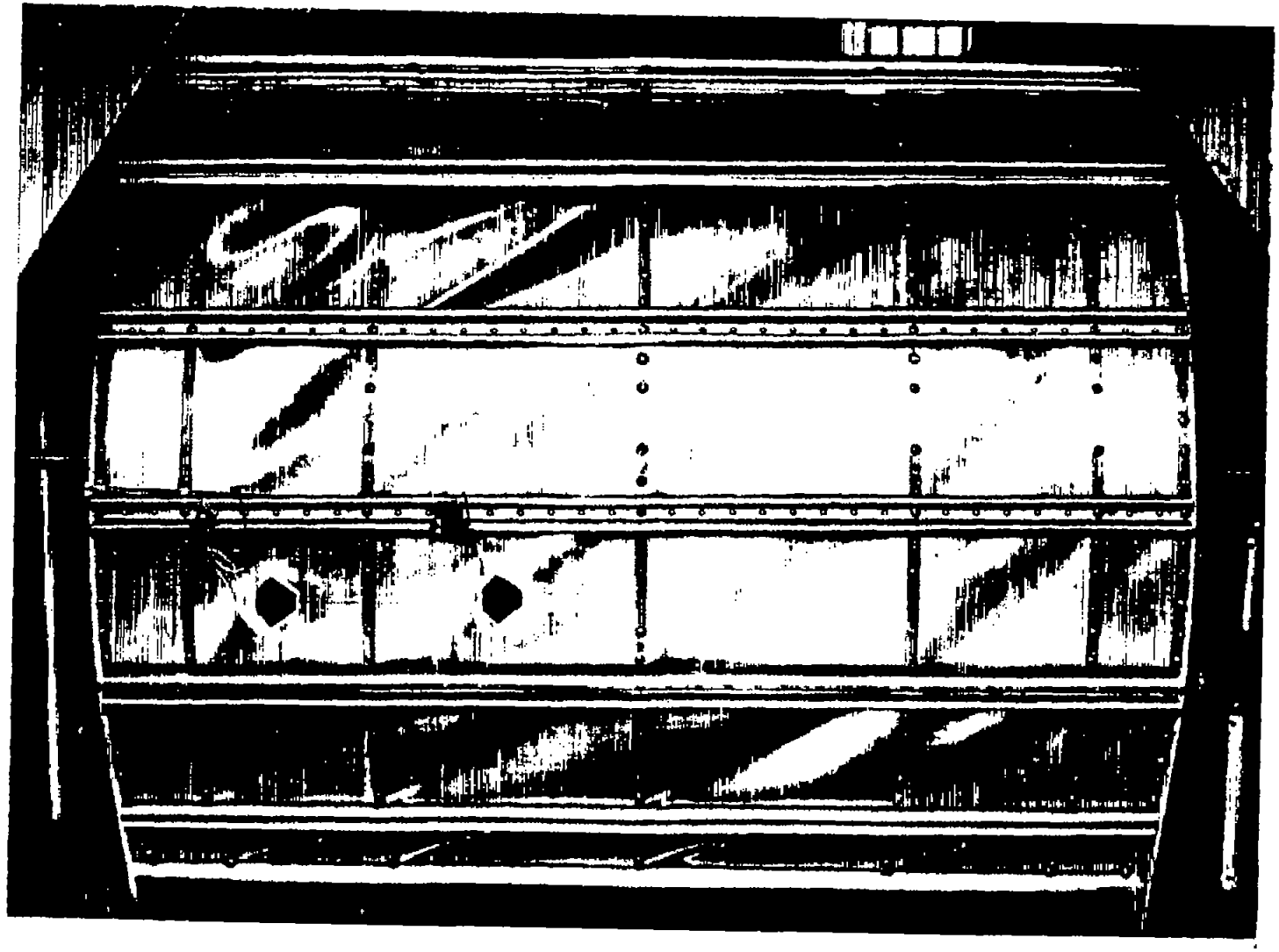


Figure 13.- Specimen 12 after failure.

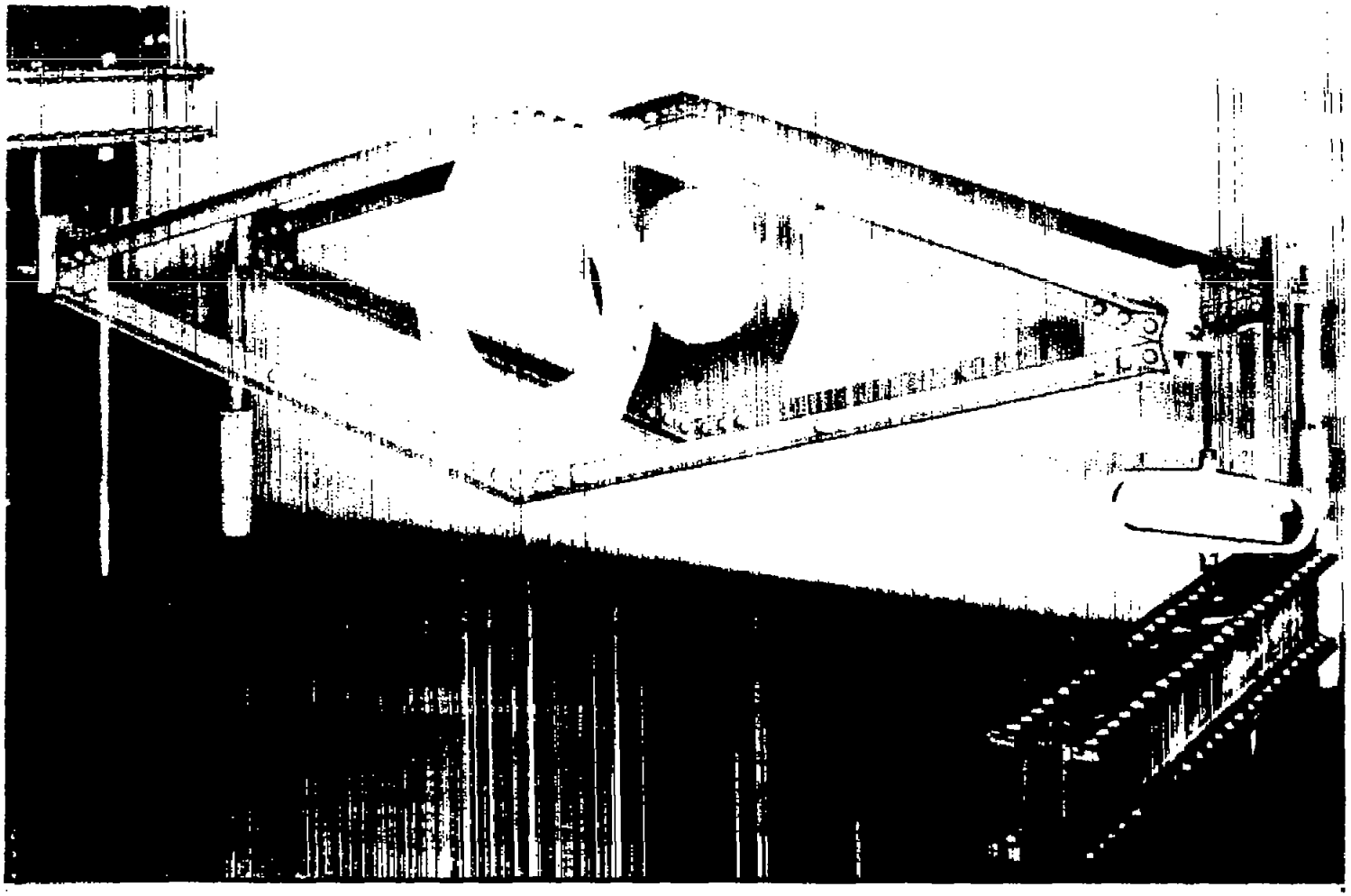


Figure 14.- Torsion loading fixture having a capacity of 60,000 foot-pounds.

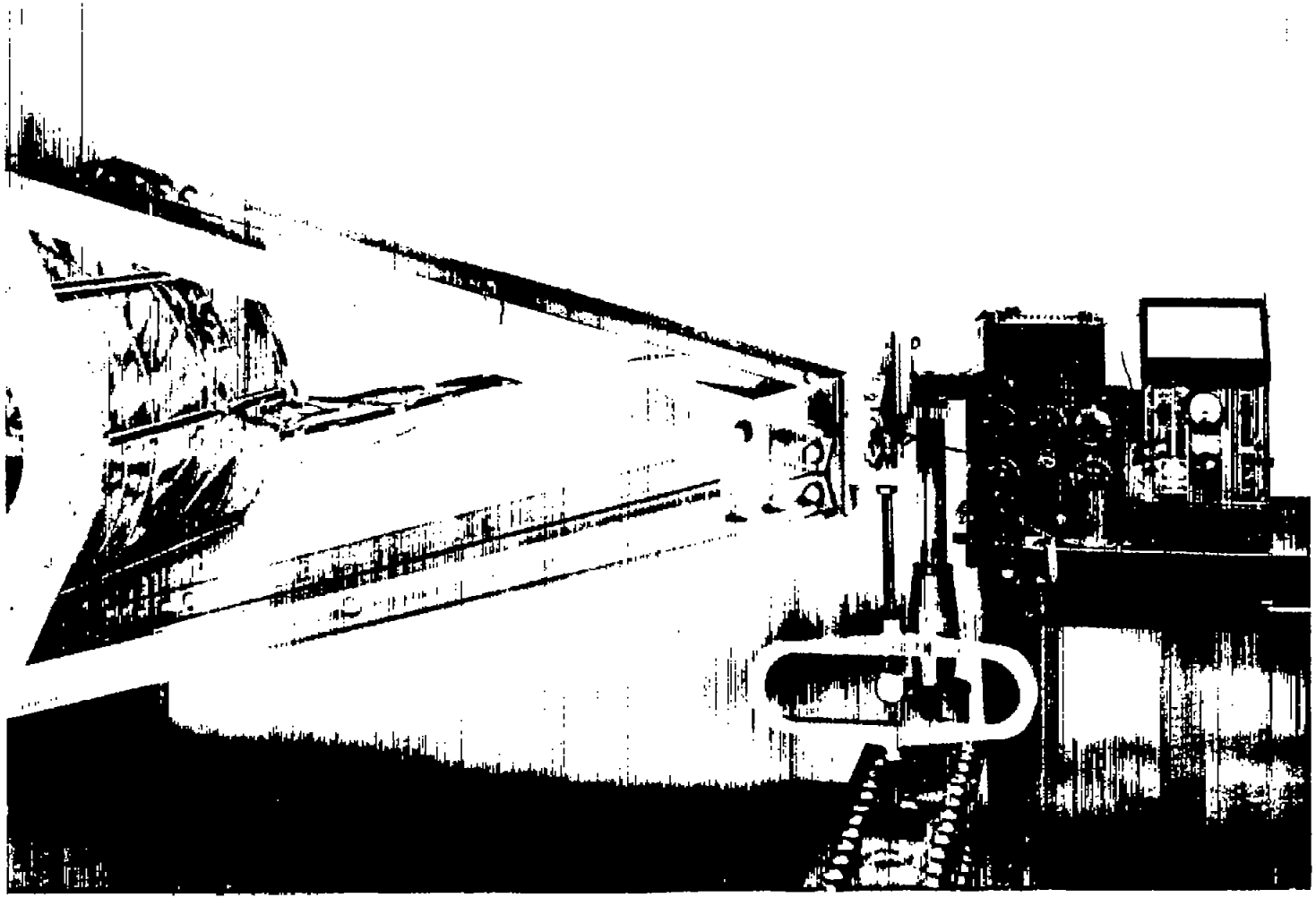


Figure 15.- Load and strain measuring apparatus for torsion tests of cylinders.

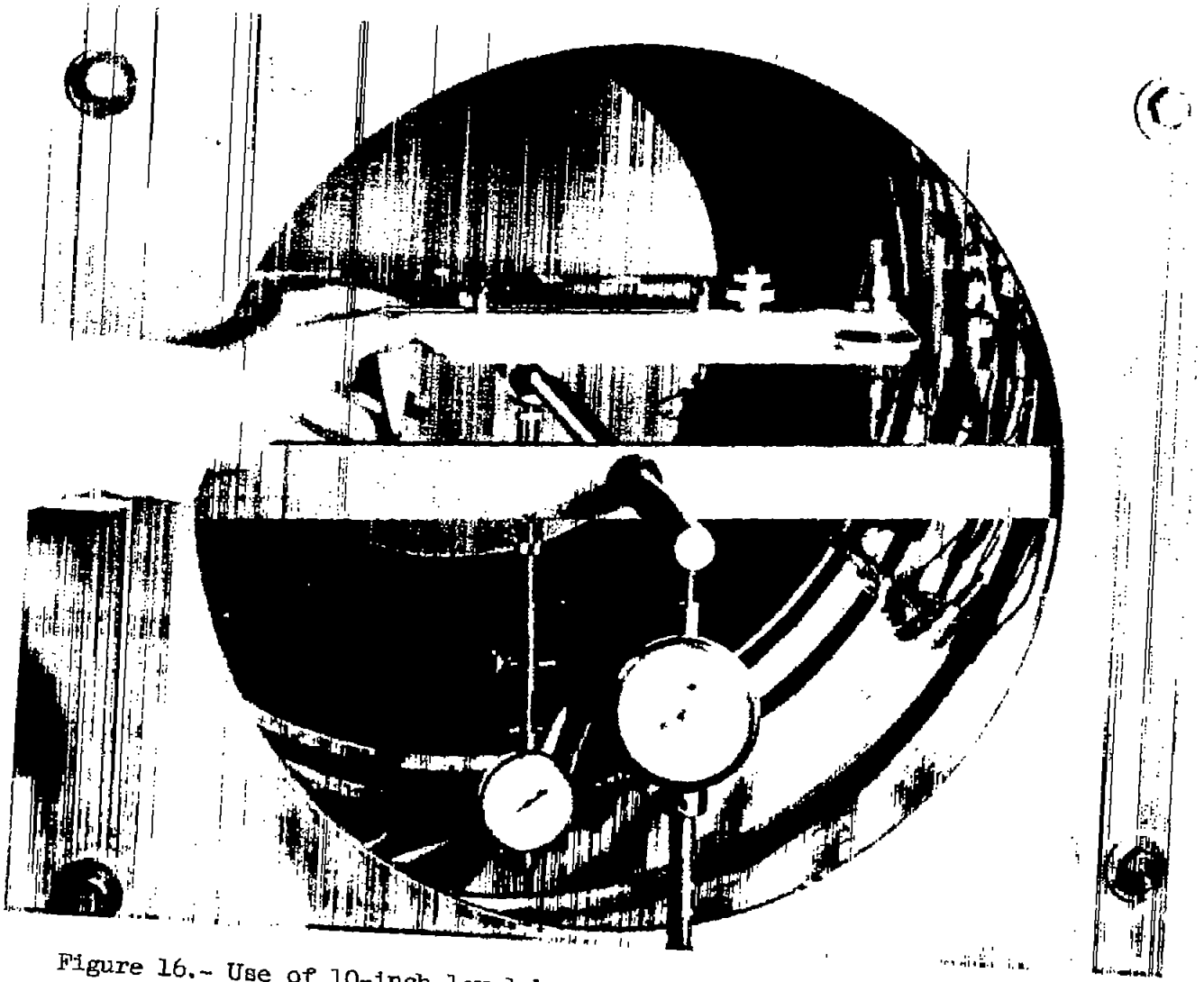


Figure 16.- Use of 10-inch level bar for measuring twist. Dial indicator in foreground used to keep rotating end of cylinder in fixed position relative to floor.

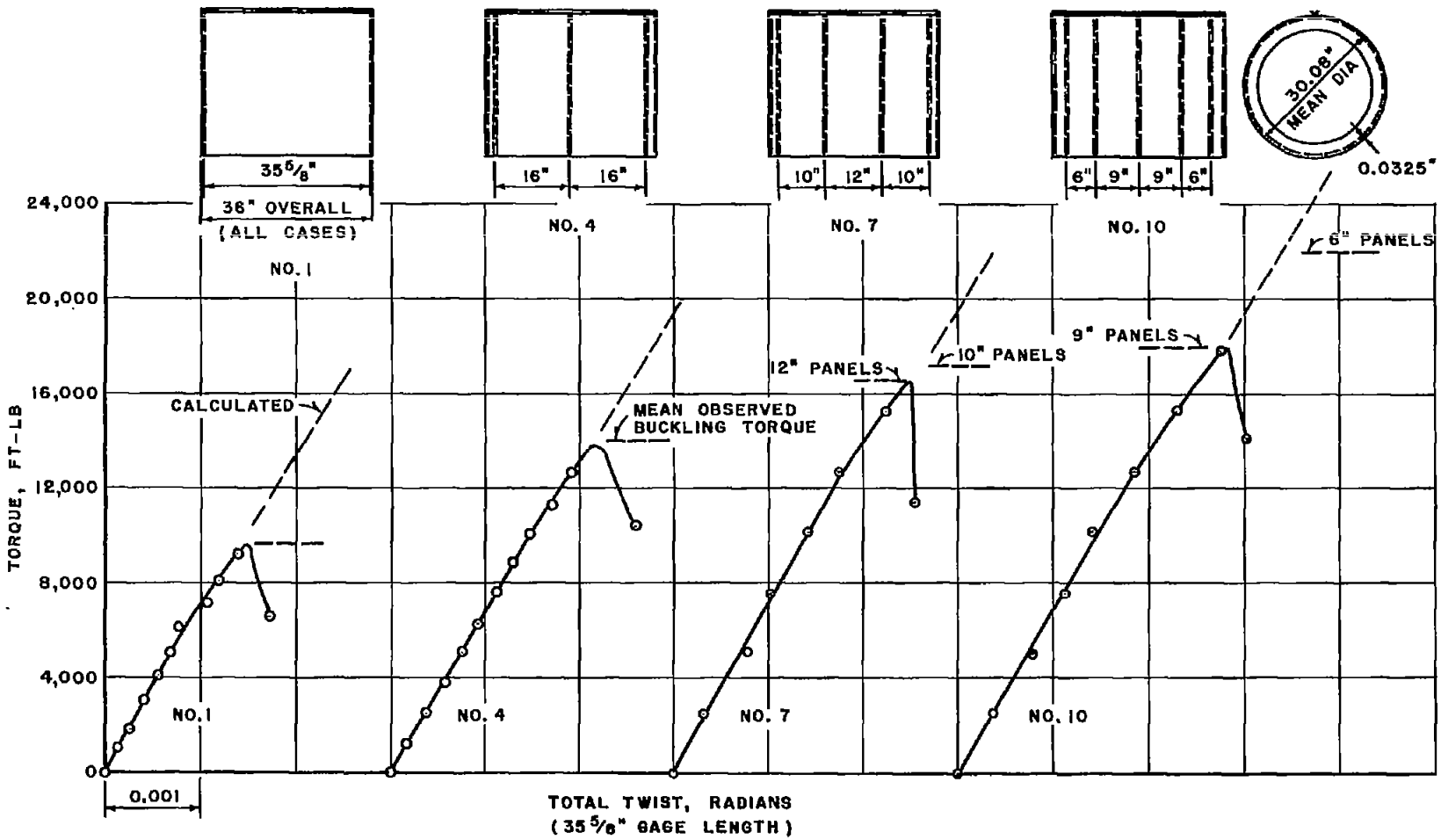


Figure 17.- Torque-twist curves for cylinders having ring stiffeners only. Curves are for first loading. On cylinders 4, 7, and 10 the first panels to buckle were stiffened with additional rings and the cylinders reloaded to obtain buckling of other panels.

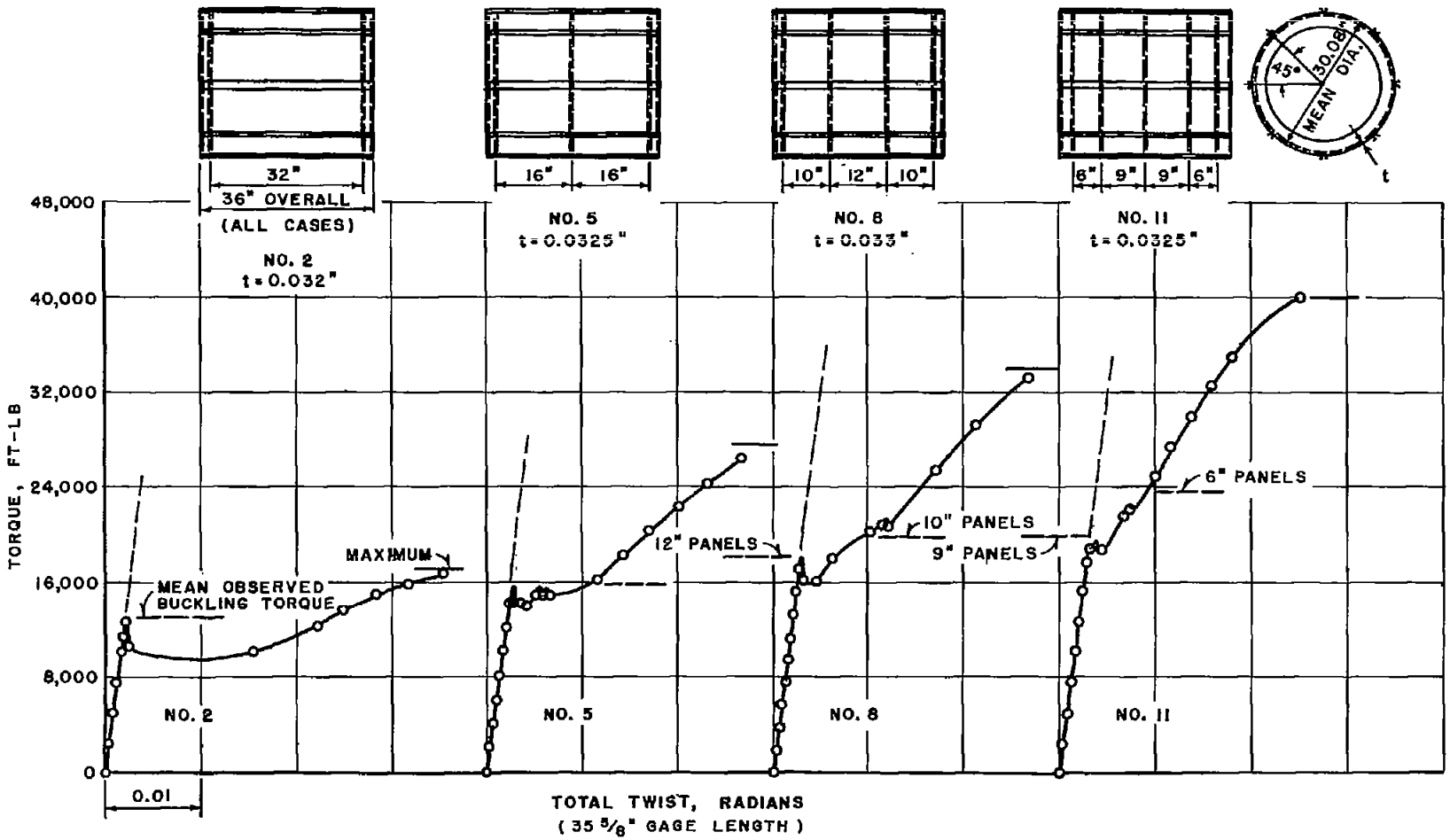


Figure 18.- Torque-twist curves for cylinders with eight longitudinal stiffeners.

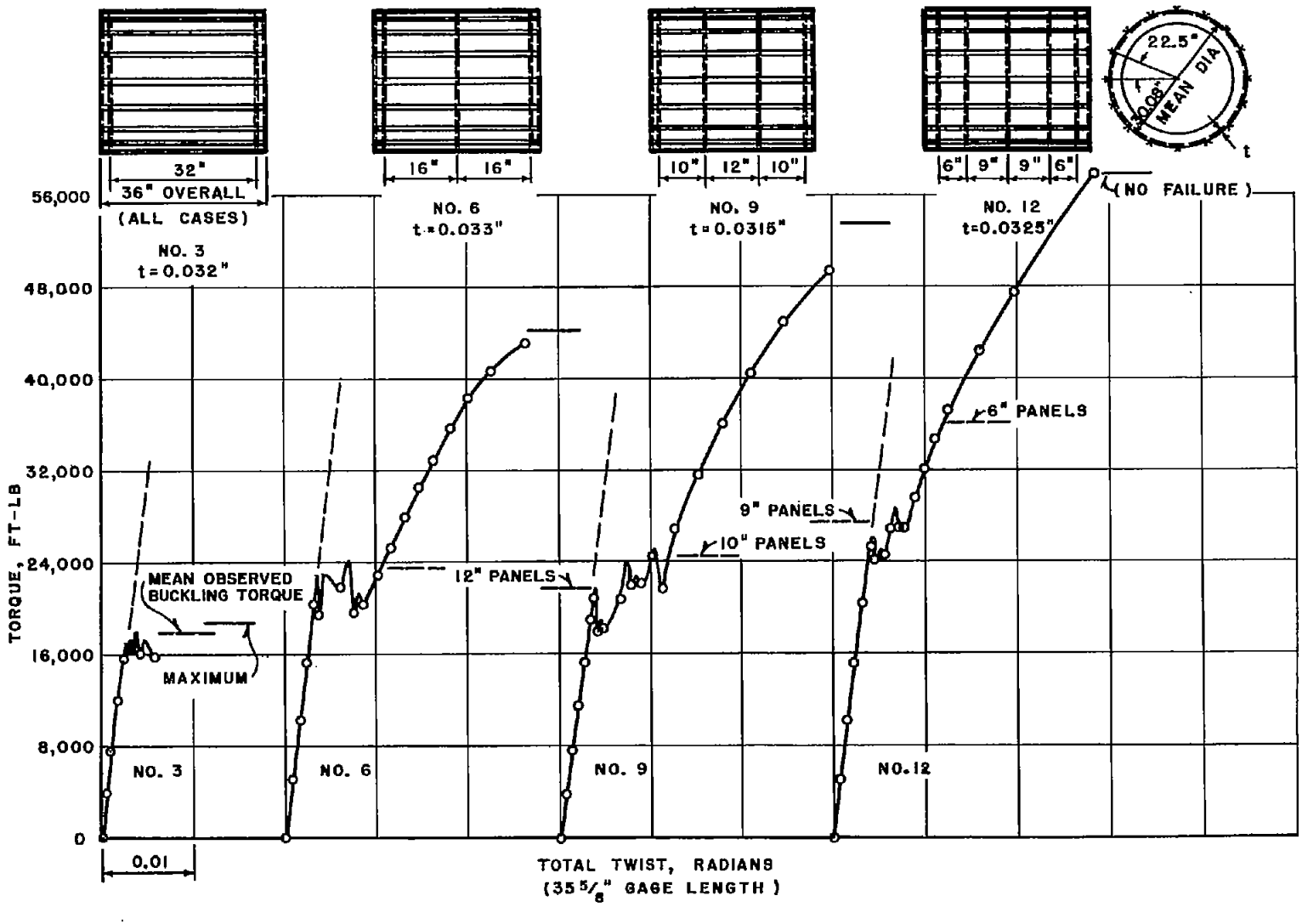


Figure 19.- Torque-twist curves for cylinders with 16 longitudinal stiffeners.

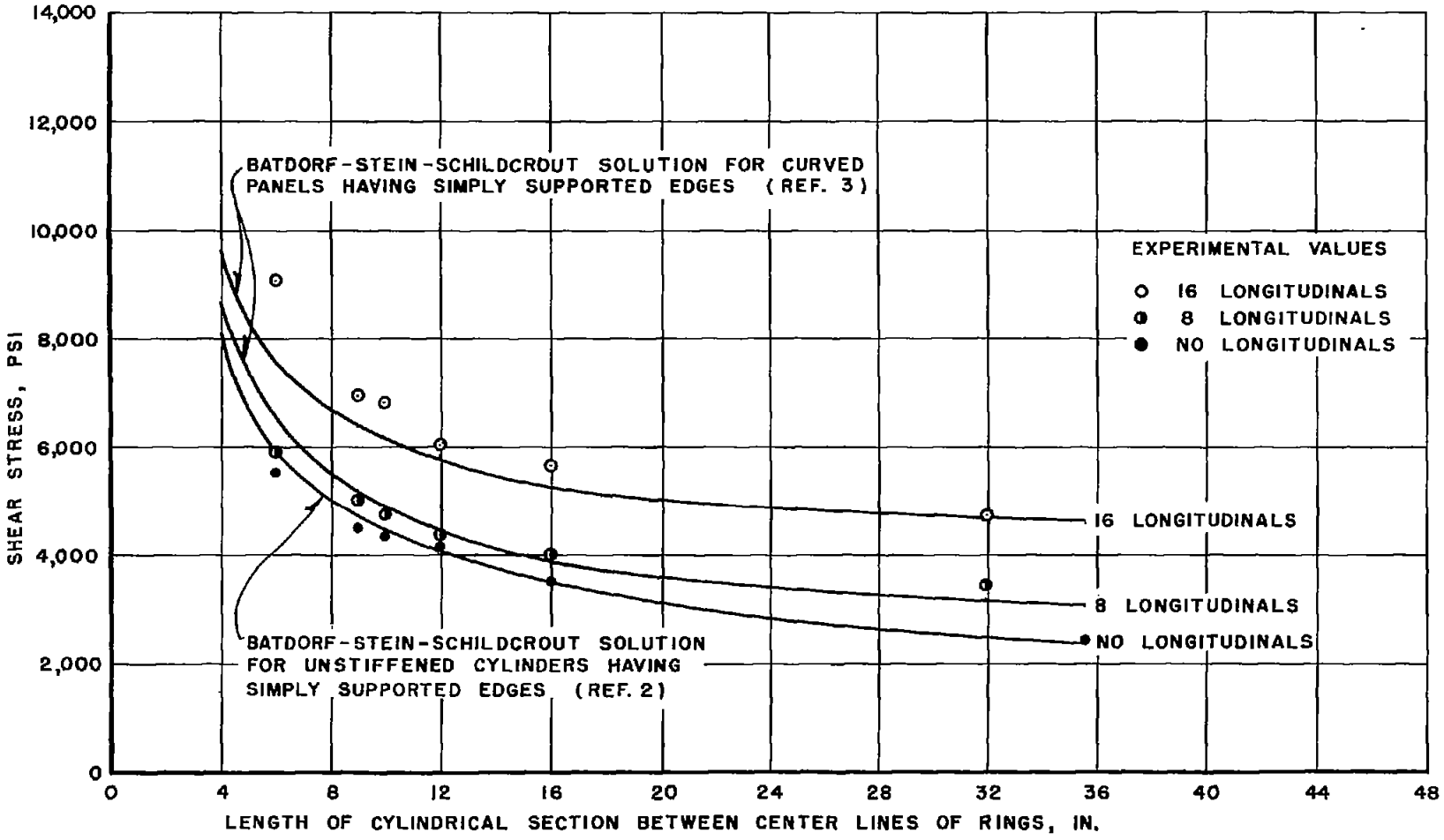


Figure 20.- Shear-buckling stresses for cylinders of 0.032-inch sheet. Mean observed buckling stresses from table I were multiplied by ratio $(0.032 \text{ in.}/\text{Sheet thickness})^2$ to adjust them to nominal thickness of 0.032 inch.

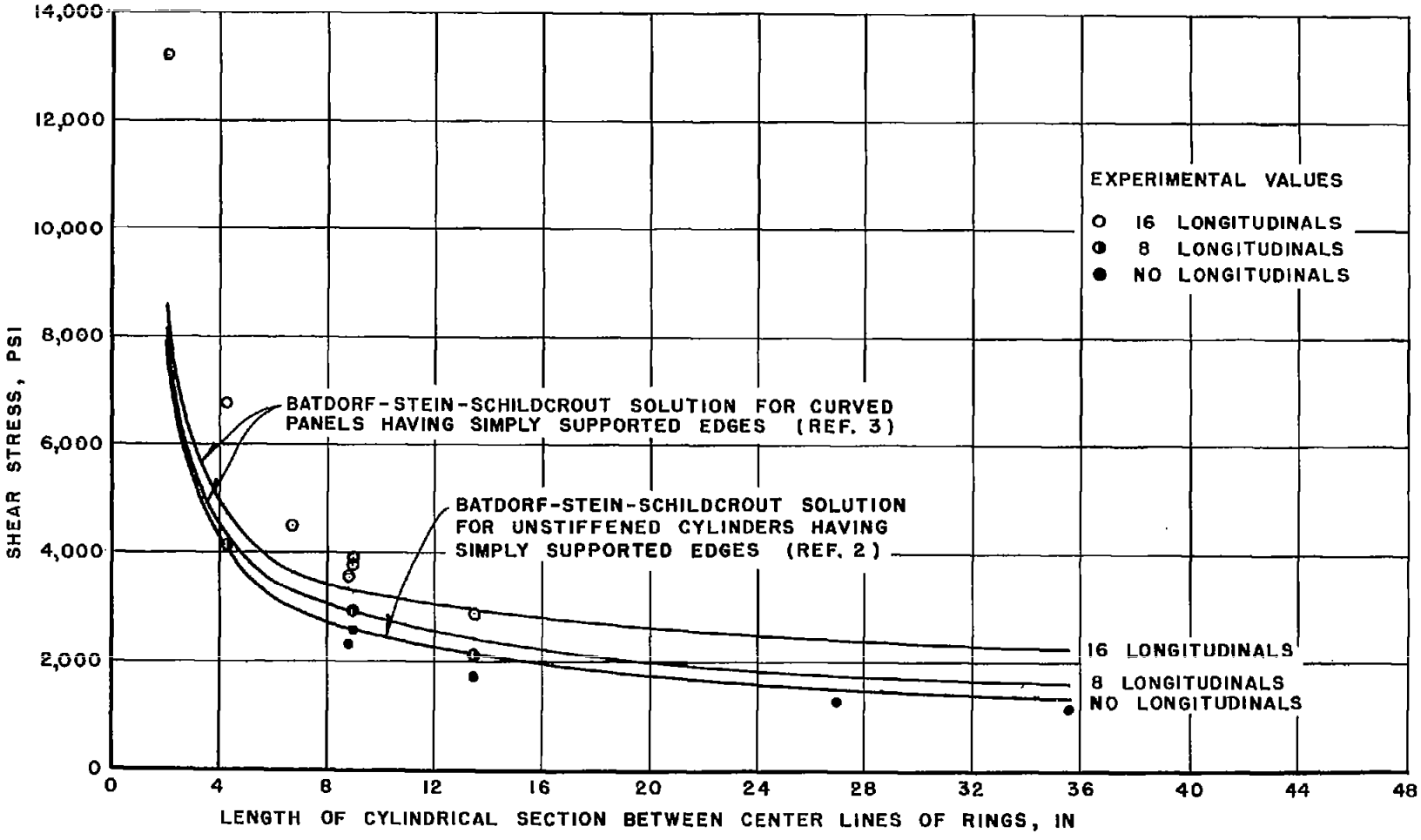
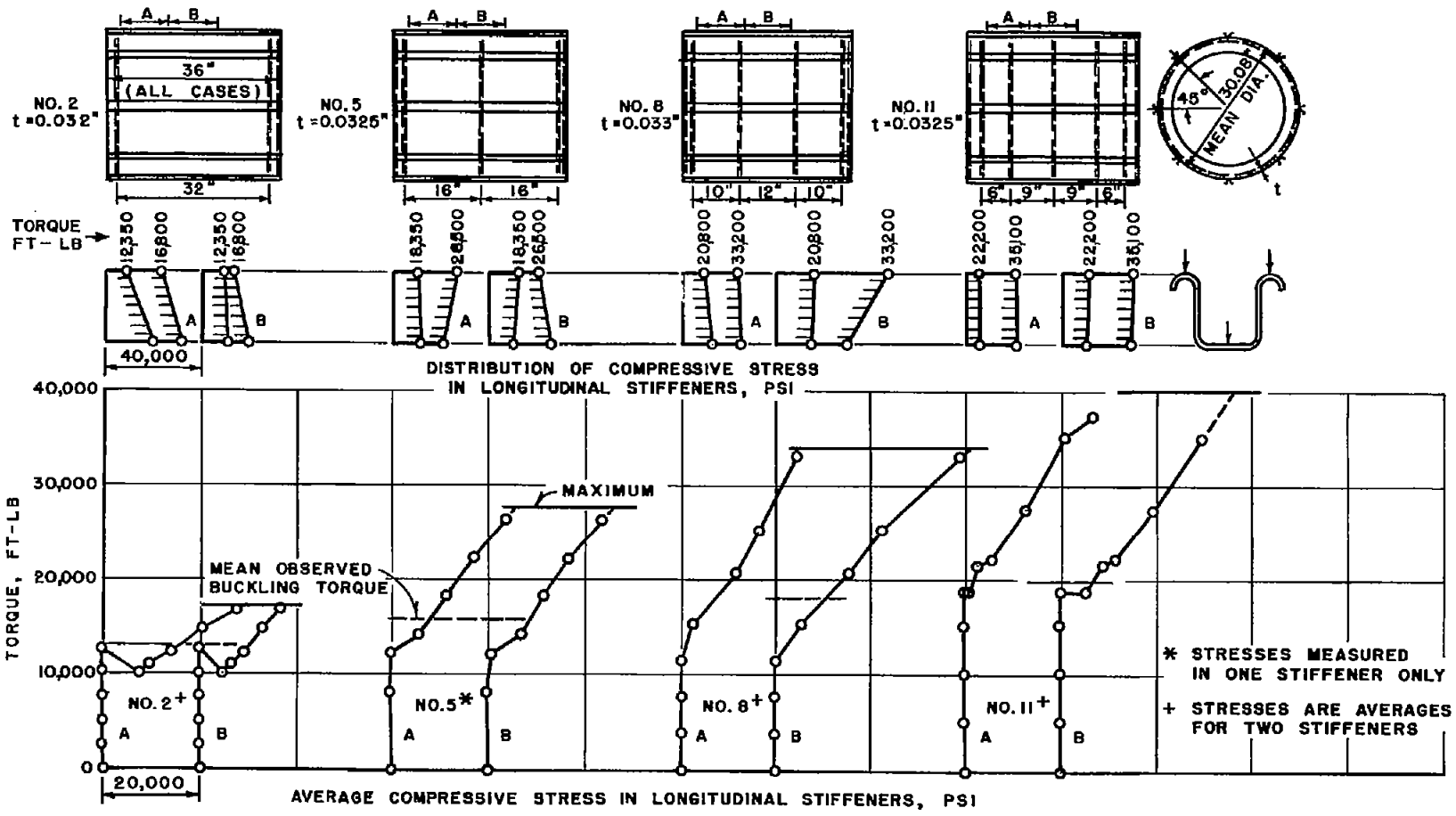
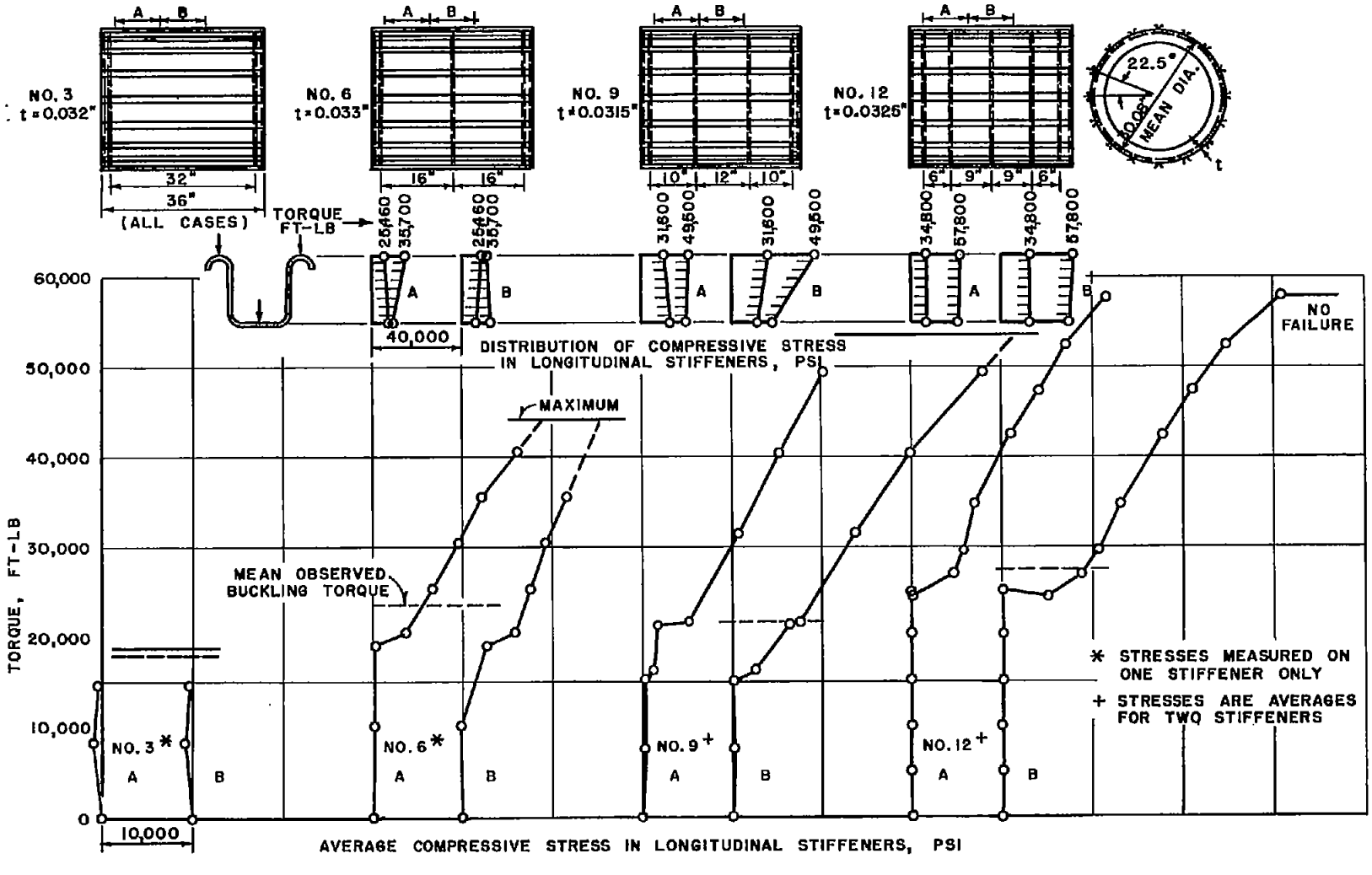


Figure 21.- Shear-buckling stresses for cylinders of 0.020-inch sheet. Mean observed buckling stresses from reference 1 were multiplied by ratio $(0.020 \text{ in.}/\text{Sheet thickness})^2$ to adjust them to nominal thickness of 0.020 inch.



(a) Cylinders 2, 5, 8, and 11.

Figure 22.- Stresses in longitudinal stiffeners. Stresses measured by means of Whittemore strain gages on 10-inch gage lengths A and B.



(b) Cylinders 3, 6, 9, and 12.

Figure 22.- Concluded.

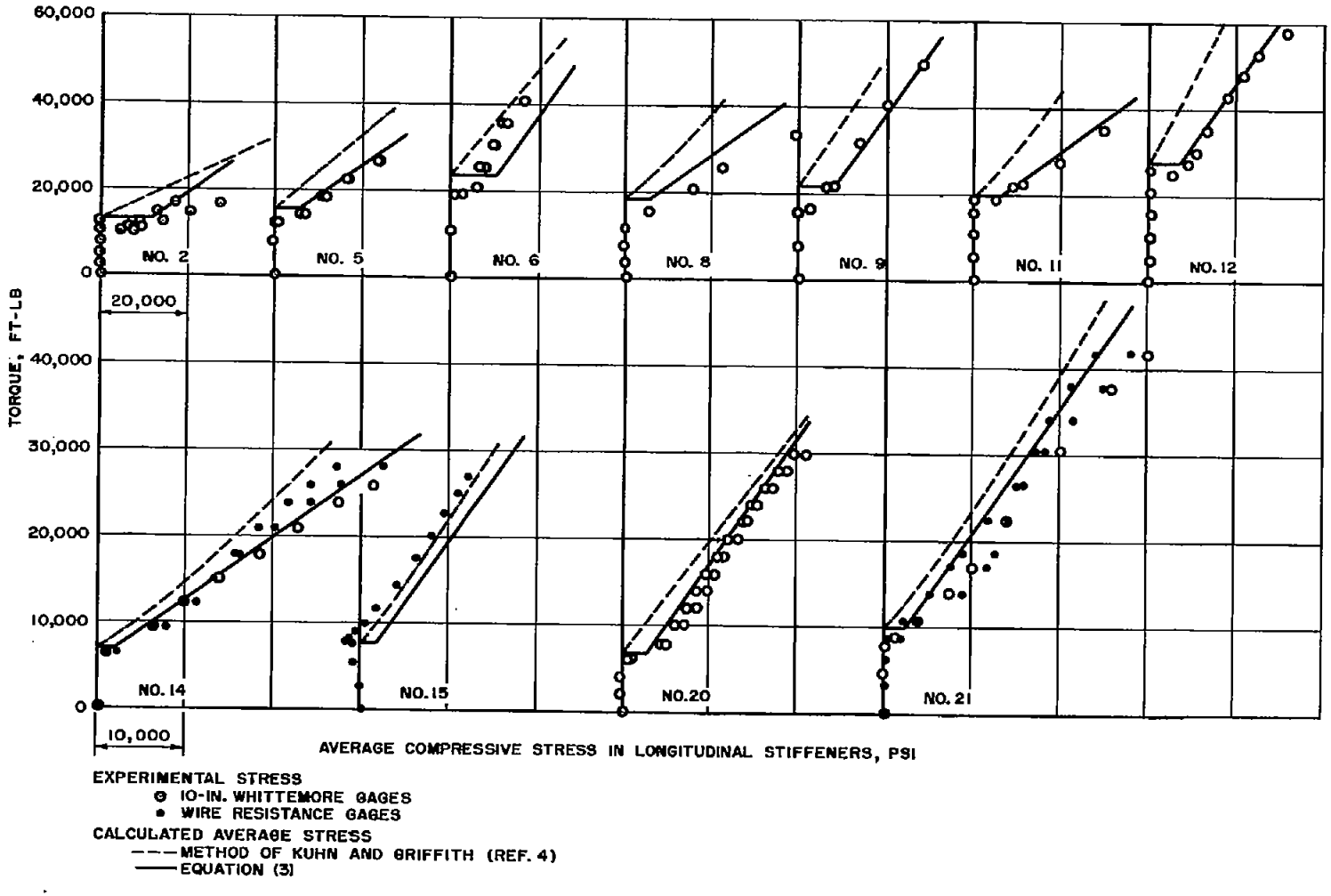


Figure 23.- Comparison of measured and calculated stresses in longitudinal stiffeners of cylinders tested at Aluminum Research Laboratories. (Data for cylinders 14, 15, 20, and 21 from reference 1.)

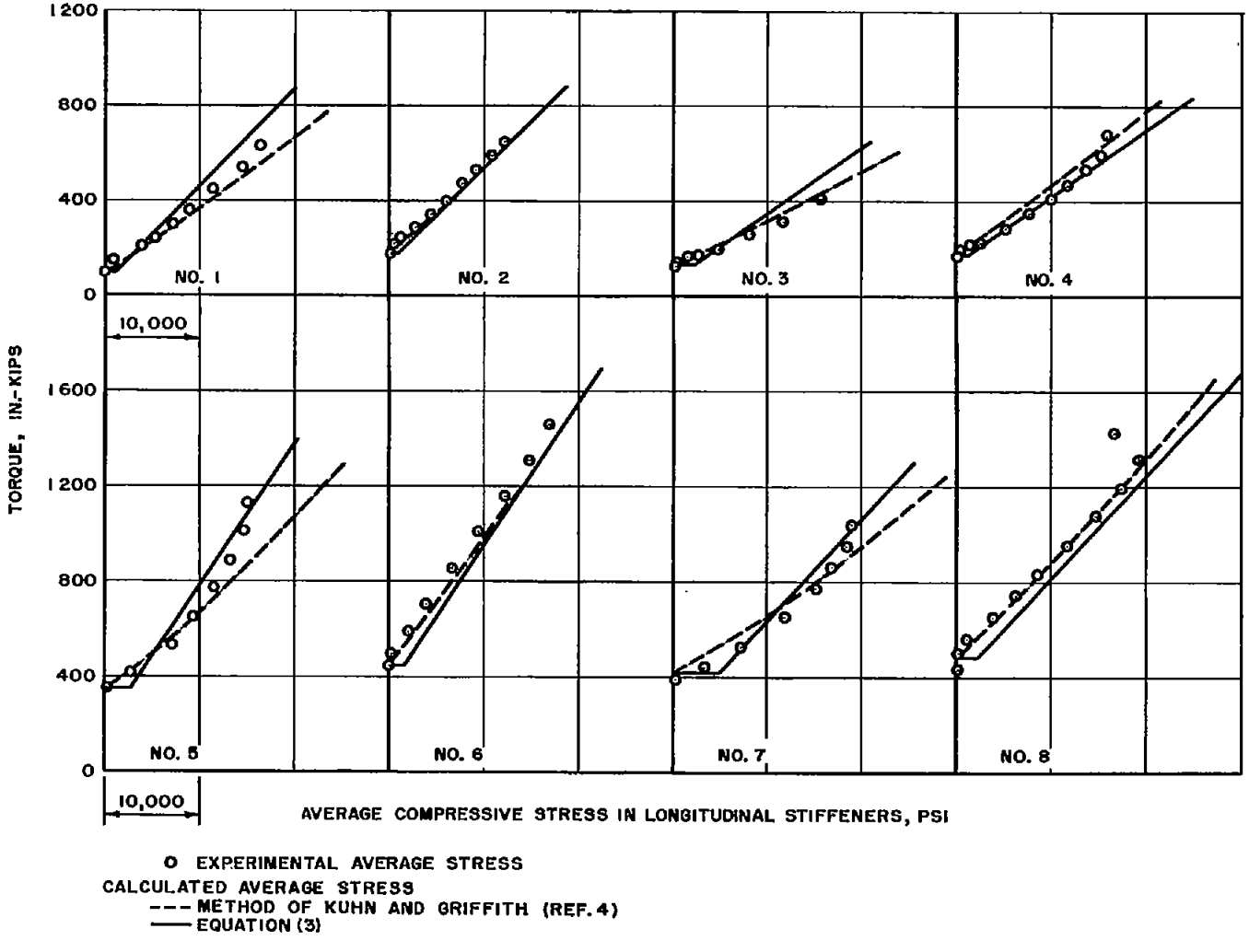


Figure 24.- Comparison of measured and calculated stresses in longitudinal stiffeners of cylinders tested at NACA Langley Aeronautical Laboratory. (Data from reference 4.)

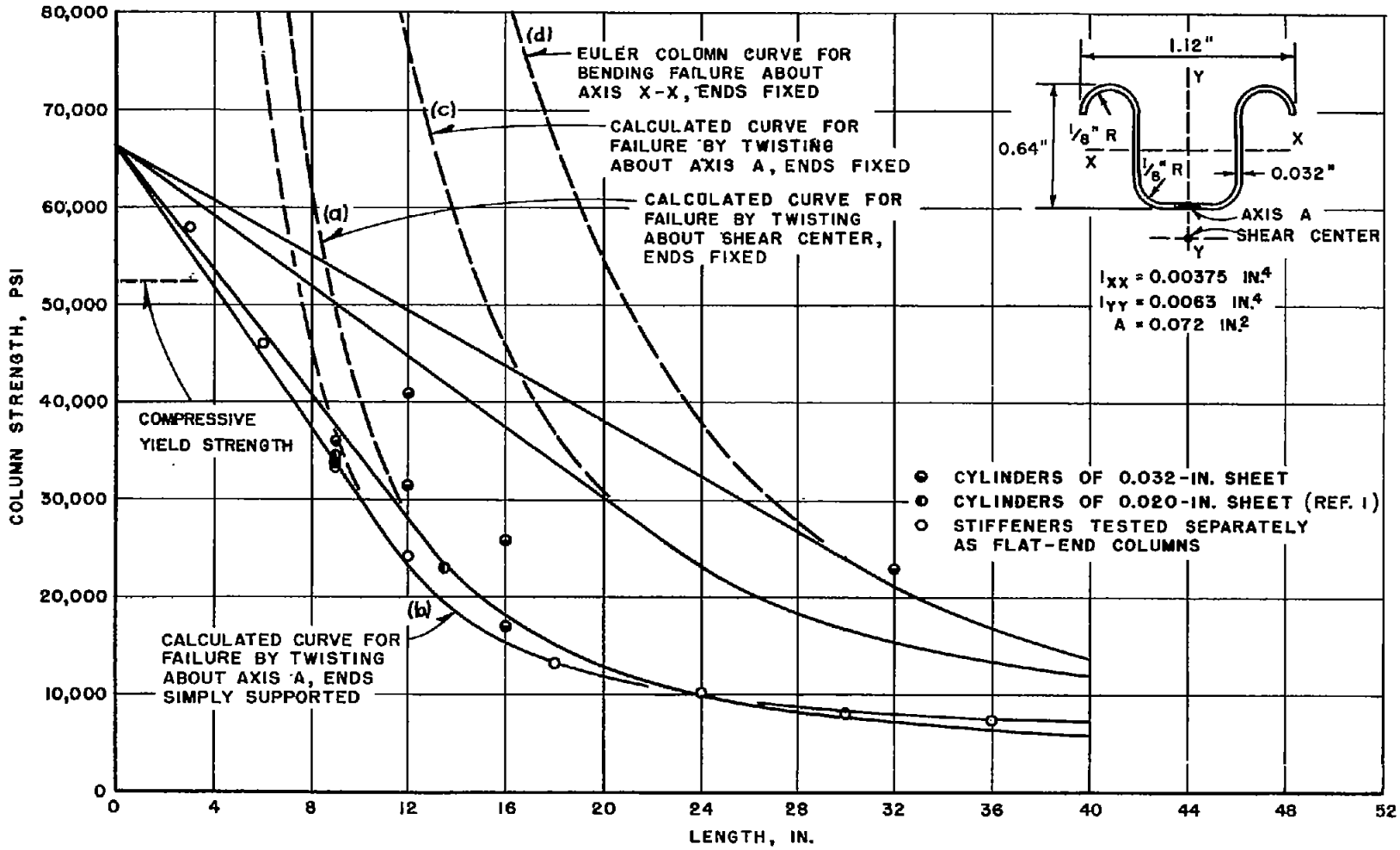


Figure 25.- Column strength of longitudinal stiffeners. Length of stiffeners on cylinders is taken to be spacing of ring stiffeners in central panel in inches.

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