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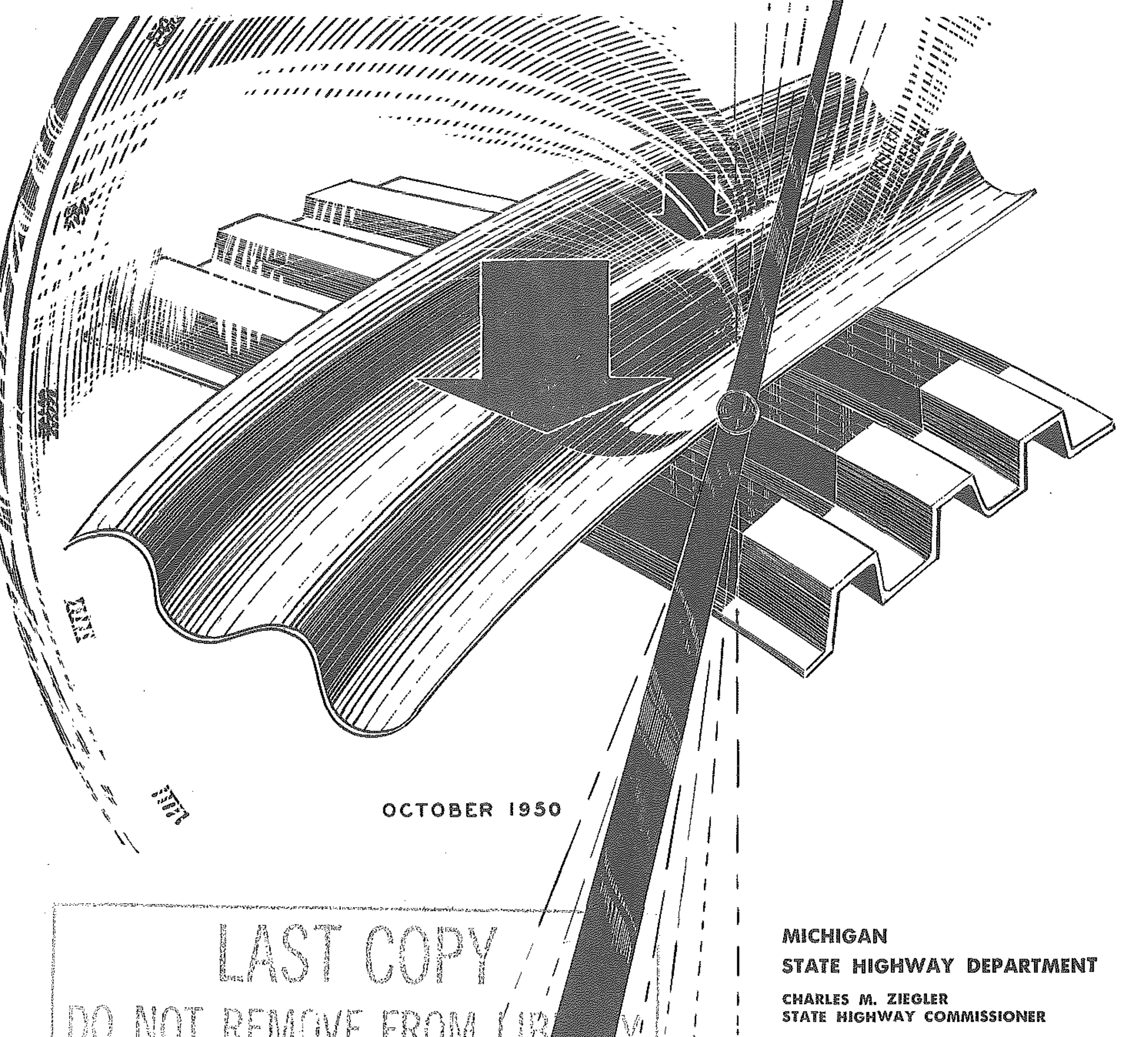
LOAD DEFLECTION TESTS on CORRUGATED METAL SECTIONS



OCTOBER 1950

MICHIGAN
STATE HIGHWAY DEPARTMENT

CHARLES M. ZIEGLER
STATE HIGHWAY COMMISSIONER

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Charles M. Ziegler
State Highway Commissioner

LOAD DEFLECTION TESTS ON CORRUGATED METAL SECTIONS

By

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An Investigation for the AASHO Bridge Committee, by the Michigan State Highway Department in cooperation with the Bureau of Public Roads; the Armco Drainage and Metal Products Company Inc.; the Republic Steel Corporation; and United Steel Fabricators, Inc.

Research Laboratory
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LOAD DEFLECTION TESTS ON CORRUGATED METAL SECTIONS

SYNOPSIS

Sample sections of corrugated metal plate of four different metal thicknesses and three types of corrugations were tested as beams and columns. Beam tests were made on plates formed to two curvatures, and column loading was applied to plates of three curvatures, one being the straight section. The connections were also studied.

Some of the outstanding results are: (a) the order of ability to support load is, first, the 2- by 6-in. box type, second, the 2- by 6-in. circular arc, and third, the 1-3/4- by 6-in. circular arc; (b) within each type, the strength increased with metal thickness; (c) the lap joint is more efficient than the butt joint for all tests except the straight columns; (d) double bolting of lap joints is more efficient than single bolting in the transfer of thrust as demonstrated in the short column tests; and (e) the fiber stresses at failure are practically the same for each curvature studied.

An important conclusion is that culverts may be designed on the basis of section modulus for 1-1/2-in., 1-3/4-in., and 2-in. depth for the circular arc type corrugation and 2-in. depth for the circular arc type corrugation and 2-in. depth for the box type.

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PREFACE

Most of the published research in the field of flexible metal culverts has been done on 1-1/2- by 6-in. circular arc corrugations. Recently, 1-3/4- by 6-in., 2- by 6-in. circular arc and 2- by 6-in. box type corrugations have been produced and further testing has become necessary in order to evaluate these corrugations.

In 1948, the Bridge Committee of the AASHO proposed a comprehensive investigation of corrugated metal plates and structures for the purpose of assisting in the development of a rational basis for the design of structures using the new sections. The proposal included (1) laboratory load tests on various sizes, shapes, and gages of corrugated plate sections, and (2) field investigations on flexible structures under different loading conditions. This report is confined only to the laboratory tests.

In order to expedite the work, a meeting of the following group was arranged in Washington, D. C. for the purpose of establishing ways and means of carrying out the laboratory testing program:

Eric L. Erickson, Chairman	- Chief, Bridge Division, Bureau of Public Roads
Dudley P. Babcock	- Highway Bridge Engineer, Bureau of Public Roads
Earl F. Kelley	- Chief, Division of Physical Research, Bureau of Public Roads
Raymond Archibald	- Chairman, AASHO Bridge Committee
George M. Foster	- Bridge Engineer, Michigan State Highway Department
Tage Beck	- United Steel Fabricators, Inc.
C. R. Clauer	- United Steel Fabricators, Inc.
David Henderson	- Armco Drainage and Metal Products Co.
George E. Shafer	- Armco Drainage and Metal Products Co.

T. F. deCapiteau - Republic Steel Corporation

W. R. Fraser - Republic Steel Corporation

At this meeting, the Michigan State Highway Department, represented by George M. Foster, Bridge Engineer, agreed to provide laboratory facilities and to perform the laboratory tests. The three steel plate fabricators agreed to furnish the necessary test specimens and to cooperate in the investigation.

The above committee voted to place the responsibility for working out the details of the laboratory tests in the hands of a subcommittee consisting of E. L. Erickson, Chairman, G. M. Foster, and a representative appointed by each company, namely, C. R. Clauer for United Steel Fabricators, T. F. deCapiteau for Republic Steel Corporation, and George E. Shafer for Armco Drainage & Metal Products Co. At a meeting of this subcommittee in Lansing on February 25, 1949, tentative plans and procedures were established for doing the laboratory testing. It was agreed that the work should be done by the Research Laboratory of the Michigan State Highway Department and that it would consist of simple load-deflection tests on parallel specimens of corrugated plate sections currently being produced by the three participating fabricators.

As testing of specimens progressed, the subcommittee was given the opportunity of inspecting the laboratory technique and procedure. At such a meeting on August 23, 1949, the following matters were discussed: bearings for specimens; bolt torque; bolt strain measurements; extent to which plates should be deformed under load; double bolting of joints; and an interim report. Similarly, on January 24, 1950, after observing a test, the subcommittee went into executive session and discussed the following: an outline of the final report; method of graphical presentation of data; strain measurement on plates at point of maximum moment; modulus of rigidity; comparison of modulus of rupture for plates of large and small radius of curvature, ultimate torque resistance of bolts; and tests on bolted samples at 100 ft.-lb. and 200 ft.-lb. bolt torque.

At a meeting on May 10, 1950, the committee discussed the theory of flexible structures and pointed out the advantages obtained by using ultimate strengths and modulus of rupture values for comparison of corrugation stability. The result was a decision to tabulate the unit stress at yield point and the modulus of rupture at ultimate load for each plate.

At a meeting in East Lansing on August 29, 1950 the committee reviewed a preliminary report of the complete results of the investigation. A draft of the final report incorporating the findings of the Research Laboratory and conclusions formulated in the committee was approved for presentation in brochure form. It was understood that this report was to be subject to final committee approval before publication.

LOAD DEFLECTION TESTS ON CORRUGATED METAL SECTIONS

INTRODUCTION

Purpose of Investigation:

The tests on corrugated plates were designed to furnish data which would aid in the solution of the following three problems:

1. Are cross-sectional area and section modulus sufficient information upon which to compute the strength of corrugated metal under bending and direct stress?

2. Can the experience in the use of the old style 1-1/2-in. corrugation be used for the design of 1-3/4-in. and 2-in. corrugation depths with proper allowance for the increased section modulus?

3. Do the methods of joining the plates fully develop the strength of the plates in bending and thrust?

The answers to these questions required many tests together with a correlation of the test results. In order to keep the laboratory program as simple as possible, the work was segregated with the following specific aims in mind:

1. To study the influence of size and shape of corrugation on the plate deflections due to loads.

2. To observe the effect of metal thickness upon plate deflections.

3. To compare the efficiency of single-bolted and double-bolted fastenings.

4. To observe the performance of butt joints versus lap joints.

5. To investigate the effect of bolt torque on joint action.

6. To measure the stresses in the bolts at plate failure.

7. To study the influence of plate curvature upon the magnitude of the extreme fiber stress.

Scope of Investigation

Specimens to be tested were obtained from three sources, each supplier furnishing at least one style of corrugation. Three parallel samples were submitted for each of ten tests for each metal gage. Two suppliers furnished some old-style material in addition to the style currently being manufactured in order that there might be some basis for correlating the results of the present test with those performed earlier by Jamison Vawter.(1)

Specimen Description - The corrugation designated as Type A is a circular arc type. The depth is 1-3/4 in. and the pitch 6 in. Details are given in Figure 1 A. Sections are joined by a lap joint with high tensile bolts spaced as shown in the sketch.

Another style plate submitted by the same manufacturer is also shown in Figure 1 B. This OA type has a corrugation depth of 1-1/2 in. and a 6-in. pitch. The lap seam is used for assembling as in Type A, but the bolts are slightly smaller. Spacing details are shown in the figure.

Another circular arc style is labeled Type R. This has a 2-in. depth and 6-in. pitch. The joint is similar to that of Type A with a small difference in the bolts. Figure 1 C shows these differences. From this same source, comes Type OR which is similar to the OA style These details are given in Figure 1 D.

A new corrugation commonly known as the box type is called style U. It is in reality a modified trapezoidal shape with a high section modulus due to the large surface in the outer fiber region. A butt seam is used for joining these plates. Details are shown in Figure 1 E and F.

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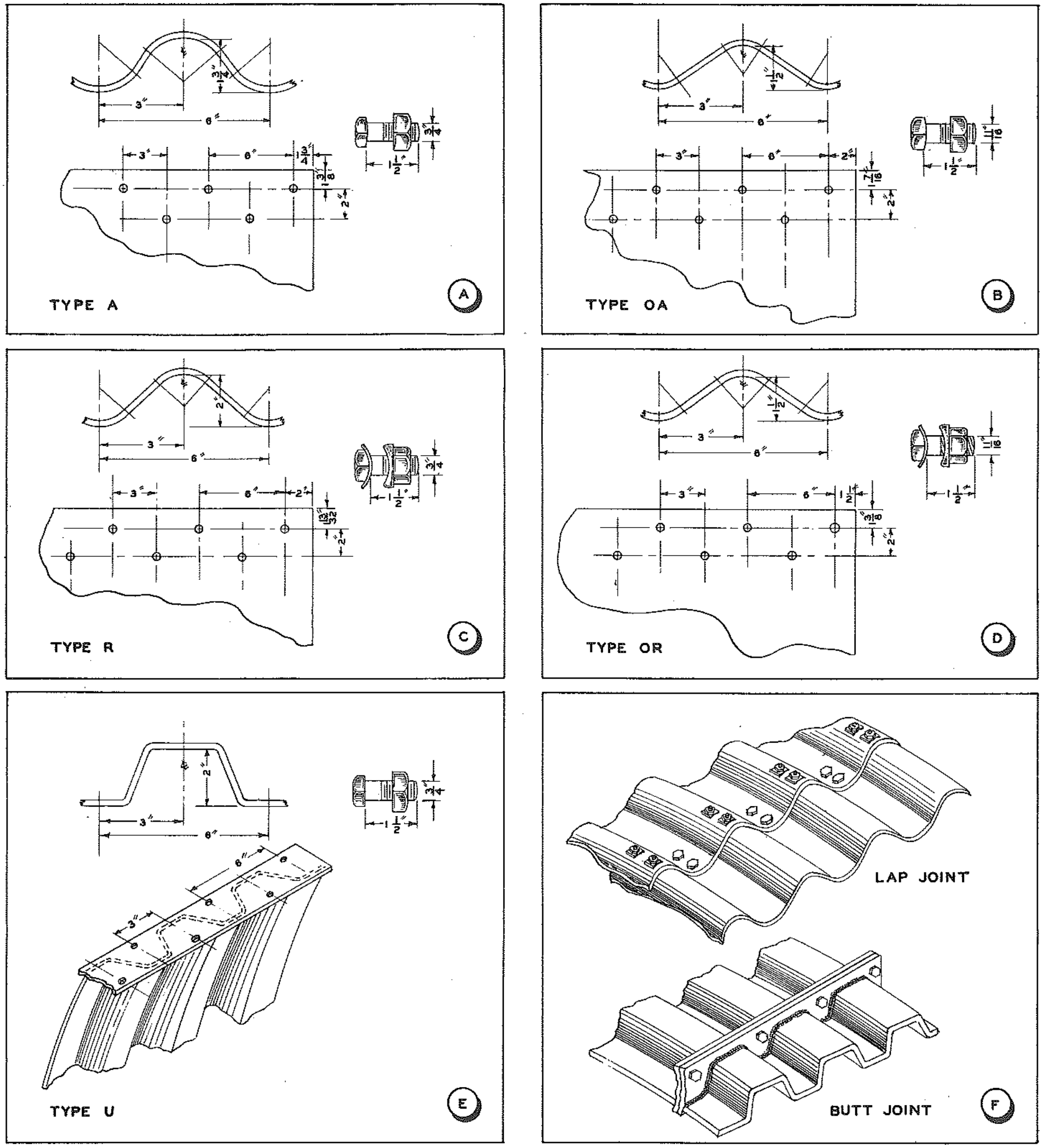
[1] Tests on Curved Corrugated Beams by Jamison Vawter, University of Illinois.



DETAILS of PLATES and JOINTS

FIGURE 1

The average length of specimens used in all tests except Test 2 was 52-3/4 in. This dimension was the same whether the specimen was straight or curved. The specimens used in Test 2 were 24 in. in length. The average width of the specimens is given below in relation to specimen type.

Type A	width	21-3/4 in.
Type R	width	22 in.
Type U	width	21 in.
Type OA	width	21-5/8 in.
Type OR	width	21-3/4 in.

More complete details showing manufacturer's data for each of these styles of corrugation may be found in Table 1, Appendix.

<u>Bolt Description</u> - The bolts supplied with specimen Type A and OA and Types R and OR were high tensile strength bolts with an average ultimate strength of approximately 132,000 psi. Bolts furnished with Type U specimens were of A-7 grade metal with a lower ultimate strength value than material used in other bolts.

The shank length of all the bolts used was 1-1/2 in., but they varied in diameter. The diameter of the bolts for Types A-R and V was 3/4 in. and for Types OA and OR it was 11/16 in.

<u>The Six Tests</u> - To make the laboratory study of corrugated metal plates as complete as possible, the investigation was organized about six fundamental tests. Three of these were devised to measure horizontal and vertical deflections under column loading, one test was a measure of joint slippage in a column, and the remaining two were designed to give horizontal and vertical deformations when the specimens were

acting as beams. The different tests are diagrammed in Figure 2.

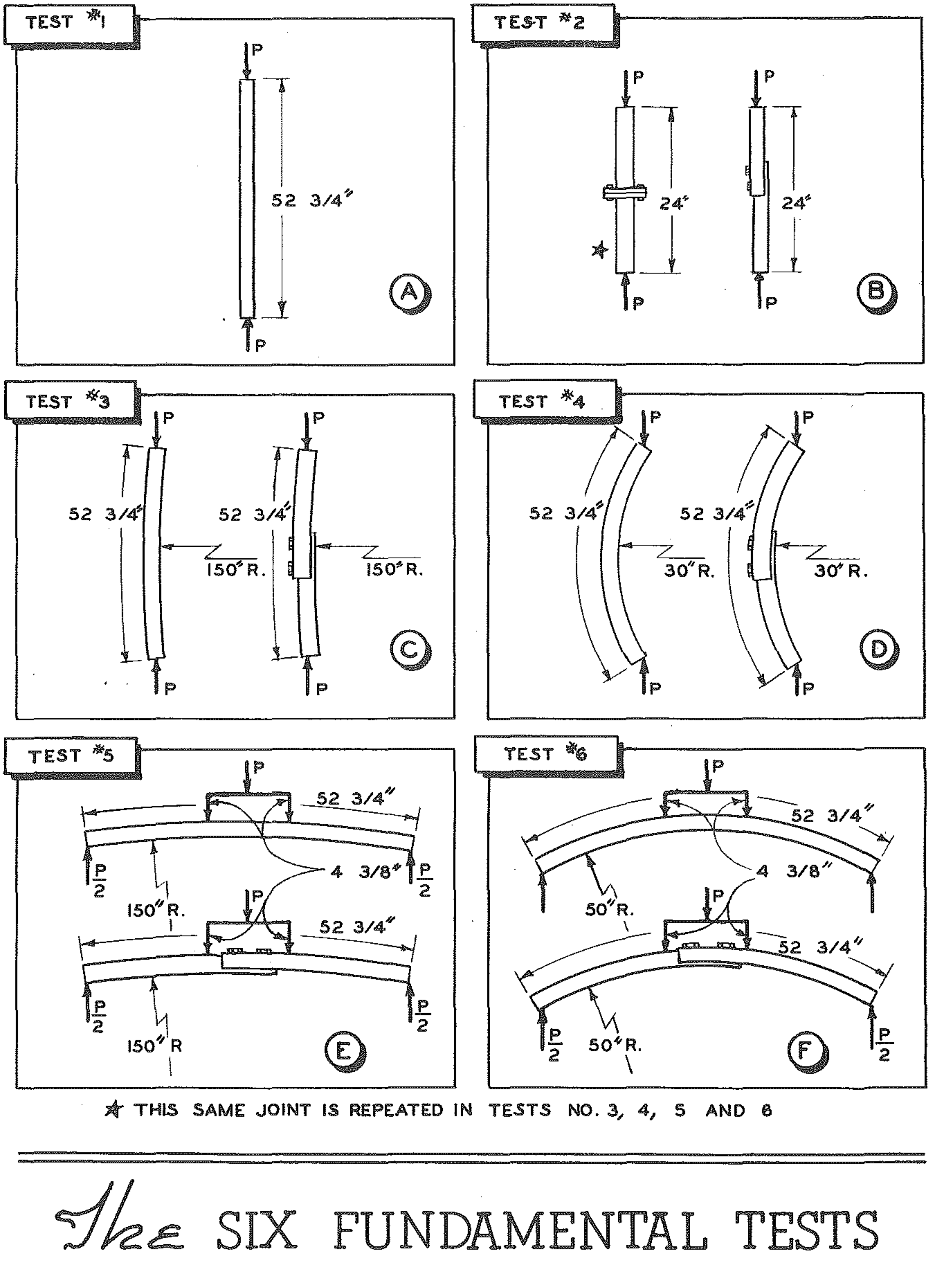
Test 1 was a straight compression column. The specimens provided were plain, that is, there was no seam or joint. The plates had no curvature. The assembly was 52-3/4 in. long. The purpose of the test was to observe the type of failure and note the strength of straight corrugated metal sheets when subjected to column loading.

Test 2 was a test on short columns made up of two straight sections bolted together. The assembly was 24 in. long. The test was designed to measure slippage between the plates and to determine the strength of the seam in shear. The exception, of course, was the butt connection in which there was pure compression and no shear. These samples were tested to plate failure.

Tests 3 and 4 were identical except for curvature of test specimens. In Test 3 the specimens were formed to a radius of 150 in. as compared to a 30-in. radius in Test 4. In both tests the specimens were supported on edge with the chord vertical and tested as columns. The samples consisted of both plain and bolted specimens. The purposes of both of these curved column studies were to observe the extent of deformation, the resistance to load, and extent to which the seam developed the full strength of the plates.

Test 5 was a sample beam test in which the specimens were supported at both ends and subjected to a downward force at the center. Measurements were made of both horizontal and vertical displacements. The specimens used in this test were identical to those used in Test 3.

Test 6 differed from 5 only in the radius to which the plates were formed. In this case, a radius of 50 in. was used as against 150 in. in Test 5. Both plain and bolted samples were subjected to beam loading.



★ THIS SAME JOINT IS REPEATED IN TESTS NO. 3, 4, 5 AND 6

The SIX FUNDAMENTAL TESTS

FIGURE 2

These last two tests were formulated for the purpose of measuring the plate, the characteristics of the failed section, and the efficiency of the joint while the plate was acting as a beam.

The Number of Samples - From the previous section it is seen that Test 1 required a plain sample, Test 2 a bolted sample, and the remaining four each required both a plain and bolted specimen. Thus, there were in reality ten tests. Three gages of metal were provided, namely, 1, 7, and 12 and sufficient samples were furnished so that each test could be repeated twice for each gage.

Certain additional plates were supplied from 10-gage stock. In Tests 5 and 6, the 10-gage samples were submitted from all sources. A few specimens of 3-gage material were received for Tests 1 and 2. In all, 352 plates were supplied and all were tested except a few old-style samples which were badly rusted.

System of Identification - Each plate was given a sample number when it was received. The system used was suggested by G. E. Shafer. It consisted of a group of numbers and letters in the following sequence: source, test number, a distinguishing letter for the individual plate, the nominal metal gage, and a letter indicating whether the plate was plain or bolted. Thus, we had a five-character symbol for each sample.

The following characters were used: The source was A, R, U, OA or OR. The test numbers were 1, 2, 3, 4, 5, and 6. X, Y, and Z provided symbols to distinguish the three parallel test specimens. Metal gages were 1, 3, 7, 10, and 12. The distinction between plain and bolted or seamed specimens was made by using letters P (plain) and S (seamed), respectively. Thus, a plate labeled A6X1S was from source A, for Test 6, the first of 3 samples, of 1-gage metal, and was a bolted specimen. Complete summary of test specimens used in the investigation will be found in Table 1.

<u>Supplementary Studies</u> - Although each plate carried a symbol indicating the exact test to be performed upon it, there was some small deviation from the schedule. The subcommittee approved the proposal that the "Z" plate of each group need not be tested if the results of X and Y correlated closely. This left quite a number of plates free for miscellaneous testing described as follows.

1. Seam Strength. A large number of bolted Z plates from Test 3 were subjected to beam loading with the seam reinforced by a double row of bolts. This was done in an effort to learn whether or not the standard bolting method developed the full strength of the joint.

2. Residual Deformation. Some of the plain Z samples were tested as beams under a special beam loading program in which the load was released after each application. The intent here was to observe the rate of increase in permanent deformation.

3. Fiber Stresses. In Test 4, some SR-4 electric strain gages were cemented to the curved columns at anticipated points of maximum fiber stress. These strains were measured both on the inside and outside of the plate. The purpose here was to make measurements to compare with the theoretical values obtained from standard formulas.

4. Bolt Stresses. While conducting the beam tests, several sets of bolts were fitted with SR-4 Type A-8 strain gages to make measurements of bolt tension. Much difficulty was encountered due to the slippage in the joint. Considerable shear seemed to develop which, of course, could not be measured by the gages.

TEST NO.	NOMINAL GAGE	STYLE A				STYLE R				STYLE U				OLD STYLE				
		DEVELOPED LENGTH	CHORD LENGTH	WIDTH	THICKNESS	DEVELOPED LENGTH	CHORD LENGTH	WIDTH	THICKNESS	DEVELOPED LENGTH	CHORD LENGTH	WIDTH	THICKNESS	DEVELOPED LENGTH	CHORD LENGTH	WIDTH	THICKNESS	STYLE
1 P	1	52.8	----	21.4	.278	53.0	----	22.0	.302	53.0	----	21.1	.270					
	7	52.6	----	21.4	.191	53.0	----	21.7	.205	53.0	----	21.1	.172	53.0	----	21.5	.191	OA
	12	53.0	----	21.3	.114	53.0	----	21.9	.122	53.0	----	20.9	.111	53.0	----	21.4	.109	OA
2 S	1	24.0	----	21.4	.283	24.0	----	21.6	.287	24.0	----	21.0	.274					
	7	24.0	----	21.4	.190	24.0	----	21.6	.185	24.0	----	20.9	.180	24.0	----	21.5	.198	OA
	10					24.0	----	21.6	.142									
	12	24.0	----	21.6	.118	24.0	----	21.9	.121	24.0	----	20.8	.105					
3 P	1	Nominal length 52 3/4 in.	52.2	21.4	.283	Nominal length 52 3/4 in.	52.1	21.9	.302	Nominal length 52 3/4 in.	52.1	21.1	.276	Nominal length 52 3/4 in.	51.0	21.8	.276	OR
	7		52.1	21.3	.185		52.1	21.7	.193		52.1	21.0	.183		51.0	21.6	.184	OA
	12		52.4	21.4	.107		52.1	21.8	.116		52.4	21.0	.108		51.0	21.6	.113	OA
3 S	1		52.4	21.6	.286		52.1	21.9	.292		52.0	21.0	.277					
	7		52.2	21.4	.196		52.0	21.8	.190		52.0	21.1	.183		51.0	21.6	.193	OA
	12		52.3	21.6	.114		52.2	21.6	.117		52.3	20.9	.107		51.0	21.7	.110	OA
4 P	1		47.0	21.5	.284		47.0	22.0	.298		48.0	21.2	.273		46.0	21.6	.282	OR
	7		47.0	21.1	.188		47.0	21.4	.191		47.3	21.1	.179		46.0	21.7	.191	OA
	12		47.2	21.3	.114		47.0	21.6	.118		47.3	21.1	.108					
4 S	1		47.0	21.5	.286		47.0	21.7	.291		48.0	21.0	.272					
	7		47.2	21.4	.195		47.0	21.6	.187		48.0	21.1	.177		46.0	21.6	.185	OA
	12		47.0	21.6	.116		47.0	21.9	.117		48.0	21.1	.109					
5 P	1		52.3	21.5	.281		52.6	22.0	.294		52.3	21.1	.276		52.0	21.6	.285	OR
	7		52.2	21.6	.180		52.3	21.7	.192		52.2	21.0	.181					
	10		52.2	21.4	.141		52.3	21.7	.144		52.0	21.2	.135		51.6	21.6	.153	OR
	12		52.3	21.4	.114		52.4	21.9	.112		52.3	20.7	.107		52.3	21.6	.119	OA
5 S	1		52.1	21.5	.283		52.4	21.9	.295		52.4	21.0	.276		52.1	21.7	.284	OR
	7		52.4	21.2	.187		52.3	21.6	.187		52.3	21.0	.178					
	10		52.1	21.1	.130		----	----			52.2	21.0	.137		51.9	21.8	.152	OR
	12		52.4	21.6	.114		52.1	21.8	.118		52.3	20.9	.107		52.0	21.6	.111	OA
6 P	1		49.8	21.3	.276		49.6	21.8	.292		49.7	21.1	.274					
	7		49.7	21.2	.184		49.8	21.6	.186		49.9	20.9	.175					
	10		50.0	21.3	.142		----	----			49.8	21.2	.135		50.3	21.8	.154	OR
	12		49.8	21.6	.116		49.3	21.5	.117		49.4	21.1	.108		50.1	21.6	.101	OR
6 S	1		49.6	21.4	.282		49.6	21.9	.291		49.8	21.1	.282					
	7		49.6	21.3	.188		49.6	21.7	.188		49.5	21.0	.175					
	10		49.7	21.3	.131		----	----			49.3	20.7	.132		50.3	21.9	.150	OR
	12		49.7	21.4	.115		49.6	21.8	.113		49.6	21.0	.106		50.3	21.8	.111	OR

TABLE I

CORRUGATED PLATE SIZES
(All dimensions in inches)

5. Resistance of Bolts to Torque. Near the conclusion of the experimental work, a few plates were assembled and the bolts twisted until failure. Measurements were made with a torque wrench.

6. Tests on the Metal. Samples were cut from the plates and tested for Brinell hardness. Several samples were obtained from each different heat where such data could be ascertained. In other instances, random sampling was used. Larger sections of the same plate were sent to the Testing Laboratory of the Bureau of Public Roads for physical and chemical tests.

7. Joint Slippage. The behavior of a seam under shearing action was another feature investigated. While the short columns were being tested, some of the Z plates were assembled with bolts at 100-lb.-ft. torque, some at 200-lb.-ft. and others at 300-lb.-ft. Some were tested with a double row of bolts also.

Although the miscellaneous tests were more or less incidental to the main plan of study, they contributed a good share of interesting information.

TESTING PROGRAM

Description of Apparatus

As noted above, four of the six types of tests to be conducted were on a column type structure. Each of the first four tests provided a slightly different problem in assembling the test apparatus.

Test 1 required that the jaws of the loading machine be 52-3/4 in. apart after the different load transfer devices were placed in the machine and it also required a maximum load of approximately 300,000 lb. Existing testing apparatus available to the Highway Department did not satisfy these conditions and it was necessary to design and build a loading machine to meet these requirements. The machine designed may be seen in Figures 3 and 4. It consisted of two H columns joined at the top by a fixed cross member and at the bottom by a movable cross member. The load was applied through a hydraulic jack capable of exerting 150-ton load. The plate being tested was free at both ends to rotate in the direction of the least horizontal dimension of the plate. This was accomplished by clamping large loading heads on top and bottom of the column and having a round member fastened to the top of the loading head. The 1-in. round was free to rotate in a circular grooved plate attached to the top and bottom cross members.

The actual load being applied was measured through a dynamometer ring. Two dials were used to measure vertical deflection and two more dials were used to measure the horizontal deflection at the center of the plate.

Test 2 was also a column test but only 24 in. long. There was a 75-ton Universal Riehle testing machine available which had jaws large

TESTING METHODS

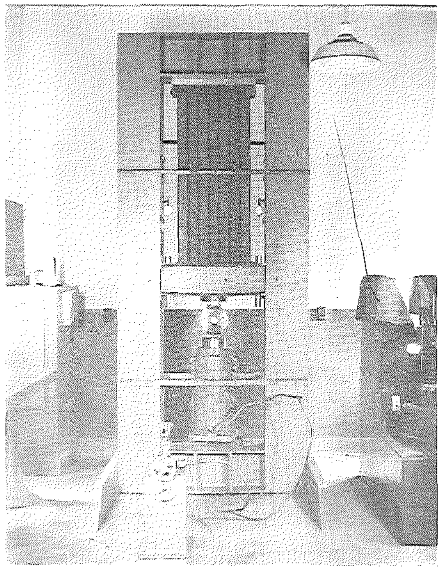


FIGURE 3. 150-TON PRESS ASSEMLED FOR TEST NUMBER 1.

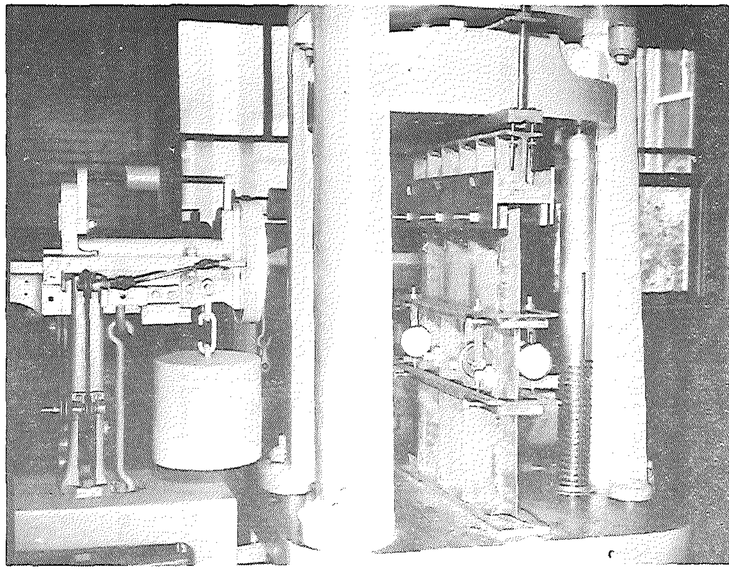


FIGURE 5. TEST FOR JOINT SLIPPAGE IN UNIVERSAL RIEHLE TESTING MACHINE.

FIGURE 4. 150-TON PRESS ASSEMBLED FOR TEST NUMBER 2.

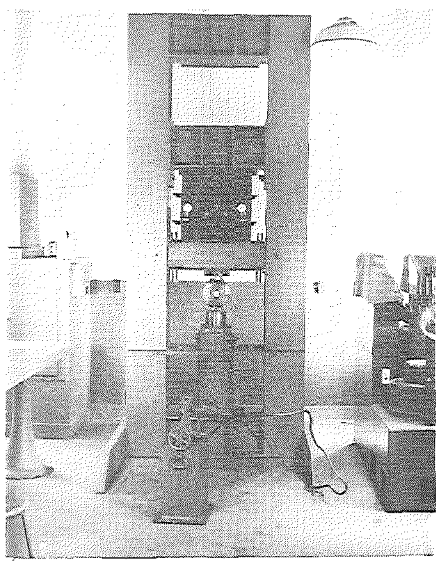
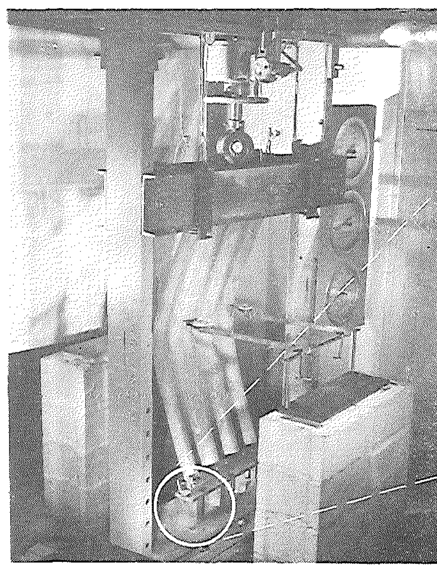
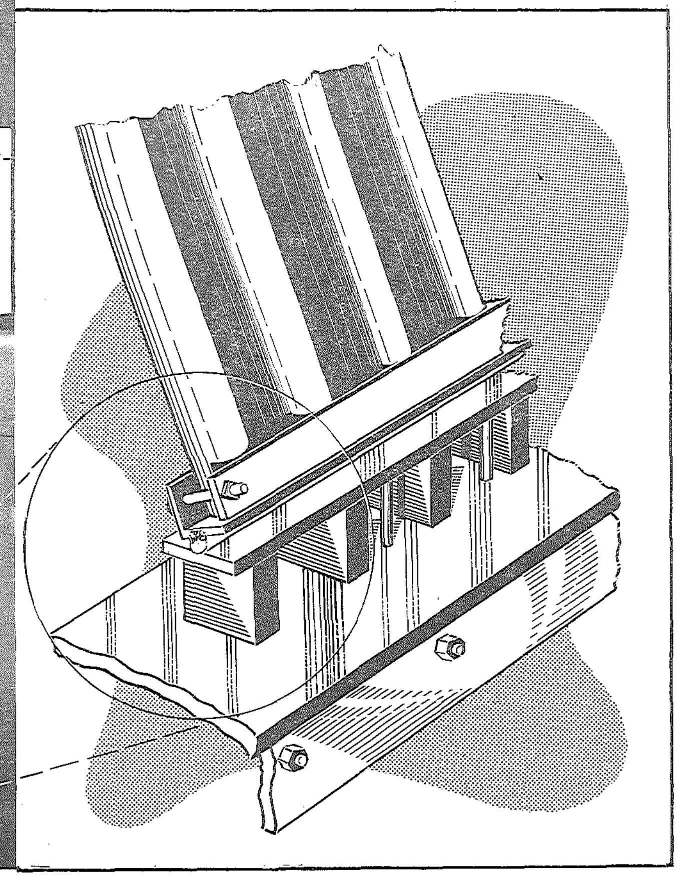


FIGURE 6.

A CURVED COLUMN SECTION BEING FAILED IN A 50-TON PRESS.





enough for 24-in. specimens. About half of the specimens in this test required a load greater than 75 tons and these were tested on the apparatus discussed above for Test 1. The upper head was lowered to allow for the difference in length between specimens 24 in. long and those 52-3/4 in. long. See Figure 4. Only the slippage at the joint between the two plates was measured for Test 2.

The remainder of the samples for Test 2 were tested on the 75-ton Riehle testing machine shown in Figure 5. The specimens being tested rested on a flat plate at the bottom and the load was applied to the top through a loading head which was of sufficient cross section to insure uniform distribution of the load over the entire plate.

Four dials were used to measure the slippage between the two plates. The photograph shows their arrangement. As the two plates were pushed past each other, the indicators registered the movement in thousandths inches. The applied load was measured by the beam balance of the Riehle testing machine.

The equipment used for Tests 3 and 4 was identical in all respects. The load was applied to the columns through a 50-ton hand-pumped hydraulic jack unit set in a frame constructed from I-beam and channel sections. Figure 6 shows this unit.

The top and bottom of these columns were fixed with load transfer devices which insured freedom from restraint on the ends. Figures 7 and 8 picture these devices. The load applied to the columns was measured through a dynamometer ring. Two pairs of dials were used to measure the deflection of the plates, one pair to measure the horizontal deflection of the center of the column and the other pair to measure the

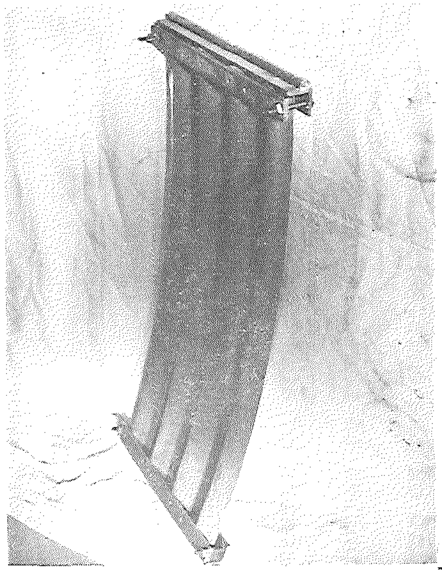
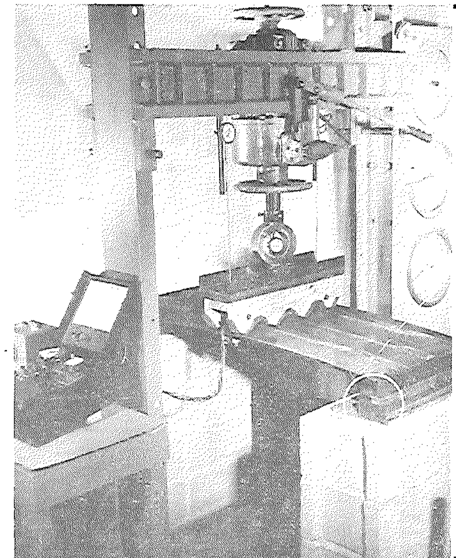


FIGURE 7. TRANSFER DEVICES USED TO PREVENT RESTRAINT AT THE COLUMN ENDS.



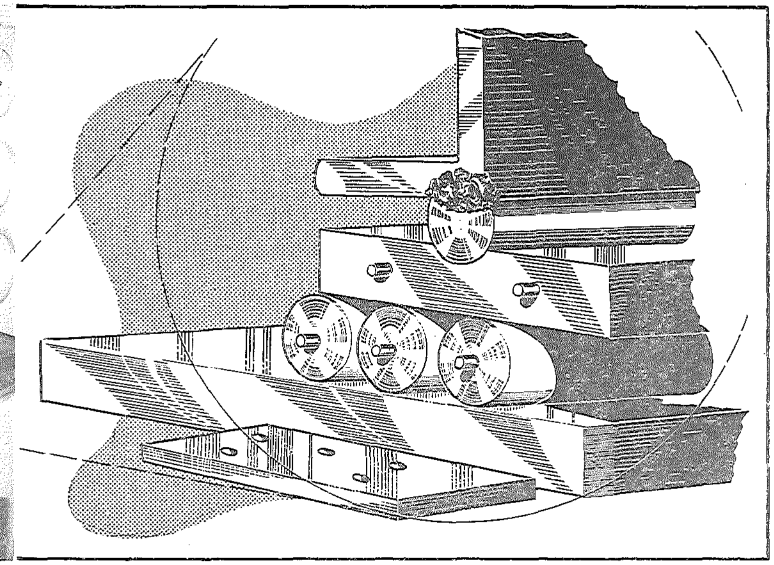
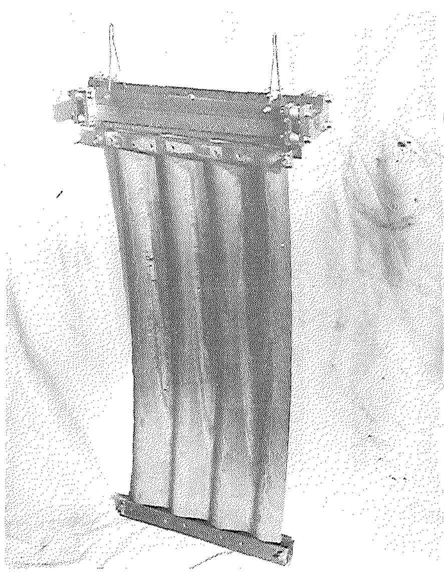


FIGURE 9. ARRANGEMENT FOR TESTS 5 AND 6.

FIGURE 8. UPPER LOADING HEAD IN POSITION AS USED IN COLUMN TEST.



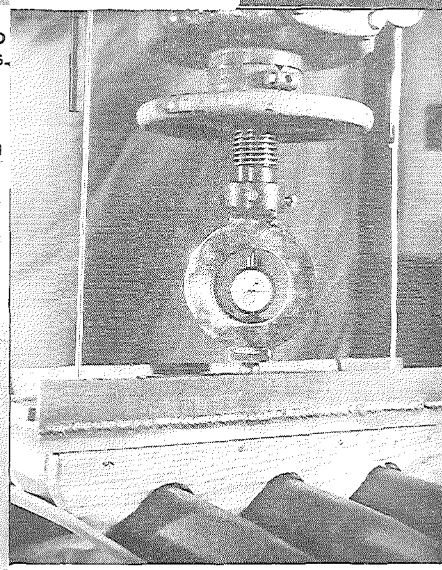
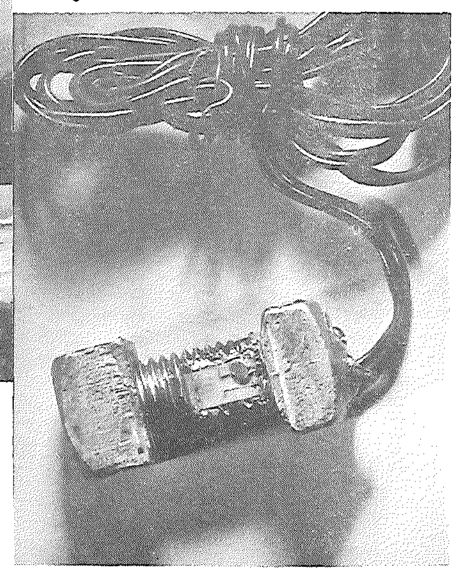


FIGURE 10. METHOD OF DISTRIBUTING LOAD THROUGH BEAMS.

FIGURE 11. GAGE ATTACHED TO BOLT FOR MEASUREMENT OF TENSILE STRAINS.



TESTING METHODS

vertical deflection. This arrangement may be seen in Figure 6.

This same 50-ton hydraulic press used for the column tests was also used for the beam tests 5 and 6. The ends of the beams rested on two concrete block piers capped with a 1- by 8- by 24-in. cold rolled steel plate. The plates were machined to a smooth finish and set at the same elevation.

In order to insure freedom from horizontal constraints on the ends of the beam specimens, a special load transfer device was designed. Each end of the corrugated metal plate specimen was set into the vertex formed by a 2-1/4- by 2-1/4-in. steel angle. To each angle was welded a 1-in. round steel bar. The round steel bars rested in a groove of 1-in. diameter milled in a flat steel plate. The flat steel plate, in turn, rested on three 1-in. round steel rollers which, in turn, rested on the steel caps of the two concrete block piers mentioned above. A photograph and diagram of this arrangement is shown in Figure 9.

Two-point loading was used to transfer the load from the hydraulic press to the beam being tested. It was impossible to use single-point loading at the center of the beam because the joint fastenings on the bolted sections interfered with this procedure. The span of the two-point loading was made just wide enough to clear the joints in the plates. For the sake of uniformity, the same type loading was also used on the unbolted plates.

Wooden patterns were cut to fit each of the various types of corrugation used in order to insure uniform distribution of the load across the test specimen. These patterns were lined with heavy rubber sheeting for a more perfect fit. The load was applied to a steel loading head through a 1-in. round ball bearing. Figure 10 exhibits the steel head and wooden patterns used to distribute the load.

The vertical deflections of the center of the beam were measured with two 0.001-in. dials. The dials were attached rigidly to the frame of the testing machine and extensions from the stem of the dial were put through openings in the loading head directly to the corrugated plate. Changes in the span of the beam were measured to 1/64 in. with a steel straight-edge.

Incidental equipment used included a torque wrench and a Baldwin Southwark indicator to measure the strains in various parts of the specimens.

Test Procedure

The procedure in all of the six fundamental tests was essentially the same. The special angle pieces were clamped onto the ends of the specimen; it was placed in the press and seated; the dials were adjusted; and the load was applied through the hydraulic jack in previously calculated increments. Application of the load continued through the yield point until a maximum value was reached after which succeeding deformations resulted from loads below this ultimate figure.

A special study of permanent deformations was made on some of the specimens. The loading program was altered by releasing the load between applications to obtain alternate no load conditions. Dial readings at no load showed progressive permanent deformation.

The bolted specimens were subjected to the same type of test as the plain specimens. The seams were first bolted together to a designated bolt torque value by the use of a torque wrench. The assembled plate was then installed and tested in the manner described.

Since there was some difference in joint reaction caused by variation in torque applied to the bolt it was necessary to determine a torque that would approximate the force applied by the average laborer in the field. Using a wrench slightly smaller than that employed in the field, five highway employees found that the average torque they could apply was 157 ft.-lb. Assuming that the laborer in the field has a larger wrench and also a better knack for using such tools it was agreed that a torque of 200 ft.-lb. would be very near to field usage. All bolts used in fastening joints for the plates were tightened with a torque of 200 ft.-lb. except in a few instances where changes were made for experimental purposes.

In all of the tests except number two, the short column bolted plate study, both horizontal and vertical deflections were measured. In Tests 1, 3, and 4, measurements were all made with 0.001-in. dials. In Tests 5 and 6 the vertical deflections were read from dials but the horizontal spread of the beam ends was read on a scale graduated in 64ths of an inch. No horizontal readings were taken on Test 2. This test was designed for the measurement of resistance to direct thrust and only the slippage at the lapped joint was recorded. The butt joints resisted the thrust by pure compression, and in these cases total vertical deflections of the assemblies were the only data taken.

When two or more similar plates were subjected to the same test, the results were averaged and the averages tabulated. The figures from the permanent deformation study and the experiment with double bolting were obtained from a single sample of each type. The data originally recorded were the load increments and the horizontal and vertical deflections from the 0.001-in. dials. The load increment varied according to the requirements of the test and was determined by the number of values needed to draw a smooth curve of the action of the plate under load. In Tests 1 and 2 it was 10000 lb. In Test 3 increments of 2000 lb. to 5000 lb. were used. Tests 4, 5, and 6 required smaller intervals, and the increments chosen for these tests were from 500 to 1000 lb.

Miscellaneous Tests

At opportune times during the regular testing program some supplementary studies were made. Strains in the outer fibers of the plates were measured on a few of the plates of Test 4. Several SR-4 type strain gages were attached to each side of the plate in tandem on the extreme fiber of the corrugations near the point of maximum bending moment of the plate. The data from the gage which produced the largest reading was selected as typical.

Tensile stresses on bolts were measured also. SR-4 strain gages were cemented to the bolts as shown in Figure 11. The joints were assembled with 200-lb.-ft. bolt torque and the plates were tested in the usual method.

The apparent strength of a number of bolts used in the joint assemblies was checked by actually twisting them by means of a torque wrench until failure, and measuring the ultimate torque in foot pounds.

Characteristics of the metal were also studied. Chemical analysis was furnished by the manufacturer. Brinell hardness tests using a 10 mm ball with a load of 500 kilograms were performed in the laboratory on small 2- by 2-in. specimens cut from the sheets. Test results will be found in Table 2, Appendix. Larger 12- by 15-in. samples were sent to the Bureau of Public Roads for determination of chemical and physical properties and modulus of elasticity. These data are presented in Table 3 A, B, and C, Appendix.

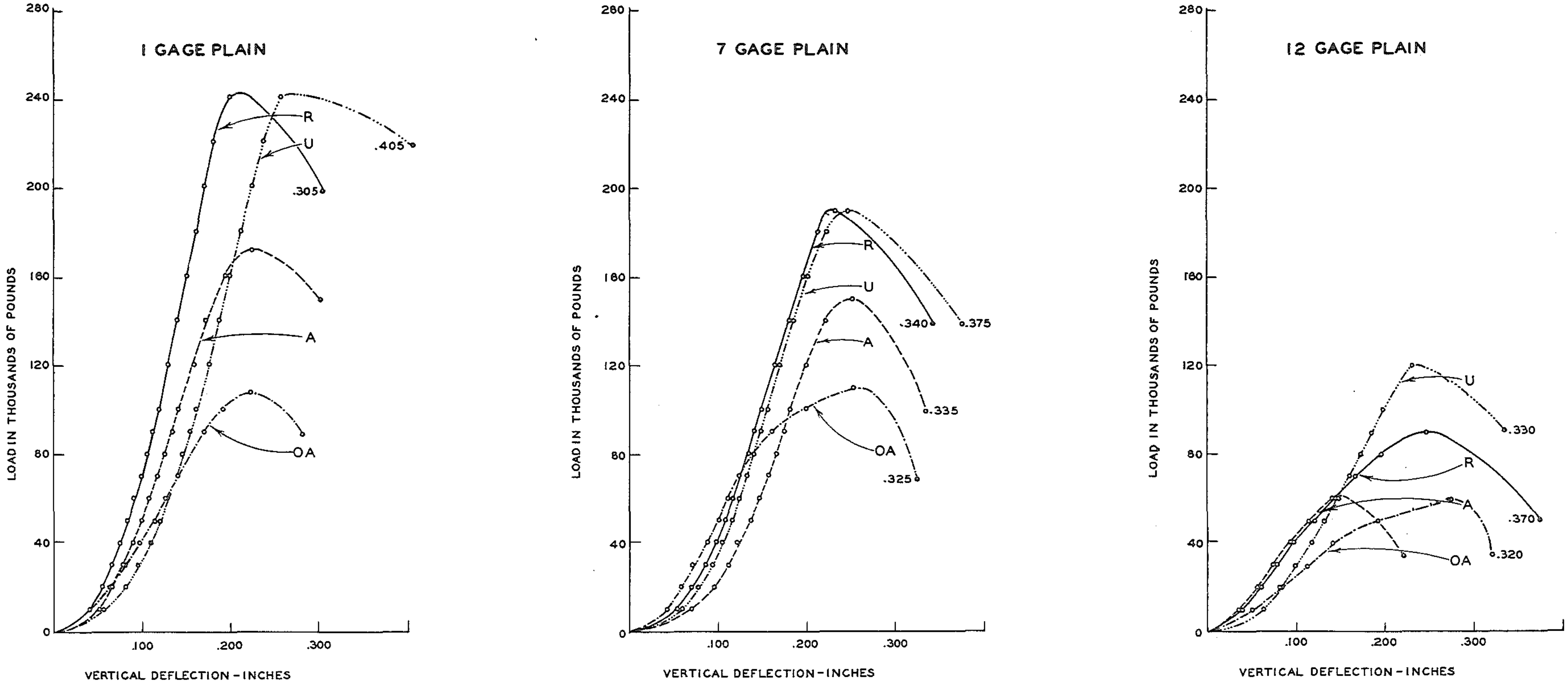
OBSERVATIONS

The results of the series of six tests are found in Tables 4 through 17 of the Appendix. The data therein has been used to construct graphs for a ready comparison of the influence of the various factors upon plate performance. The resulting curves are grouped where possible to bring out the effect of corrugation style in one case and effect of gage or plate thickness in another. Not all of the data is shown in graphic form because of the similarity in the shape and order of the curve.

Further comparisons are made on the basis of computed unit stress at the elastic limit and the modulus of rupture. These values were computed using the manufacturers' tabulated data for moment of inertia and section modulus. Measurements in Table 1 show that the measured values for thickness check within reasonable limits with the manufacturers' data shown in Table 1 of the Appendix. Other measurements that determine the moment of inertia were found to be within the same limits so that it was felt that the use of the tabulated values for section modulus and moment of inertia would be consistent with the degree of accuracy of the load deflection data.

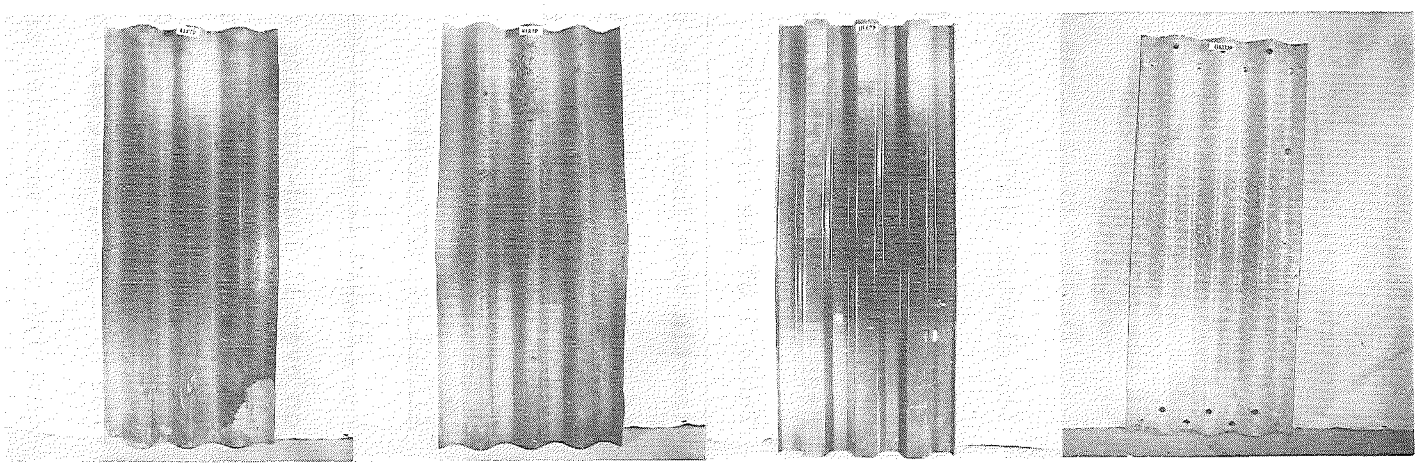
Effect of Corrugation

Figure 12 illustrates graphically the effect of style of corrugation on overall load-carrying capacity when acting as intermediate columns. Types U and R have very nearly the same capacity, Types A and OA have progressively lower load-carrying ability. These curves are drawn on the assumption that all the plates had the same overall dimension and that the only variables are the factors that determine the section modulus. The section moduli for Types U, R, A, and OA are progressively



INFLUENCE OF CORRUGATION ON DEFLECTIONS – TEST I.

FIGURE 12



TYPE A – 7 GAGE

TYPE R – 7 GAGE

TYPE U – 7 GAGE

TYPE OA – I GAGE

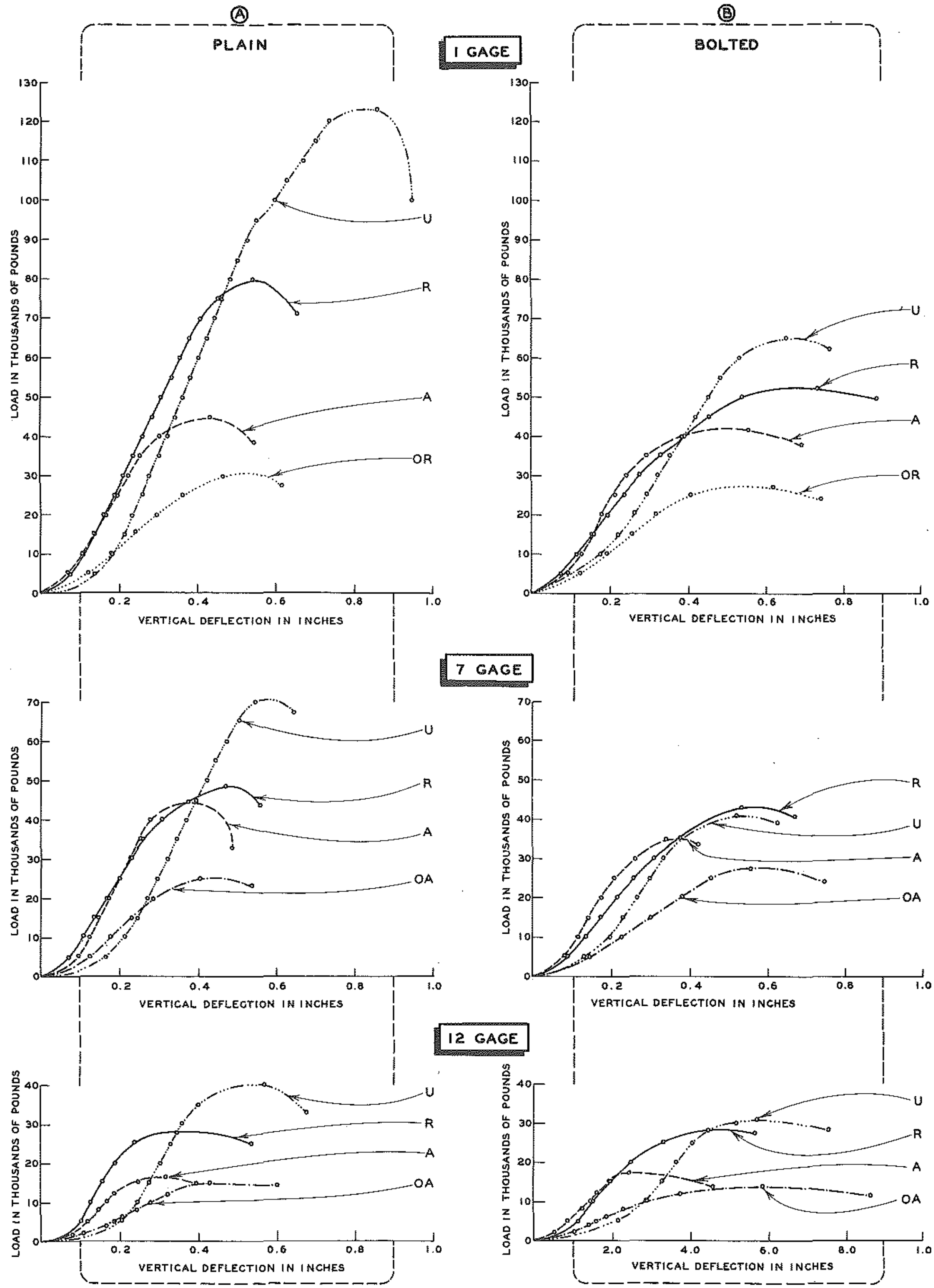
SPREADING OF SPECIMENS IN FAILURE – TEST I

FIGURE 13

less and except for the similarity in curves U and R the loads are in proportion to the load carrying ability. The close agreement in the loads carried by Types U and R would indicate that in the case where these plates are acted on as slender columns either Type R is more efficient than in succeeding tests or that Type U is not developing its full load carrying capacity.

In all styles of corrugation tested there was a progressive spreading and consequent reduction of depth in the cross section of the plates at the center. This reduction of depth decreased the moment of inertia of the plates and failure progressed rapidly when the spreading became apparent. Photographs of four types of specimens from Test 1 are shown in Figure 13.

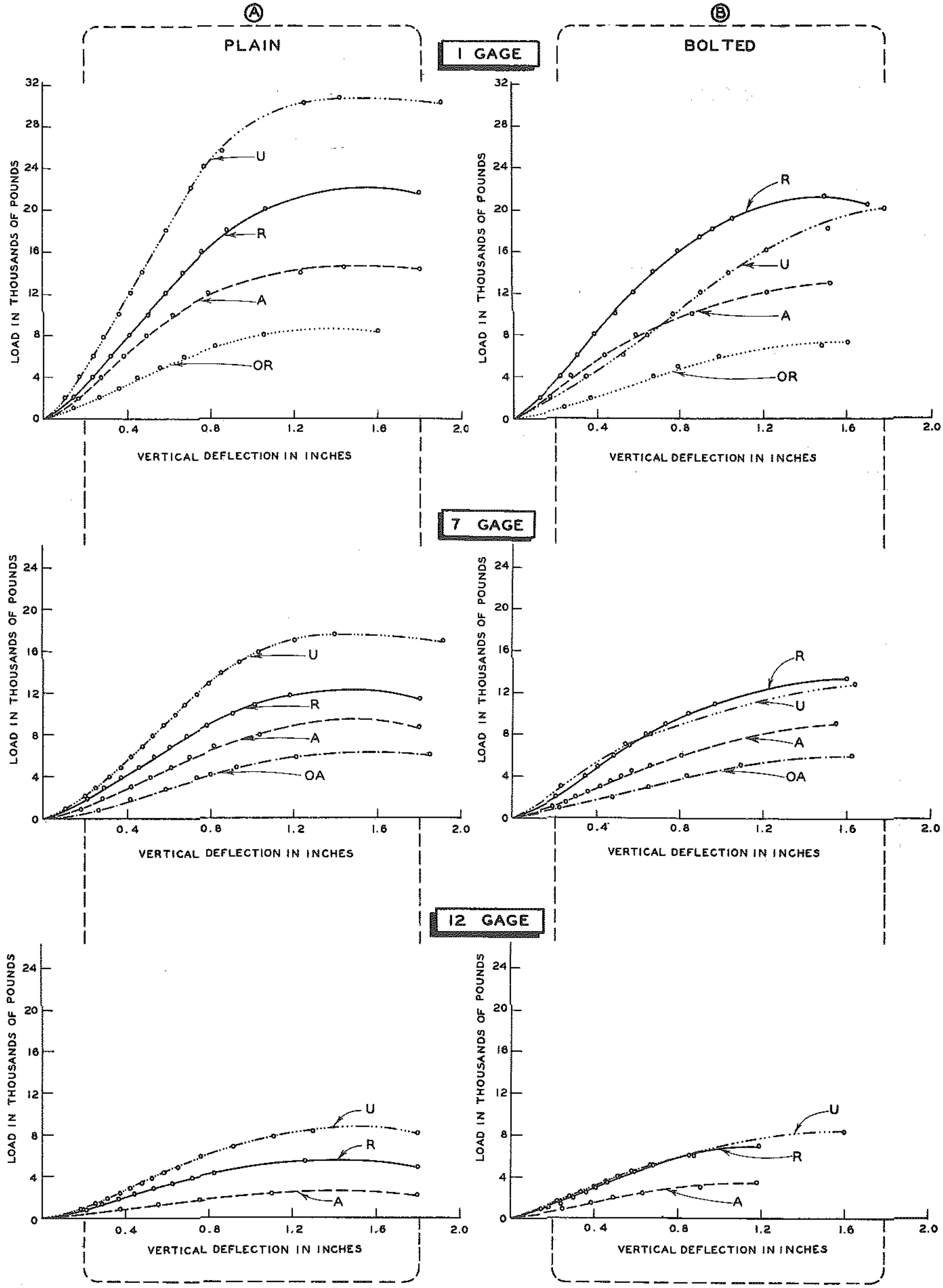
Tests 3 and 4 are further column tests except that the columns are curved having radii of 150 in. and 30 in., respectively. (See Figure 2) The graphs for these load-deflection tests are found in Figures 14 and 15. The curves for the unbolted specimens (Figure 14 A and 15A) have very nearly the same pattern as those for Test 1 shown in Figure 12. Here the difference between the load carrying capacity of Types U, R, A, OA, and OR are more apparent and are of the same order as the different section moduli. A different pattern may be noted for the bolted plates in Tests 3 and 4, as shown in Figure 14B and 15 B. The superiority of the U type is not nearly as evident in this case. In fact, in the bolted specimens of Test 4, the Type R corrugation is superior to Type U. This will be discussed further in the section on joint efficiency.



INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 3

FIGURE 14



INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 4

FIGURE 15

Strain Measurements - For a further analysis of the effect of corrugation, strain gages were placed as nearly as possible to the point of maximum strain on specimens in Test 4. One sample of each of the three corrugation styles was analyzed in this manner. The resulting data is shown in Table 2. A coefficient of elasticity (E) of 29,000,000 psi. was assumed.

TABLE 2

LOAD VS. STRAIN IN EXTREME FIBERS OF CORRUGATED PLATE

Load in Thousand Pounds	Fiber Strain *Micro. in./in. Convex surface Spec. U4Z1P	Fiber Strain Micro in./in. Convex surface Spec. R4Z1P	Fiber Strain Micro. in./in. Concave surface Spec. R4Z1P	Fiber Strain Micro. in./in. Convex surface Spec. A4Z1P
1				172
2	163	210	-248	280
3				387
4	259	417	-489	487
5				610
6	436	617	-718	742
7				873
8	565	740	-930	965
9				1140
10	710	928	-1136	1303
11				1522
12	859	1153	-1378	1873
13				2352
14	983	1366	-1540	3500
15				at 14.0
16	1104	1581	-1645	
17				
18	1254	1931	-1785	
19				
20	1404	2353	-2030	
21				
22	1552	3256	-2990	
23		7662	-8570	
24	1758	at 22.5	at 22.5	
25				
26	2464			
27				
28	3145			
29	over 5000			
30	at 29.8			

*micro-in. is .000001 in.

The unit stress at the elastic limit has been computed from the observed elastic limits in Figure 15 A. These elastic limits are found to be:

Type A - 10,000 lb.
Type R - 16,000 lb.
Type U - 22,000 lb.

From the observed strain readings at these points (Table 2) the computed stresses are:

Type A - tension face - 37,800 psi
Type R - tension face - 45,850 psi
Type R - compression face - 47,700 psi
Type U - tension face - 45,000 psi

Computing the stresses for these same three specimens using the manufacturers' tabulated values for section modulus and substituting in the eccentric column formula $S = P/A + MC/I$ the computed stresses are:

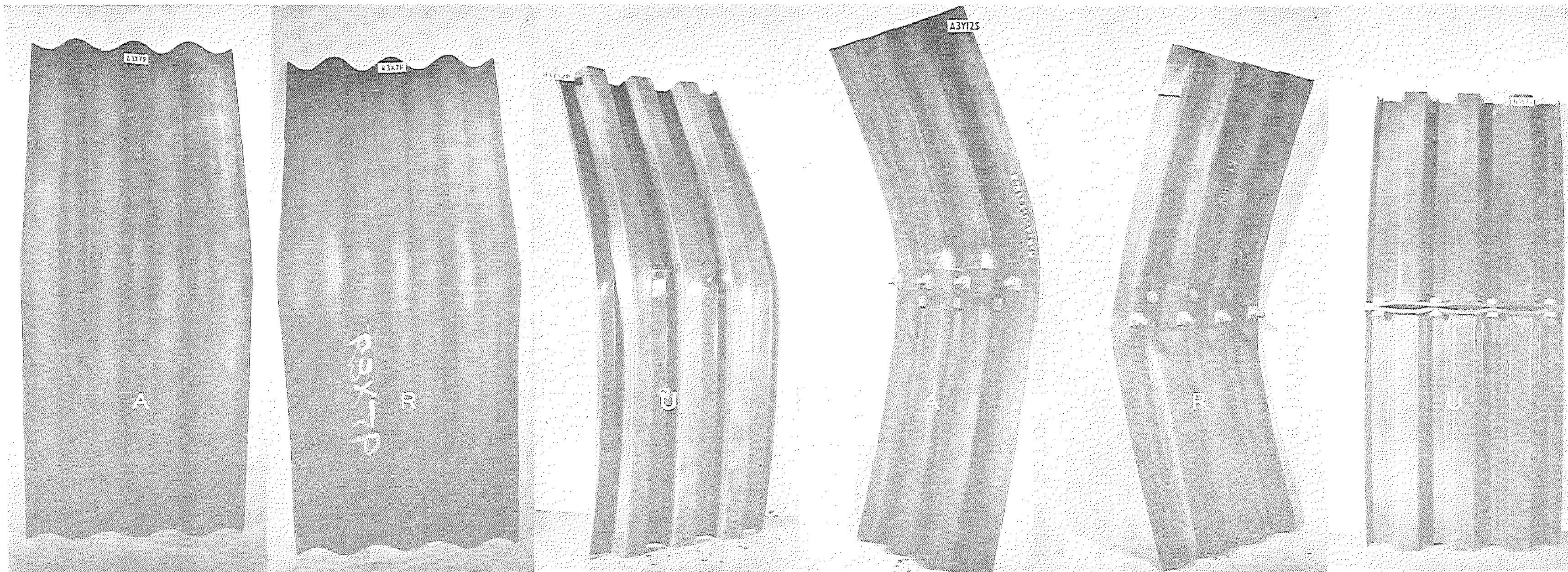
Type A - tension face - 38,230 psi
Type R - tension face - 53,570 psi
Type R - compression face - 57,830 psi
Type U - tension face - 45,750 psi

The two methods of computing stress compare quite favorably, indicating the section modulus as furnished for these style corrugations furnishes reasonable stress values.

The characteristic failure of the principal styles of corrugation subject to loading conditions such as those in Test 3 and 4 are illustrated in Figures 16 and 17. The circular arc type corrugations both have the characteristic spreading that occurs when the plates are subjected to column action. The box type corrugation is also subject to some spreading under load and as shown in Figure 16, there is also evidence of localized buckling near the section in maximum stress.

The load deflection data for Tests 5 and 6 are shown in Figures 18 and 19 and make possible an evaluation of the effect of corrugation

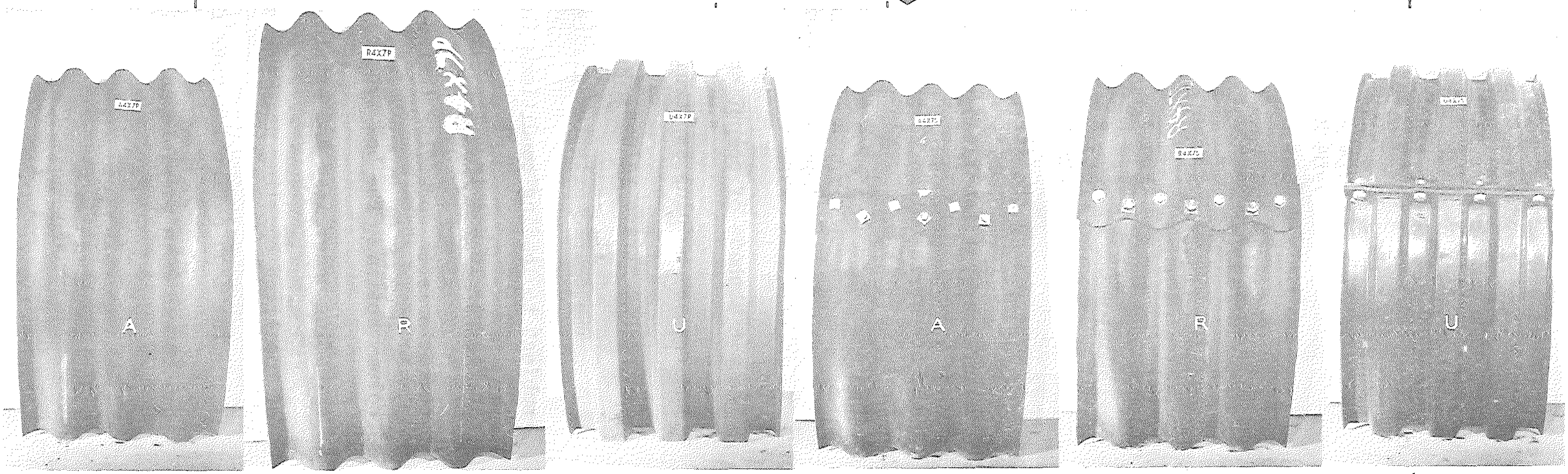
PLAIN BOLTED

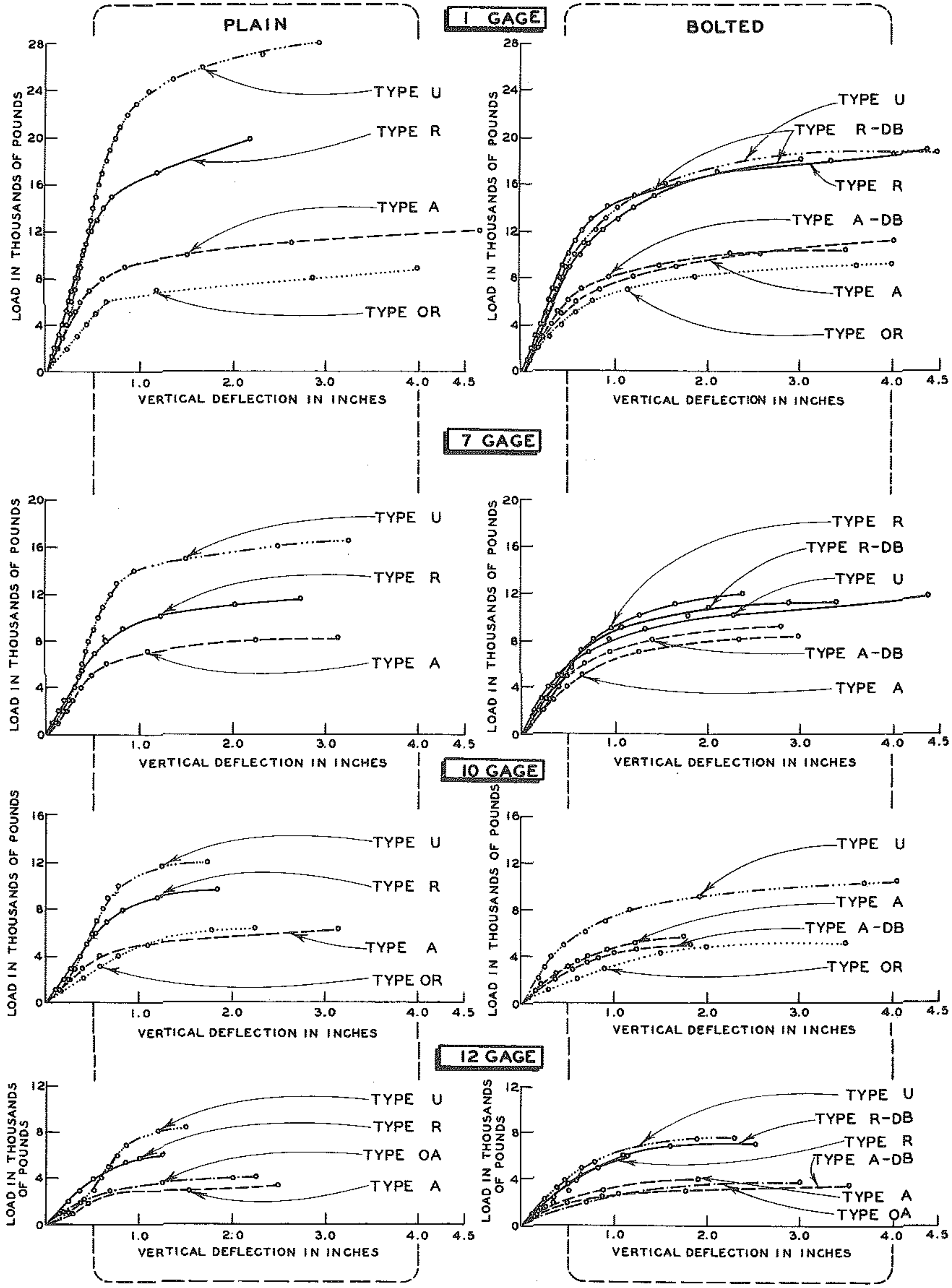


TYPICAL FAILURES

TEST 3 - FIGURE 16

TEST 4 - FIGURE 17

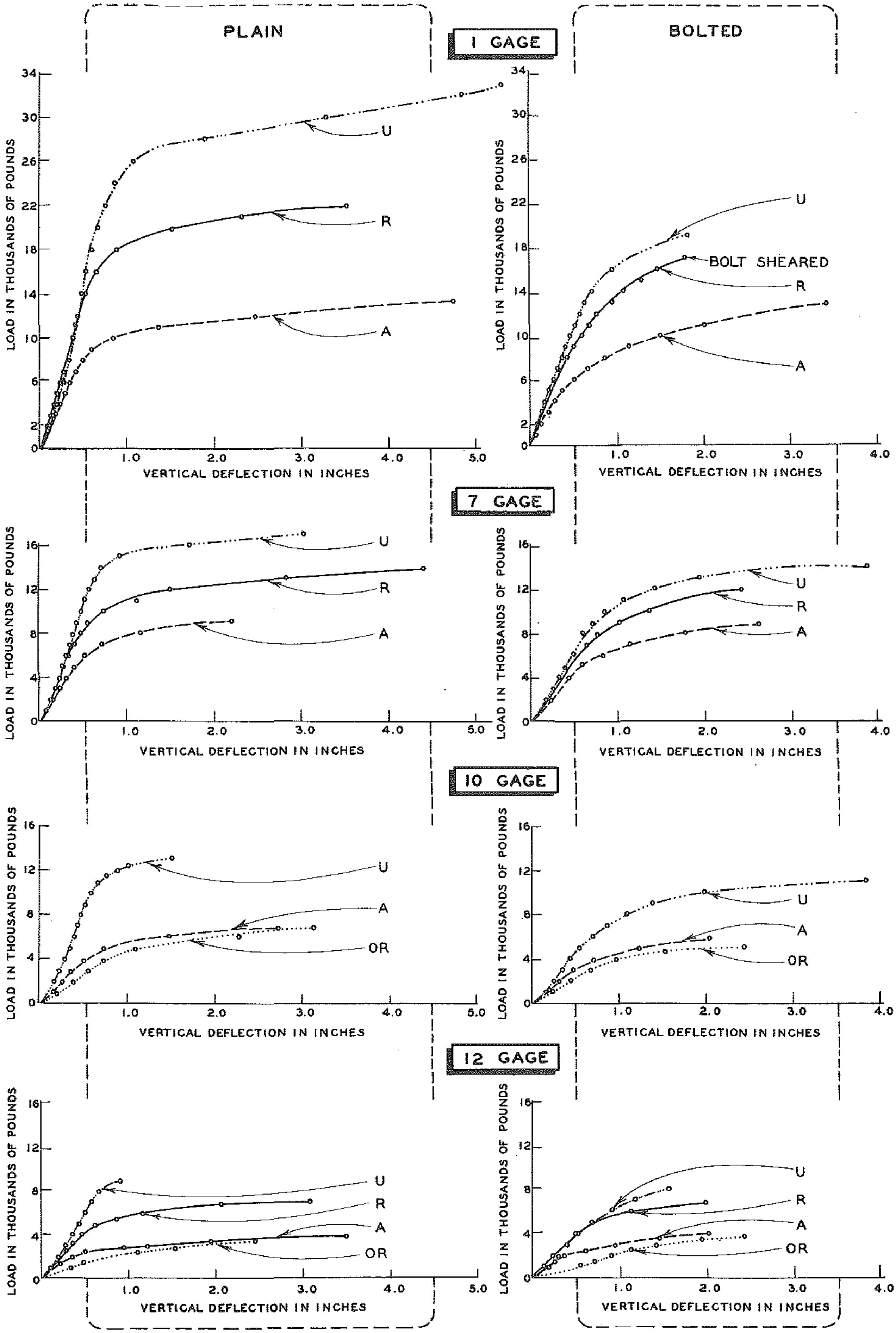




INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 5

FIGURE 18



INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 6

FIGURE 19

style upon plate performance from two points of view, namely, the behavior in the elastic range and the performance in the yielding range up to the point of ultimate load.

In the elastic portion of the curve the stiffness of the plate is indicated by the slope of the straight line section. From Figures 18 and 19 one observes that for plain specimens, plates U, R, and A have a comparable degree of stiffness in gages 1 and 7. The lighter gages do not follow any well-defined pattern. The elastic limits are highest for U, less for R, and lowest for A style plates. Unit stress values at elastic limits for Tests 5 and 6 are presented in Tables 3 and 4.

There are at least two methods of evaluating performance above the elastic limit. The first and most direct is a comparison of ultimate loads, and the second is a comparison of modulus of rupture values.

Again reference to Figures 18 and 19 shows that among the three newer corrugations the ultimate loads are greatest for the U style, and lowest for the A style. For further analysis in this respect, Table 5 has been prepared. Values of the section modulus (I/C), and ultimate load have been tested for three types of corrugation and for four metal gages. The ratios in the third and fifth column are the quotient of the corresponding entries in columns two and four by the lowest values in that group.

The pattern of Table 5 substantiates the observations from the graphs in that the ultimate loads are greatest for the U style, less for R and least for A, This is to be expected since the section modulus values decrease in the same order. A further examination shows that the ratios of ultimate loads are greater than the ratio of the section moduli except in one instance.

TABLE 3

UNIT STRESS AT ELASTIC LIMIT - TEST 5

Specimen	(1) Load at Elastic Limit (lb.)	(2) Working Length (L - 4.38) (in.)	(3) Bending Moment $(3)=\frac{(1)x(2)}{4}$ (in.-lb.)	(4) Total Section Modulus (in.^{3})	(5) Unit Stress at Elastic Limit (5) = (3) ÷ (4) (psi)	Average (psi)
U5X1P	17000	48.12	204400	5.11	40000	
U5Y1P	17000	48.07	204300	5.11	40000	
U5Z1P	19000	48.15	228600	5.11	44800	41600
U5X7P	11000	48.04	132000	3.405	38800	
U5Y7P	11000	48.04	132200	3.405	38800	
U5Z7P	12000	48.07	144200	3.405	42350	39983
U5X10P	9500	47.76	113500	2.615	43400	
U5Y10P	9000	47.95	107800	2.615	41200	
U5Z10P	9000	48.10	108100	2.615	41400	42000
U5X12P	7000	48.13	84200	2.066	40800	
U5Y12P	7000	48.18	84300	2.066	40800	
U5Z12P	5000	48.12	60200	2.066	29200	36930
R5X1P	11000	- - -	- - -	- - -	- - -	
R5Y1P	12000	48.39	145000	3.19	45400	
R5Z1P	12000	48.33	144800	3.19	45400	45400
R5X7P	7000	47.96	83800	2.165	38700	
R5Y7P	6000	48.17	72300	2.165	33400	
R5Z7P	7000	48.23	84400	2.165	39000	37030
R5X10P	6000	48.15	72200	1.641	43900	
R5Y10P	6000	48.10	72200	1.641	43900	
R5Z10P	6000	48.03	72200	1.641	43900	43900
R5X12P	3500	48.20	42200	1.288	32775	
R5Y12P	4000	48.03	48000	1.288	37375	
R5Z12P	4000	48.12	48120	1.288	37375	35842
A5X1P	6000	48.03	72100	2.782	25900	
A5Y1P	6000	48.00	72000	2.782	25850	
A5Z1P	7000	48.00	84000	2.782	30200	27320
A5X7P	4500	48.21	54200	1.882	28800	
A5Y7P	4500	48.20	54200	1.882	28800	
A5Z7P	5000	48.09	60100	1.882	31900	29830
A5X10P	3000	48.03	36100	1.438	25100	
A5Y10P	3000	47.82	35900	1.438	25000	
A5Z10P	3000	48.07	36100	1.438	25100	25067
A5X12P	2000	48.06	24030	1.131	21250	
A5Y12P	2000	48.01	24000	1.131	21250	
A5X12P	2000	47.98	23990	1.131	21250	21250
OR5X1P	6000	47.85	71775	2.006	35432	35432
OR5X10P	4500	47.98	53977	1.045	51652	
OR5Y10P	4500	48.09	54101	1.045	51771	51711
OA5X12P	3000	48.34	36255	0.807	44926	
OA5Y12P	3000	48.15	36.113	0.807	44750	44838

TABLE 4

UNIT STRESS AT ELASTIC LIMIT - TEST 6

Specimen	(1) Load at Elastic Limit (lb.)	(2) Working Length (L - 4.38) (in.)	(3) Bending Moment (3)=(1)x(2)/4 (in.-lb.)	(4) Total Section Modulus ($in.^3$)	(5) Unit Stress at Elastic Limit (5) = (3)÷(4) (psi)	Average (psi)
U6X1P	20000	45.82	229100	5.11	44800	
U6Y1P	18000	45.73	206000	5.11	40300	
U6Z1P	19000	46.00	218500	5.11	42700	42600
U6X7P	11500	45.75	131700	3.405	38700	
U6Y7P	12000	45.96	137800	3.405	40400	
U6Z7P	12000	45.79	137300	3.405	40300	39800
U6X10P	10000	45.73	114500	2.615	43800	
U6Y10P	10000	45.90	114500	2.615	43800	
U6Z10P	10000	45.95	114600	2.615	43800	43800
U6X12P	7000	45.48	79600	2.064	38600	
U6Y12P	7500	45.82	85900	2.064	41500	
U6Z12P	8000	45.60	91200	2.064	44200	41433
R6X1P	12000	45.70	137200	3.189	43000	
R6Y1P	12000	45.54	136800	3.189	42900	
R6Z1P	11000	45.31	124500	3.189	39100	41670
R6X7P	7000	45.67	79800	2.165	36800	
R6Y7P	7000	45.73	80100	2.165	36800	
R6Z7P	8000	46.09	92200	2.165	42600	38730
R6X12P	4000	45.87	45870	1.288	35600	
R6Y12P	4000	45.50	45500	1.288	35400	
R6Z12P	4500	45.48	51100	1.288	39700	36900
A6X1P	8000	45.73	91460	2.782	32800	
A6Y1P	8000	45.73	91460	2.782	32800	
A6Z1P	7000	45.78	80200	2.782	28800	31450
A6X7P	5000	45.46	56800	1.882	30200	
A6Y7P	5000	45.68	57100	1.882	30300	
A6Z7P	5000	45.70	57200	1.882	30400	30300
A6X10P	4000	46.00	46000	1.438	32000	
A6Y10P	4000	46.17	46170	1.438	32100	
A6Z10P	3500	45.78	40100	1.438	27900	30650
A6X12P	2000	45.57	22780	1.131	20200	
A6Y12P	2000	45.76	22880	1.131	20200	
A6Z12P	2000	45.50	22750	1.131	20200	20200
OR6X10P	4000	46.18	46180	1.045	44191	
OR6Y10P	4000	46.35	46350	1.045	44354	44272
OR6X12P	1500	46.00	17250	0.8228	20965	
OR6Y12P	1500	46.25	17344	0.8228	21079	21022

TABLE 5

EFFECT OF CORRUGATION AND SECTION MODULUS ON
ULTIMATE LOAD AND MODULUS OF RUPTURE

(Based on Test 5)

Type and Gage of Corrugation	I/C	Ratio	Ultimate Load (in lb.)	Ratio	Modulus of Rupture (in psi)	Ratio
U 1 gage	5.11	1.84	28,000	2.31	66,406	1.26
R 1 gage	3.189	1.15	18,900	1.56	72,454	1.38
A 1 gage	2.782	1.00	12,100	1.00	52,595	1.00
U 7 gage	3.405	1.81	16,600	1.98	59,090	1.09
R 7 gage	2.165	1.15	11,500	1.37	64,873	1.20
A 7 gage	1.882	1.00	8,400	1.00	54,066	1.00
U 10 gage	2.615	1.82	11,800	1.88	54,385	1.03
R 10 gage	1.641	1.14	9,750	1.43	72,055	1.36
A 10 gage	1.438	1.00	6,300	1.00	52,929	1.00
U 12 gage	2.063	1.82	8,400	2.25	49,235	1.23
R 12 gage	1.288	1.14	6.070	1.62	57,123	1.43
A 12 gage	1.131	1.00	3,740	1.00	39,960	1.00

Another basis for evaluation of corrugation efficiency is a comparison of moduli of rupture. These cannot be seen graphically but are computed by the formula

$$S_r = PKC/I$$

where P is the ultimate load, K is moment arm at ultimate load position, and the ratio I/C is section modulus of the plate. Modulus of rupture values for all plates in Tests 5 and 6 have been computed and are listed in Tables 6 and 7. However, for immediate comparison these figures have been grouped and averaged and are shown in columns 6 and 7 of Table 5 in such a way that the trend is evident.

The ratios of the modulus of rupture figures do not follow the same pattern as the ultimate loads. In this case the R type corrugation seems superior, while next in order are U and A. There is apparently no direct relationship between modulus of rupture and section modulus. Possible reasons for this fact are: first, the corrugation shape changes with a consequent change in section modulus value at the point of failure, and second, the stress formula is applied in a yield region where elastic relationships no longer exist.

Figures 20 and 21 illustrate typical failures for plain and bolted circular type corrugated specimens in Tests 5 and 6. As expected the maximum deflection occurs at the point of maximum bending moment. In the bolted specimens the maximum bending appears to occur at the row of bolt holes in the "top" plate at the joint. Figure 22 illustrates typical failures for the box-type corrugation. There is evidence of localized buckling in this style corrugation, and in the jointed specimens failure occurs more readily in the joint than in the corrugations themselves.

TABLE 6

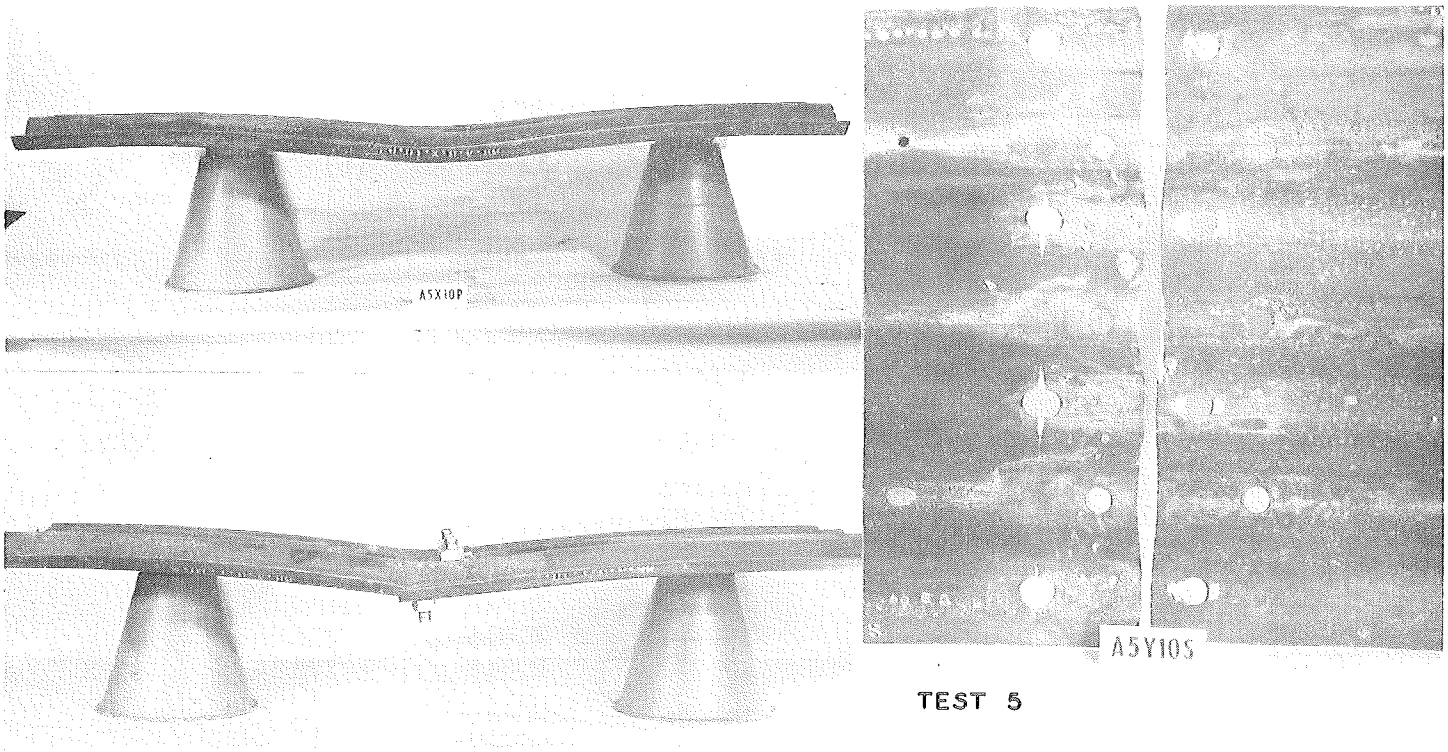
MODULUS OF RUPTURE - TEST 5

Specimen	(1) Ultimate Load (lb.)	(2) Working Length (L - 4.38) (in.)	(3) Bending Moment (3)=(1)x(2)/4 (in.-lb.)	(4) Total Section Modulus ($in.^3$)	(5) Modulus of Rupture (5) = (3)÷(4) (psi)	Average (psi)
U5X1P	28000	48.48	339360	5.11	66411	
U5Y1P	28000	48.38	338660	5.11	66274	
U5Z1P	28000	48.57	339990	5.11	66534	66406
U5X7P	16800	48.37	203154	3.405	59663	
U5Y7P	16850	48.29	203422	3.405	59742	
U5Z7P	16240	48.38	196423	3.405	57866	59090
U5X10P	12000	48.01	144030	2.615	55078	
U5Y10P	12000	48.20	144600	2.615	55296	
U5Z10P	11400	48.43	138026	2.615	52782	54385
U5X12P	8100	48.31	97828	2.066	48298	
U5Y12P	9000	48.38	108855	2.066	52689	
U5Z12P	8000	48.26	96520	2.066	46718	49235
R5X1P	17400	- - -	- - -	- - -	- - -	
R5Y1P	19300	48.62	234590	3.19	73539	
R5Z1P	18600	48.96	227664	3.19	71368	72454
R5X7P	11520	48.67	140170	2.165	64744	
R5Y7P	11800	48.68	143606	2.165	66330	
R5Z7P	11300	48.70	137578	2.165	63546	64873
R5X10P	9720	48.51	117879	1.641	71834	
R5Y10P	10000	48.46	121150	1.641	73826	
R5Z10P	9550	48.46	115698	1.641	70505	72055
R5X12P	5720	48.45	69284	1.288	53792	
R5Y12P	6500	48.49	78796	1.288	61177	
R5Z12P	6000	48.43	72645	1.288	56401	57123
A5X1P	12180	48.41	147408	2.782	52986	
A5Y1P	12180	48.21	146799	2.782	52767	
A5Z1P	12000	48.25	144750	2.782	52031	52595
A5X7P	8000	48.45	96900	1.882	51488	
A5Y7P	8500	48.46	102978	1.882	54717	
A5Z7P	8700	48.45	105379	1.882	55993	54066
A5X10P	6180	48.46	74870	1.438	52065	
A5Y10P	6125	48.37	74067	1.438	51507	
A5Z10P	6550	48.49	79402	1.438	55217	52929
A5X12P	3600	48.38	43542	1.131	38498	
A5Y12P	3620	48.28	43693	1.131	38632	
A5Z12P	4000	48.35	48350	1.131	42750	39960
OR5X1P	8500	48.28	102595	2.006	51144	51144
OR5X10P	6300	48.12	75789	1.045	72525	
OR5Y10P	6360	48.37	76908	1.045	73596	73060
OA5X12P	4440	48.54	53879	0.807	66765	
OA5Y12P	3940	48.31	47585	0.807	58965	62865

TABLE 7

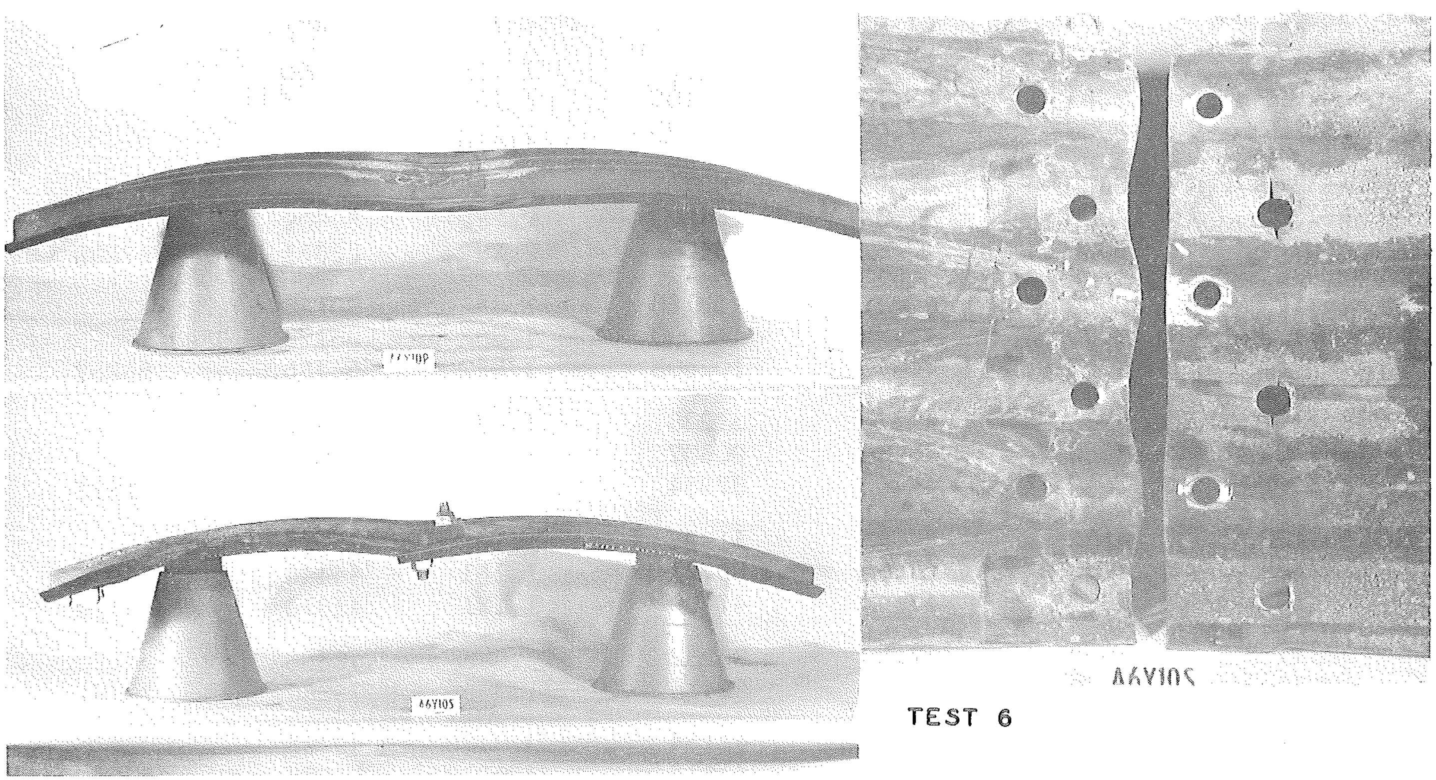
MODULUS OF RUPTURE - TEST 6

Specimen	(1) Ultimate Load (lb.)	(2) Working Length (L - 4.38) (in.)	(3) Bending Moment $(3) = \frac{(1) \times (2)}{4}$ (in.-lb.)	(4) Total Section Modulus (in.^{3})	(5) Modulus of Rupture $(5) = (3) \div (4)$ (psi)	Average (psi)
U6X1P	33850	47.73	403915	5.11	79044	
U6Y1P	33850	47.56	402476	5.11	78762	
U6Z1P	32000	48.04	384320	5.11	75209	77672
U6X7P	17300	47.21	204183	3.405	59966	
U6Y7P	17200	47.57	204551	3.405	60074	
U6Z7P	17400	47.37	206050	3.405	60514	60185
U6X10P	12300	46.82	143970	2.615	55055	
U6Y10P	12000	46.73	140190	2.615	53610	
U6Z10P	13195	47.07	155270	2.615	59376	56013
U6X12P	9180	45.85	105220	2.064	50979	
U6Y12P	9300	46.28	107600	2.064	52132	
U6Z12P	9300	46.15	107300	2.064	51986	51699
R6X1P	21000	47.40	248850	3.189	78034	
R6Y1P	21860	47.57	259970	3.189	81521	
R6Z1P	23000	47.32	272090	3.189	85321	81625
R6X7P	13800	47.57	164116	2.165	75804	
R6Y7P	13650	47.95	163630	2.165	75580	
R6Z7P	14000	47.56	166460	2.165	76887	76090
R6X12P	7220	47.31	85394	1.288	66300	
R6Y12P	7055	47.12	83107	1.288	64524	
R6Z12P	8000	47.09	94180	1.288	73121	67982
A6X1P	13650	47.59	162401	2.782	58376	
A6Y1P	14000	47.54	166390	2.782	59809	
A6Z1P	13000	47.62	154765	2.782	55631	57939
A6X7P	9600	47.15	113160	1.882	60128	
A6Y7P	10000	47.56	118900	1.882	63178	
A6Z7P	8650	47.40	102503	1.882	54465	59257
A6X10P	6800	47.78	81226	1.438	56485	
A6Y10P	7560	47.94	90607	1.438	63009	
A6Z10P	7410	47.43	87864	1.438	61101	61413
A6X12P	4385	47.43	51995	1.131	45973	
A6Y12P	4220	47.65	50271	1.131	44448	
A6Z12P	4000	47.40	47400	1.131	41910	44110
OR6X10P	7000	47.59	83282	1.045	79696	
OR6Y10P	6930	47.57	82415	1.045	78866	79281
OR6X12P	3500	47.01	41134	0.8228	49993	
OR6Y12P	3500	47.56	41615	0.8228	50577	50285



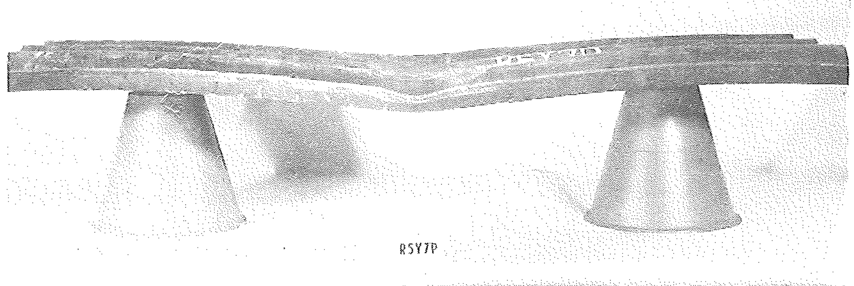
TEST 5

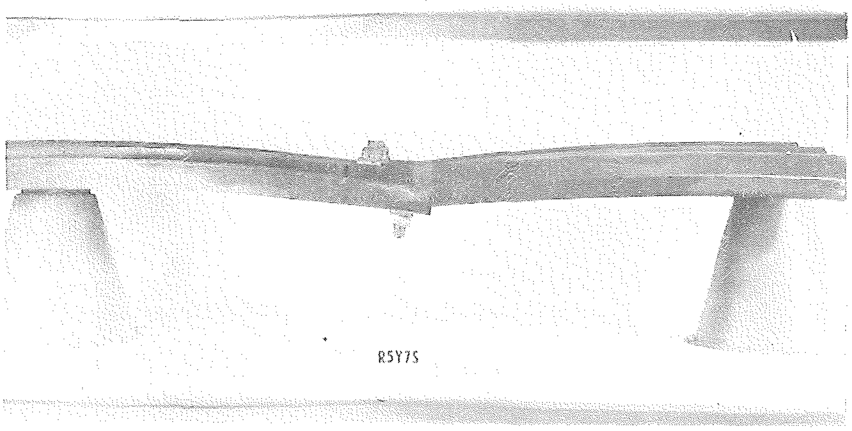
TYPICAL FAILURES, PLAIN & BOLTED, TYPE A

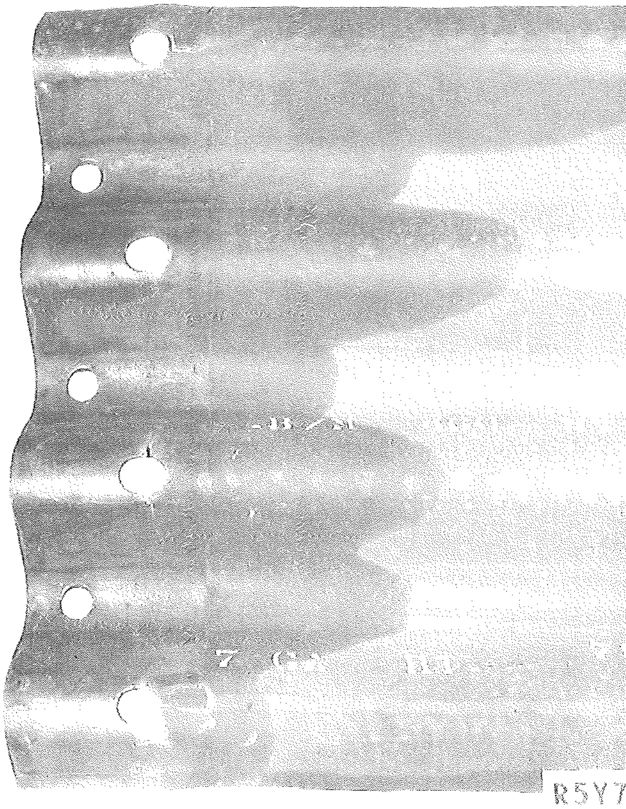


TEST 6

FIGURE 20





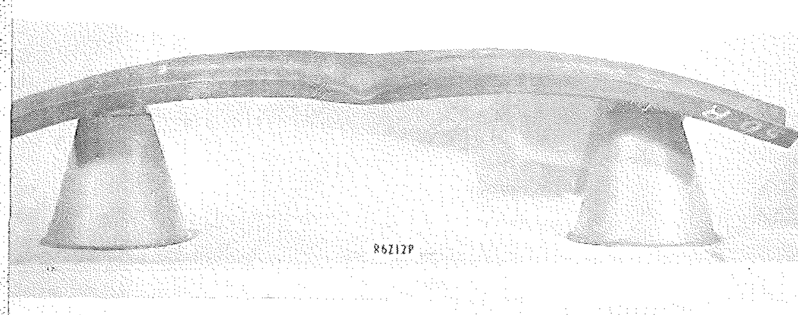


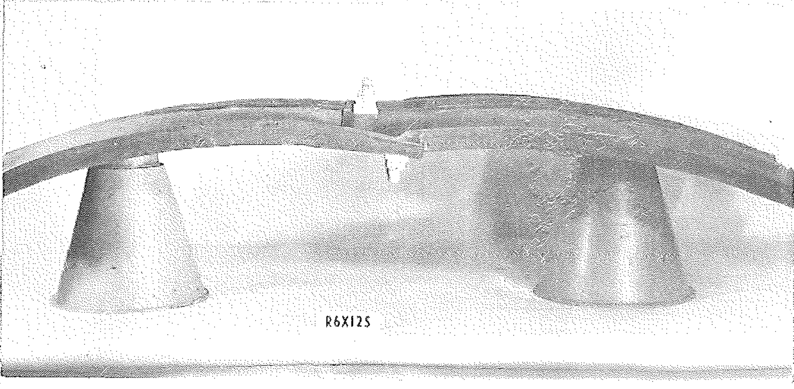
TEST 5

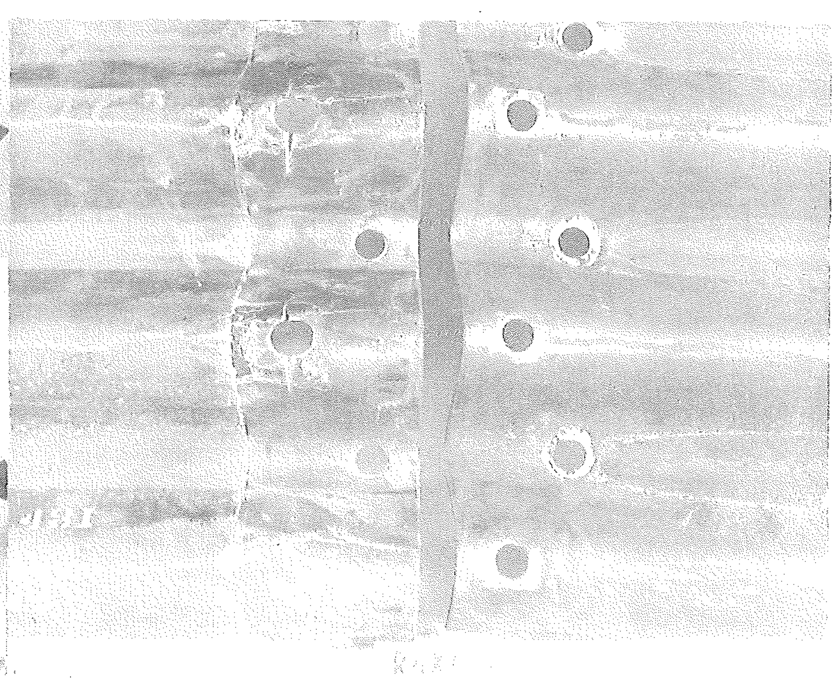
TYPICAL FAILURES, PLAIN & BOLTED, TYPE R

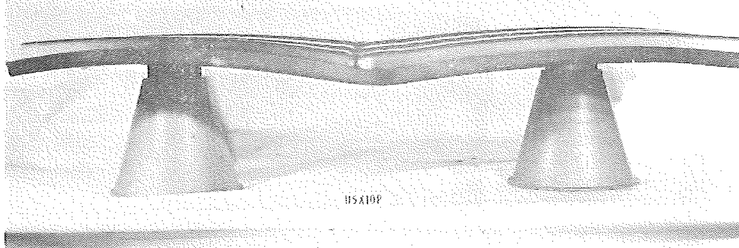
FIGURE 21

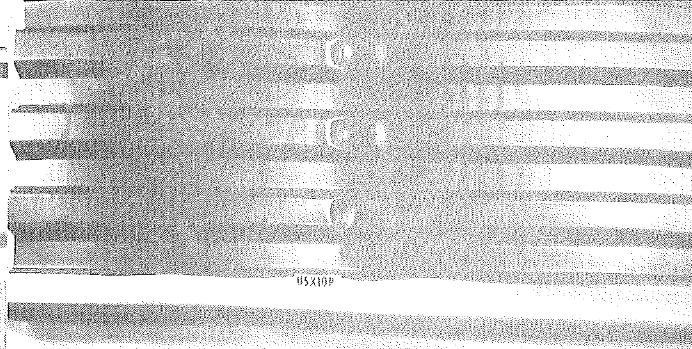
TEST 6

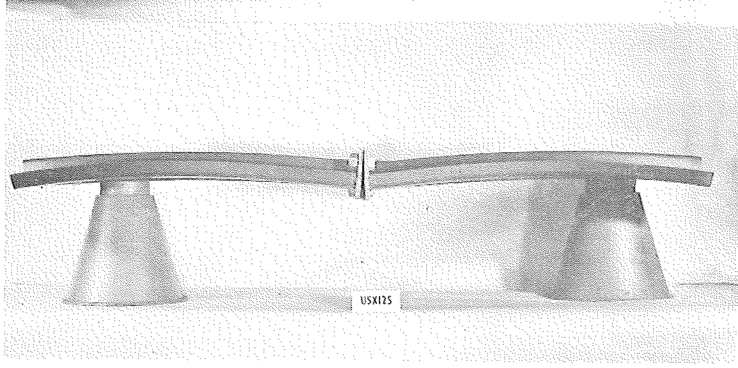


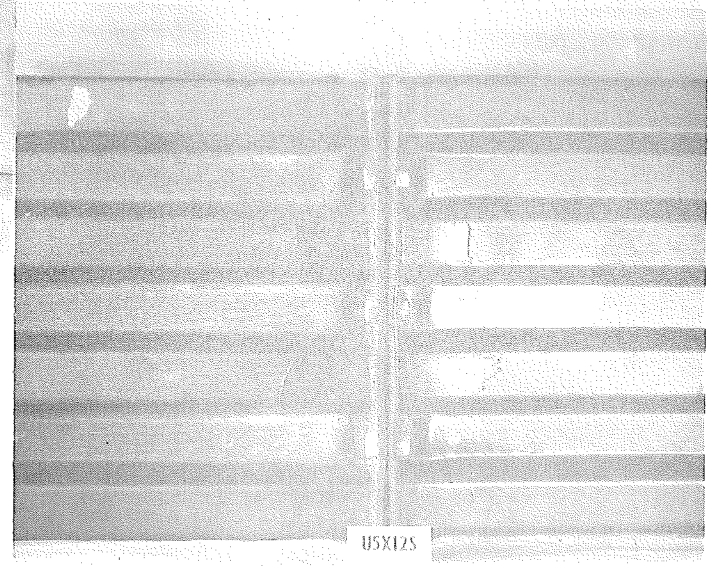










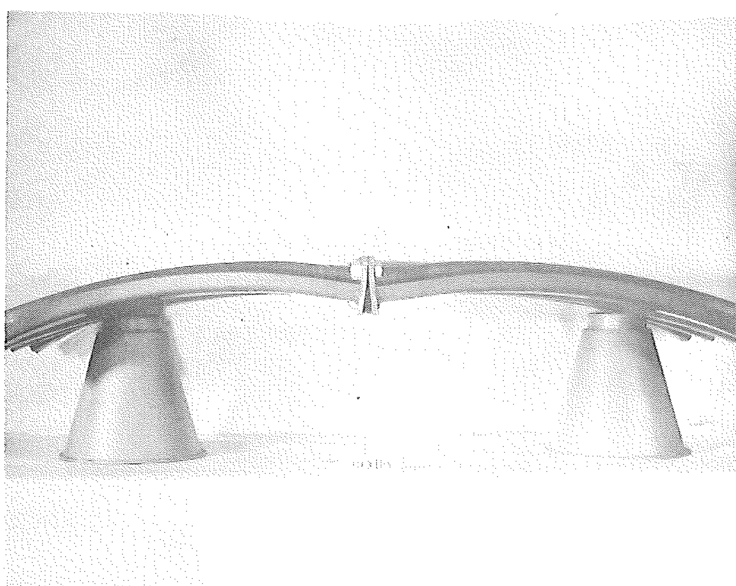


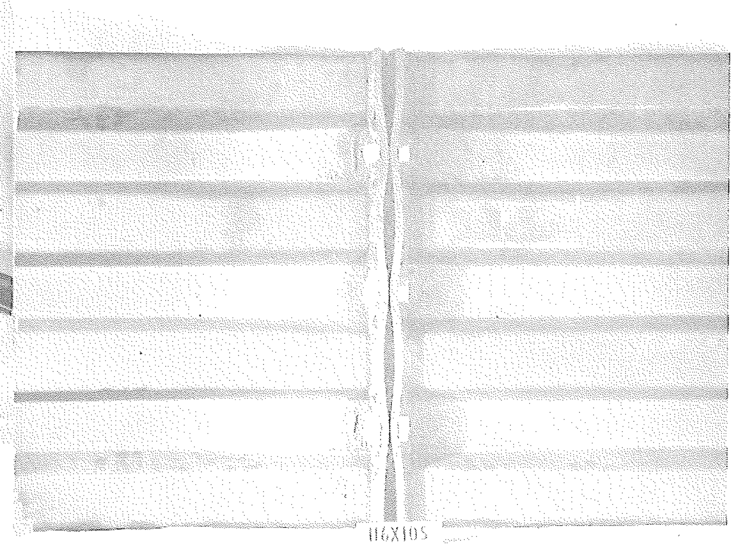
TEST 5

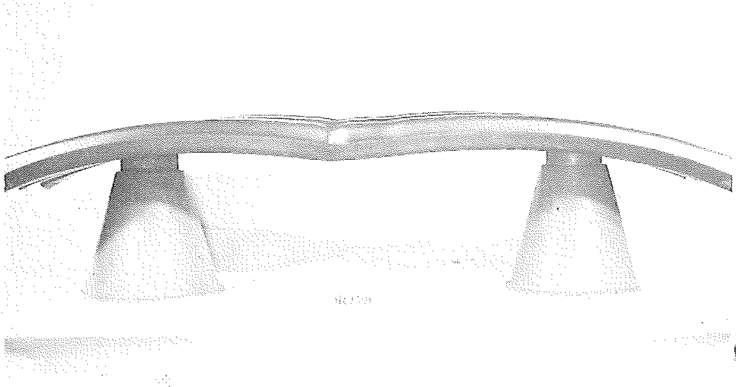
TYPICAL FAILURES
TYPE U
PLAIN & BOLTED

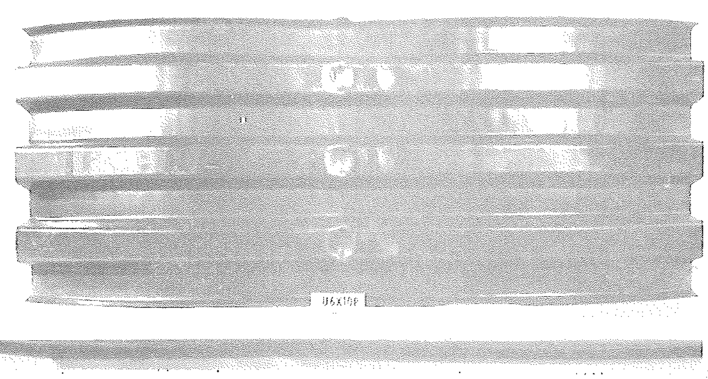
FIGURE 22

TEST 6









It is evident from the above observations that there is a relationship between published section modulus and the load carrying capacity of the various corrugations. This relationship is not linear but rather as the section modulus increases the load carrying capacity increases at an even greater rate.

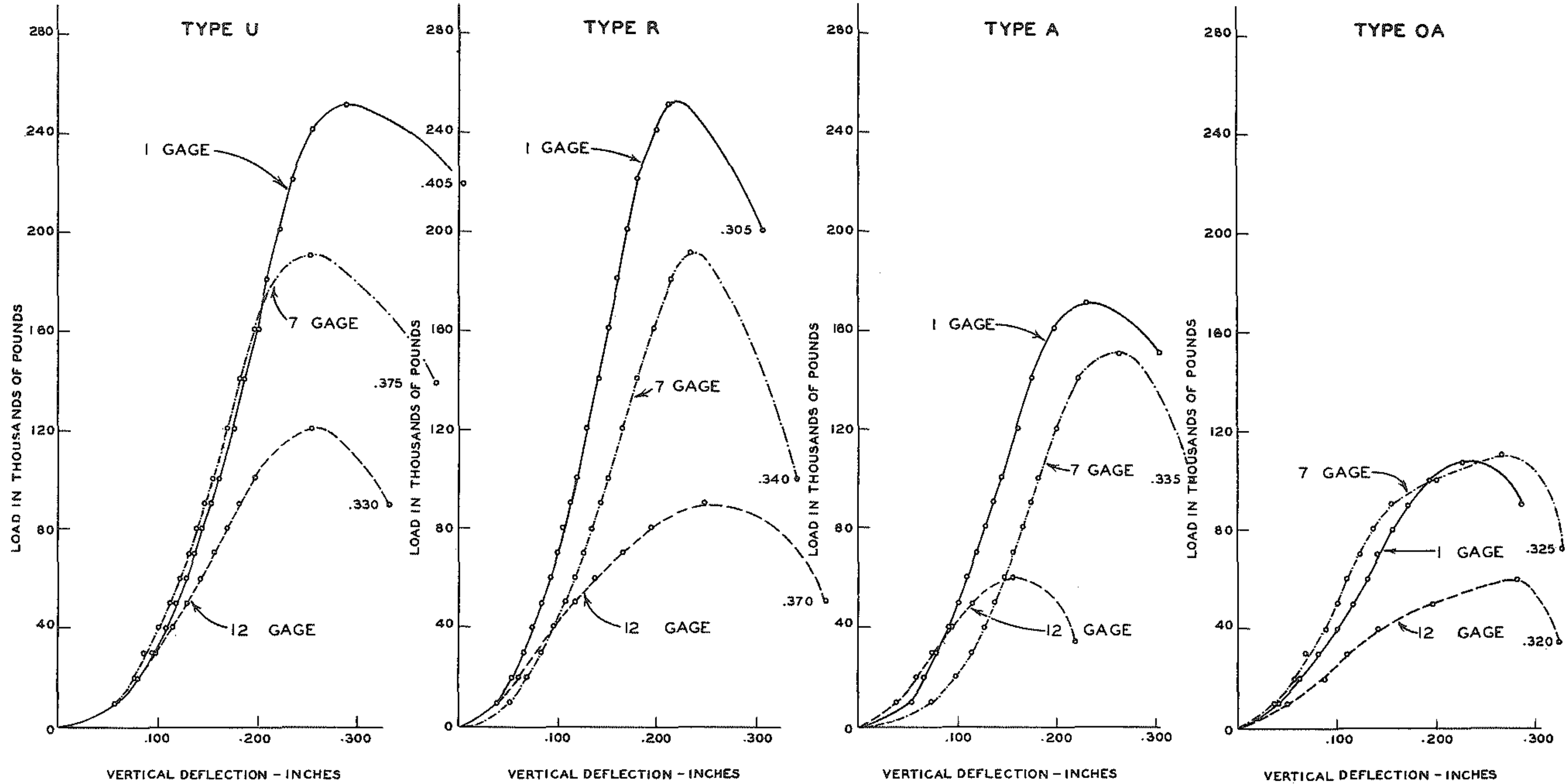
Effect of Gage

Figures 23, 24, and 25 illustrate the influence of gage on overall strength of the plates for the column tests 1, 3, and 4, respectively. Without exception, these curves show that as the metal thickness is increased the load at which the plates failed increases also. This further illustrates the point that as the section modulus (a function of the gage) increases, the load carrying capacity of the plates is also increased.

Figures 26 and 27 illustrate the same relationship for Tests 5 and 6. In this case again there is a progressive increase in load carrying capacity.

It is seen that the stiffness of the corrugated sheet is influenced to a great extent by metal thickness. Comparison of 1 gage and 12 gage curves, for example, illustrate that an increase in metal thickness from 0.105 in. to 0.275 in. trebles the ability to carry loads.

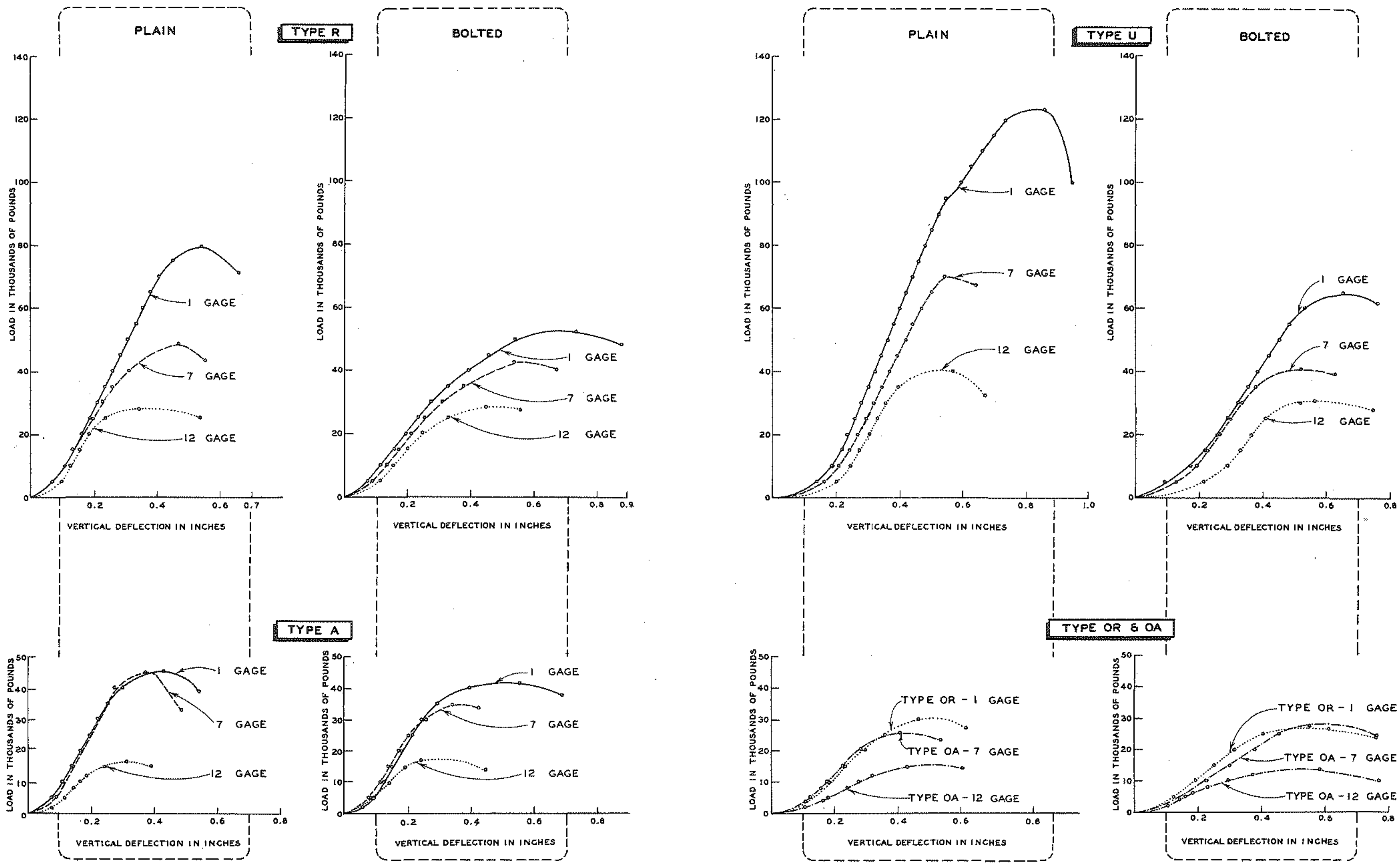
Since metal gage is a factor in the determination of section modulus Table 8 has been computed. Here plates from each of the three principal sources have been grouped by gage, section modulus and ultimate load figures have been tabulated, and two ratio columns have been formed by dividing the section modulus and ultimate load values, respectively, by the lowest entries in each group. The ratio columns show a variation



TEST 1

INFLUENCE of METAL THICKNESS on ON DEFLECTION

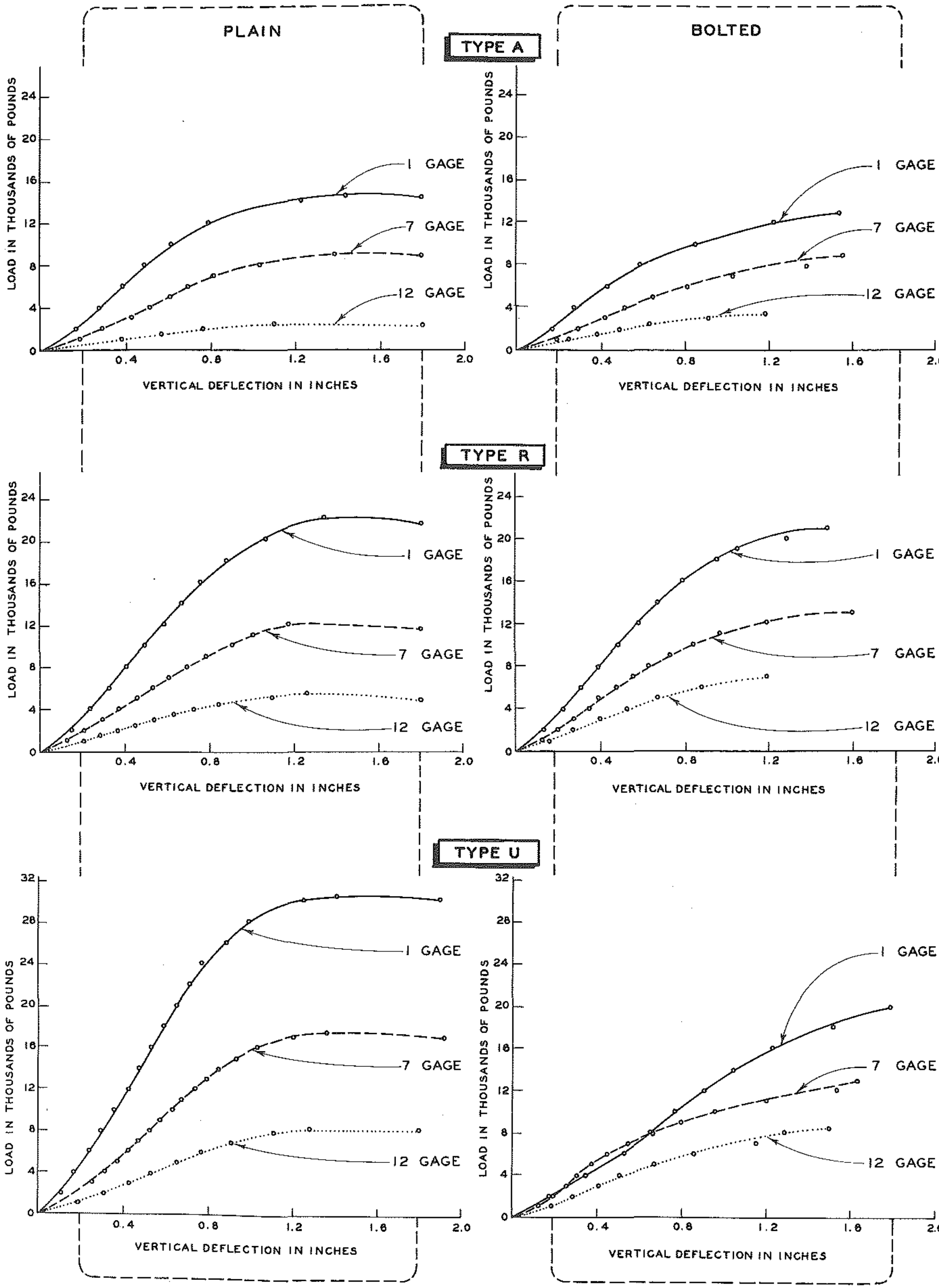
FIGURE 23



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS

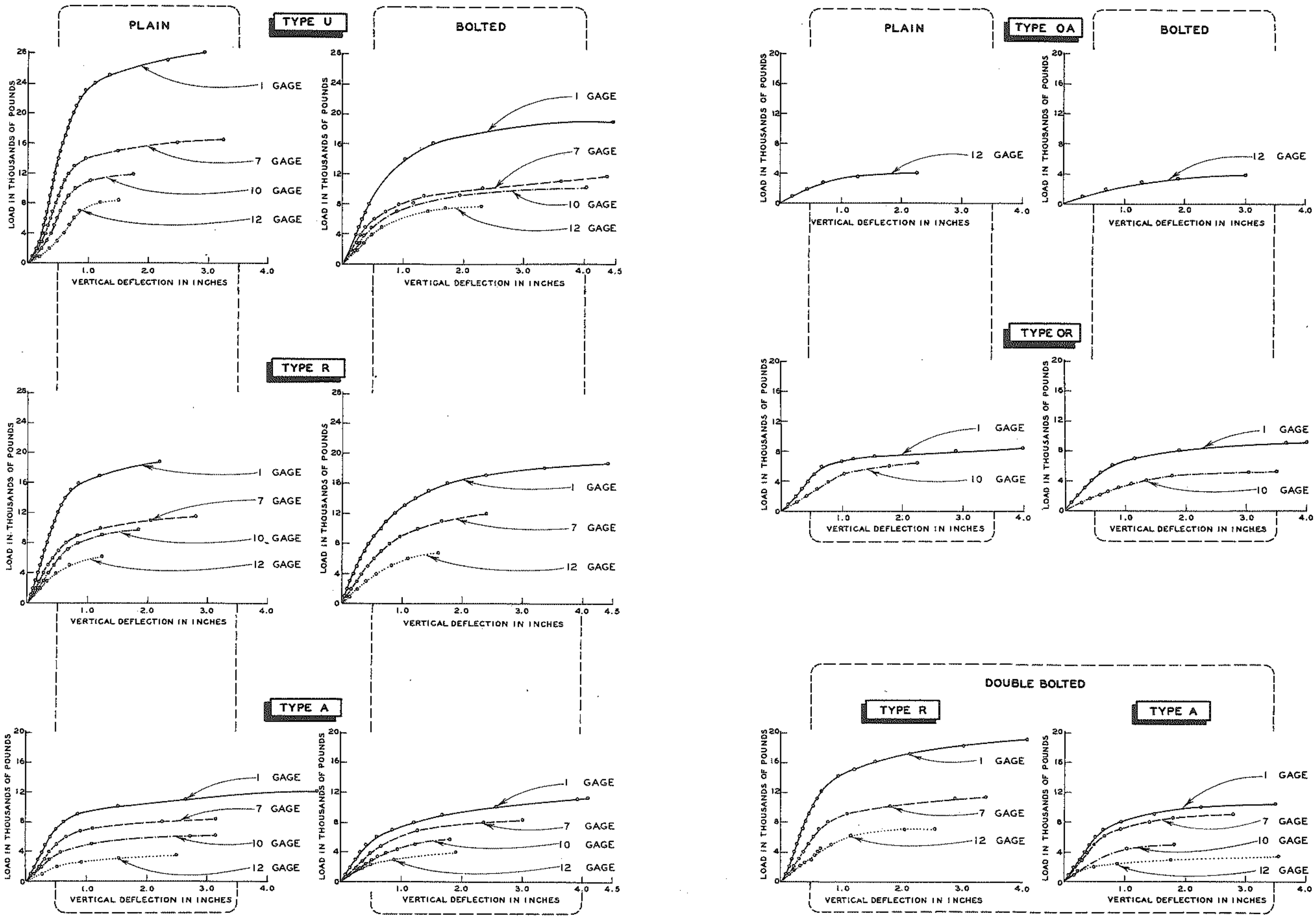
TEST 3

FIGURE 24



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS
TEST 4

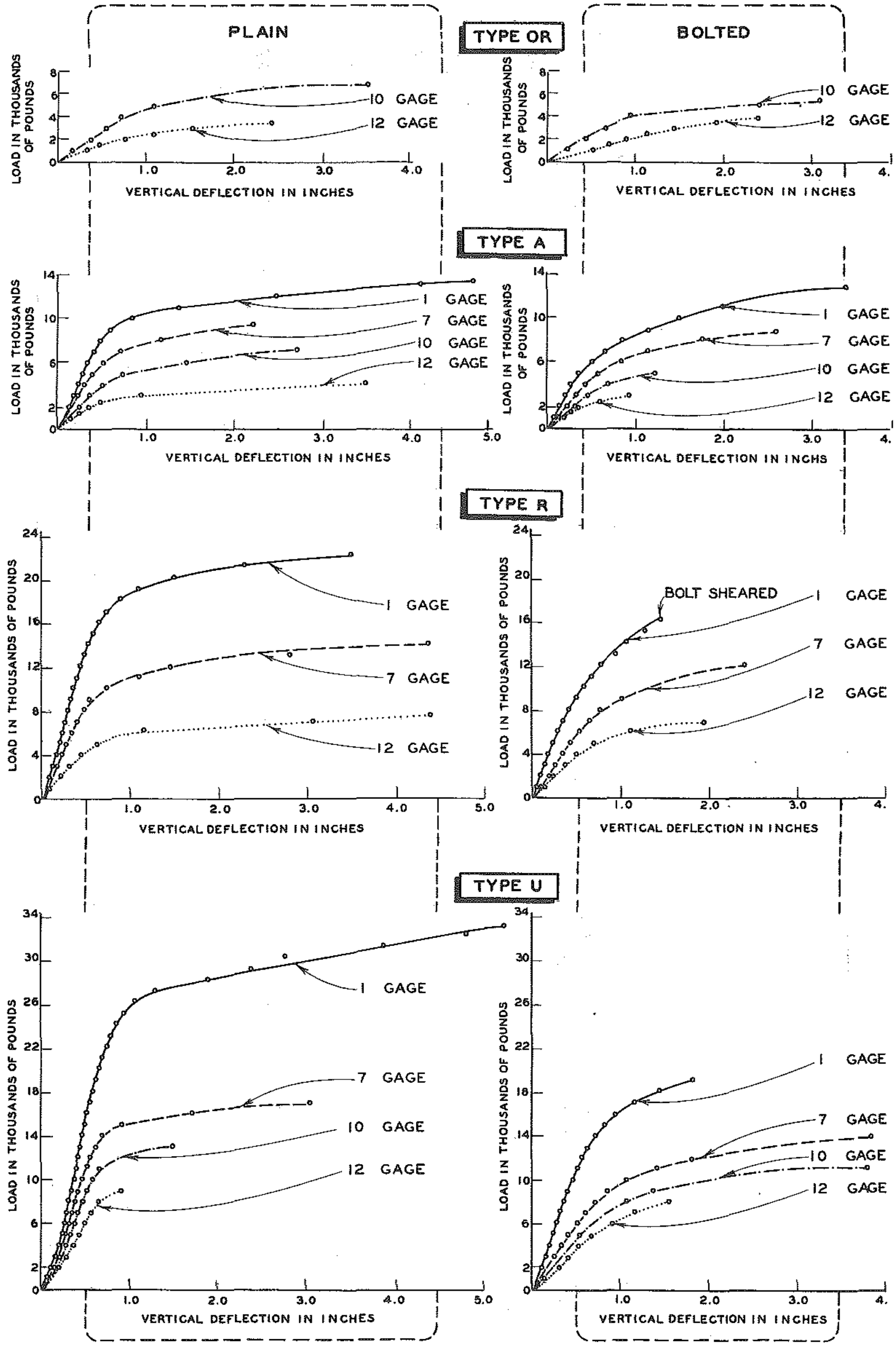
FIGURE 25



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS

TEST 5

FIGURE 26



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS

TEST 6

FIGURE 27

in section modulus ratios from 1 to almost 2.5 while the ultimate load ratios vary from 1 to 3.34.

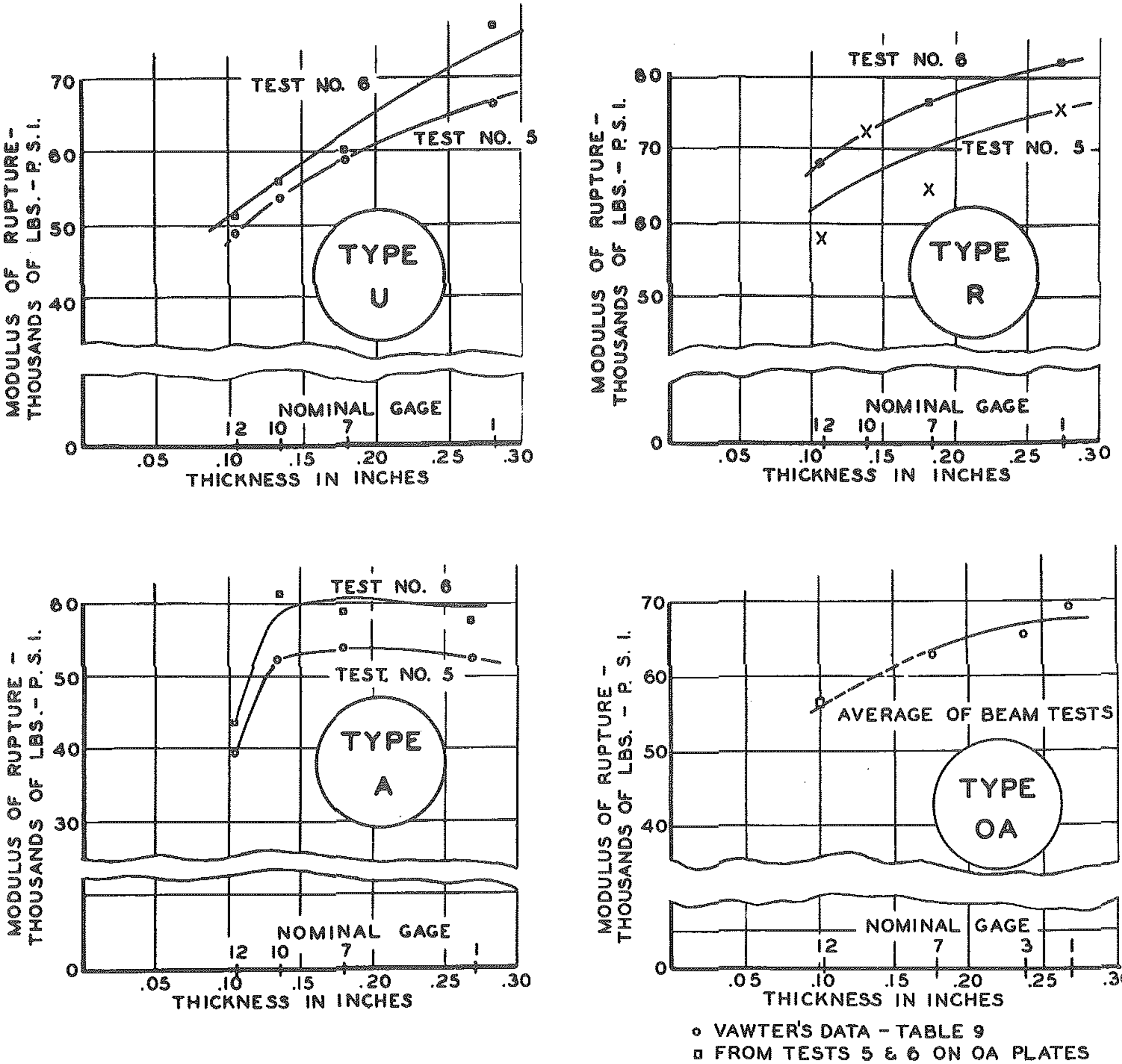
The effect of metal thickness on modulus of rupture can be readily ascertained by use of the values listed in Tables 6 and 7. By averaging the entries in these tables in such a way as to obtain a representative modulus of rupture value for each gage for each manufacturer we are able to produce Figure 28.

TABLE 8

EFFECT OF GAGE ON SECTION MODULUS AND ULTIMATE LOAD
(Based on Test 5)

Gage	I/C	Ratio	Ultimate load (in pounds)	Ratio
Type U				
1	5.11	2.47	28000	3.34
7	3.405	1.65	16600	1.98
10	2.615	1.26	11800	1.41
12	2.066	1.00	8400	1.00
Type R				
1	3.19	2.48	18900	3.11
7	2.165	1.68	11500	1.89
10	1.641	1.27	9750	1.61
12	1.288	1.00	6070	1.00
Type A				
1	2.782	2.46	12100	3.24
7	1.882	1.66	8400	2.25
10	1.438	1.27	6300	1.68
12	1.131	1.00	3740	1.00

Included in Figure 28 and illustrating the 1-1/2-in. type corrugations (OA and OR) are values of unpublished data by Jamison Vawter, Professor of Civil Engineering, University of Illinois. This is a report of tests on beams made of corrugated plate much the same as Tests 5 and 6 of this present project. All of Vawter's tests were made on Type OA corrugation and the principal results are shown in Table 9.



MODULUS *of* RUPTURE *vs.* GAGE *of* METAL

FIGURE 28

TABLE 9

AVERAGE MODULUS VALUES FOR OA PLATES

by Vawter

Test No.	Gage	Radius inches	Total load pounds	Average Span inches	Section Modulus in.^{3}	Modulus of Rupture psi.
2	7	50	9900	50.88	1.872	67300
3	5	50	11710	50.82	2.166	68700
4	3	50	13370	50.76	2.454	69100
1	1	50	15130	50.41	2.694	70800
7	7	100	8850	52.06	1.872	61500
8	5	100	10910	52.14	2.166	65700
5	3	100	12120	52.10	2.454	64300
6	1	100	14130	51.93	2.694	68100
10	7	150	8580	52.06	1.872	59700
9	5	150	10390	52.06	2.166	62400
11	3	150	11900	51.98	2.454	63000
12	1	150	14210	52.12	2.694	68700

The values for modulus of rupture in Table 9 compare favorably with the values for Type OA as secured by this series of tests. Vawter's values in Table 9 have been averaged and presented graphically in Figure 28 together with data from tests on OA plates in this investigation.

The curves for Types U and R corrugations in Figure 28 are somewhat similar in that modulus of rupture increases with metal thickness, although the pattern for Test 5 of Type R is not clear. Type A and OA exhibit a different trend. Although the modulus of rupture value for 12 gage material is low, there is no increase in ordinate for gages heavier than number 10. In all cases, however, the 12 gage has a low modulus of rupture value. This would seem to indicate that none of the corrugation styles efficiently develop the metal strength to its fullest extent for this thin metal. It is also possible that some of the apparent loss of efficiency is due to the type of loading used in Tests 5 and 6. The two point loading head used is more likely to cause localized buckling in thinner plates than will occur in the heavier gages. Such point loading does not occur in actual practice and this fact may be kept in mind when analyzing this data.

Performance and Efficiency of Joints

This phase of the project may be further subdivided into two parts, 1) Lap joint versus butt joint, and 2) single bolting versus double bolting (lap joint only). The lap joint versus butt joint may be further analyzed by comparing their action first as in a beam and secondly as in direct shear.

As a basis for the evaluation of joint performance it was decided that plates with seams were to be tested in a manner identical to that for plain plates. Thus, the efficiency of the fastening could be judged by finding the ratio of the load carried by the seamed sample to the load carried by the plain plate. Table 10 has been compiled on this basis.

Joint efficiency may be computed at any load, and for comparison these efficiency ratings have been listed for both elastic limit and ultimate load in Tests 5 and 6. It may be noticed that with very few exceptions the efficiency rating is higher at the point of ultimate load than at elastic limit. Most of this is a result of slippage and internal adjustment which causes the elastic limit to be lower than it might otherwise be. In the curved beams the butt joint as used in Type U is about 20% less "efficient" than the lap joint. This is also evident by comparing the curves drawn from the load deflection test. It was previously pointed out that in curves drawn for the different tests comparing the plain and bolted sections that the Type U specimen has

Specimen	CURVED COLUMNS						CURVED BEAMS												
	Test #3			Test #4			Test #5						Test #6						
	Ultimate loads		% Eff.	Ultimate loads		% Eff.	Elastic limits		% Eff.	Ultimate loads		% Eff.	Elastic limits		% Eff.	Ultimate loads		% Eff.
	plain	bolted		plain	bolted		plain	bolted		plain	bolted		plain	bolted		plain	bolted	
U 1 ga	123000	65000	53	30400	20000	66	17670	9000	51	28000	18800	67	19000	11000	58	32800	20000	61
U 7 ga	70000	40800	58	17400	13000	75	11330	4000	35	16600	11800	71	12000	6000	50	17000	14000	82
U 10 ga							9160	3000	33	11800	10300	87	10000	5000	50	13000	11000	85
U 12 ga	40000	30800	77	8400	8400	100	6330	2000	32	8400	7500	89	7500	4000	53	9000	8000	89
R 1 ga	79700	52300	66	22000	21000	96	11670	8000	69	18900	19000	100	11700	7000	60	22000	18000	82
R 7 ga	48600	42800	88	12000	13000	100	6670	5000	75	11500	11900	100	7300	6000	82	13800	12000	87
R 12 ga	28000	28200	100	5500	7000	100	3830	4000	100	6070	6800	100	4200	3500	83	7600	69000	91
A 1 ga	45000	41800	93	14500	13000	90	6330	4000	63	12100	11100	92	8000	4000	50	13500	12700	94
A 7 ga	44600	34800	78	9000	9000	100	4670	4000	86	8400	8400	100	5000	4000	80	9400	8900	95
A 10 ga							3000	2000	67	6300	5700	90	3500	3000	86	7300	5800	79
A 12 ga	16700	17100	100	2500	3500	100	2000	2000	100	3740	3900	100	2000	2000	100	4200	4000	95

% Efficiency is ratio, expressed as percent, of load bolted to load plain.

Specimen	Test #5										Test #6									
	Elastic limit					Ultimate					Elastic limit					Ultimate				
	plain	bolted	% Eff.	double bolted	% Eff.	plain	bolted	% Eff.	double-bolted	% Eff.	plain	bolted	% Eff.	double bolted	% Eff.	plain	bolted	% Eff.	double bolted	% Eff.
R 1 ga	11670	8000	69	10000	86	18900	19000	100	19000	100	11700	7000	60			22000	18000	82		
R 7 ga	6670	5000	75	6000	90	11500	11900	100	11200	97	7300	6000	82	7000	96	13800	12000	87	10780	78
R 12 ga	3830	4000	100	4500	100	6070	6800	100	7000	100	4200	3500	83	4000	95	7600	6900	91	6930	91
A 1 ga	6330	4000	63	5000	79	12100	11100	92	10500	87	8000	4000	50	5000	62	13500	12700	94	14180	100
A 7 ga	4670	4000	86	5000	100	8400	8400	100	9000	100	5000	4000	80	4000	80	9400	8900	95	8720	93
A 10 ga	3000	2000	67	3000	100	6300	5700	90	5000	79	3500	3000	86	3500	100	7300	5800	79	5775	80
A 12 ga	2000	2000	100	2000	100	3740	3900	100	3560	95	2000	2000	100	2000	100	4200	4000	95	3320	79

TABLE 10

EFFICIENCY OF JOINTS

Bolted at 200 ft.-lb. bolt torque.

consistently higher values than the R and A. In the bolted specimens the advantage of the U type corrugation is no longer apparent.

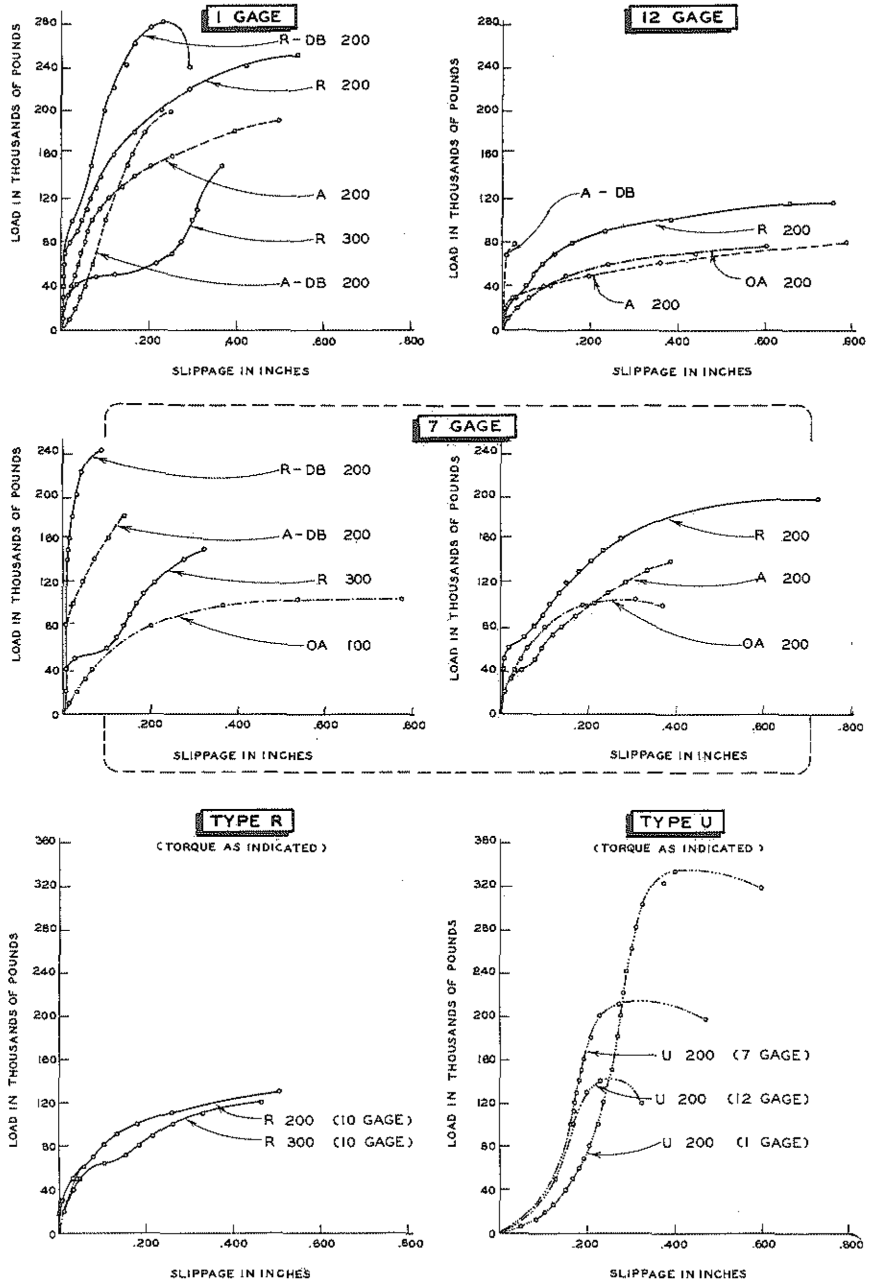
In Test 2 the joints were subjected to vertical thrust. In this test the criterion for evaluation was plate slippage. The data for Test 2 is given in Table 5 of the Appendix and the curves are shown in Figure 29. The U style corrugation shows a marked superiority in this particular test. It is obvious from Figure 30 A that there is no opportunity for slippage to take place in the joint. Instead the plate fails by buckling of the metal near the ends or near the seam.

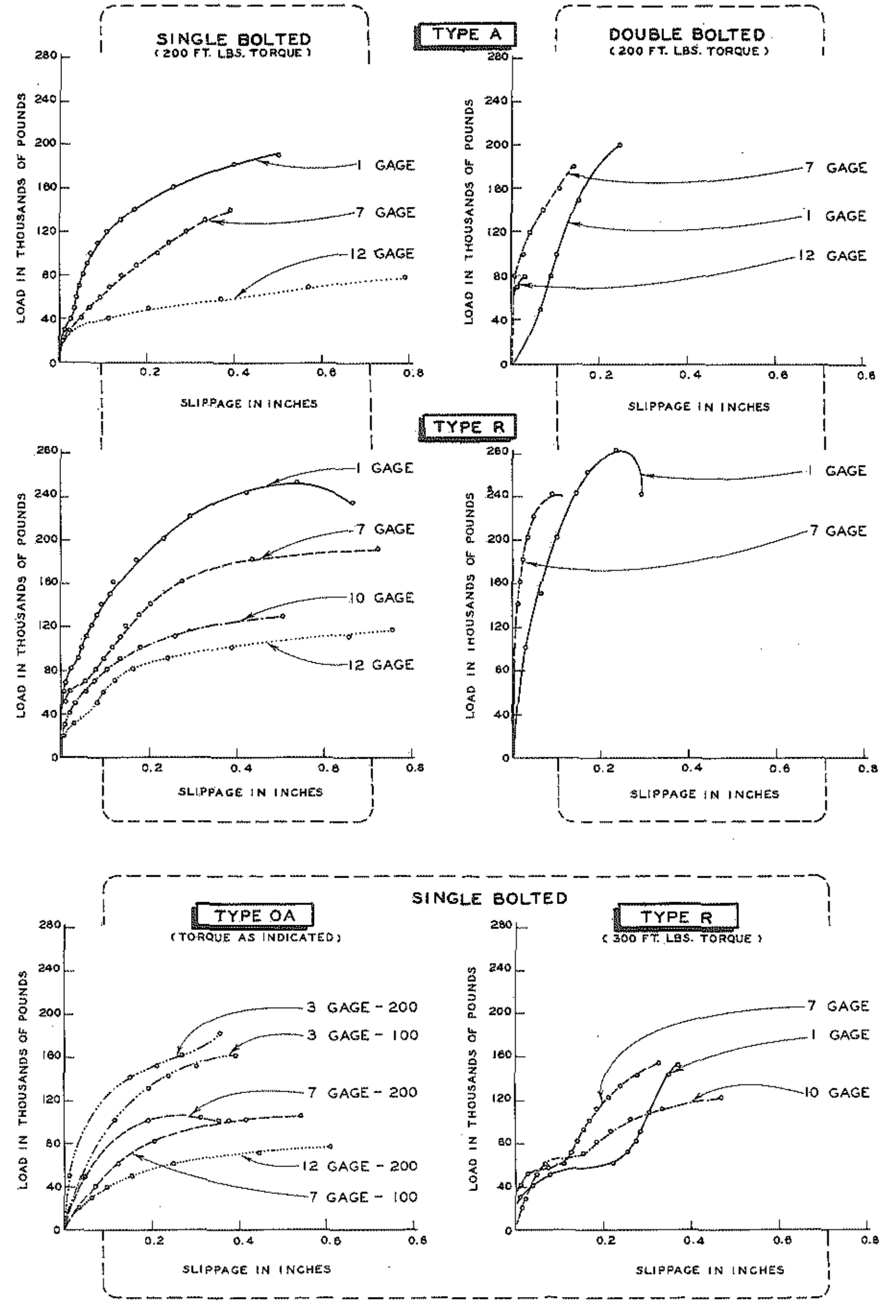
Of the two remaining styles of corrugation the Type R joint shows some superiority over the Type A joint in resistance to direct shear. The type of failure common to the lap joint when subject to direct shear is shown in Figure 30 B and C.

Double bolting was tried on the lap joints to see if such a method of fastening could be used to fully develop the plate metal strength. Table 10 shows data relative to the performance of double bolted joints. There is approximately a 10 percent increase in efficiency at the elastic limit but there is no increase in efficiency apparent at the ultimate load.

A Discussion of Joint Action

Test 2 was designed primarily to investigate the strength of the joints under direct thrust. When testing the lap type joint in which the bolt torque was 300 ft.-lb. there was a sudden slipping between the two plates at about 70,000 lb. This was probably due to the fact that all of the load up to the point of slippage was carried by friction between the plates. When friction no longer could carry the entire load there was sudden slipping and the bolts and bearing surfaces of the bolt holes





KEY: A, R, U, ETC. = TYPE DB = DOUBLE BOLTED 200, 300, ETC. = FT. LBS. BOLT TORQUE

SEAM STRENGTH UNDER COLUMN LOADING
CLASSIFIED BY METAL THICKNESS

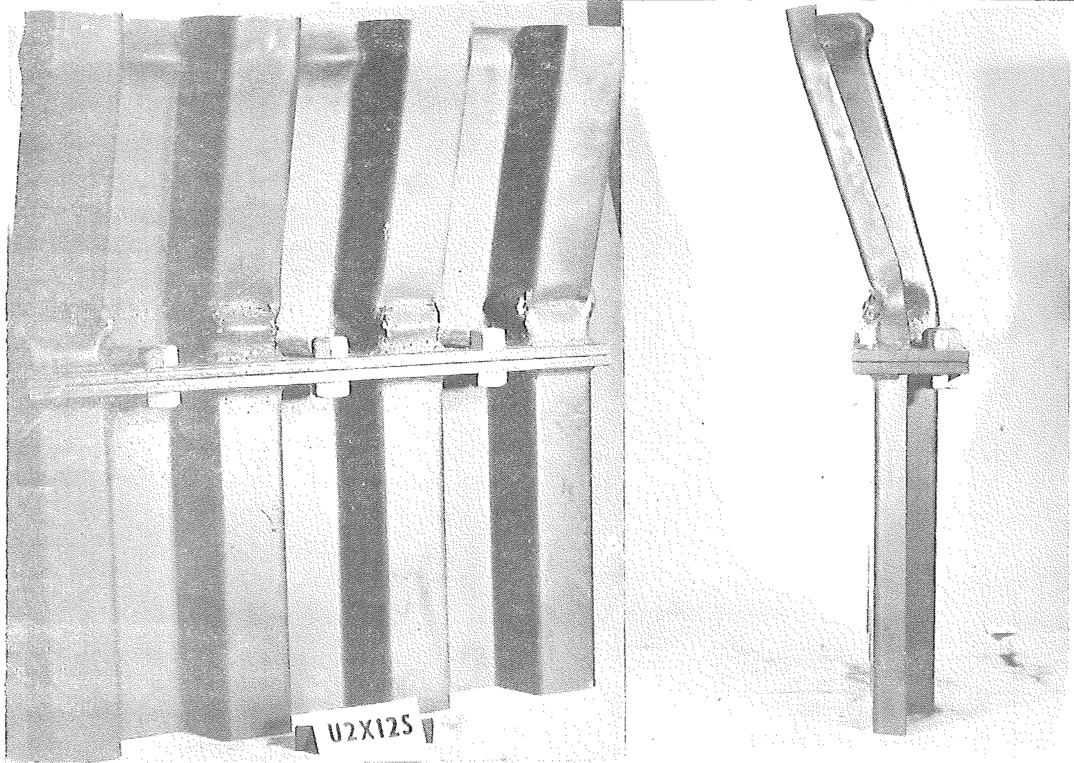
SEAM STRENGTH UNDER COLUMN LOADING
CLASSIFIED BY CORRUGATION TYPES

TEST 2

FIGURE 29

TYPICAL FAILURES AT JOINTS

TYPE U



TYPE R

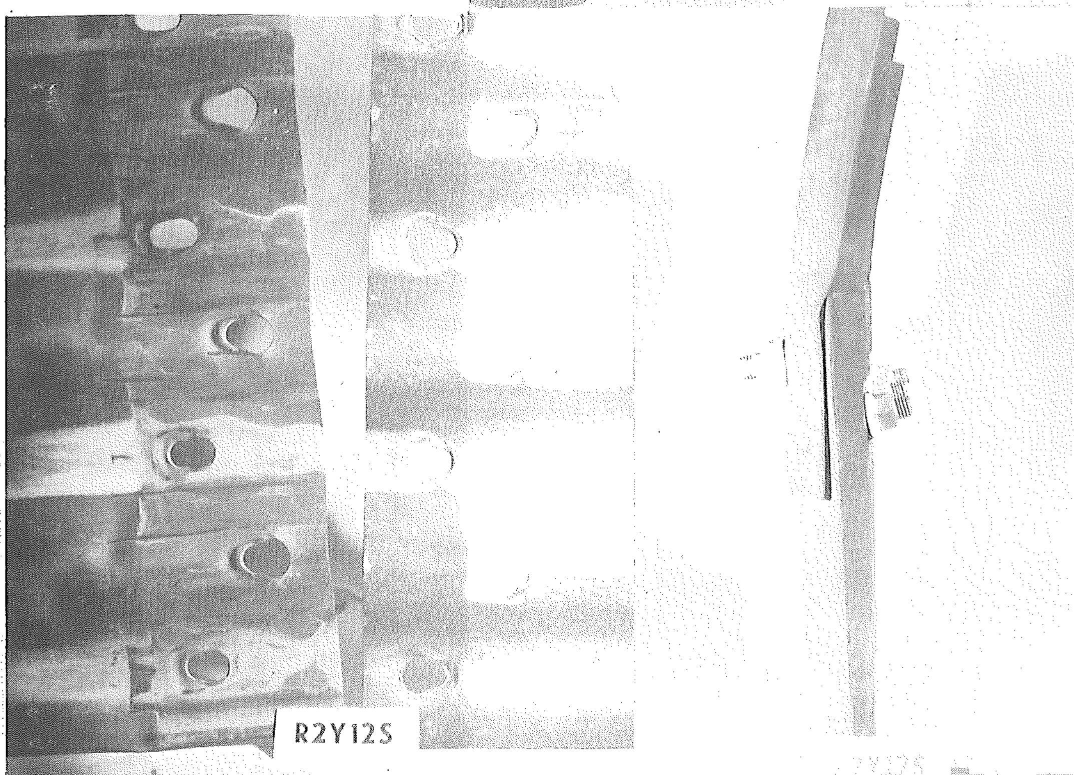
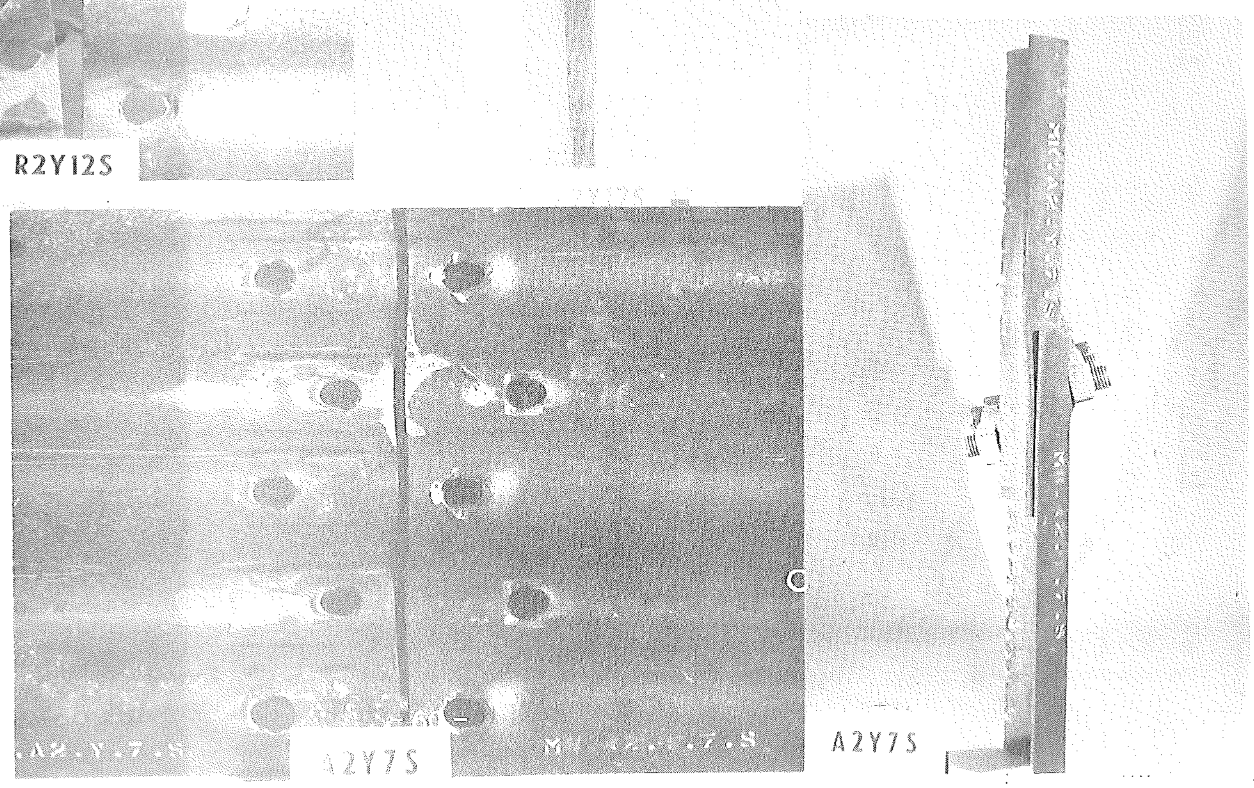


FIGURE 30

TYPE A



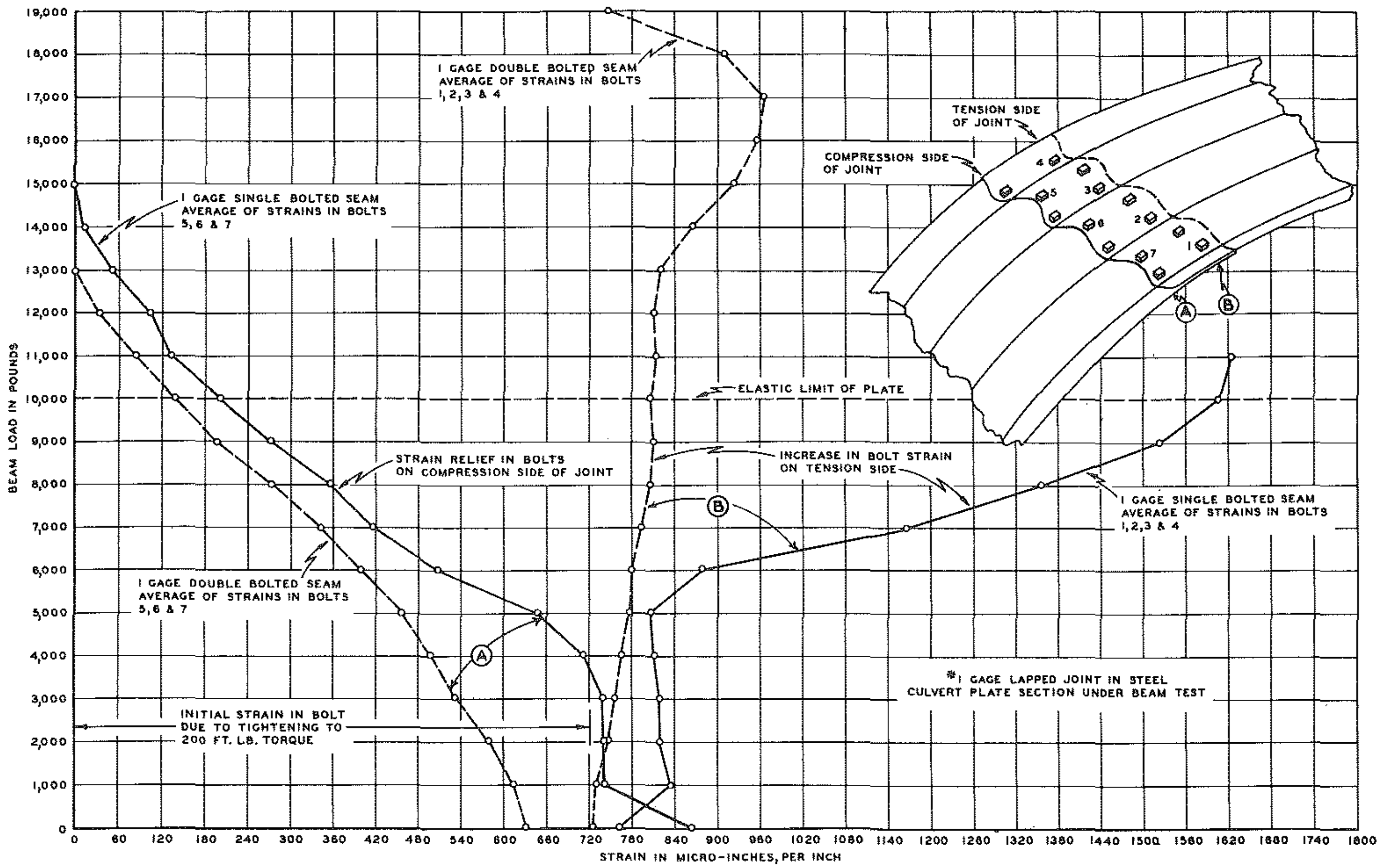
carried the load with a normal elastic action.

When the bolts were tightened to 200 ft.-lb. torque the load in the joint was carried immediately by the bolt and the metal and there was no sudden deformation. The torque with which the bolts were tightened did not apparently affect the ultimate load which the joint carried in direct thrust.

An analysis of Figures 31 and 32 of lap and butt joints acting in pure bending (Tests 5 and 6) show the following characteristics: First, in a lap joint the "B" row of bolts functioned in tension. The "B" row, shown in Figure 31, is the row farthest from the edge of the metal when one looks in the direction of the load. Second, as the load increased, the outside row of bolts loosened, and the portion of load carried in tension by these bolts approached zero. Third, when the metal at the joint definitely failed, the tension on the inside row of bolts was also decreased and the corrugated plate itself began to fail rapidly.

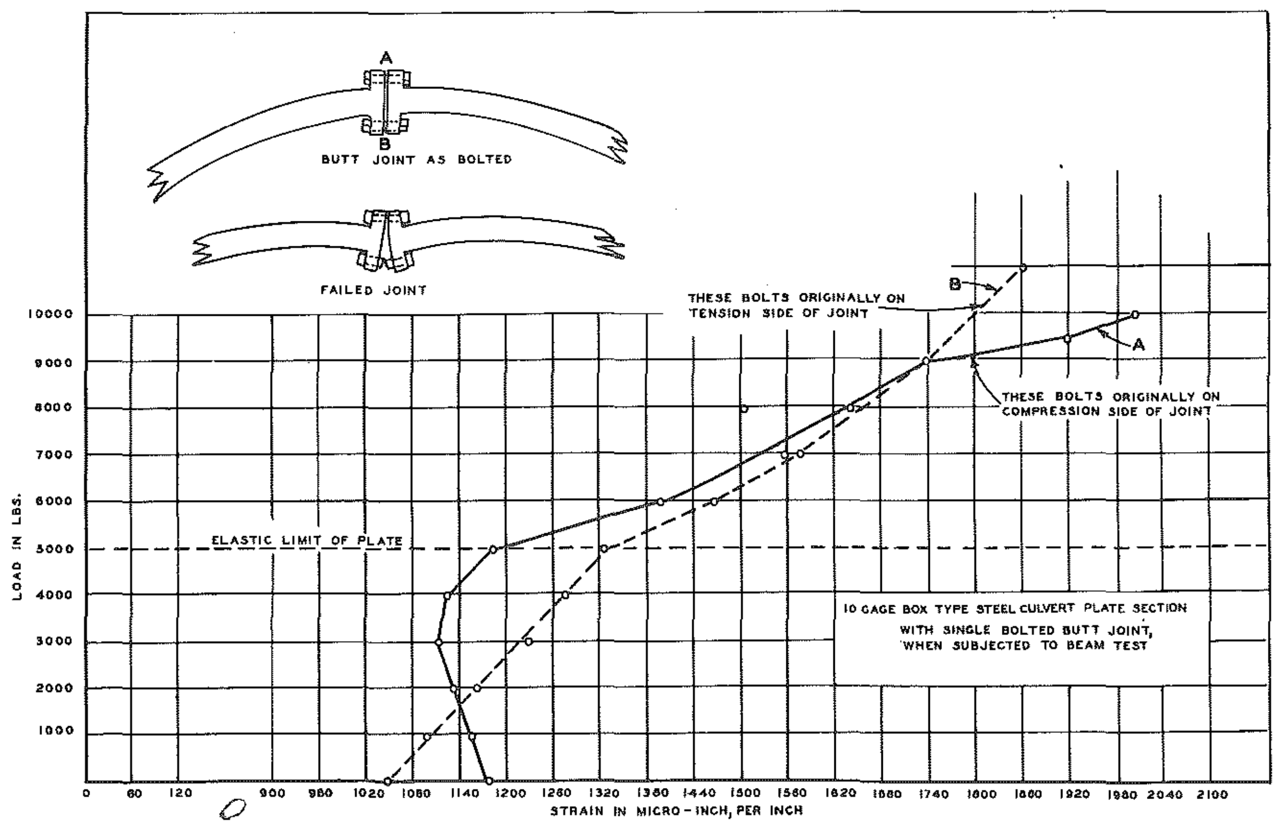
The analysis of the butt joint is somewhat different. Curve B of Figure 32 shows the tensile stress in the lower row of bolts in a butt joint. The stress increases rather uniformly as the load increases.

Curve A shows the tensile stress in the upper row of bolts of the butt joint. As the load is increased the tensile stress due to tightening the bolts is decreased probably due to the fact that the two butt plates are moved toward each other. The load continues to decrease for several 1000-lb. load increments and then increases. This increase probably begins when the butt joint begins to spread at the bottom and pivots about the upper edge of the butt plate. This stage is shown in the failed joint in Figure 32, except that the bolt does not usually fail.



BOLT STRAINS IN
DOUBLE AND SINGLE BOLTED LAPPED JOINT

FIGURE 31



BOLT STRAINS IN BUTT JOINT

FIGURE 32

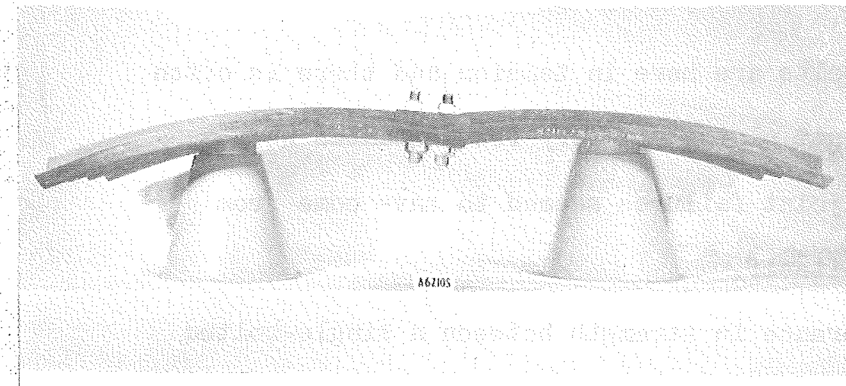
Both upper and lower rows of bolts are here in tension and there is often excessive deformation in the butt plate. In very few instances were there bolt failures, but most joint failures seemed to have come from the failure of the butt-plate itself.

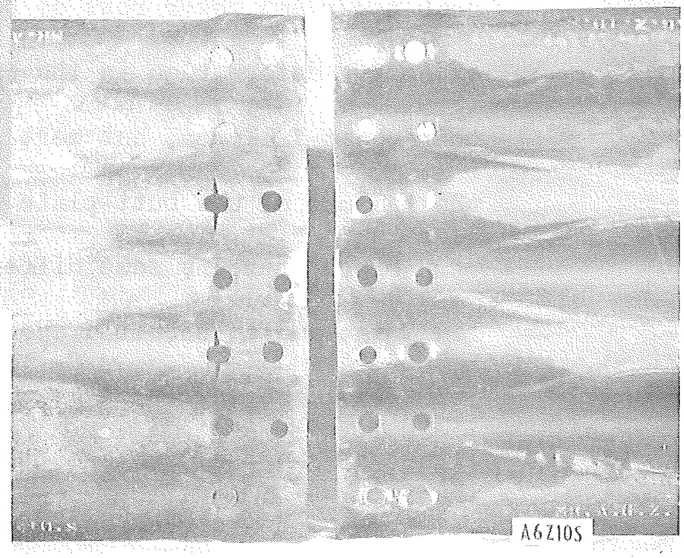
Since there is some difference in strength between a single-bolted lap joint and an unbolted specimen, it was felt that the strength of the joint could be increased by doubling the number of bolts in the joint. Figure 33 shows a double-bolted joint.

The dashed curves on Figure 31 show the tensile bolt strains of the double-bolted specimens. Curve A shows that the A row of bolts decreases in tensile strain from an initial strain due to torque down to zero. Practically the same action is taking place as occurs in the single-bolted plates.

There is much more variation in the "B" row of bolts subject to tension. The dashed curve B shows these bolt strains. The strain increases only slightly beyond the initial strain introduced by tightening the bolts up to a point just beyond the elastic limit of the beam. Then the strain increases more rapidly for several thousand pounds and starts to decrease again when the metal in the joint fails. It will be noted that the strain curve for the bolts in the double-bolted joints varies considerably from the strain curve for the bolts in the single-bolted joints.

At the elastic limit there is a tendency for the double-bolted joint to be more efficient than the single-bolted joint, but at the ultimate strength of the plates neither type of joint has a decided advantage. With this thought in mind it is very probable that there is no advantage in double-bolting a plate except in case of direct thrust, especially since

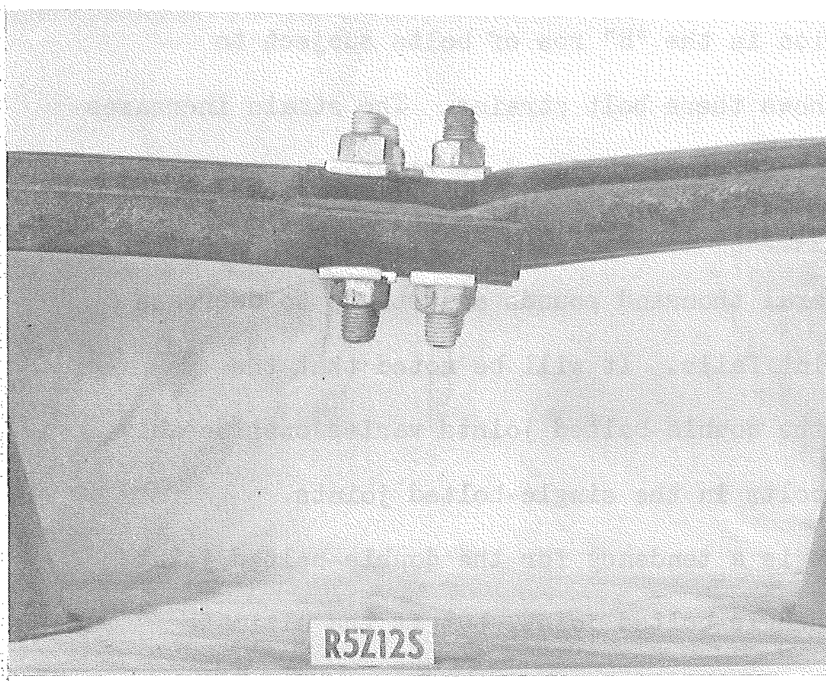


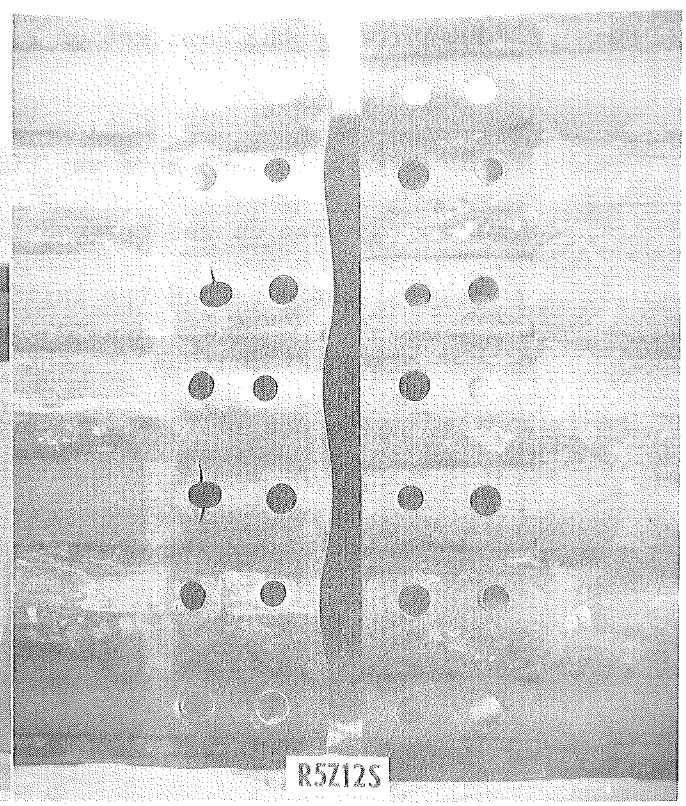


TYPE A

FIGURE 33

TYPE R





TYPICAL FAILURE - DOUBLE BOLTED JOINTS

the decrease in bolt stress caused by double bolting is of no great value because the greater bolt stress in single-bolted joints is not detrimental to the joint.

Bolt Strains

On certain plates in Test 5, strain gages were cemented to the bolts used in the plate seams for the purpose of observing the strain pattern. These data are shown in Table 11. Two graphs which portray the typical behavior of longitudinal bolt strains are shown in Figures 31 and 32.

Figure 32 is the set of curves for the butt joint. The initial stresses are incurred in the tightening process. As the load is applied vertically downward some relief is seen in the upper row of bolts. After the elastic limit of the metal was reached both rows increased in tension.

Bolt strains in a lap joint are shown in Figure 31. For single bolting there was not much change in bolt tension for the first 5000-lb. load. Above that value the "A" row of bolts obtained rapid relief and the tension increased more rapidly in the "B" row.

Double bolting aided the strains in the "B" row. Throughout the test the increase in strain in these bolts was very small for a double-bolted joint. The "A" row behaved in a manner similar to that shown for single bolting.

Effect of Varying the Radius of Curvature

Tests 5 and 6 differed only in the plate curvature. The plates for Test 5 were formed to a 150-in. radius of curvature while the samples used in Test 6 were curved to a 50-in. radius. An inspection of Figures 18, 19, 26, and 27 shows slightly higher ultimate values for Test 6 than Test 5. This was to be expected because of the difference in the span.

TABLE 11
TENSILE STRAINS IN BOLTS - TEST 5

Strain in microinches per inch for indicated load in pounds on bolted beams

Plate Iden.	Bolts	Row Fig. 31-32	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000	16000	17000
U 1 ga	S	A	1040	1000	920	850	760	690	600	700	810	910	1020	1080	1140	1200	1250	1250	1220	1020
		B	1470	1430	1510	1500	1660	1780	1890	2080	2170	2210	2230	2260	2290	2320	2400	2550	2610	2760
U 10ga	S	A	1180	1160	1130	1120	1130	1180	1400	1540	1640	1740	2000							
		B	1050	1100	1170	1230	1270	1325	1470	1580	1640	1740	1810							
U 12ga	S	A	1230	1290	1350	1430	1470	1530	1600	1695	1710									
		B	1300	1290	1260	1160	1160	1180	1080	1120	750									
R 1 ga	D	A	630	610	580	530	500	460	400	340	270	200	140	80	30	0				
		B	730	730	740	760	770	780	780	800	810	810	810	800	810	820	860	920	950	970
R 1 ga	S	A	870	730	740	740	710	650	500	410	350	270	200	130	100	50	10	0		
		B	760	830	820	820	810	800	880	1170	1350	1530	1600	1630	Fail					
R 7 ga	S	A	1563	1600	1543	1310	1135	948	700	588	420	235	198	98	0					
		B	740	734	740	770	833	875	953	1081	1188	1323	1661	Fail						
A 1 ga	D	A	668	622	555	445	350	230	47	63	52	95	100	70						
		B	544	566	541	579	552	592	640	695	785	878	880	970						
A 1 ga	S	A	750	705	620	503	347	232	168	180	198	197	218	253						
		B	845	822	859	815	838	885	895	1096	1255	1383	1658	2152						
A 7 ga	S	A	554	561	576	555	576	545	524	340	189	108	34							
		B	764	786	864	934	1044	1068	1151	1213	1419	1656	1812							
A 7 ga	D	A	647	605	532	405	278	243	222	153	138	70	70							
		B	750	795	855	865	910	970	1040	1105	1230	1335	1480							
A 10ga	S	A	720	650	510	405	296	180												
		B	665	682	690	720	680	650												

There was some question, however, as to the relative magnitude of the fiber stresses at these different curvatures. Tables 3 and 4 list the fiber stress at the elastic limit and Tables 6 and 7 give the modulus of rupture at ultimate load. A direct comparison of average unit stresses at elastic limit for Test 5 with those of Test 6 produces no deviation that can be attributed to curvature. Major discrepancies occur in the U 12 gage, A 1 gage, and A 12 gage with values from Test 5 exceeded by those of Test 6; and R 1 gage, OR 10 gage, and OA 12 gage where Test 5 shows the larger values. However, modulus of rupture figures are higher in Test 6 than in Test 5 for all samples except OA 12 gage.

Bolt Torque Tests

Three sets of corrugated plates from each manufacturer were fastened together with the bolts supplied for that purpose. These were tightened with a torque wrench until failure occurred. The data presented in Table 12 shows that the high tensile bolts furnished with the A and R specimens withstood about 700 ft.-lb. torque while the standard bolts supplied for the U styles failed at a lower value. In either case, however, the 200 ft.-lb. torque value used for fastening the seamed specimens throughout this test was well within the working limits of the bolt metal.

TABLE 12

ULTIMATE BOLT TORQUE IN FOOT-POUNDS

Style	1 ga.		7 ga.		12 ga.		Average
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	
A	680	720	710	730	720	720	713
R	720	750	730	690	680	710	715
U	605	580	590	575	580	620	592

SUMMARY OF PRINCIPAL CONCLUSIONS

1. Culverts may be designed on the basis of section modulus for 1-1/2-, 1-3/4-, and 2-in. depths for circular arc type corrugation and 2-in. depth for the box type.

2. There is some indication that the effectiveness of 1-3/4- and 2-in. depth corrugations begins to fall off when a thickness of metal is decreased to 12 gage.

3. The standard lap joint detail is not quite able to develop the strength of the metal at ultimate stresses and the joint lowers substantially the effective elastic limit. Double bolting tends to bring the effective elastic limit back to normal but it has little or no effect on the ultimate strength in bending. The tests indicate that double bolting increases the stress of the joint in thrust.

4. The butt joint used developed the box-type corrugation in thrust but not in bending.

5. Even when bolt nuts are set up with a torque wrench to a given torque, the tension in the shanks varies greatly from joint to joint. The torque adopted in the tests for tightening the nuts (200 ft.-lb.) appears to be a good one to use in practice.

6. Plate curvature had little effect on magnitude of extreme fiber stress.

Errata, p. 50, Michigan Engineering Experiment Station Bulletin 109

Conclusion 1 should read:

> "When using 1-3/4 and 2-in. circular arc type and 2-in. box type corrugations in the design of culverts, experience with the old type 1-1/2 in. depth material may be used by assuming that corrugations having the same section modulus will give the same strength against bending."

Also, in Conclusion 2, delete "1-3/4 and 2-in. depth" and replace by "all".

DETAILED ANALYSIS OF CONCLUSIONS

1. Design by Use of Section Modulus - In order to state that corrugated metal structures may be designed on the basis of the section modulus, one must show that if figured by the use of the section modulus the resulting stresses correspond fairly well with those obtained in the tests. A study was made of Table 2 showing strain gage readings on three specimens, viz. one 1-3/4-in. depth specimen, one 2-in. specimen, and one 2-in. box section. If the published section moduli are used the extreme fiber stresses may be computed.

These may be compared with the stresses computed from the observed strains. At approximately the elastic limit the following stresses were computed using the published section moduli:

1-3/4-in.	corrugation	tension face	-	38,230 psi
2-in.	corrugation	tension face	-	53,570 psi
2-in.	corrugation	compression "	-	57,830 psi
box	corrugation	tension face	-	44,750 psi

If these stresses are computed from the observed strains assuming a coefficient of elasticity of 29,000,000 we have:

1-3/4-in.	corrugation	tension face	-	37,800 psi
2-in.	corrugation	tension face	-	45,850 psi
2-in.	corrugation	compression "	-	47,700 psi
box	corrugation	tension face	-	45,000 psi

Thus the two methods of obtaining the stress compare quite favorably. A more indirect test of the validity of the section modulus may be had by using it to compute the ultimate stresses from Tables 10, 11, and 15, Appendix. Table 10, Appendix covers fifteen tests of seamless specimens in pure bending. Computing the moduli of rupture by use of the section moduli we obtain an average value of 60,100 psi with a maximum of 74,600 psi and a minimum of 39,900 psi. For the corresponding values in Table 11, Appendix, covering tests of bolted specimens we have:

Average modulus of rupture		54,600 psi
	maximum	72,200 psi
	minimum	41,500 psi

For Table 15, Appendix, the values are:

Seamless average		64,000 psi
	maximum	82,600 psi
	minimum	44,200 psi

All these figures tend to show that the published values of section moduli give reasonable stress values. If now these tests are grouped according to the type of corrugation we have for the moduli of rupture:

1-1/2-in.	corrugation	69,200 psi
1-3/4-in.	corrugation	54,300 psi
2-in.	corrugation	72,500 psi
box type	corrugation	63,000 psi

These values are averages for all bent column and pure bending tests on seamless specimens.

2. Gage Efficiency with 1-3/4- and 2-in. Depth of Corrugation

The following table gives the average ultimate strength or modulus of rupture obtained from all available seamless and single bolted tests on the circular arc type sections under pure bending and combined bending and direct stress:

Gage	Depth of Corrugation	Average Ultimate Stress	
1	1-3/4		56,400 psi
	2		75,900 psi
		Aver.	66,200 psi
7	1-3/4		61,000 psi
	2		71,000 psi
		Aver.	66,000 psi
10	1-3/4		52,100 psi
	2		71,600 psi
		Aver.	61,900 psi
12	1-3/4		41,600 psi
	2		66,100 psi
		Aver.	53,800 psi

From the above table it is seen that the average ultimate stress for circular arc type corrugations of 1, 7, and 10 gage lies above 60,000 psi, whereas the average ultimate stress for 12 gage is 53,800 psi. It may be that under ultimate stress the thin gage metal deforms to such an extent that the section modulus is not entirely effective.

For the box section we have:

Gage	Average Ultimate Stress
1	62,200
7	54,200
10	52,100
12	52,000

Here the falling off of efficiency for 12 gage is less than that for the circular arc types although the same tendency is evident.

3. Efficiency of Lap Joints - The tests for bolted and seamless straight columns are not comparable because the former specimens were only 24 in. long whereas the latter were 52-3/4 in. long. In the other tests the ultimate strengths could be compared because the specimens were otherwise identical. The average ultimate stresses were as follows:

	Seamless	Bolted
150-in. radius column test (see Table 7, Appendix)	73,700	65,400
30-in. radius column test (see Table 9, Appendix)	59,900	58,300
150-in. radius pure bending test (see Tables 10 and 11, Appendix)	60,100	54,600
50-in. radius pure bending test (see Table 15, Appendix)	64,000	54,000

The "efficiency" percentages given in Table 10 show the lap joints in a somewhat more favorable light than the ultimate loads given above. If the percentages given in this table for lap joints are averaged for each depth of corrugation and each test number and these averages averaged we obtain:

For ultimate loads	97% efficiency
For elastic limit	79% efficiency

In other words the standard lap joint nearly develops the ultimate strength of the corrugated metal but slippages and yielding take place which makes the elastic limit appear considerably lower.

The lower part of Table 10 shows that for pure bending the use of double bolting increases the lowered elastic limit about 20 percent but it lowers the efficiency at ultimate load for pure bending by about 2 percent. One very marked effect of double bolting is the reduction in tension bolt stress (See Figure 31). For pure compression (the straight column test) Table 5 shows an increase in the average ultimate stress due to double bolting from 31,600 psi to 36,200 psi or 14 percent. Attention should be called to the fact that the columns had an unsupported length of only 24 in.

4. Efficiency of Butt Joints - Table 10 shows an average efficiency of the butt joint of about 75 percent at ultimate loads and about 45 percent at the elastic limits in bending. Under pure compression (straight column tests) Tables 4 and 5, Appendix, show that the butt jointed column is stronger than the seamless column. Thus, under pure compression the butt joint developed the full strength of the section.

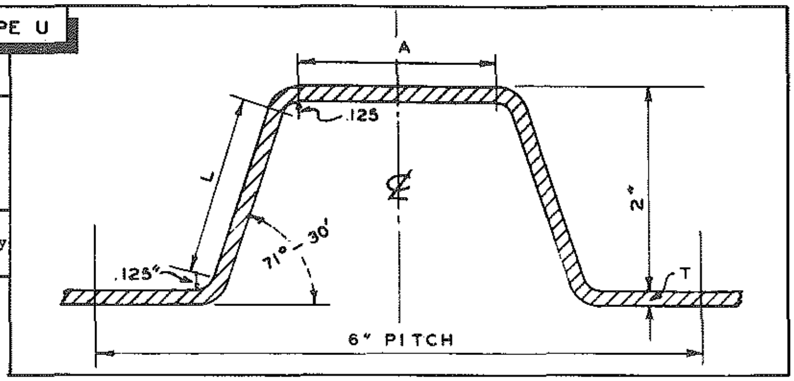
5. Bolt Torque - Table 11 gives the bolt strains for eleven test specimens under various loads up to 19,000 lb. All bolts were tightened with a torque wrench to 200 ft.-lb., yet the recorded bolt strains vary all the way from 544 to 1,563. Assuming the modulus of elasticity as 29,000,000, the stress varied from 15,770 to 45,400 psi. The stress in some bolts, therefore, must have been three times that in others. The cause

of this may be due to the variation in the coefficient of friction between nut and plate and between nut and bolt shank, at the time the nuts were tightened.

Table 12 shows the ultimate bolt torque on the three types of bolts used. The lowest value recorded was 680 ft.-lb. and the highest 750 ft.-lb. Thus, the torque adopted for the tests (200 ft.-lb.) is about 2/7 the ultimate and appears to be a reasonable one to use in practice.

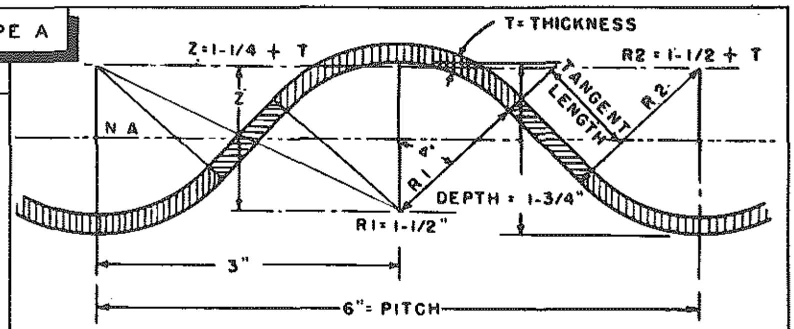
TYPE U

Gage	Thickness T in inches	Tangent Length L in inches	Angle θ in degrees	Moment of Inertia I in.⁴/in.	Section Modulus S in.³/in.	A Type U Only in inches
1	.2813	1.7265	71°30'	0.2773	0.2431	1.9483
7	.1793	1.7999	71°30'	0.1768	0.1623	2.0217
10	.1345	1.8322	71°30'	0.1327	0.1244	2.0540
12	.1046	1.8537	71°30'	0.1034	0.0983	2.0755



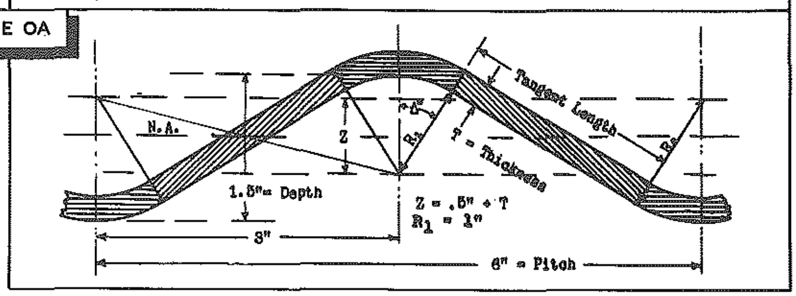
TYPE A

Gage	Thickness T in inches	Tangent Length L in inches	Angle Δ in degrees	Moment of Inertia I inches⁴	Section Modulus S in.³/ in.
1	.2690	0.785	49°46'	0.1288	0.1280
7	.1793	0.968	47°37'	0.0841	0.0865
10	.1345	1.050	46°37'	0.0630	0.0660
12	.1046	1.103	46°19'	0.0483	0.0520



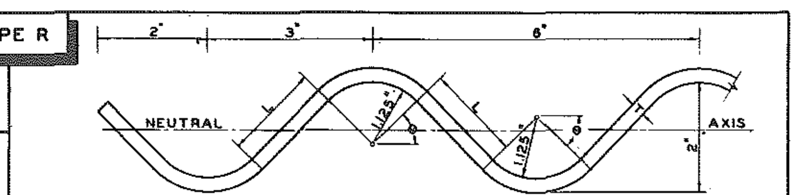
TYPE OA

Gage	Thickness T in inches	Tangent Length L in inches	Angle Δ in degrees	Moment of Inertia I inches⁴	Section Modulus S in.³/ in.
1	.2690	2.11	32°46'	0.0768	0.0868
3	.2391	2.13	32°37'	0.0681	0.0784
7	.1793	2.17	32°21'	0.0508	0.0606
10	.1345	2.20	32°10'	0.0382	0.0467
12	.1046	2.22	32°02'	0.0297	0.0371



TYPE R

Gage	Thickness T in inches	Tangent Length L in inches	Angle θ in degrees	Moment of Inertia I in.⁴/ in.	Section Modulus S in.³/ in.
1	.2744	1.7037	43°56'	.16488	.1450
7	.1829	1.8080	44°50'	.10741	.0984
10	.1372	1.8577	45°14.5'	.07976	.0746
12	.1067	1.89025	45°31'	.06166	.0585



TYPE OR

Gage	Thickness T in inches	Tangent Length L in inches	Angle θ in degrees	Moment of Inertia I in.⁴/ in.	Section Modulus S in.³/ in.
1	.2690	1.92156	56°06'	.08069	.09123
3	.2391	1.94490	56°15'	.07104	.08170
7	.1793	1.98960	56°32'	.05236	.06236
10	.1345	2.02370	56°45'	.03884	.04752
12	.1046	2.04542	56°53'	.03001	.03740

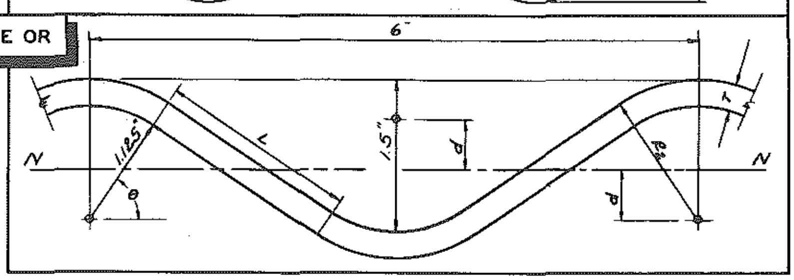


TABLE 1 APPENDIX
MANUFACTURERS DATA ON SPECIMENS

APPENDIX

TABLE 2

CHEMICAL ANALYSIS AND BRINELL HARDNESS*

Specimen	Rockwell B.	Brinell Hardness	C	Mn	S	P	Si	Cu	Mo.
U5Z1P	B56	90	.080	.300	.038	.016		.27	
U5Z1S	B59	93	.080	.300	.038	.016		.27	
U6Z1P	B66	104	.090	.390	.042	.015		.25	
U6Z1S	B67	105	.090	.390	.042	.015		.25	
U5Z7P	B65	103	.019	.028	.026	.006	.004		
U5Z7S	B59	93	.019	.028	.026	.006	.004		
U6Z7S	B64	101	.019	.028	.026	.006	.004		
U5Z10S	B60	95	.019	.028	.026	.006	.004		
U6Z10P	B60	95	.019	.028	.026	.006	.004		
U6Z10S	B65	103	.019	.028	.026	.006	.004		
R5X1P	B68	107	.05	.13	.030	.014		.43	.07
R5X1S	B64	101	.04	.11	.034	.010		.49	.08
R6Z1P	B68	107	.05	.13	.030	.014		.43	.07
R3Z1S	B69	109	.04	.11	.034	.010		.49	.08
R5X7P	B73	116	.04	.13	.026	.011		.44	.08
R5Z7S	B73	116	.04	.11	.033	.010		.48	.08
R6X7P	B70	110	.04	.13	.026	.011		.44	.08
R6Y7S	B72	114	.04	.11	.033	.010		.48	.08
R5X10P	B72	114	.05	.15	.025	.010		.54	.09
R5Z10P	B77	124	.05	.15	.025	.010		.54	.09
R5X12P	B73	115	.05	.16	.030	.010		.44	.05
R5Z12S	B71	112	.05	.16	.030	.010		.44	.05
R6X12P	B75	121	.05	.16	.030	.010		.44	.05
OR5X10P	B71	112		No		Data			
A6Z1S	B56	90							
A2Y7S	B67	105	Typical limits - No specific data						
A5X7P	B60	95	for this group						
A5X10S	B72	114							
A5Z10S	B72	114							
A5Z12S	B68	107	.02	.01-.02	.015-.022	.003-.007		.04-.05	
A6X12P	B58	92							
A6Z12S	B67	105							
OA5Y12P	B67	105							
OA5Y12S	B63	99							
			Typical analysis Bolts						
Type U Bolts			.18-.23	.30-.60	.05 max.	.04 max.			
Type R Bolts		258	.39	.66	.033	.019		.25	
Type A Bolts		269	.46	.80	.043	.010			

*Note: Chemical Analysis data furnished by Manufacturers.
Brinell hardness of plates performed by laboratory using 500 kg. load and 10 mm. ball. Bolt hardness values furnished by fabricator.

APPENDIX

TABLE 3 A

PHYSICAL TESTS ON PLATE SPECIMENS
(by Bureau of Public Roads)

Specimen No.	Yield Strength Offset .05 percent	Ultimate Strength	Modulus of Elasticity
	P.s.i.	P.s.i.	x 10^3
U5Z1P	30,444	49,427	30,393
U5Z1S	29,158	48,020	29,725
U6Z1P	32,374	50,000	29,247
U6Z1S	29,675	50,397	29,061
U5Z7P	39,781	48,798	30,642
U5Z7S	43,255	51,394	30,263
U5Z10S	38,784	52,026	32,069
U6Z10S	43,153	56,348	32,241
Ave.	35,828	50,801	30,455
R5X1S	31,849	48,288	28,804
R3Z1S	34,530	49,378	29,783
R5Z7S	44,737	52,053	29,497
R6X7P	42,857	54,416	28,529
R5Z10P	41,250	50,764	30,119
R5Z12S	45,455	52,196	28,633
R6X12P	44,007	52,862	29,481
OR5X10P	39,867	49,600	28,525
Ave. of new plates	40,669	51,422	29,264
A6Z1S	20,430	41,219	29,885
A2X7S	31,380	46,183	30,676
A5X7P	35,196	43,296	29,707
A5X10S	38,923	48,154	29,945
A5Z12S	24,779	41,681	28,471
A6X12P	24,091	41,182	27,049
OA5Y12P	46,223	53,237	31,357
OA5Y12S	43,363	51,150	31,907
Ave. of new plates	29,133	43,619	29,289

APPENDIX

TABLE 3 B

ADDITIONAL PHYSICAL TESTS ON PLATES AND BOLTS
(by Bureau of Public Roads)

Specimen No.	Yield Strength Offset .10 percent P.s.i.	Tension Tests		Rockwell Hardness Tests		
		Reduction in Area, Percent	Elongation Percent	Small Squares Tested by Michigan	Tension Specimens After Tests	
					Grip End	Reduced Section
U5Z1P	31,519	67	33	B58	B58	B79
U5Z1S	30,454	68	37	B59	B53	B79
U6Z1P	33,453	70	24	B56	B63	B77
U6Z1S	31,769	72	32	B63	B66	B82
U5Z7P	40,328	57	18	B60	B63	B74
U5Z7S	42,140	51	25	B62	B64	B74
U5Z10S	40,376	48	18	B64	B66	B78
U6Z10S	46,220	46	16	B63	B66	B78
Ave.	37,032					
R5X1S	33,219	68	35	B55	B55	B74
R3Z1S	34,876	69	32	B60	B65	B78
R5Z7S	45,053	63	22	B64	B70	B77
R6X7P	44,493	62	21	B63	B68	B74
R5Z10P	43,472	65	28	B72	B71	B81
R5Z12S	-	56	26	B74	B69	B80
R6X12P	44,544	59	18	B65	B71	B74
OR5X10P	40,800	58	23	B69	B65	B74
Ave. of new plates	40,943					
A6Z1S	20,789	67	41	B48	B51	B71
A2X7S	33,817	58	23	B59	B56	B64
A5X7P	35,307	63	31	B63	B56	B66
A5X10S	38,769	54	26	B60	B59	B74
A5X12S	25,133	64	38	B40	B41	B71
A6X12P	24,273	62	35	B38	B45	B70
OA5Y12P	46,583	45	16	B67	B68	B72
OA5Y12S	43,717	45	18	B67	B64	B70
Ave. of new plates	29,681					

APPENDIX

TABLE 3 C

CHEMICAL TESTS ON PLATES AND BOLTS
(by Bureau of Public Roads)

Identification No.	Chemical Analysis. Percent by weight						
	C	S	Mn	P	Si	Cu	Mo
			PLATES				
U5Z1P	.08	.035	.26	.012	.001	.24	--
U6Z1P	.08	.035	.25	.013	.003	.25	--
U5Z7P	.03	.025	.024	.004	.001	.00	--
U5Z10S	.02	.031	.033	.003	.001	.00	--
R5X1S	.03	.012	.12	.004	.001	.50	.08
R5Z7S	.04	.016	.10	.002	.002	.46	.07
R5Z12S	.04	.018	.12	.007	.002	.52	.07
A5X10S	.02	.019	.015	.017	.001	.03	--
A6X12P	.02	.019	.017	.006	.001	.03	--
OA5Y12P	.02	.030	.044	.004	.000	.11	--
OA5Y12S	.02	.033	.042	.005	.002	.12	--
			BOLTS				
U - White (1)	.16	.027	.53	.008	.002	.09	--
R - Yellow (1)	.42	.036	.75	.019	.004	.05	--
A - Green (1)	.42	.023	.71	.011	.003	.01	--

TABLE 3 D

PHYSICAL TESTS ON BOLTS

Company Submitting Specimens	Stress Tension P.s.i.	Rockwell Hardness
	Ave. of 7	Ave. of 2
United	80,057	B62
Republic	137,357	B100
Armco	129,779	B96

TABLE 4

PLATE DEFLECTIONS DUE TO COLUMN LOADING - TEST #1

Plain Specimens - No Curvature

Load in Thousand Pounds	Vertical Deflections (Thousandths Inches) TYPE OA			TYPE A			TYPE R			TYPE U			Horizontal Deflections (Thousandths Inches) TYPE OA			TYPE A			TYPE R			TYPE U		
	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.
10	40	42	49	51	74	37	39	51	39	57	59	114	13	17	26	0	0	18	2	6	17	0	0	0
20	62	56	85	65	96	55	54	68	60	80	76	132	36	35	56	6	1	35	7	9	27	0	0	0
30	78	66	108	77	111	73	65	83	77	94	86	148	58	44	96	7	5	61	13	17	36	4	0	0
40	97	87	138	88	124	92	74	95	97	109	101	166	87	78	161	17	11	87	19	25	52	11	6	0
50	113	98	186	98	135	112	82	107	119	119	112	180	117	124	352	20	18	160	25	32	76	16	11	6
60	126	107	275	107	144	153	91	115	135	129	121	194	146	140	580	23	22	460	29	37	93	23	15	10
70	138	120	@60	117	155	@60	99	124	164	137	131	209	177	165	@60	29	29	@60	35	43	145	27	20	23
80	152	133		125	164		104	133	193	145	139	221	220	224		30	35		40	49	262	33	24	32
90	168	150		134	172		111	141	245	153	146	232	280	290		34	42		46	56	460	38	28	40
100	190	197		141	178		118	148	@90	161	155	246	307	355		36	50		51	63	@90	42	33	51
120	222	260		158	198		129	164		176	170	303	390	480		44	70		63	77		52	43	340
140	@107	@110		171	218		140	178		187	183	@120	@107	@110		52	100		76	91		61	57	@120
160				193	258		150	195		198	200					75	145		92	107		72	86	
180				225	@150		159	211		210	220					105	@150		108	140		86	152	
200				@170			169	230		223	255					@170			132	195		107	285	
220							178	@190		235	@190								156	@190		136	@190	
240							197			255									244			209		
260							208			289									360			310		
							@250			@250									@250			@250		

Note: The final entry in each column is the ultimate load in thousand pounds.

Load and deflection values beyond ultimate load are shown on load-deflection curves.

TABLE 5

SLIPPAGE IN BOLTED SEAMS - TEST #2

Average Vertical Movement (Thousandths Inches)

Load in Thousand Pounds	SINGLE BOLTED 200 lb. ft. bolt torque TYPE A			TYPE R				TYPE U*			TYPE OA			300 lb. ft. torque TYPE R			100 lb. ft. torque TYPE OA		DOUBLE BOLTED 200 lb. ft. torque TYPE A			TYPE R	
	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	10 ga.	12 ga.	1 ga.	7 ga.	12 ga.	3 ga.	7 ga.	12 ga.	1 ga.	7 ga.	10 ga.	3 ga.	7 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.
10		1	3	1	2	2	1						10	1	2	6					2		
20	2	5	6	1	2	4	4						31	2	3	9		31			3		
30	5	19	23	2	2	6	30						60	7	5	20					4		
40	19	45	106	3	2	18	53						91	37	6	32		66					
50	28	65	196	4	4	30	72	169	127	129	5	43	147	77	26	43	34		61		6	1	1
60	34	83	362	5	16	56	90						240	214	103	61		115					1
70	41	110	560	8	54	77	117						439	251	124	152					11		2
80	49	136	780	19	76	101	159						600	271	137	180		201		6	28		2
90	58	170	@80	38	97	129	237						@77	283	152	212					@80		3
100	66	218		46	111	176	384	223	159	168	77	187		295	165	257	111	409	99	25		23	4
110	84	245		55	130	257	650					307		305	183	328		533					5
120	106	283		64	145	415	750				100	@104		316	207	462	144	@105		41			6
130	138	330		79	173	500	@116			197	143			328	235	@120	188						8
140	164	385		87	202	@130				230	148			344	273		234			70			10
150	203	@140		109	230			255	186	@140	209			362	319		297		148			67	12
160	252			118	271						265			@150	@150		385			106			14
180	395			166	431						347						@160			138			22
200	493			229	718			274	227		@180								245	@180		95	32
220	@190			289	@195			280	270										@200				43
240				419				288	@210													145	88
260				538				296														165	@240
280				@250				309														229	
300								322														@280	
320								372															
340								396															
360								@330															

Note: The final entry in each column is the ultimate load in thousand pounds.

*Vertical Deflections

TABLE 6

VERTICAL DEFLECTIONS FROM TEST #3 - 150" RADIUS COLUMNS

Deflections (Thousandths Inches)

Load in Thousand Pounds	PLAIN SPECIMENS TYPE U			TYPE R			TYPE A			TYPE OR	TYPE OA		BOLTED SPECIMENS TYPE U			TYPE R			TYPE A			TYPE OR		TYPE OA	
	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	10 ga.	7 ga.	12 ga.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2									76			106									54		103		104
4								[illegible]	[illegible]		110	162											147		141
5	139	162	202	70	69	97	78	93	117	120	123	182	91	128	215	75	90	115	95	80	88	125	168	145	159
6												206											193		185
8									148		156	241									125		235		231
10	188	209	246	107	107	122	110	120	167	184	175	278	174	194	290	114	136	153	125	115	145	194	283	225	294
12									186		195	320									165		342		375
15	212	243	276	134	131	153	139	145	243	235	230	429	219	227	330	158	173	200	150	140	195	255	466	300	582
20	232	268	306	161	165	185	167	170	314	298	284	@15	259	264	365	194	212	248	180	175	242	315	542	380	@13.8
25	260	295	329	188	198	235	195	200	@16.7	360	360		292	299	410	234	255	330	215	205	@17.1	405	@16	455	
30	279	319	360	211	228	342	223	222		466	403		324	335	520	277	310	448	245	260		617		553	
35	303	346	397	235	260	@28	255	250			@25.5		355	377	568	329	378	@28.2	295	344		@27		@27.5	
40	327	369	571	260	310		302	275		@30			384	460	@30.8	392	534		397	@34.8					
45	344	393		284	469		432	374					430	521		456	@42.8		559						
50	365	421	@40	308	@48.6		@45	@44.6					453	@40.8		540			@41.8						
55	382	442		336									486			732									
60	402	472		356									535			@52.3									
65	424	504		379									656												
70	442	546		407									@65												
75	462			452																					
80	485	@70		542																					
85	505			@79.7																					
90	530																								
95	550																								
100	600																								
105	630																								
110	670																								
115	705																								
120	740																								
123	866																								
	@123																								

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 7

HORIZONTAL DEFLECTIONS FROM TEST #3 - 150" RADIUS COLUMNS

Deflections (Thousandths Inches)

Load in Thousand Pounds	PLAIN SPECIMENS TYPE U			TYPE R			TYPE A			TYPE OR	TYPE OA		BOLTED SPECIMENS TYPE U			TYPE R			TYPE A			TYPE OR		TYPE OA	
	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	10 ga.	7 ga.	12 ga.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2											45	91									35		105		106
4											89	175									84		190		202
5				24	30	72	42	23	107	124						40	50	85	40	25	184	120		160	
6											137	266											290		318
8									175		180	373									169		387		451
10				48	72	137	86	67	228	235	221	461				82	114	185	91	84	221	220	498	290	622
12									278		268	596									270		643		880
15			43	75	106	203	128	110	435	352	340	969	42	58	78	135	170	277	125	135	683	340	941	430	1518
20			95	101	148	266	169	148	772	468	503	@15	79	104	167	185	246	420	179	222	@17.1	477	1139	581	@13.8
25		34	139	130	189	398	215	195	@16.7	620	901		115	161	310	244	327	650	230	330		725	@16	785	
30		60	210	157	236	808	258	245		912	@25.5		158	239	638	321	440	1039	315	500		1370		1139	
35		88	310	183	302	@28	319	300					204	369	1131	413	592	@28.2	460	794		@27		@27.5	
40	21	115	578	212	410		437	390		@30			259	901	@30.8	541	995		769	@34.8					
45	34	146		238	939		865	880					323	@40.8		686	@42.8		1432						
50	51	180	@40	267	@48.6		@45	@44.6					395			892			@41.8						
55	65	217		303									483			1416									
60	84	261		332									626			@52.3									
65	104	323		377									1083												
70	121	433		431									@65												
75	140			546																					
80	165	@70		830																					
85	180			@79.7																					
90	220																								
95	260																								
100	300																								
105	330																								
110	370																								
115	405																								
120	470																								
	863																								
	@123																								

Note: The final entry in each column is the ultimate load in thousand pounds.

Load and deflection values beyond ultimate load are shown on load-deflection curves.

Load in Thousand Pounds	PLAIN SPECIMENS											BOLTED SPECIMENS										
	TYPE A			TYPE OA	TYPE R			TYPE OR	TYPE U			TYPE A			TYPE OA	TYPE R			TYPE OR	TYPE U		
	1 ga.	7 ga.	12 ga.	7 ga.	1 ga.	7 ga.	12 ga.	1 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	7 ga.	1 ga.	7 ga.	12 ga.	1 ga.	1 ga.	7 ga.	12 ga.
1		126	300	204		97	161	99		81	141		132	223	175		78	125	120		61	112
1.5			448				227				186		172	345				184				141
2.0	108	215	608	325	80	168	299	189	58	146	231	126	212	437	402	80	157	238	244	116	88	178
2.5			775				372				272		260	565				294				224
3.0		321	@2.5	465		244	454	268		203	314		307	809	576		200	355			125	252
3.5							529				352		347	1155				410				284
4.0	192	397		582	150	306	613	334	99	250	385	223	395	@3.5	751	148	257	470	467	260	160	316
4.5							701				424		438					540				357
5.0		469		733		376	930	413		292	460		510		999		316	607	580		214	423
6	281	540		953	212	437	1190	506	137	321	517	343	647		1429	213	375	800	751	404	273	546
7		637		1105		501	@5.5	628		353	581		840		@6.0		447	930	1183		363	763
8	363	821		@6.5	270	573		818	173	383	677	482	1146			280	515	@7.0	@7.5	496	454	1040
9		1045				652		950		416	735		1510				608				581	1220
10	457	@9.0			343	762		@8.5	207	447	@8.4	733	@9.0			367	707			606	720	@8.4
11						852				476							822				937	
12	601				410	985			246	509		1076				449	1031			714	1236	
13						@12.0				543		1280					1410				1680	
14	1019				472				280	580		@13.0				535	@13.0			832	@ 13	
15	1155									640												
16	@14.5*				544				312	720						644				996		
17										847												
18					649					920						798				1247		
19										@17.4						891						
20					805				392							1017				1650		
22					1090				424							1165				@20		
24					@22.0				472							@21.0						
26									544													
28									640													
30									919													
									1060													
									@30.4													

* Indicates maximum load in thousand pounds

TABLE 8

HORIZONTAL DEFLECTIONS DUE TO COLUMN LOADING - TEST #4

Deflections (Thousandths Inches)

Load in Thousand Pounds	PLAIN SPECIMENS											BOLTED SPECIMENS										
	TYPE A			TYPE OA	TYPE R			TYPE OR	TYPE U			TYPE A			TYPE OA	TYPE R			TYPE OR	TYPE U		
	1 ga.	7 ga.	12 ga.	7 ga.	1 ga.	7 ga.	12 ga.	1 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	12 ga.	7 ga.	1 ga.	7 ga.	12 ga.	1 ga.	1 ga.	7 ga.	12 ga.
1		184	380	266		127	204	146		109	195		187	243	222		121	149	249		122	182
1.5			563				283				253		247	380				213				232
2	167	293	760	415	143	210	365	268	105	182	317	176	296	485	465	136	200	272	394	178	194	285
2.5			1100				446				373		357	627				336				360
3.0		424	@2.5	588		294	539	362		253	426		413	903	644		276	399			257	408
3.5							630				482		461	1180				457				459
4	275	514		733	239	369	723	452	165	315	591	275	515	@3.5	829	227	343	520	677	350	303	504
4.5							825				593		565					595				569
5		610		922		455	1096	555		376	652		649		1094		395	668	793		371	664
6	385	699		1210	321	527	1260	668	239	421	762	434	804		1626	308	478	878	990	528	444	855
7		816		1420		601	@5.5	821		472	918		1027		@ 6		557	1185	1493		545	1154
8	486	1037		@6.5	404	686		1055	298	521	1107	586	1380			389	629	@ 7	1610	641	655	1280
9		1390				780		1289		576	1280		1550				730		@7.5		795	1500
10	616	@9.0			498	907		@8.5	358	628	@8.4	854	@ 9			489	840			765	953	@8.4
11						1010				677							964				1195	
12	788				584	1175			421	735		1324				582	1193			901	1536	
13						@ 12				792		1530					1600				1640	
14	1229				664				476	849		@ 13				676	@ 13			1041	@ 13	
15	1440									936												
16	@14.5*				758				527	1038						794				1224		
17										1205												
18					879				585	1360						954				1511		
19										@17.4						1058						
20					1064				649							1289				1790		
22					1340				712							1480				@ 20		
24					@ 22				769							@ 21						
26									885													
28									990													
30									1252													
									1405													
									@30.4													

* Indicates maximum load in thousand pounds.

TABLE 9

VERTICAL DEFLECTIONS DUE TO COLUMN LOADING - TEST #4

Deflections (Thousandths Inches)

Load in Thousand Pounds	TYPE U				TYPE R				TYPE OR		TYPE A				TYPE OA
	1 ga.	7 ga.	10 ga.	12 ga.	1 ga.	7 ga.	10 ga.	12 ga.	1 ga.	10 ga.	1 ga.	7 ga.	10 ga.	12 ga.	12 ga.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	73	95	149	216	51	69	100	122	102	178	74	117	152	277	191
2.0	136	174	246	389	96	135	184	227	231	404	126	209	259	455	435
3.0	178	241	322	502	141	203	273	361	330	582	185	300	398	1533	689
3.5															1265
4.0	219	290	376	600	177	269	352	494	435	762	240	378	579	2500	1850
4.5														@3.74	2250
5.0	256	343	438	676	217	342	445	698	546	1036	299	494	1088		@ 4.2
6.	290	385	491	765	253	434	540	1250	654	1782	376	666	2734		
7	318	397	549	857	286	520	661	@6.07	1187	2250	479	1104	3150		
8	344	460	607	1208	319	635	827		2889	@ 6.3	607	2265	@ 6.3		
9	371	507	661	1500	360	830	1243		4000		860	3150			
10	403	559	798	@8.4	407	1219	1850		@8.5		1528	@8.4			
11	430	611	1054		454	2045	@9.75				2664				
12	462	676	1750		507	2800					4688				
13	488	763	@11.8		559	@11.5					4850				
14	514	952			621						@12.1				
15	546	1513			707										
16	576	2491			855										
17	625	3250			1202										
18	675	@16.6			1600										
19	700				2200										
20	776				@18.9										
21	816														
22	876														
23	979														
24	1125														
25	1371														
26	1698														
27	2341														
28	2949														
	@ 28														

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 10

VERTICAL DEFLECTIONS FROM TEST #5 - 150" RADIUS PLAIN BEAMS

Deflection (Thousandths Inches)

Load in Thousand Pounds	SINGLE BOLTED														DOUBLE BOLTED						
	TYPE U				TYPE R			TYPE A				TYPE OR		TYPE OA	TYPE R			TYPE A			
	1 ga.	7 ga.	10 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	10 ga.	12 ga.	1 ga.	10 ga.	12 ga.	1 ga.	7 ga.	12 ga.	1 ga.	7 ga.	10 ga.	12 ga.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	80	78	91	125	59	90	151	74	127	171	176	102	286	316	75	117	139	107	77	175	175
1.5										236			420				207				215
2.0	116	129	185	221	99	169	274	155	231	311	349	206	588	694	125	212	277	184	164	354	494
2.5										394			705				371				873
3.0	182	202	262	347	148	258	421	230	341	512	889	327	887	1280	176	302	502	270	301	550	1768
3.5										598			1100	1878			506				3548
4.0	227	277	347	468	209	341	551	311	470	742	1900	424	1342	3000	214	372	599	332	396	819	@3.5
4.5										931	@3.9		1767	@3.8			649				
5.0	276	376	459	630	256	435	836	416	641	1226		566	3042		256	462	836	409	494	1824	
6	326	534	686	916	319	546	1100	589	700	1800		777	3500		301	534	1151	515	678	@5.0	
7	385	718	901	1417	383	660	1600	856	1258	@5.7		1140	@5.2		346	626	2540	658	950		
8	430	946	1171	2300	456	787	@6.8	1220	2354			1896			402	773	@7.0	948	1420		
9	493	1342	1930	@7.5	539	971		1680	3000			3634			465	1092		1500	2815		
10	583	2299	3700		656	1272		2574	@8.4			4000			518	1803		2272	@9.0		
11	694	3636	4050		735	1667		3934				@9.2			589	2891		3500			
12	806	4400	@10.3		894	2400		4100							666	3400		@10.5			
13	911	@11.8			1094	@11.9		@11.1							778	@11.2					
14	1050				1214										946						
15	1230				1447										1223						
16	1505				1723										1568						
17	2120				2380										2139						
18	2900				3363										3031						
19	4500				4421										4094						
20	@18.8				@19.0										@19.0						

TABLE 11

VERTICAL DEFLECTIONS FROM TEST #5 - 150" RADIUS BOLTED BEAMS

Deflections (Thousandths Inches)

Note: The final entry in each column is the ultimate load in thousand pounds. Load and deflection values beyond ultimate load are shown on load-deflection curves.

TABLE 12

RESIDUAL VERTICAL DEFLECTIONS FROM TEST #5 - 150" RADIUS BEAMS

Permanent Deformation (Thousandth Inches)

PLAIN

Load in Thousand Pounds	TYPE U 1 ga.	TYPE U 7 ga.	TYPE U 10 ga.	TYPE U 12 ga.	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 10 ga.	TYPE R 12 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 10 ga.	TYPE A 12 ga.
0	0	0	0	0	0	0	0	0	0	0	0	0
1	6	5	0	5	2	3	3	6	3	1	3	233
2	5	3.5	0	6	3	4	3	7	3.5	4	5	236
3	5	4	0	25	4	8	5	45	10.5	6	24	1014
4	5	4.5	.5	58	5	16	13	95	12	14	73	2358
5	5	4.5	1	76	5	32	42	200	19	46	283	@3.74
6	5	4.5	6	116	6	64	74	1964	44	109	754	
7	5	5	48	184	8	111	169	@6.07	76	310	@6.3	
8	5	5.5	54	853	12	194	322		160	1075		
9	5	9.5	78	@8.4	18	364	1031		376	@8.4		
10	6	23	307		32	940	@9.75		1192			
11	9		807		44	2043			2682			
12	14	60	@11.8		64	@11.5			4589			
13	19	87			89				@12.1			
14	25	194			125							
15	32	620			187							
16	44	1590			375							
17	64	@16.6			766							
18	79				1384							
19	98				2644							
20	121				@18.9							
21	142											
22	186											
23	248											
24	327											
25	467											
26	825											
27	1412											
28	2112											
	@ 28											

SINGLE BOLTED

Load in Thousand Pounds	TYPE U 1 ga.	TYPE U 7 ga.	TYPE U 10 ga.	TYPE U 12 ga.	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 12 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 12 ga.
0	0	0	0	0	0	0	0	0	0	0
1	1	6	6	4	2	5	22	6	11	9
2	3	18.5	13	10	2	11	30	18	31	44
3	4	28.5	17	41	7	32	90	35	56	292
4	8	47.5	28	50	21	53	106	61	115	@3.9
5	15	60	48	63	27	74	212	92	205	
6	20	98	95	182	40	113	458	162	418	
7	33	189	198	379	57	174	@6.8	328	802	
8	45	383	409	@7.5	78	250		612	2605	
9	66	815	1197		107	458		1052	@8.4	
10	100	2129	2564		190	854		2098		
11	157	3090	@10.3		218	1419		3574		
12	205	4872			288	2735		@11.1		
13	282	@11.8			387	@11.9				
14	366				540					
15	510				753					
16	685				1033					
17	1196				1750					
18	2377				2696					
19	@18.8				3871					
20					@19.0					

DOUBLE BOLTED

Load in Thousand Pounds	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 12 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 10 ga.	TYPE A 12 ga.
0	0	0	0	0	0	0	0
1	4	16	20	14	0	15	21
2	23	28	33	27	0	46	115
3	31	45	63	48	15	124	1295
4	35	42	129	68	45	268	@ 3.5
5	41	65	316	100	93	1133	
6	49	78	548	157	205	@5.0	
7	59	139	1823	252	409		
8	73	227	@7.0	476	904		
9	95	480		964	2138		
10	116	1137		1692	@9.0		
11	150	2177		@10.5			
12	186	@11.2					
13	256						
14	368						
15	583						
16	890						
17	1414						
18	2276						
19	3318						
20	@19.0						

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 13

HORIZONTAL DISPLACEMENT FROM TEST #5 - 150" RADIUS PLAIN BEAMS

Chord Length (Inches)

Load in Thousand Pounds	TYPE U 1 ga.	TYPE U 7 ga.	TYPE U 10 ga.	TYPE U 12 ga.	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 10 ga.	TYPE R 12 ga.	TYPE OR 1 ga.	TYPE OR 10 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 10 ga.	TYPE A 12 ga.	TYPE OA 12 ga.
0	52.32	52.25	52.04	52.28	52.56	52.33	52.31	52.36	52.03	52.13	52.27	52.44	52.25	52.27	52.48
1	.34	.29	52.122	.36	.58	.37	.32	.38	.06	.22	.29	.46	.29	.34	.52
1.5										.25					
2.0	.35	.33	.19	.42	.60	.38	.35	.42	.09	.30	.32	.50	.32	.40	.56
2.5										.32					
3.0	.36	.34	.21	.46	.60	.41	.39	.46	.13	.35	.33	.52	.35	.60	.62
3.5										.37				.71	.70
4.0	.38	.35	.23	.48	.61	.43	.42	.50	.16	.39	.34	.53	.42	@ 3.74	.78
4.5										.42					@ 4.2
5.0	.39	.36	.25	.50	.62	.45	.44	.59	.19	.45	.36	.56	.52		
6	.40	.37	.27	.52	.63	.48	.47	.83	.23	.60	.38	.58	.75		
7	.42	.39	.28	.54	.64	.50	.49	@ 6.07	.37	@ 6.3	.40	.66	@ 6.3		
8	.43	.40	.31	.60	.66	.55	.55		.63		.43	.79			
9	.44	.41	.32	@ 8.4	.67	.61	.64		@ 8.5		.47	@ 8.4			
10	.45	.42	.34		.69	.70	@ 9.75				.62				
11	.46	.42	.40		.70	.88					.75				
12	.46	.44	@11.8		.70	@11.5					.74				
13	.47	.45			.72						@12.1				
14	.47	.49			.74										
15	.48	.58			.75										
16	.48	.70			.78										
17	.49	@16.6			.84										
18	.50				.93										
19	.50				53.09										
20	.51				@18.9										
21	.52														
22	.54														
23	.56														
24	.58														
25	.61														
26	.67														
27	.76														
28	52.83														
	@28														

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 14

HORIZONTAL DISPLACEMENT FROM TEST #5 - 150" RADIUS BOLTED BEAMS

Chord Length (Inches)

SINGLE BOLTED

Load in Thousand Pounds	Y TYPE U 1 ga.	TYPE U 7 ga.	TYPE U 10 ga.	TYPE U 12 ga.	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 12 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 10 ga.	TYPE A 12 ga.	TYPE OR 1 ga.	TYPE OR 10 ga.	TYPE OA 12 ga.
0	52.42	52.32	52.17	[illegible]	51.94	52.12	52.12	52.27	52.39	52.25	52.36	51.63	51.87	51.67
1	.44	.34	.24	.39	.98	.14	.15	.28	.42	.29	.38	.66	.97	52.11
1.5										.32			52.00	
2	.46	.36	.30	.43	.99	.15	.20	.30	.43	.33	.43	.69	.06	.16
2.5										.36			.11	
3	.49	.38	.32	.47	52.00	.18	.24	.32	.45	.39	.55	.72	.16	.30
3.5										.41	@3.9		.20	.37
4	.49	.41	.34	.49	.01	.20	.28	.35	.48	.44		.75	.25	@3.8
4.5										.48			.34	
5	.51	.43	.37	.54	.03	.23	.35	.38	.52	.53		.84	.55	
6	.52	.48	.45	.64	.05	.25	.42	.41	.57	@5.7		.87	@5.2	
7	.54	.54	.53	.75	.07	.29	@6.8	.48	.64			52.00		
8	.56	.60	.61	@7.5	.11	.32		.54	.74			.14		
9	.57	.72	.81		.14	.35		.58	@8.4			.39		
10	.59	.93	53.06		.17	.45		.68				@9.2		
11	.63	53.11	@ 10.3		.20	.54		.74						
12	.67	@11.8			.25	@11.9		@11.1						
13	.70				.30									
14	.74				.35									
15	.81				.43									
16	.87				.52									
17	53.02				.60									
18	53.31				.80									
19	@18.8				.87									
20					@19.0									

DOUBLE BOLTED

Load in Thousand Pounds	TYPE R 1 ga.	TYPE R 7 ga.	TYPE R 12 ga.	TYPE A 1 ga.	TYPE A 7 ga.	TYPE A 10 ga.	TYPE A 12 ga.
0	51.61	52.20	52.06	51.94	52.45	52.23	52.25
1	.64	.23	.16	.95	.48	.28	.28
1.5			.19				.29
2	.66	.25	.20	52.00	.50	.32	.32
2.5			.23				.39
3	.67	.26	.25	.00	.53	.34	.52
3.5			.28				.61
4	.70	.29	.32	.02	.55	.41	@3.5
4.5			.33				
5	.72	.33	.37	.03	.58	.55	
6	.72	.36	.44	.08	.61	@5.0	
7	.73	.39	.69	.11	.66		
8	.75	.45	@7.0	.17	.72		
9	.78	.55		.29	.84		
10	.79	.69		.44	@9.0		
11	.83	.83		@ 10.5			
12	.84	@11.2					
13	.87						
14	.92						
15	52.02						
16	.13						
17	.23						
18	.39						
19	.48						
20	@ 19.0						

Load and deflection values beyond ultimate load are shown on load-deflection curves.

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 15

LOAD-DEFLECTION DATA FROM TEST #6 - CORRUGATED PLATE 50" RADIUS - BEAM TEST

Vertical Deflections (Thousandths Inches)

PLAIN SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type OR 10 ga.	Type OR 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
1	71	88	142	156	174	341	55	71	105	63	73	82	112
1.5				241		484							
2	127	155	247	350	372	760	95	126	208	105	130	150	204
2.5				493		1098							
3	178	236	366	942	541	1511	134	178	305	152	177	219	293
3.5				1925		2425							
4	230	302	500	3209	715	@3.5	169	231	430	191	222	271	361
4.5				3450									
5	278	388	726	@4.2	1089		198	283	601	224	271	330	436
6	337	505	1473		2265		234	339	1152	260	316	380	500
7	405	700	2300		3500		268	407	3060	288	353	427	571
8	480	1152	2700		@7.0		297	474	4400	314	386	470	651
9	589	1750	@7.3				323	543	@7.6	341	422	519	901
10	839	2200					363	734		372	467	580	@9
11	1366	@9.4					396	1112		395	503	664	
12	2455						444	1493		424	552	899	
13	4113						505	2821		444	642	1500	
14	4700						529	4375		465	700	@13	
15	@13.5						585	@13.8		494	934		
16							642			516	1716		
17							742			550	3050		
18							883			588	@17		
19							1094			615			
20							1495			653			
21							2316			686			
22							3500			740			
23							@22			789			
24										866			
25										934			
26										1066			
27										1284			
28										1878			
29										2377			
30										2764			
31										3881			
32										4812			
33										5250			
										@32.8			

BOLTED SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type OR 10 ga.	Type OR 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
1	74	119	180	189	225	512	46	110	132	58	103	154	153
1.5				265		698							
2	137	221	316	361	444	881	90	189	240	103	171	245	287
2.5				608		1112							
3	213	337	469	930	661	1430	136	275	371	155	247	347	411
3.5				1300		1920							
4	278	433	689	2000	955	2400	173	335	496	195	323	425	524
4.5				@4		@3.9							
5	366	579	1218		2405		221	417	684	227	406	530	660
6	505	835	2000		3100		277	524	1117	275	502	686	901
7	666	1139	@5.8		@5.5		331	641	1950	315	600	842	1163
8	857	1763					405	761	@6.9	356	708	1052	1543
9	1131	2600					493	1007		394	842	1369	@8
10	1491	@8.9					580	1363		454	1056	1961	
11	1999						669	1725		513	1403	3796	
12	2475						779	2400		557	1936	@11	
13	3400						952	@12		622	2646		
14	@127						1072			714	3850		
15							1277			826	@14		
16							1452			937			
17							1767			1155			
18							(Bolt)			1440			
19							Failed			1765			
20										@20			

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 16

RESIDUAL VERTICAL DEFLECTIONS FROM TEST #6 - 50" RADIUS BEAM

Permanent Vertical Deformation (Thousandths Inches)

PLAIN SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
0	0	0	0	0	0	0	0	0	0	0	0
1	13	0	0	0	3	0	2	5	0	2.5	3
1.5											
2	13	0	0	26	4	0	4	5	1	4.5	6
2.5											
3	13	0	14	252	3	0	18	6	2	6	8
3.5											
4	17	5	72	2411	3	4	64	7	14	8.5	9.5
4.5				@4							
5	21	27	197		2	10	135	18	10	13.5	11
6	30	88	599		4	23	426	19	5	13.5	14
7	54	263	1862		5	40	2070	19	6	17	19.5
8	111	939	3170		6	70	3096	16	7	23	40
9	156	2190	@7.4		17	142	@8	28	11	37	215
10	495	@8.6			28	378		38	17	66	1062
11	1062				34	448		23	26	130	@9.3
12	2549				43	935		30	46	270	
13	4850				56	1528		40	78	620	
14	@13				71	3437		33	176	2030	
15					145	@14		30	631	@13.2	
16					174			31	1385		
17					222			42	2493		
18					291			65	3379		
19					381			72	@17.4		
20					625			94			
21					1007			113			
22					1895			134			
23					3240			175			
24					@23			221			
25								273			
26								409			
27								741			
28								1507			
29								2309			
30								2705			
31								3748			
32								6083			
33								@32			

BOLTED SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
0	0	0	0	0	0	0	0	0	0	0	0
1	0	7	29	9.5	5.5	13	0	1	31	17	9
1.5			33	12.5			0				
2	2	18	44	29	1.5	18	0	4	80	17	32
2.5			164	278			8				
3	15	44	183	812	1	25	25	7	49	40	25
3.5			204	@3			43				
4	27	59	254		0.5	33	65	12	94	60	38
4.5			372				107				
5	45	112	693		1	46	170	17	115	98	75
6	77	248	2280		1.5	70	605	23	118	159	166
7	131	528	@5.7		7	109	2175	28	150	240	418
8	195	1108			37	166	@6.9	43	201	383	718
9	401	2256			70	362		56	273	711	@8
10	579	@8.7			102	901		84	418	1260	
11					130	2194		120	721	3627	
12	1419				167	@10.8		135	905	@11	
13	2220				285			171	1391		
14	2761				361			230	2177		
15	@14.2				552			314	3282		
16					698			430	@14.5		
17					1024			643			
18					1922			1284			
19					@18			(Bolt)			
20								Failed			

Note: The final entry in each column is the ultimate load in thousand pounds.

TABLE 17

HORIZONTAL DISPLACEMENT FROM TEST #6 - 50" RADIUS BEAM

Chord Length (Inches)

PLAIN SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type OR 10 ga.	Type OR 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
0	49.81	49.71	50.00	49.78	50.26	50.17	49.60	49.79	49.64	49.79	49.83	49.81	49.51
1	.86	.77	.12	.89	.35	.39	.64	.87	.72	.83	.87	.88	.66
1.5				.94		.50							
2	.89	.83	.19	.99	.60	.65	.65	.90	.79	.86	.91	.92	.77
2.5				50.14		.83							
3	.93	.87	.28	50.36	.60	.99	.68	.94	.88	.90	.95	.99	.84
3.5				.76		51.45							
4	.96	.91	.37	51.40	.70	@3.5	.71	.98	.98	.93	.98	50.02	.89
4.5				52.0									
5	50.00	.99	.51	@4.2	.90		.72	50.01	50.09	.94	50.02	.09	.93
6	.05	50.06	51.09		51.42		.75	.05	.43	.95	.05	.13	.94
7	.10	.21	52.06		.97		.77	.12	51.35	50.00	.08	.16	50.00
8	.14	.47	@7.3		@7.0		.80	.18	51.90	.02	.10	.18	.04
9	.20	51.14					.84	.24	@7.6	.03	.13	.20	.17
10	.37	@9.4					.86	.37		.06	.15	.24	@9
11	.64						.89	.45		.07	.18	.30	
12	51.18						.91	.78		.09	.22	.44	
13	.72						.95	51.41		.11	.25	.59	
14	51.99						.97	51.91		.13	.30	@13	
15	@13.5						50.03	@13.8		.13	.45		
16							.06			.15	.78		
17							.13			.18	51.45		
18							.23			.20	@17		
19							.36			.22			
20							.60			.23			
21							.95			.25			
22							51.13			.28			
23							@22			.32			
24										.36			
25										.40			
26										.48			
27										.57			
28										.88			
29										51.18			
30										.35			
31										.68			
32										.98			
33										52.34			
										@32.8			

BOLTED SPECIMENS

Load in Thousand Pounds	Type A 1 ga.	Type A 7 ga.	Type A 10 ga.	Type A 12 ga.	Type OR 10 ga.	Type OR 12 ga.	Type R 1 ga.	Type R 7 ga.	Type R 12 ga.	Type U 1 ga.	Type U 7 ga.	Type U 10 ga.	Type U 12 ga.
0	49.64	49.65	49.69	49.80	50.33	50.34	49.56	49.65	49.31	49.78	49.42	49.30	49.43
1	.68	.77	.81	.91	.45	.62	.59	.70	.39	.84	.49	.45	.55
1.5				.97		.70							
2	.72	.83	.92	50.04	.58	.76	.62	.75	.47	.86	.55	.53	.69
2.5				.18		.87							
3	.78	.91	50.05	.37	.70	51.08	.65	.81	.57	.90	.64	.60	.83
3.5													
4	.82	.98	.16	50.77	.87	51.37	.68	.86	.68	.92	.68	.67	.94
4.5				@4		@3.9							
5	.87	50.06	.47		51.43		.70	.90	.80	.94	.76	.78	50.03
6	.98	.22	50.71		51.71		.74	.97	50.07	.98	.84	.91	.23
7	50.07	.41	@5.8		@5.5		.77	50.03	50.36	50.01	.91	50.04	.42
8	.17	.74					.82	.10	@6.9	.04	50.01	.21	.63
9	.33	51.05					.86	.23		.06	.10	.48	@8
10	.51	@8.9					.92	.43		.10	.28	.67	
11	.82						.97	.65		.14	.47	50.54	
12	51.24						50.05	51.08		.17	.80	@11	
13	@12.7						.13	@12		.21	51.17		
14							.21			.29	51.58		
15							.32			.37	@14		
16							.42			.43			
17							.60			.58			
18							51.13			.75			
19							(Bolt)			.93			
20							(Failed)			51.19			
21										@20			

Load and deflection values beyond ultimate load are shown on load-deflection curves.

Note: The final entry in each column is the ultimate load in thousand pounds.