AN INVESTIGATION OF METAL CULVERT PLATE

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This is to certify that the

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MATTHEW JOSEPH HUBER

has been accepted towards fulfillment
of the requirements for

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C. M. Cade
Major professor

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AN INVESTIGATION OF METAL CULVERT PLATE

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I SYNOPSIS

A series of corrugated culvert plates with different sizes and shapes of corrugation and of various gages were tested as beams. There were three styles of corrugation and four gages. The beam tests were made on plates formed to two curvatures. The value of different joint fastenings were also considered.

The outstanding results: (a) the load carrying capacities of the corrugated plates are in order, first, the 2 by 6 inch box type, second, the 2 by 6 inch circular arc, and third, the 1½ by 6 inch circular arc; (b) for each type of corrugation the load carrying capacity increased as the thickness increased; (c) the lap joint is more efficient than the butt joint when subject to beam loading conditions; (d) the radius to which the beams are curved does not affect the unit fibre stress of the plates; (e) double bolting of joints does not materially increase the efficiency of joints subject to beam action.

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III INTRODUCTION

Purpose of the Investigation

The purpose of this investigation is to conduct static load tests on corrugated metal plates of various cross-sections to determine their relative stability under different load conditions. At the present time the design of structures of corrugated metal plates is based wholly on empirical methods. Past experience has proven the best guide in the design of new structures is to use data already gathered from previous successful installations. Recently manufacturers have introduced two new variables which have made the use of data gathered from previous installations rather questionable.

These two variables are the introduction of corrugation with a $1\frac{3}{4}$ inch and 2 inch depth in place of the $1\frac{1}{2}$ inch deep corrugation and second, a new type of corrugation, the "box" style which consists of rectangular cross-section rather than the circular cross-section.

This investigation, then, is to answer the following questions:

1) Is there any relationship between the section modulus of the plates and the load carrying capacity regardless of the size and shape of the corrugation?

2) Do the types of fastenings used fully develop the strength of the metal when subject to bending stress?

History and Use of Corrugated Metal Plate

Corrugated metal plate has long been a popular material for construction of culverts in highway and railway work. Its chief advantages have been rapidity and ease of construction, high salvage value and ease of maintenence. Pipes of this type are manufactured in sizes varying from 8 inches in diameter up to 96 inches in diameter. Beyond this size there are practical limitations of strength and shipping difficulties which make the 8 foot pipe the maximum usable size.

To satisfy the demand for pipes of larger size Armco Drainage and Metal Products, Inc. in 1931 introduced nested sections of corrugated metal plate which are later bolted together in the field. The nesting of the sections overcame the shipping difficulties previously mentioned and to increase the strength of the plates the depth of the cross-section was increased from ½ inch to 1½ inches thereby increasing the moment of inertia of the cross-section of the metal plates. Several manufacturers followed suit and manufactured plates of the same cross-section. This cross-section was used until the period immediately following World War II. All of the design

criteria of structures using sections of culvert plate were based on this style.

Immediately following World War II the major manufacturers of corrugated metal plate introduced a new style of corrugation. One manufacturer increased the depth of his section to $1\frac{3}{4}$ inch, another increased the depth to 2 inches. A third manufacturer introduced a new shape of corrugation, the "box" type which was radically different from the existing styles of corrugation. The values of these changes in the size and shape of corrugation are being studied under laboratory studies such as this present series of tests as well as under field conditions in actual installations.

The principal use of corrugated metal plate is in highway and railroad culverts and in airport drainage structures. The sections are cut and punched in the shop and are ready for assembly when received in the field. The finished assemblies may be of either the circular pipe or arch-type shape. Pipe culverts may be assembled in diameters ranging from 5 feet to 15 feet while arches may be constructed with spans ranging from 6 feet minimum to a maximum of 30 feet.

Other uses of culverts of this style are as replacement or supplement for existing structures. In instances where concrete or masonry arches have deteriorated beyond reason-

able safety limits corrugated metal arches are assembled immediately beneath the existing structure on new or existing footings and grout is forced between the bottom of the old arch and the top of the new arch to insure transfer of load to the new arch. These plates are also used in some instances for constructing pipes used in sewerage and irrigation projects.

<u>Outline of the Tests</u>

In order to answer the questions relative to the new styles of corrugation, a series of 6 tests was developed. Three of the tests were to measure vertical and horizontal deflections of columns subject to loads applied at the ends of the column. A fourth test was devised to measure the slippage of joints subject to direct compression and the remaining two tests were used to measure horizontal and vertical deflections on plates acting as beams. The six tests are shown schematically in Fig. 1.

This report is concerned only with the results and interpretation of the beam tests, tests 5 and 6. Test 5 consists of a simply supported beam, curved to a radius of 150 inches. A vertical load was applied at two points near the center of the beam and the horizontal and vertical movements were recorded. Both bolted and unbolted specimens were used for this test.

Test 6 is identical to test 5 except that in this case

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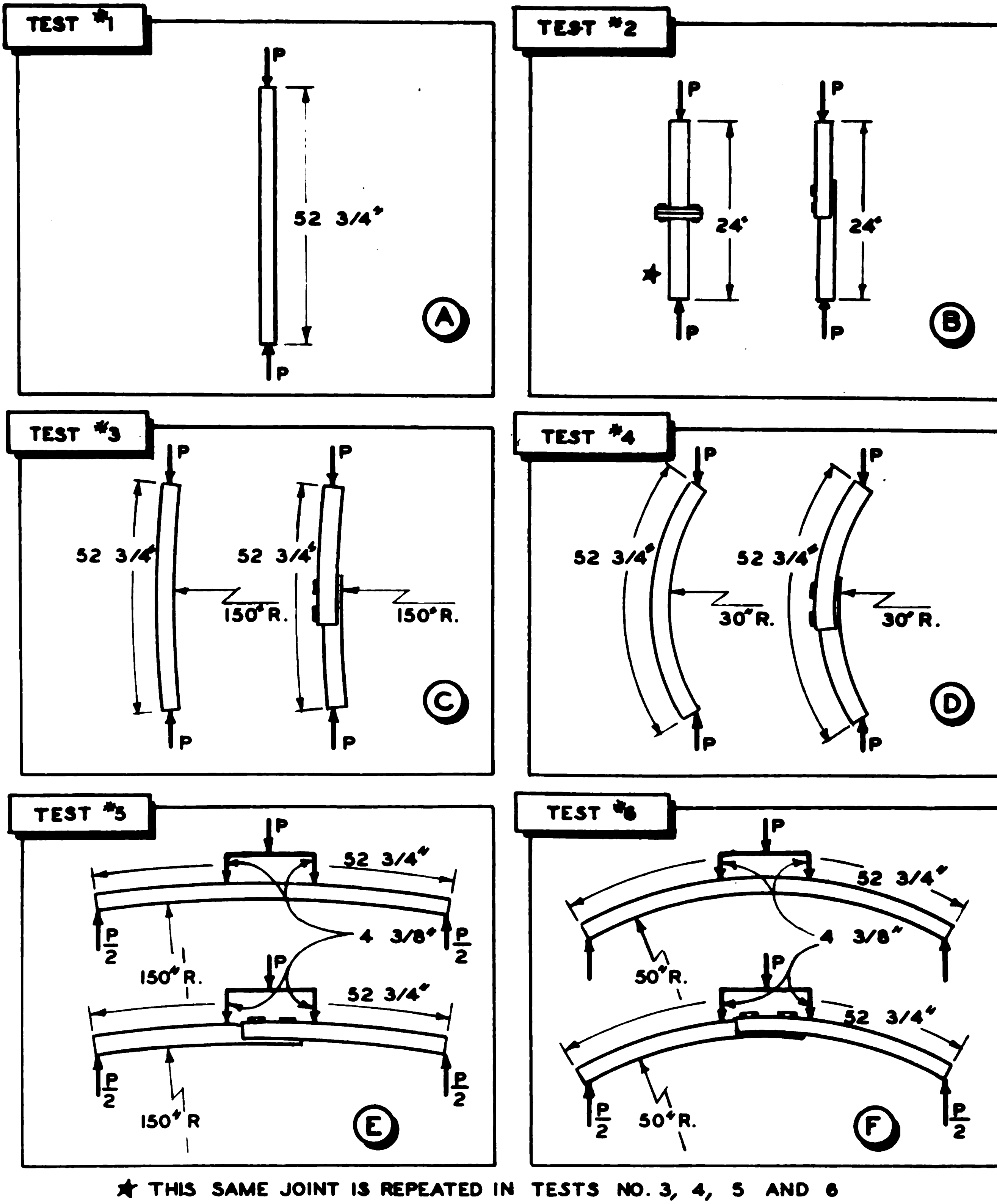


The SIX FUNDAMENTAL TESTS

Figure 1

the radius of the beams was reduced to 50 inches. These two tests measured load carrying ability and joint action of plates acting as beams.

IV MATERIALS INVESTIGATED

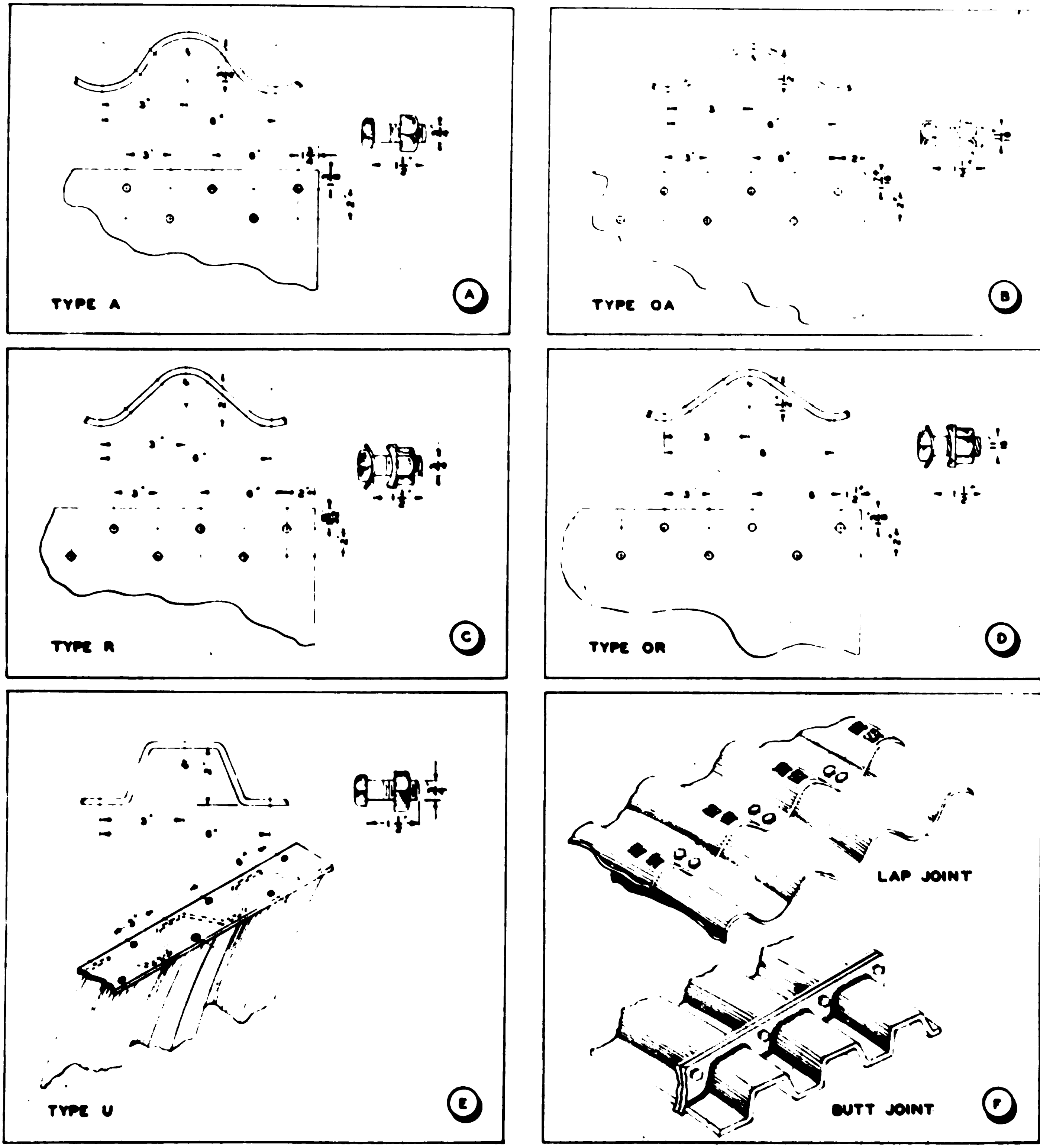
Sources

The materials for the test were supplied by three manufacturers each of which uses a different type of corrugation. Each manufacturer in turn provided plates of four different gages in both bolted and unbolted sections.

The style of corrugation used by manufacturer A is illustrated in Fig. 2A. It is of the circular arc type with a pitch of 6 inches and a depth of $1\frac{3}{4}$ inches. The plates are fastened together with a lap joint using high tensile bolts spaced as shown in 2A.

Manufacturer R also uses a circular type corrugation as illustrated in Fig 2C. The pitch is again 6 inches but the depth of the section has been increased to 2 inches. A lap joint is also used for this style corrugation and spacing of bolt holes are as illustrated in Fig. 2C.

The new "box" style of corrugation, developed by manufacturer U, is illustrated in Fig. 2E. The section is a modified trapezoid with a 6 inch pitch and a 2 inch deep corrugation. The joint used is the butt type which consists of a heavy butt plate welded at right angles to the cross-section of the corrugated metal plate. Two



DETAILS *of* PLATES *and* JOINTS

Figure 2

adjacent sections of this style plate are jointed by bolting the two butt plates together. Bolt spacings are shown in Fig. 2E.

The lap joint and the butt joint are both illustrated in Fig. 2F. The lap joint shown is the double-bolted joint. In normal installation, the bolt holes are staggered and only one bolt is inserted in each valley and crest rather than the two shown.

All of the plates furnished were 52¾ inches long before being formed to the different radii and were of the following width:

type A	21¾ in.
type R	22 in.
type U	21 in.

<u>Physical Properties</u>

Complete data showing details of each of the three styles of corrugation may be found in Table 1 of the appendix together with data for moment of inertia and section modulus of the plates. Chemical composition and hardness data for the different materials are found in Table II of the appendix.

The dimensions of the bolts furnished with each of the three styles of corrugations are illustrated with their respective corrugations in Fig. 2. The bolts used for types A and R were high tensile strength bolts with an average ultimate strength value of approximately 132,000 psi. The bolts used for type U plate were of A-7 grade metal with lower strength characteristics than the other bolts used.

Outline of Tests

Tests 5 and 6 were made on both plain and bolted samples and in effect amounted to 4 different tests. Each of the manufacturers, A,R, and U provided samples for each of these 4 tests in 4 different gages, 1, 7, 10 and 12 and enough identical samples were furnished so that each test could be repeated three times if necessary. (Manufacturer R provided 10 gage only for the unbolted portion of test 5.)

Identification of Specimens

In a test involving such large numbers of specimens an identification system was deemed necessary to facilitate classification of material and results. The code that was developed consisted of a series of letters and numbers in the following sequence: source, test number, letter identifying which plate of three identical plates, metal gage and letter telling whether the plate was bolted or unbolted.

The systen is as follows. The source may be A, R, or U. Test number 5 and 6. X,Y,and Z distinguished between the three identical plates. The gage symbol was 1, 7, 10 or 12. The last letter was either P (plain) or S (seam). In this system a plate identified as A6X12S indicates type A corrugation, test 6, first of three identical specimens, 12 gage, and has a joint. R5Z7P indicates a plate supplied by manufacturer R, test 5, the third of three identical specimens, 7 gage metal and an unbolted plate.

Supplementary Tests

Not all of the plates were tested as indicated in the above schedule. In most instances the information gathered from tests on plates X and Y provided all of the data needed for that particular test. The Z specimen was then used for supplementary studies. The supplementary studies discussed in this report include the following:

1. Seam strength Many of the bolted Z plates were reinforced at the seam by a double row of bolts before being subject to beam loading. This test was an effort to determine if there was any merit in the practice of double-bolting joints subject to severe bending.

2. Bolt Stresses Strain measurements of bolts used in tests 5 and 6 were made at various phases of the test. SR-4 type A-8 strain gages were attached to the bolts in order to measure tension in the bolt.

3. Bolt Torque In order to determine the maximum torque to which bolts should be subjected a limited number of bolts were twisted to failure. Measurements of torque were made with a torque wrench.

V EXPERIMENTAL PROCEDURE

Description of Apparatus

The load for the beam tests was applied through a 50-ton hand-pumped hydraulic jack set in a frame constructed from I-beam and channel sections as shown in Fig. 3. The ends of the beams rested on two concrete block piers which were capped with 1 inch by 8 inch by 24 inch steel plates. The plates were machined to a smooth finish and set at the same elevation.

The load is transfered to the plate by means of the loading head shown in Fig. 4. The dynamometer ring is used to measure the magnitude of the applied load. A 1 inch round ball bearing between the dynamometer ring and the steel loading head insured freedom of movement in all directions. The load transfer device itself consists of a reinforced channel section placed over a wooden pattern. The wooden patterns were cut out to fit the different types of corrugation and lined with rubber to insure a perfect fit.

Freedom from restraint on the ends of the beam was guaranteed by the load transfer device shown in detail in Fig. 3. The ends of the plate rested in the vertex formed by a $2\frac{1}{4}$ by $2\frac{1}{4}$ inch steel angle. The angle rested in a groove in a machined flat steel plate.

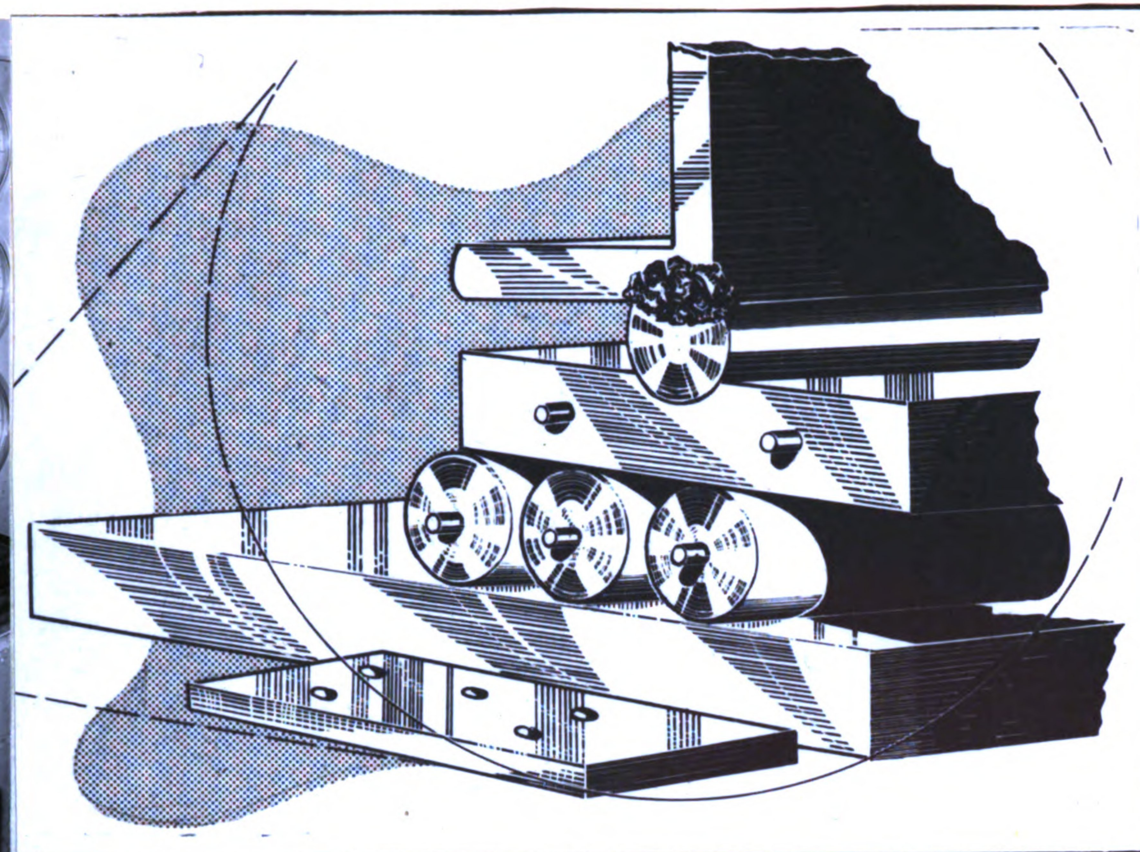


FIGURE 3 - ARRANGEMENTS FOR TESTS 5 and 6

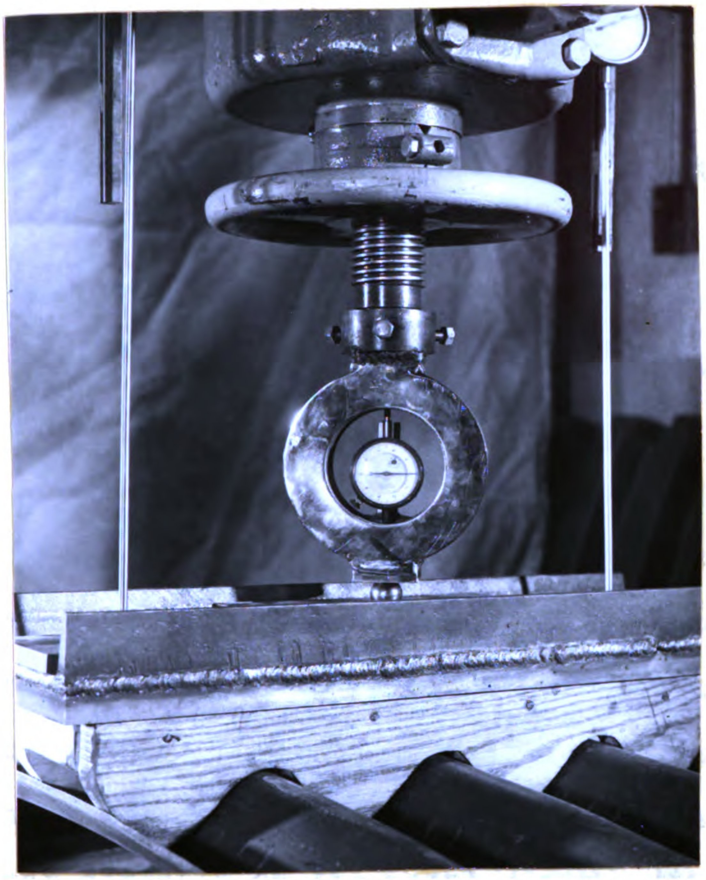


FIGURE 4- LOAD TRANSFER HEAD

FIGURE 5 - STRAIN GAGE ATTACHED TO BOLT

The flat steel plate rested on three 1 inch steel rollers which acted as roller bearings on the steel caps of the piers.

It was necessary to use two-point loading at the center of the beam since single-point loading would interfere with the fastenings used on the unbolted sections. The same pattern was used on the unbolted specimens to insure uniform loading conditions.

Two dials, each graduated to 1/1000 inch were used in recording the deflection at the center of the beam. In order to insure that the deflection measured is that of the beam and not the compression of the loading device the rods leading to the dials do not touch the loading device. Instead they pass through holes in the loading head and bear directly on the metal plate. The dials are shown in position on either side of the hydraulic pump in Fig. 3. Horizontal measurements were made with a steel straight-edge graduated to 1/64 inch.

Miscellaneous equipment used included a Baldwin Southwark indicator used to measure bolt strains and a torque wrench. A strain gage is shown in place on a bolt in Fig. 5.

Test Procedure

The procedure used in tests 5 and 6 was identical. The plates were inserted in the end loading devices and the loading head slipped into place. After the plate was centered the load was applied in 1000-lb. increments. Vertical and horizontal displacements were recorded as each load increment was applied. The load was continued until the ultimate loads were reached and further increases in deflection were possible without increases in load.

The same procedure was followed with the bolted specimens except that the bolts in the joint were tightened with a torque of 200 ft-lbs. A uniform torque was adopted after a series of tests showed that variation in torque effected the results of the load deflection studies.

To determine a suitable torque, a wrench slightly smaller than that employed in the field, was used by five highway employees who found that they could apply an average torque of 157 ft-lbs. Assuming that the laborer in the field had a larger wrench and a better knack for using the tools, it was felt that a torque of 200 ft-lbs. would very nearly satisfy field conditions.

Miscellaneous Tests

In order to test the effectiveness of increasing the number of bolts in a joint extra holes were drilled in those plates used and another set of bolts inserted. The rest of the procedure was as previouly indicated. By nature of the fastening used it was not possible to increase the number of bolts in the butt-type joint.

Bolt strains were measured by inserting strain gages on the bolts and then placing them in the joint. As each increment of load was applied strains were recorded from readings on the strain indicator.

The maximum torque was determined by twisting the bolt to failure with a torque wrench. The torque at failure was recorded in ft-lbs.

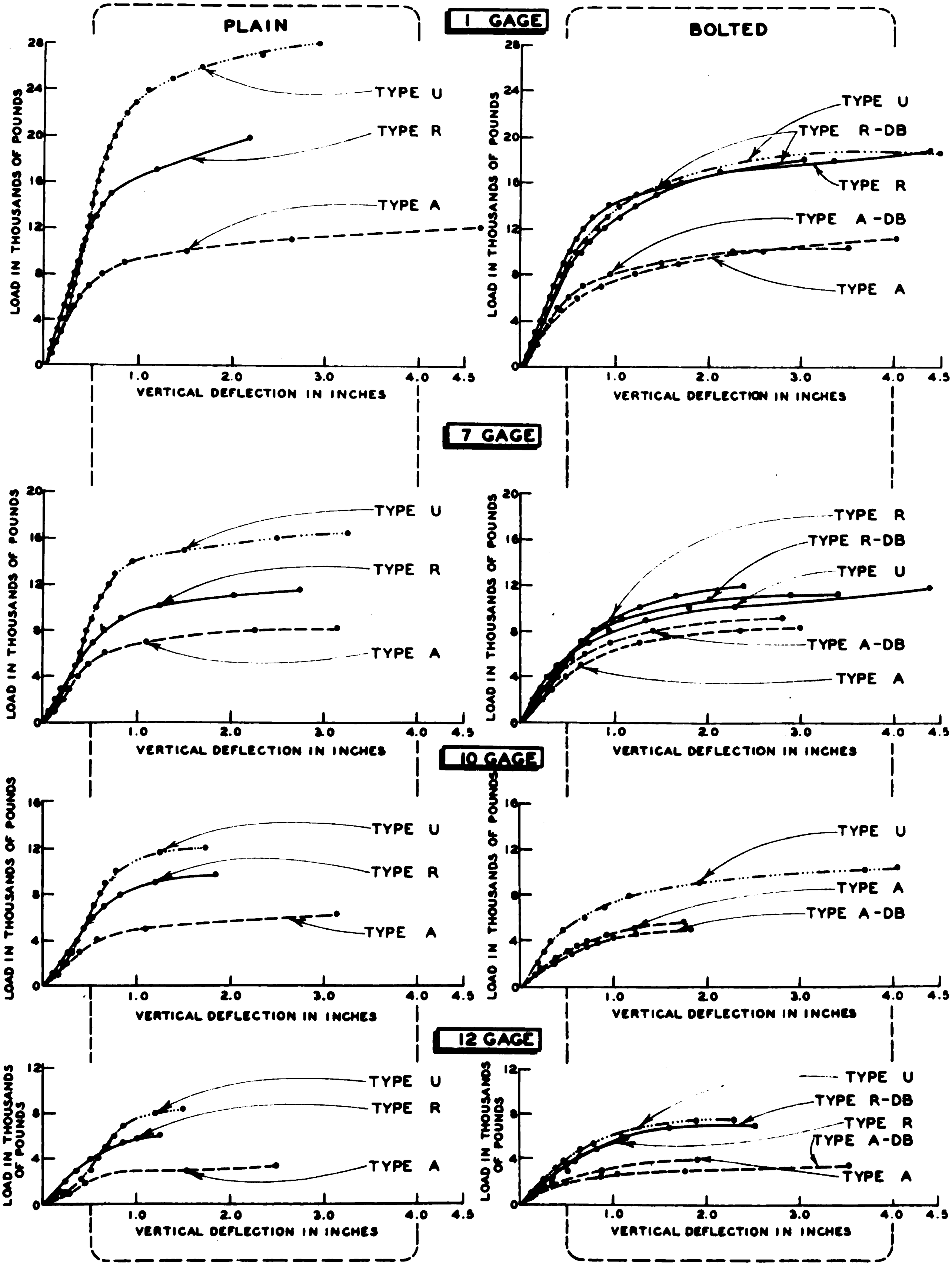
VI EXPERIMENTAL RESULTS AND INTERPRETATION

Load-Deflection Data

The load deflection data for tests 5 and 6 is presented graphically in Figs. 6 and 7. Each curve is the average of one, two or three specimens, whichever number were used for each particular test. Each group of curves is classified by gage of metal used and whether plain or bolted specimens. Those curves on the left side of the page represent the plain specimens and those on the right half of the page represent the bolted specimens. The type of corrugation used is indicated for each individual curve. Included with the curves for the bolted specimens. are the curves for the double bolted specimens. These curves are noted by a symbol DB-(double bolted).

Influence of Corrugation

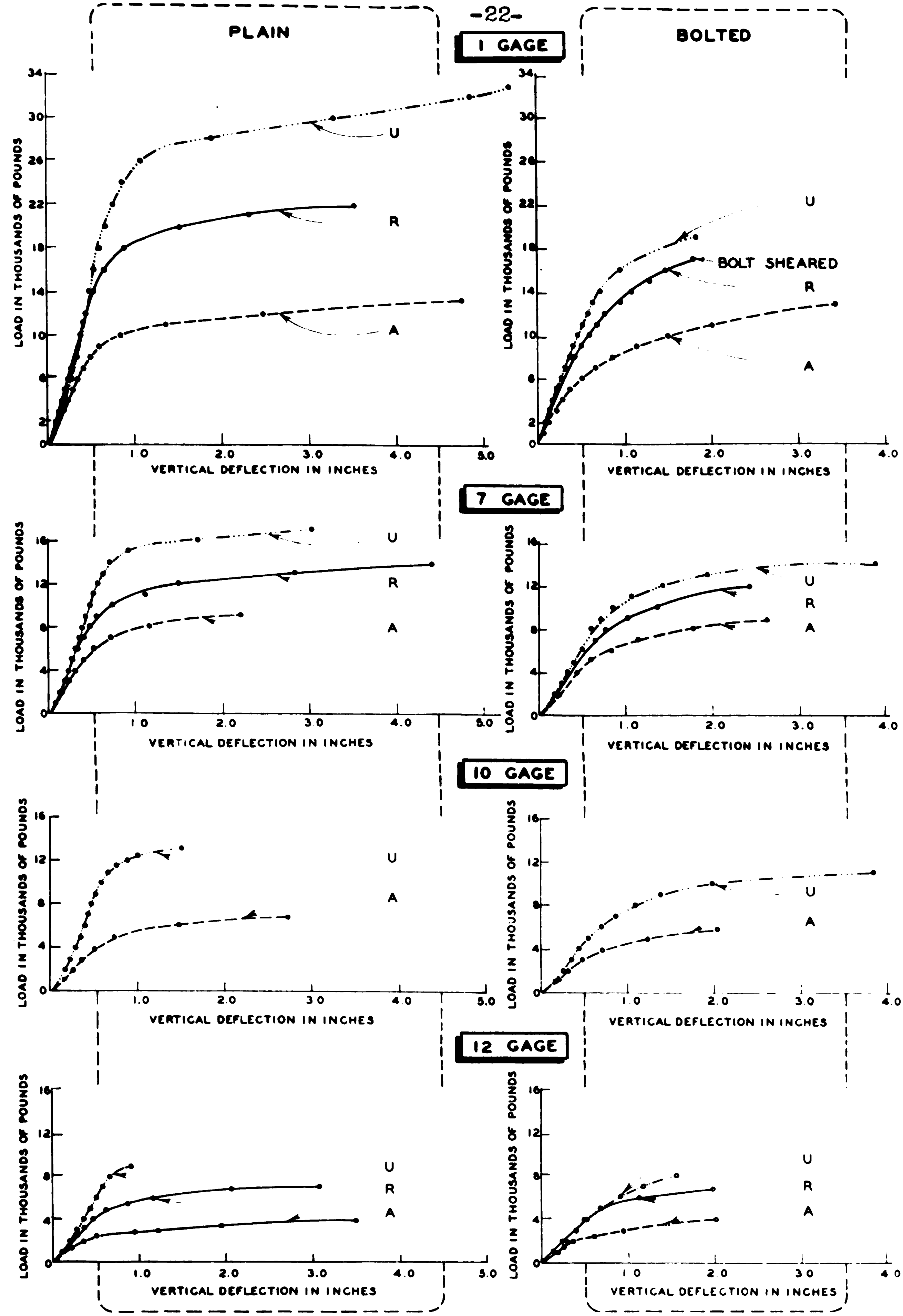
Figs. 6 and 7 have been arranged so that a graphical analysis may be made of the influence of corrugation on load-deflections. The nominal overall dimensions of each of the plates is the same; each curve is grouped with others of the same gage, so that for the unbolted specimens the only factor that determines the maximum load carried by the plates is the variation in type of corrugation.



INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 5

Figure 6



INFLUENCE OF CORRUGATION ON DEFLECTIONS

TEST 6
Figure 7

In both tests 5 and 6, plain specimens, it will be readily observed that the load carried by the type U corrugation is notably higher than the R style corrugation which in turn is able to support a greater total load than the A style corrugation. This relationship between the load carrying capacity of the different types of corrugation is of the same pattern as the relationship between their respective section moduli. The section modulus for type U is higher than for type R which in turn is higher than A. Such a trend would seem to indicate that there is a relationship between section modulus and load carrying capacity of a plate.

In curves for bolted specimens the differences between types of corrugation are not nearly so evident. In this case the type of joint used has also become a factor in determination of strength. It will also be noted that the presence of a joint reduces to some extent the load carrying capacity of very nearly all of the plates regardless of the type of joint used.

In the elastic range of the curves for the heavier gages the slopes of the straight lines are very nearly parallel indicating that types U, R and A have comparable degrees of stiffness. The computed unit stress values at the elastic limit for tests 5 and 6 are tabulated in Tables 1 and 2. The actual values for the unit stress at

TABLE 1

UNIT STRESS AT ELASTIC LIMIT - TEST 5

Specimen	Load at Elastic Limit (lbs.)	Unit Stress at Elastic Limit (psi)	Average (psi)
U5X1P	17000	40000	
U5Y1P	17000	40000	
U5Z1P	19000	44800	41600
U5X7P	11000	38800	
U5Y7P	11000	38800	
U5Z7P	12000	42350	39983
U5X10P	9500	43400	
U5Y10P	9000	41200	
U5Z10P	9000	41200	42000
U5X12P	7000	40800	
U5Y12P	7000	40800	
U5Z12P	5000	29200	36930
R5X1P	11000	- - -	
R5Y1P	12000	45400	
R5Z1P	12000	45400	45400
R5X7P	7000	38700	
R5Y7P	6000	33400	
R5Z7P	7000	38700	36930
R5X10P	6000	43900	
R5Y10P	6000	43900	
R5Z10P	6000	43900	43900
R5X12P	3500	32775	
R5Y12P	4000	37375	
R5Z12P	4000	37375	35842
A5X1P	6000	25900	
A5Y1P	6000	25900	
A5Z1P	7000	30200	27320
A5X7P	4500	28800	
A5Y7P	4500	28800	
A5Z7P	5000	31900	29830
A5X10P	3000	25100	
A5Y10P	3000	25100	
A5Z10P	3000	25100	25100
A5X12P	2000	21250	
A5Y12P	2000	21250	
A5Z12P	2000	21250	21250

TABLE -2

UNIT STRESS AT ELASTIC LIMIT - TEST 6

Specimen	Load at Elastic Limit (lbs.)	Unit Stress at Elastic Limit (psi)	Average (psi)
U6X1P	20000	44800	
U6Y1P	18000	40300	
U6Z1P	19000	42700	42600
U6X7P	11500	38700	
U6Y7P	12000	40400	
U6Z7P	12000	40400	39800
U6X10P	10000	43800	
U6Y10P	10000	43800	
U6Z10P	10000	43800	43800
U6X12P	7000	38600	
U6Y12P	7500	41500	
U6Z12P	8000	44200	41433
R6X1P	12000	43000	
R6Y1P	12000	43000	
R6Z1P	11000	39100	41670
R6X7P	7000	36800	
R6Y7P	7000	36800	
R6Z7P	8000	42600	38730
R6X12P	4000	35500	
R6Y12P	4000	35500	
R6Z12P	4500	39700	36900
A6X1P	8000	32800	
A6Y1P	8000	32800	
A6Z1P	7000	28800	31450
A6X7P	5000	30300	
A6Y7P	5000	30300	
A6Z7P	5000	30300	30300
A6X10P	4000	32000	
A6Y10P	4000	32100	
A6Z10P	3500	27900	30700
A6X12P	2000	20200	
A6Y12P	2000	20200	
A6Z12P	2000	20200	20200

the elastic limit and the ultimate strength were determined by the Bureau of Public Roads from samples of metal cut from the test specimens. This data presented in Table 3 of the appendix.

Table 3 is a comparison of the values for unit stress at the elastic limit as determined directly by the Bureau of Public Roads and as computed from the information gained from the load-deflection curves. The table shows that for A and R there is very close agreement between the computed and measured values for unit stress and that for type U the agreement is reasonably good. This would indicate that the curves as drawn show an accurate relationship between the different styles of corrugation up to the elastic limit. It would further indicate that up to the elastic limit the shape and style of the corrugation does not greatly effect the relationship between the section modulus (I/c) and the load carried by the plates.

Table 3

COMPUTED UNIT STRESS VALUES VS.

MEASURED UNIT STRESS VALUES (at elastic limit)

	Computed values	Measured values
type U	41014	35828
type R	39924	40669
type A	27008	29133

Beyond the elastic limit unit stresses are not as readily determined. The "flexure formula" $S = \frac{Mc}{I}$ is applicable only when computing unit stresses in beams when the unit stress at the outer fibre does not exceed the elastic limit of the metal. As previously discussed, the ultimate loads, as indicated by the curves in Figs. 6 and 7, are in the same order as are the section moduli so that beyond the elastic limit there is still evidence that the relationship between section modulus and load carrying capacity is not effected by changes in the style of corrugation.

Typical failures of circular-type corrugations (A & R) are illustrated in Figs. 8 and 9. The maximum deflection occur at the center of the plate as might be expected. In the bolted specimens there is tearing in the row of holes most distant from the punched end of the top plate in the lap joint. Fig. 10 illustrates typical failures for the box type corrugation. In the plain specimens there is evidence of local failure in the corrugation while in the bolted joint there is a "spread" failure in the butt-plate used for the joint. It is the failure of the butt plate that reduces the effectiveness of this type of joint when subject to bending.

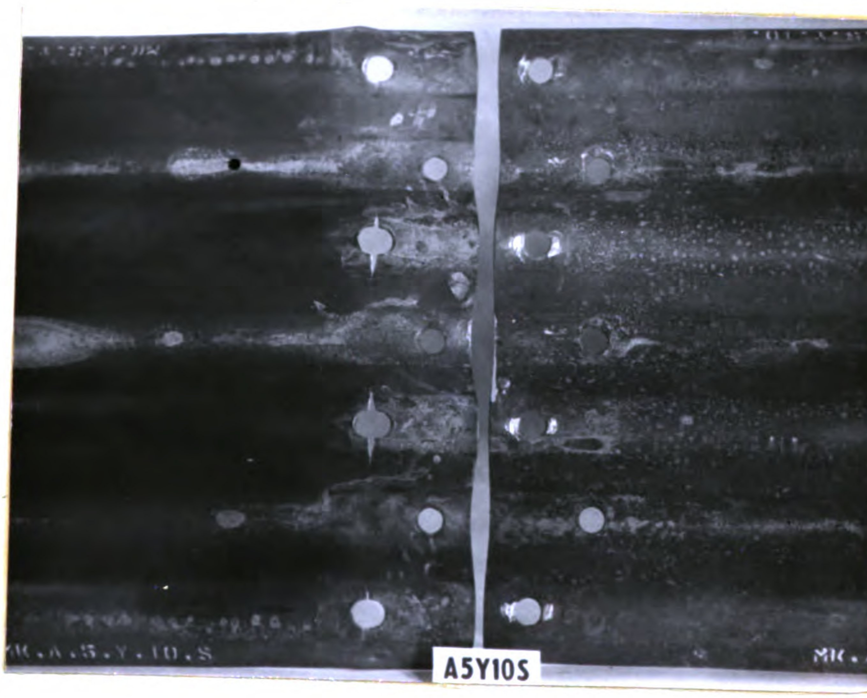


FIGURE 8 - TYPICAL FAILURES - TYPE A

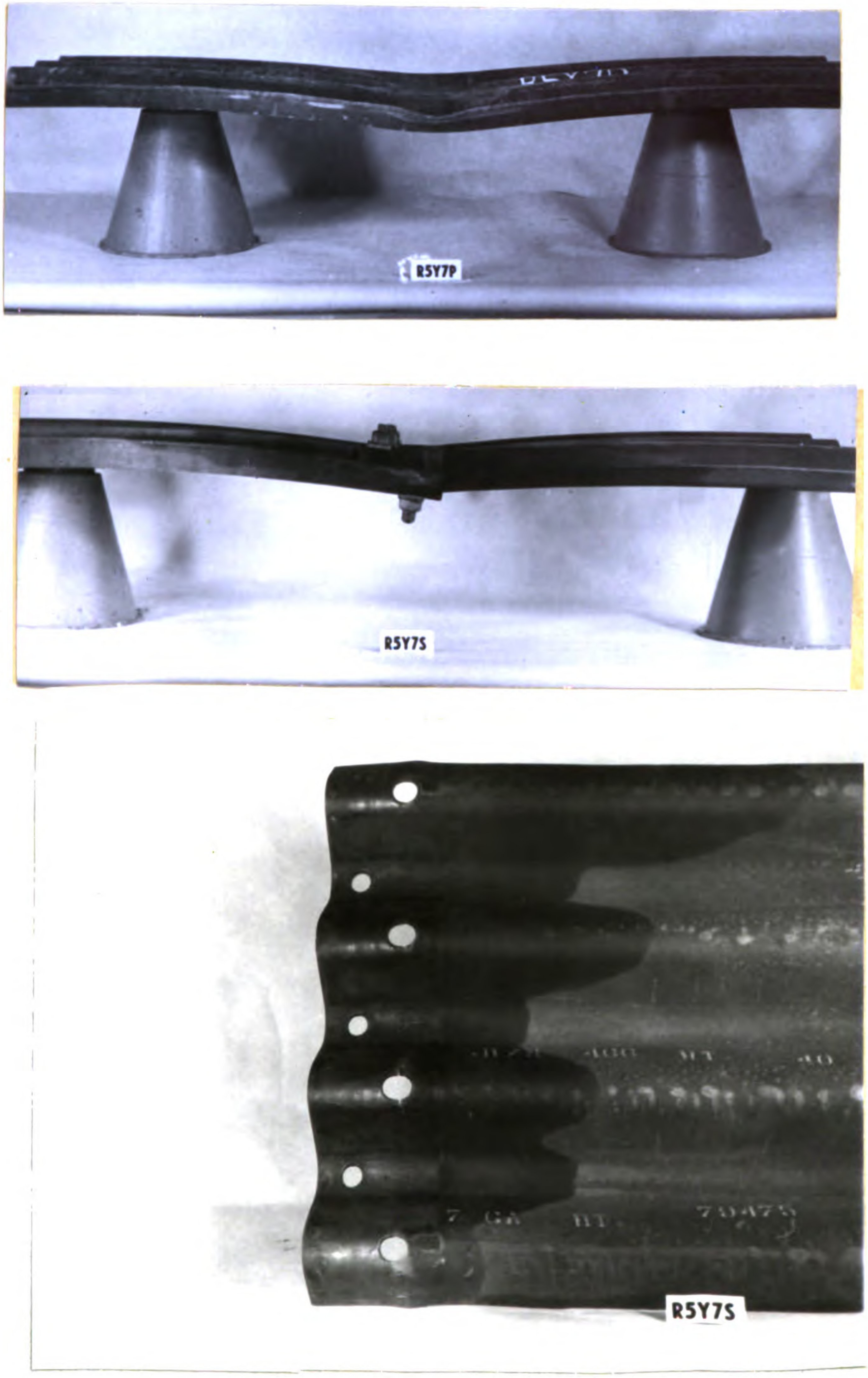


FIGURE -9- TYPICAL FAILURES - TYPE R

FIGURE 10 - TYPICAL FAILURES - TYPE U

Effect of gage

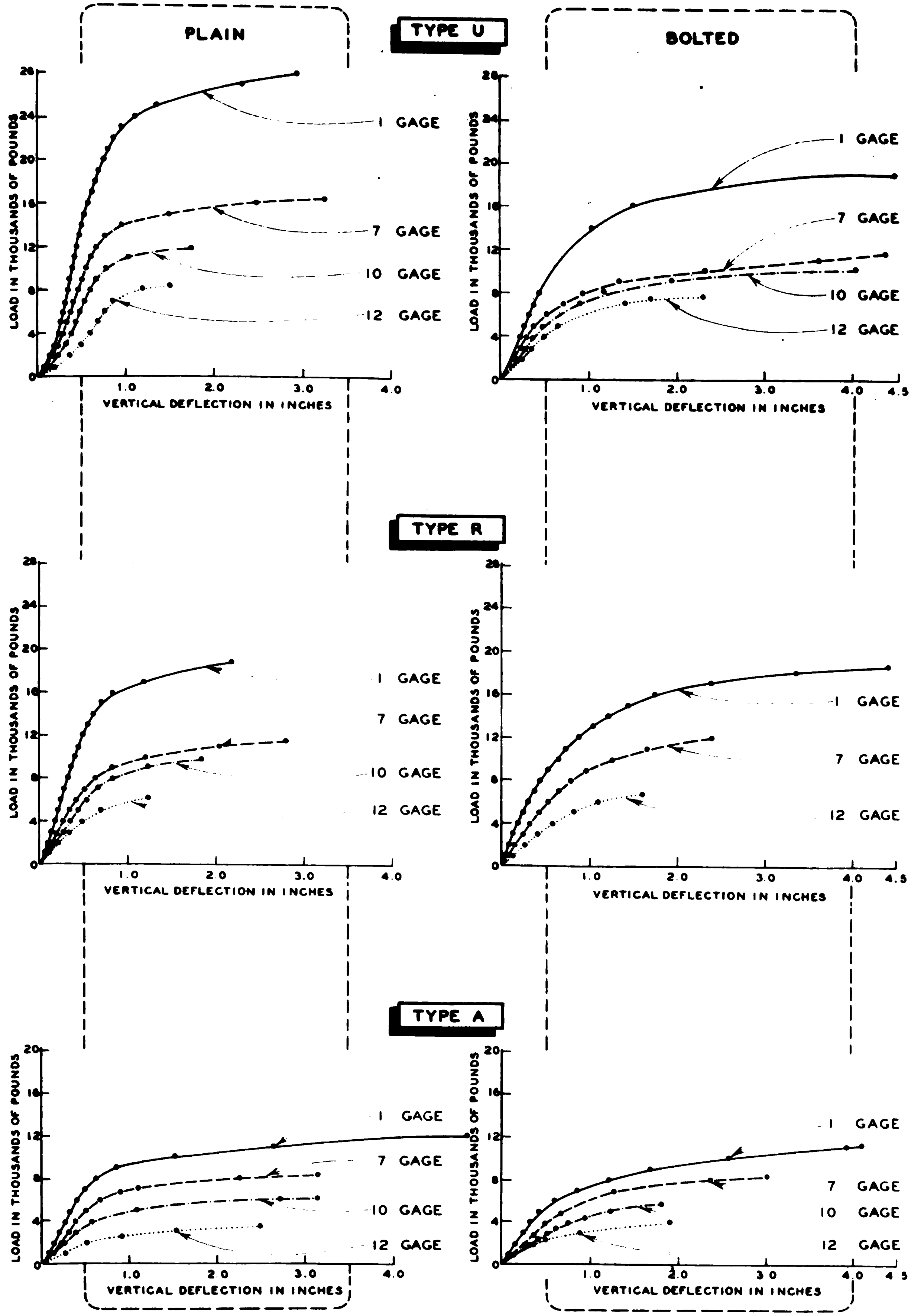
The load deflection curves for tests 5 & 6 have been regrouped in Figures 11 and 12 to graphically present the effect of gage on load carrying capacity of the metal culvert plates. In all styles of corrugation, both tests, and for plain and bolted specimens the load carrying capacity is of the same order as the thickness of metal. This further illustrates the premise that as the section modulus (a function of the gage) increases, the load carrying capacity of the plates is also increased.

It will be readily seen from the curves 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 inches to 0.275 inches trebles the ability to carry loads.

As a further basis of comparison, tables 4 & 5 have been prepared. These tables contain values for a 'Modulus of Rupture' which is found from the formula

$$Sr = PKC/I$$

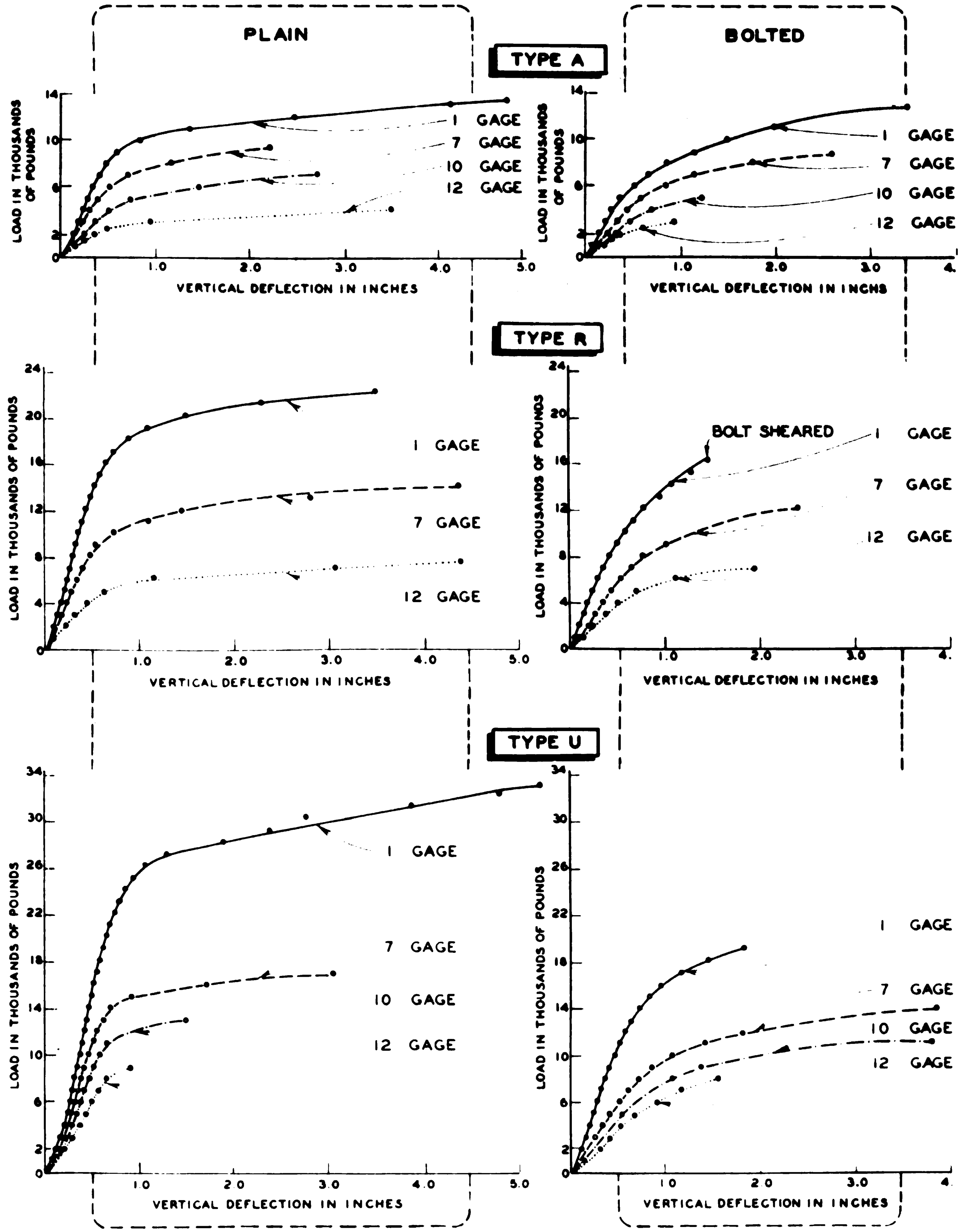
where P is the ultimate load, K is the moment arm at the ultimate load and I/c is the section modulus of the plate. Both tests 5 and 6 are included in this table. The values for each gage and for each



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS

TEST 5

Figure 11



INFLUENCE OF METAL THICKNESS ON DEFLECTIONS

TEST 6

Figure 12

TABLE 4

MODULUS OF RUPTURE - TEST 5

Specimen	Ultimate Load (lbs.)	Modulus of Rupture (psi)	Average (psi)
U5X1P	28000	66411	
U5Y1P	28000	66274	
U5Z1P	28000	66534	66406
U5X7P	16800	59663	
U5Y7P	16850	59742	
U5Z7P	16240	57866	59090
U5X10P	12000	55078	
U5Y10P	12000	55296	
U5Z10P	11400	52782	54385
U5X12P	8100	48298	
U5Y12P	9000	52689	
U5Z12P	8000	49235	49235
R5X1P	17400	- - -	
R5Y1P	19300	73539	
R5Z1P	18600	71368	72454
R5X7P	11520	64744	
R5Y7P	11800	66330	
R5Z7P	11300	63546	64873
R5X10P	9720	71834	
R5Y10P	10000	73826	
R5Z10P	9550	70505	72055
R5X12P	5720	53792	
R5Y12P	6500	61177	
R5Z12P	6000	56401	57123
A5X1P	12180	52986	
A5Y1P	12180	52767	
A5Z1P	12000	52031	52595
A5X7P	8000	51488	
A5Y7P	8500	54717	
A5Z7P	8700	55993	54066
A5X10P	6180	52065	
A5Y10P	6125	51507	
A5Z10P	6550	55217	52929
A5X12P	3600	38498	
A5Y12P	3620	38632	
A5Z12P	4000	42750	39960

TABLE 5

MODULUS OF RUPTURE - TEST 6

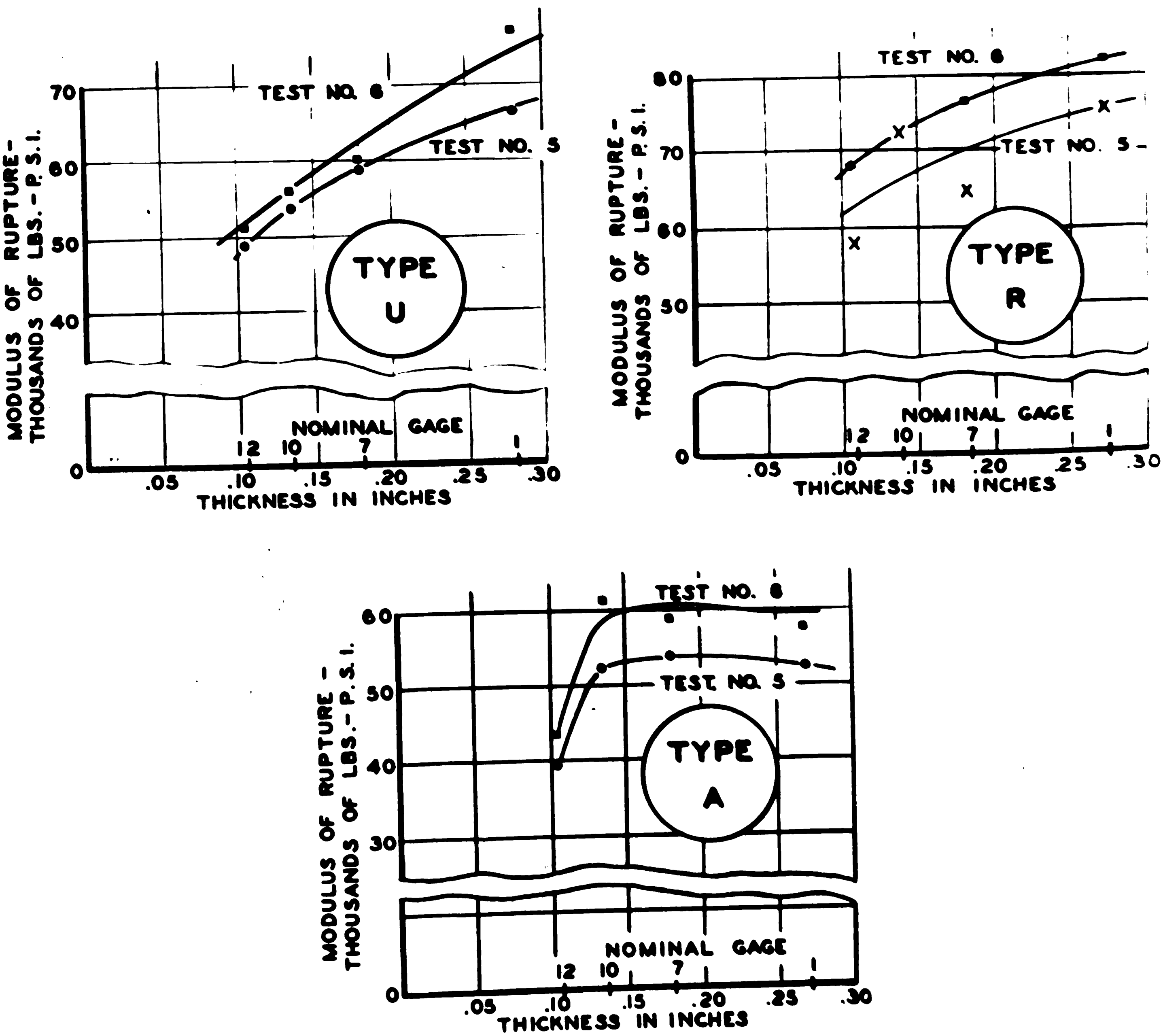
Specimen	Ultimate Load (lbs)	Modulus of Rupture (psi)	Average (psi)
U6X1P	33850	79044	
U6Y1P	33850	78762	
U6Z1P	32000	75209	77672
U6X7P	17300	59966	
U6Y7P	17200	60074	
U6Z7P	17400	60514	60185
U6X10P	12300	55055	
U6Y10P	12000	53610	
U6Z10P	13195	59376	56013
U6X12P	9180	50979	
U6Y12P	9300	52132	
U6Z12P	9300	51986	51699
R6X1P	21000	78034	
R6Y1P	21860	81521	
R6Z1P	23000	85321	81625
R6X7P	13800	75804	
R6Y7P	13650	75580	
R6Z7P	14000	76887	76090
R6X12P	7220	66300	
R6Y12P	7055	64524	
R6Z12P	8000	73121	67982
A6X1P	13650	58376	
A6Y1P	14000	59809	
A6Z1P	13000	55631	57939
A6X7P	9600	60128	
A6Y7P	10000	63178	
A6Z7P	8650	54465	59257
A6X10P	6800	56485	
A6Y10P	7560	63009	
A6Z10P	7410	61101	61413
A6X12P	4385	45973	
A6Y12P	4220	44448	
A6Z12P	4000	41910	44110

manufacturer are averaged and are used to produce Fig. 13. This illustrates the relationship between section modulus (a function of gage) and the modulus of rupture (a function of the load carrying capacity).

Theoretically the modulus of rupture values for all gages should remain the same if each gage is equally efficient. For both type U and type R there is a tendency for the modulus of rupture to decrease as the thickness is decreased. In type A all of the gages illustrate very nearly the same trend except the number 12 gage. There is a definite decrease in the modulus of rupture which is indicative of stresses other than bending stresses when such thin metal gages are used. In all three styles the thin metal are not able to efficiently develop the metal strength to its fullest extent. There is some indication that in design that 10 gage may be a practical lower limit as to thickness of metal used for corrugations as deep as those used in these types of plates.

<u>The Lap Joint vs. the Butt Joint</u>

In introducing the box style of corrugation the manufacturer used a new type of joint, the butt joint, which we have previously discussed and illustrated. So that the joints might be evaluated, the plates with seams were tested in a manner identical to that for plain plates. The efficiency of a fastening may then



MODULUS of RUPTURE vs. GAGE of METAL

Figure 13

be computed by finding the ratio of the load carried by the bolted specimen to the load carried by the plain plate. The ratios, shown as percentages are found in Table 6. This is due in a main part to the fact that slippage and readjustment in the joint produces an elastic limit lower than the elastic limit of the metal. For the lap joint the efficiency at the ultimate load is quite high with but few exceptions, varying from 79 to 100 percent efficiency. The efficiency of the butt joint is lower varying from 61 to 89 percent.

The butt joint apparently does not take advantage of the superior strength of the box-type corrugation. The failure of a butt joint is not in the plate but in the butt plate at the joint. This type failure is illustrated in Fig. 10. The failure in the lap joint occurs in the metal of the plate itself and as such the joint is weakened only by the holes punched for the bolts.

<u>Single Bolting Versus Double Bolting</u>

The lap joint was further tested by compiling data on the efficiency of double bolted joints in Table 7. At the elastic limit the double bolted joints show a significant increase in efficiency which is probably caused by a decrease in slippage and adjustment of the joint. At the ultimate load there is no great increase

TABLE 6

LAP JOINT VS. BUTT JOINT

TEST 5

Specimen	Elastic limits plain	Elastic limits bolted	% Eff.	Ultimate loads plain	Ultimate loads bolted	% Eff.
U 1 ga	17670	9000	51	28000	18800	67
U7 ga	11330	4000	35	16600	11800	71
U 10 ga	9160	3000	33	11800	10300	87
U 12 ga	6330	2000	32	8400	7500	89
R 1 ga	11670	8000	69	18900	19000	100
R 7 ga	6670	5000	75	11500	11900	100
R 12 ga	3830	4000	100	6070	6800	100
A 1 ga	6330	4000	63	12100	11100	92
A 7 ga	4670	4000	86	8400	8400	100
A 10 ga	3000	2000	67	6300	5700	90
A 12 ga	2000	2000	100	3740	3900	100

TEST 6

Specimen	Elastic limits plain	Elastic limits bolted	% Eff.	Ultimate loads plain	Ultimate loads bolted	% Eff.
U 1 ga	19000	11000	58	32800	20000	61
U 7 ga	12000	6000	50	17000	14000	82
U 10 ga	10000	5000	50	13000	11000	85
U 12 ga	7500	4000	53	9000	8000	89
R 1 ga	11700	7000	60	22000	18000	82
R 7 ga	7300	6000	82	13800	12000	87
R 12 ga	4200	3500	83	7600	6900	91
A 1 ga	8000	4000	50	13500	12700	94
A 7 ga	5000	4000	80	9400	8900	95
A 10 ga	3500	3000	86	7300	5800	79
A 12 ga	2000	2000	100	4200	4000	95

TABLE 7

SINGLE BOLTING VS. DOUBLE BOLTING

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

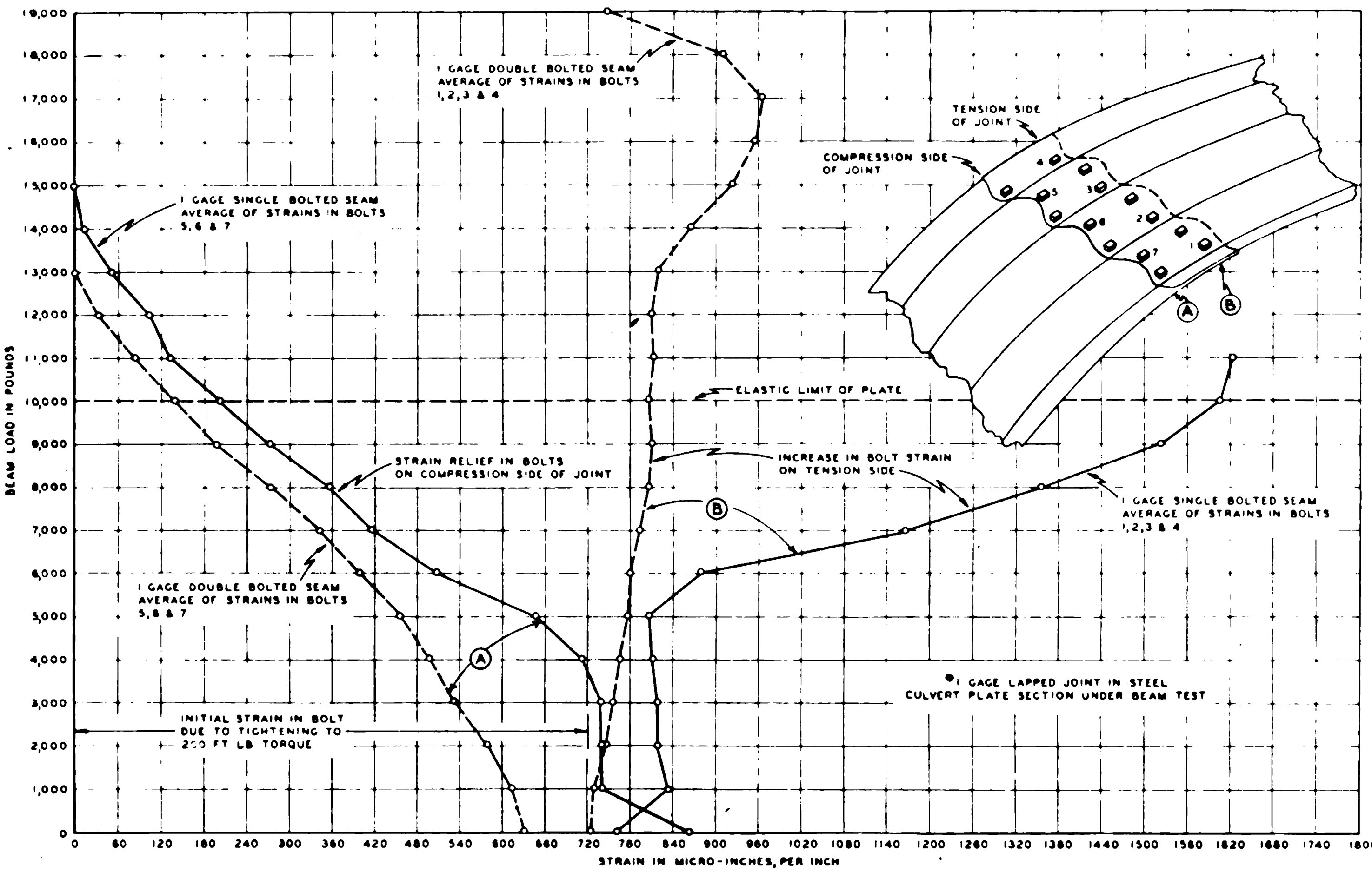
in efficiency, the range being the same as for the single bolted joints. Since in a flexible type culvert much of the strength of the culvert is derived from support at the sides of the culvert after the metal has passed the elastic limit, there is no great advantage derived by the extra expense and labor involved in the double bolting of joints. A typical double-bolted joint is shown in Fig. 14.

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. Figs. 14 and 15 were prepared on the basis obtained as a result of these tests.

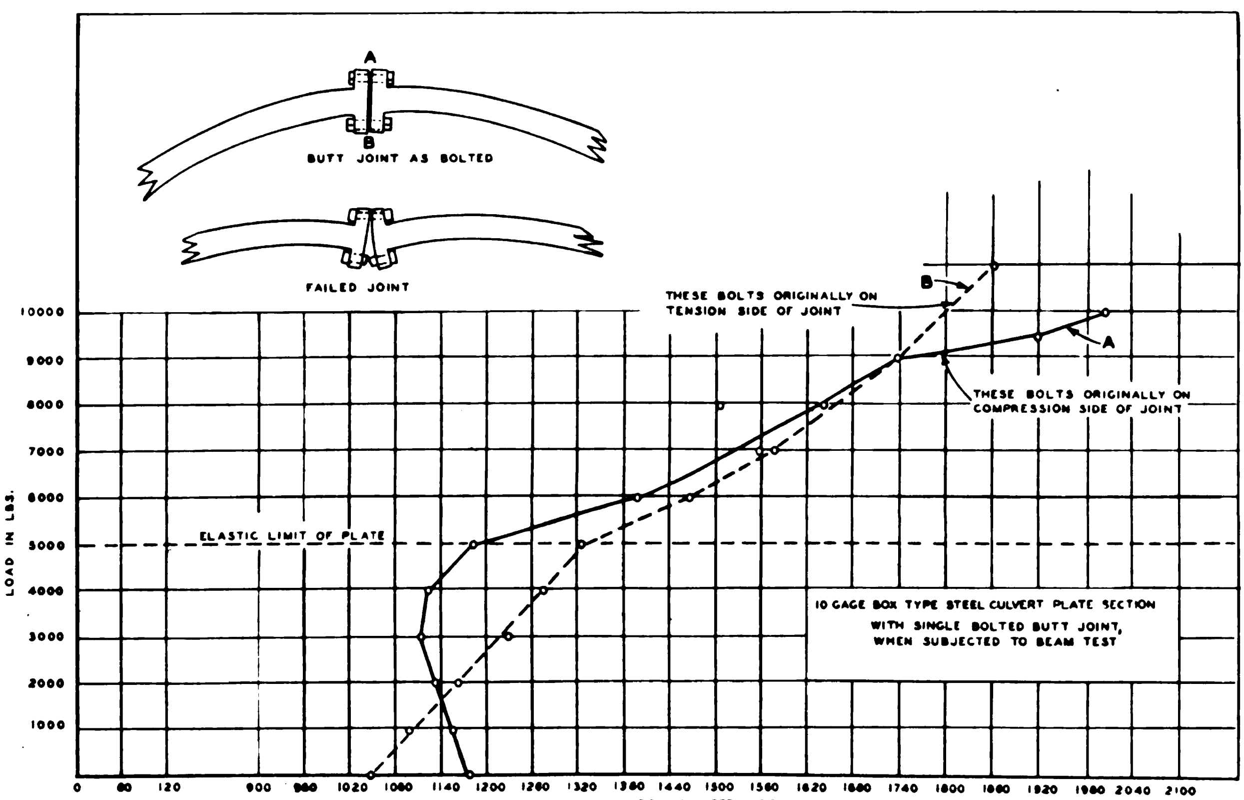
Fig. 15 illustrates the action for a butt-type joint. The initial strain is introduced by tightening the bolts with zero load applied. As the load increases the strain in the A row (heavy line on graph) is decreased as the butt plate apparently is compressed more tightly at the top of the joint. At a point just before the elastic limit the strain increases and parallels the strain curve for the B row of bolts.

The bolt strains for the lap joint are shown in Fig. 14. For single bolting (solid lines) there is apparent relief in the A row of bolts while there is



BOLT STRAINS IN
DOUBLE AND SINGLE BOLTED LAPPED JOINT

Figure 14



BOLT STRAINS IN BUTT JOINT

Figure 15

an increase in strain in the B row of bolts. The double-bolted joint (dashed line) shows a marked change in the strain pattern for the B row of bolts. There is only a small increase in strain as the load is increased as compared to the large increase in strain in the B row of bolts for a single bolted joint. The strain in the A row of bolts is very much the same for both types of joint.

Effect of Varying the Radius of Curvature

The unit stresses at the elastic limit for specimens used in Test 5 and 6 are compared in Tables 1 and 2. The only difference in the plates used for the 2 tests was the radius to which the plates were curved. Test 5 had a radius of 150 inches while Test 6 had a radius of 50 inches. A comparison of the unit stresses for the two types of plates shows no significant difference in the pattern for unit stress. On the basis of this comparison it is apparent that the radius of curvature does not effect the action of the plate.

Bolt Torque Tests

Specimens of each type of bolt furnished were twisted with a torque wrench to failure. The high tensile bolts furnished with the A & R bolts required about 700 ft-lb torque before failure occured. The bolts furnished for type U failed at a torque averaging

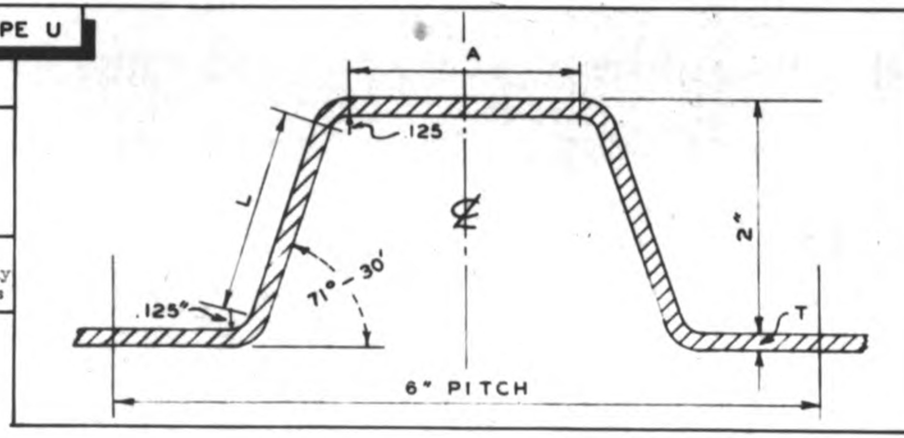
590 ft-lbs. In either case the 200 ft-lb torque used in the tests is well within the working limits of the bolt metal.

VII SUMMARY OF PRINCIPAL CONCLUSIONS

1. Culverts may be designed on the basis of section modulus for all the styles of corrugation tested.
2. The standard lap joint very nearly develops the strength of the metal at ultimate stresses but is not as efficient at the elastic limit of the metal. Double bolting increases the efficiency of the joint at the elastic limit but there is no increase in efficiency evident at the ultimate load.
3. The butt-type joint is not as good as the lap joint when subject to bending action.
4. Plate curvature has little effect on the unit stress of the plates.

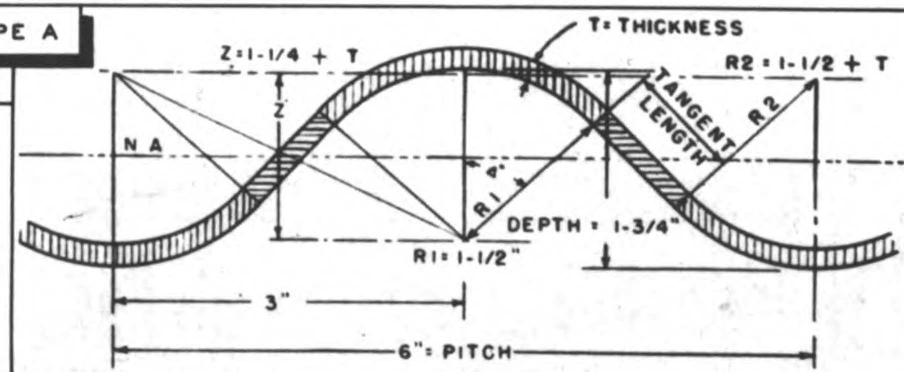
TYPE U

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 $inches^4$	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 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

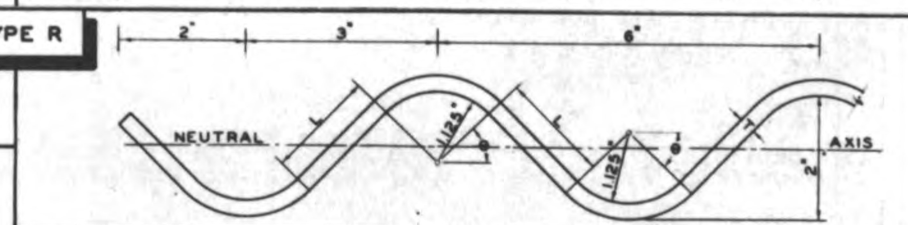


TABLE 1 APPENDIX

MANUFACTURERS DATA ON SPECIMENS

APPENDIX
TABLE 2

CHEMICAL ANALYSIS AND BRINELL HARDNESS

Specimen	Brinell Hardness	C	Mn	S	P	Si	Cu	Mo.
U5Z1P	90	.080	.300	.038	.016		.27	
U5Z1S	93	.080	.300	.038	.016		.27	
U6Z1P	104	.090	.390	.042	.015		.25	
U6Z1S	105	.090	.390	.042	.015		.25	
U5Z7P	103	.019	.028	.026	.006	.004		
U5Z7S	93	.019	.028	.026	.006	.004		
U6Z7S	101	.019	.028	.026	.006	.004		
U5Z10S	95	.019	.028	.026	.006	.004		
U6Z10P	95	.019	.028	.026	.006	.004		
U6Z10S	103	.019	.028	.026	.006	.004		
R5X1P	107	.05	.13	.030	.014		.43	.07
R5X1S	101	.04	.11	.034	.010		.49	.08
R6Z1P	107	.05	.13	.030	.014		.43	.07
R3Z1S	109	.04	.11	.034	.010		.49	.08
R5X7P	116	.04	.13	.026	.011		.44	.08
R5Z7S	116	.04	.11	.033	.010		.48	.08
R6X7P	110	.04	.13	.026	.011		.44	.08
R6Y7S	114	.04	.11	.033	.010		.48	.08
R5X10P	114	.05	.15	.025	.010		.54	.09
R5Z10P	124	.05	.15	.025	.010		.54	.09
R5X12P	115	.05	.16	.030	.010		.44	.05
R5Z12S	112	.05	.16	.030	.010		.44	.05
R6X12P	121	.05	.16	.030	.010		.44	.05
A6Z1S	90							
A2Y7S	105	Typical limits - No specific data for this group						
A5X7P	95							
A5X10S	114							
A5Z10S	114							
A5Z12S	107	.02	.01	.015	.003		.04	
A6X12P	92		to	to	to		to	
A6Z12S	105		.02	.022	.007		.05	
		Typical analysis of Bolts						
Type U Bolts		.20	.45	.05	.04			
Type R Bolts	258	.39	.66	.033	.019		.25	
Type A Bolts	269	.46	.80	.043	.010			

Note - Chemical Analysis data furnished by manufacturers

APPENDIX

TABLE 3

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

Specimen No.	Yield Strength Offset .05 percent (psi)	Ultimate Strength (psi)	Modulus of Elasticity 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
Average	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
Average	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
Average	29,133	43,619	29,289