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TESTS OF NICKEL-STEEL RIVETED JOINTS

BY

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 49 FEBRUARY 1911

TESTS OF NICKEL-STEEL RIVETED JOINTS

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS, AND HERBERT F. MOORE, ASSISTANT PROFESSOR IN THEORETICAL AND APPLIED MECHANICS

CONTENTS

I. INTRODUCTION

PAGE

1. Preliminary 3
2. The Strength of Riveted Joints 4
3. Existing Data 5
4. Acknowledgment 7

II. MATERIALS, TEST PIECES, AND METHOD OF TESTING

5. Materials 7
6. Test Pieces 9
7. Testing Machine and Its Arrangement 16
8. Measurement of Deformation 19
9. Procedure of Tests 22

III. DATA AND DISCUSSION

10. Sample Data of Tension Tests 24
11. Sample Data of Tension and Compression Tests 24
12. Tables and Diagrams of Results 28
13. Slip in Tension Tests 31
14. Yield Point in Tension Tests 39
15. Ultimate Strength in Tension Tests 40
16. Slip in Alternate Tension and Compression Tests 42
17. Yield Point in Alternate Tension and Compression Tests 42
18. Ultimate Strength in Alternate Tension and Compression Tests 42
19. Bending of Rivets 43
20. Action of Riveted Joints under Steady, Repeated, and Alternated Loads 44
21. The Basis for Design of Riveted Joints 45
22. Summary 46

LIST OF FIGURES

		Page
1.	Riveted Joint Test Pieces	10
2.	Riveted Joint Test Pieces	11
3.	Riveted Joint Test Pieces	12
4.	Riveted Joint Test Pieces	13
5.	Riveted Joint Test Pieces	14
6.	Auxiliary Apparatus for Tests in Alternate Tension and Compression	17
7.	View of Testing Machine with Auxiliary Apparatus for Tests in Alternate Tension and Compression	18
8.	View of Extensometer Attached to Test Piece	19
9.	View of Tension Test Piece with Auxiliary Apparatus for Measuring Deformation	20
10.	View of Fractured Test Pieces showing Movement of Plates	21
11.	Diagram showing Method of Measuring Bending of Rivets	22
12.	Diagram of Tension Test No. 83	24
13.	Diagram of Tension and Compression Test No. 94	26
14.	Diagram of Tension and Compression Test No. 95	29
15.	Diagram of Tension Test No. 64	29
16.	Diagram of Tension and Compression Tests under Alternations of Low Stresses	38
17.	Diagram showing Permanent Set in Tension Tests	49
18.	Diagram showing Permanent Set in Tension Tests	50
19.	Diagram showing Deformation in Tests in Tension followed by Equal Compression	51
20.	Diagram showing Deformation in Tests in Simple Tension and Simple Compression of Riveted Joints Designed for Alternated Loads	52
21.	Diagram showing Deformation in Tests in Tension followed by Half as Great Compression	52
22.	Diagram showing Deformation of Riveted Joints Tested under Alternations of Low Loads	53

LIST OF TABLES

1.	Chemical Composition of Rivet and Plate Material	8
2.	Physical Properties of Rivet and Plate Material	8
3.	Tensile Tests of Flat Specimens of Chrome Nickel Steel	9
4.	Classification of Test Joints	15
5.	Sample Data of Tension Test of Riveted Joints	25
6.	Sample Data of Test of Riveted Joints in Alternate Tension and Compression	27
7.	First Noticeable Slip of Riveted Joints	30
8.	Yield Point of Riveted Joints	32
9.	Ultimate Shearing Strength of Riveted Joints	34
10.	Alternate Tension and Compression Tests. Ultimate Shearing Strength of Riveted Joints	36
11.	Alternate Tension and Compression Tests. Yield Point of Riveted Joints	37

TESTS OF NICKEL-STEEL RIVETED JOINTS.

I. Introduction.

1. *Preliminary.*—In designing riveted joints to connect structural members certain assumptions are made concerning the action of the rivets and other parts of the joint under load. Tests of riveted joints have not yet fully established the trustworthiness of some of these assumptions. In considering the design for a bridge across the St. Lawrence river near Quebec, Canada, to replace one which had failed during construction, the Board of Engineers of the Quebec Bridge appointed by the Canadian Government desired further experimental data on the action of riveted joints, especially as they had under consideration the use of nickel-steel plates and nickel-steel rivets; and arrangements were made by which tests were conducted at the University of Illinois. Later, the Pennsylvania Steel Company, of Steelton, Pennsylvania, arranged for similar tests of riveted joints made with chrome-nickel-steel plates and rivets. This bulletin records the results of the two series of tests. Although all material in the riveted joints tested contained nickel and the bulletin is termed Tests of Nickel-Steel Riveted Joints, in order to distinguish between the two sets the first set will be called nickel-steel riveted joints and the second set chrome-nickel-steel riveted joints.

The investigation included tests in tension and in alternate tension and compression. The bending of rivets, the deformation of the joints and the slip of the plates, the yield point of the joints, and the ultimate strength of the riveted joints were investigated. The tension tests included various forms of joint,–lap joints, butt joints, joints with fillers, joints with various numbers of rivets. The alternate tension and compression tests were upon one type of joint, a butt joint with very thick plates. A feature of interest was the repetitive loading of a joint alternately in tension and compression. The determination of the bending of the rivets was also a novel feature. The riveted joints which were tested in tension duplicated in dimensions a series of carbon-steel riveted joints tested for the American Railway Engineering and Maintenance of Way Association, and hence were not suited to develop the maximum strength possible with nickel-steel plates and rivets. To distinguish between the test pieces, the riveted joints of ordinary structural steel and ordinary rivets reported by the American Railway Engineering and Maintenance of Way Association will be called carbon-steel riveted joints; and those of the tests here recorded nickel-steel and chrome-nickel-steel riveted joints.

2. *The Strength of Riveted Joints.*—When a riveted joint is subjected to tension, tensile stresses are developed in the plates, bearing stresses in the rivets and in the plates at the rivet holes, shearing and bending stresses in the rivets, and shearing stresses in the plates beyond the rivet holes. Among the assumptions ordinarily made in the designing of riveted joints are: (a) that the tension and the tensile stresses are uniformly distributed throughout the width of the plate over the net section; (b) that the load is evenly divided among the rivets of the joint whether there are one or more rows and whether one row contains fewer rivets than another; (c) that little attention need be given to the relative amount of the stretch of the plate between the different rows of rivets; and (d) that the bearing area of a rivet is the product of its diameter (or the diameter of the hole) by the thickness of the plate in which it is placed. The limiting or safe shearing unit-stress in the rivet is ordinarily taken at two-thirds to three-fourths the limiting tensile unit-stress of the rivet material, and the bearing stress of the rivets, or of the plate, at one and one-third to one and one-half times this tensile stress. Under the assumed action of the joint, and considering the assumed limits of tensile, bearing, and shearing stresses, that stress which approaches most nearly to its assumed limit of stress at the load to be carried by the joint is considered to be the critical stress, whether this be the tensile stress in the net section of the plate, the bearing on the rivets, or the shearing stress in the various rivet sections. For any joint this critical stress will control the working strength of the joint; and whether it be tensile, bearing or shearing stress will depend upon the design of the joint and upon the ratios assumed between limiting or safe values of tensile stress, bearing stress and shearing stress.

For a given type of riveted joint the design in which the tensile stress, bearing stress, and shearing stress each reaches its limiting value, will have the highest efficiency, and a departure in proportions from this design will result in lowering the efficiency of the joint. However, matters connected with fabrication generally make modifications in design necessary—the size of rivet which may be handled with the facilities available, the size of hole which may properly be punched in the given thickness of metal, the closeness of spacing necessary to give tightness in joints subject to water or steam pressure, economies of workmanship, etc., will affect the design. Frequently empirical or conventional spacing or sizes of rivets are used. In any event the proper ratios of the allowable tensile, bearing, and shearing stresses may not be definitely known. The full action of the joint under load is uncertain. At the beginning of application of load the bearing may be on a small portion of the rivet surface. The rivet may not entirely fill the hole, and the shearing stress may not be uniformly distributed over the rivet section, or among all the rivets. Friction between plates by reason of the clamping action of the rivets may affect the distribution of stresses. Repetitiòn of load may change the action of the joints and the amount of the stresses. Altogether, it is evident that fuller information on the action of riveted joints is necessary before the proper distribution of stresses may be judged. Conditions at rupture of the joint may not be applicable to working conditions, since stretch of plate, distortion of rivets, and the consequent redistribution of load beyond the yield point of the material may greatly change the action of the joint. It is evident that experimental data are needed to determine in detail the action of riveted joints under load.

3. *Existing Data.*—In the experimental study of the strength of riveted joints, the attention of English and American investigators has been directed largely to the resistance of joints to rupture; French, Dutch, and German investigators have given much attention to the frictional resistance to slip. Among European experiments those of Considere[1] in 1886, Dupuy[2], van der Kolk[3] in 1897, Bach[4] in 1894, and Pruess[5] in 1909, are worthy of special mention. The earlier of these investigators reported that the frictional hold of the rivets prevents slip in the joint up to loads slightly greater than those assumed in design practice for

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[1] Annales des Ponts et Chaussees, 1886.

[2] Annales des Ponts et Chaussees, 1895.

[3] Zeitschrift des Vereins Deutscher Ingenieure, June 26 and July 3, 1897. Le Genie Civil 1897. Practical Engineer, January 14, 1898, (Translation).

[4] Zeitschrift des Vereins Deutscher Ingenieure, 1892, p. 1142; 1894, p. 1231; 1895, p. 301.

[5] Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. 1 (1909), p. 60–95. In this memoir attention may be called to the fact that the shearing strength of specimens of rivet material (nickel steel) as given on page 76 should be divided by two, since the specimen is in double shear.

soft steel or wrought-iron plates and rivets. Considere, however, showed that if the frictional hold of the rivet is once broken the joint will afterwards slip under small loads if they are applied first in one direction and then in the other. In the experiments of Pruess (reported since the tests described in this bulletin were made) on joints having nickel-steel rivets, by the use of very sensitive extensometers, the existence of slip of joint was found at loads below those allowed in practice, and the test also showed that the use of nickel-steel rivets did not appreciably change the frictional hold of rivets on plates. All the European tests quoted above were made on joints in tension (with the exception of the few alternate stress tests of Considere) and, in general, were carried to rupture.

Among the English experiments may be mentioned those of Fairbairn[6], of Kirkaldy[7], and of Unwin and Kennedy[8]. In the experiments of Fairbairn and Kirkaldy the ultimate strength of the joint was studied. In the tests of Unwin and Kennedy a study was made of the effect of hand riveting and of hydraulic pressure riveting on both the ultimate strength and the frictional resistance of riveted joints.

In the United States the largest number of tests have been made at Watertown Arsenal[9]. In these tests deformation of joint was measured, but the efficiency of the joint was computed from the load carried at the ultimate.

In 1896 in the Laboratory of Applied Mechanics of the University of Illinois a series of tensile tests of riveted joints was made under the direction of A. N. Talbot by Van Ostrand and Thompson[10]. In these tests the slip of joint was found to begin at loads as low as those allowed in practice, and the effect of bending of rivet and of unequal distribution of stress in bearing of rivet and in shear was investigated.

In 1904 a series of tests on riveted joints in tension was carried on under the auspices of the Committee on Iron and Steel Structures of the American Railway Engineering and Maintenance of Way Association. The tests were made in the laboratory of the College of Civil Engineering of Cornell University[11]. In these tests

[6] Proceedings of the (British) Institution of Mechanical Engineers, April, 1881.

[7] American Machinist, May 11 and 18, 1893 (Condensed report of Kirkaldy's tests).

[8] Proceedings of the (British) Institution of Mechanical Engineers, 1881, 1882 and 1885.

[9] Tests of Metals (Watertown Arsenal Reports) 1885, 1886, 1887, 1896 and other volumes.

[10] Thesis of Van Ostrand and Thompson, 1896 (University of Illinois Library).

[11] Proceedings of the American Railway Engineering and Maintenance of Way Association, 1905, Vol. 6.

the deformation of joint under load, the slip of the joint, and the permanent set of joint after load were measured, and the strength of joints with filler plates between main plates and cover plates was compared with that of joints without filler plates. These tests also showed the existence of slip at working loads.

4. *Acknowledgment.*—The tests of nickel-steel riveted joints were undertaken at the request of the Board of Engineers of the Quebec Bridge, Messrs. H. E. Vautelet of Montreal, Maurice Fitzmaurice of London, England, and Ralph Modjeski of Chicago. The nickel-steel riveted joints were designed and furnished by the Board of Engineers and were manufactured under their inspection. Especial acknowledgment should be made to Mr. Ralph Modjeski for his suggestions and advice during the course of the work. The tests of chrome-nickel-steel riveted joints were undertaken at the request of the Pennsylvania Steel Company, the riveted joints following in form and dimensions the riveted joints tested for the Board of Engineers of the Quebec Bridge. Both the Board of Engineers of the Quebec Bridge and the Pennsylvania Steel Company agreed to the publication of the results of the tests by the Engineering Experiment Station of the University of Illinois. The expense of the tests was largely borne by the Board of Engineers and the Pennsylvania Steel Company.

The designing of the special auxiliary apparatus necessary for the tests and the work of testing was done by the research force of the Laboratory of Applied Mechanics of the University of Illinois. The chemical analyses of plate and rivet material were made in the laboratories of the Department of Applied Chemistry of the University of Illinois.

II. Materials, Test Pieces, and Method of Testing.

5. *Materials.*—The plates of the joints included in this investigation were nickel steel and chrome nickel steel. In Table 1 are given the results of analyses of the steel. The carbon content and the manganese content were determined by colorimetric methods. Physical tests of several samples from different plates were made, and the results of these tests are given in Table 2.

The rivets were nickel steel and chrome nickel steel. The results of analyses of sample rivet material furnished by the Pennsylvania Steel Company as representative of the rivets used in making the joints are given in Table 1. Physical tests of this

TABLE 1.

CHEMICAL COMPOSITION OF RIVET AND PLATE MATERIAL.

Element	Nickel-steel Riveted Joints		Chrome-nickel-steel Riveted Joints	
	Rivet Material per cent	Plate Material per cent	Rivet Material per cent	Plate Material per cent
Carbon*	0.141	0.258	0.136	0.191
Sulphur	0.0023	0.008	0.038	0.035
Phosphorus	0.037	0.044	0.032	0.042
Manganese*	0.442	0.700	0.696	0.485
Nickel	3.33	3.330	0.986	0.733
Chromium	......	.....	0.240	0.170

* The carbon content and the manganese content were determined by colorimetric methods.

TABLE 2.

PHYSICAL PROPERTIES OF RIVET AND PLATE MATERIAL.

All stresses are given in pounds per square inch.

Item	Nickel-Steel		Chrome-Nickel-Steel	
	Rivet Material	Plate Material	Rivet Material	Plate Material
Number of specimens tested	2	9	2	8
Stress at first noticeable set*	......	38 200	.....	29 100
Stress at limit of proportionality of stress to deformation*	......	40 200	......	27 200
Stress at yield point†	45 000	51 700	38 400	36 300
Stress at ultimate	68 500	89 700	59 000	63 900
Elongation in 2 inches, per cent†	33.5	25.0	35.2	31.7
Reduction of area, per cent	63.4	55.8	63.3	59.9
Modulus of elasticity*	......	29 950 000	......	30 750 000

* Determined from tensile tests of threaded-end specimens with 8-inch gauge length.
† Determined from tensile tests of threaded-end specimens with 2-inch gauge length.

rivet material were made, and the results of these tests are given in Table 2. A special series of tensile tests of flat specimens cut from plates of the chrome-nickel-steel riveted joints was made. Half of these specimens were tested at the Laboratory of Applied Mechanics of the University of Illinois and half at

Watertown Arsenal. Table 3 shows the principal results of these tests.

6. *Test Pieces.*—The form and dimensions of the riveted joints are shown in Fig. 1, 2, 3, 4, and 5. The joints tested in tension had the same form and dimensions as did the carbon-steel riveted joints in the series of tests made by the Maintenance of Way Association, which was noted on page 6, as the Board of Engineers desired, among other results, a comparison of the strength of carbon-steel and nickel-steel riveted joints. Fig. 5 shows the form and dimensions of the test joints used in the tests made under alternate tension and compression. The plates were made thick to avoid buckling under compression.

TABLE 3.

TENSILE TESTS OF FLAT SPECIMENS OF CHROME-NICKEL STEEL.

Item	University of Illinois Tests	Watertown Arsenal Tests
Number of specimens tested	6	6
Stress at yield point pounds per square inch..	36 500	36 800
Stress at ultimate pounds per square inch..	60 000	61 000
Elongation, per cent........	27.3*	27.1†
Reduction of area, per cent..	54.0	51.9

* Gauge length eight inches.
† Gauge length six inches.

The joints were fabricated by the Pennsylvania Steel Company at their works at Steelton, Pennsylvania. An effort was made to have the quality of the riveting representative of high-grade commercial work—made neither too well nor too poorly. The nickel-steel test pieces were made under the inspection of one of Mr. Modjeski's inspectors, acting for the Board of Engineers of the Quebec Bridge; and the inspector rejected some joints as being more tightly riveted than could be expected under ordinary conditions of structural practice. The Pennsylvania Steel Company gave their own supervision in the making of the chrome-nickel-steel test pieces.

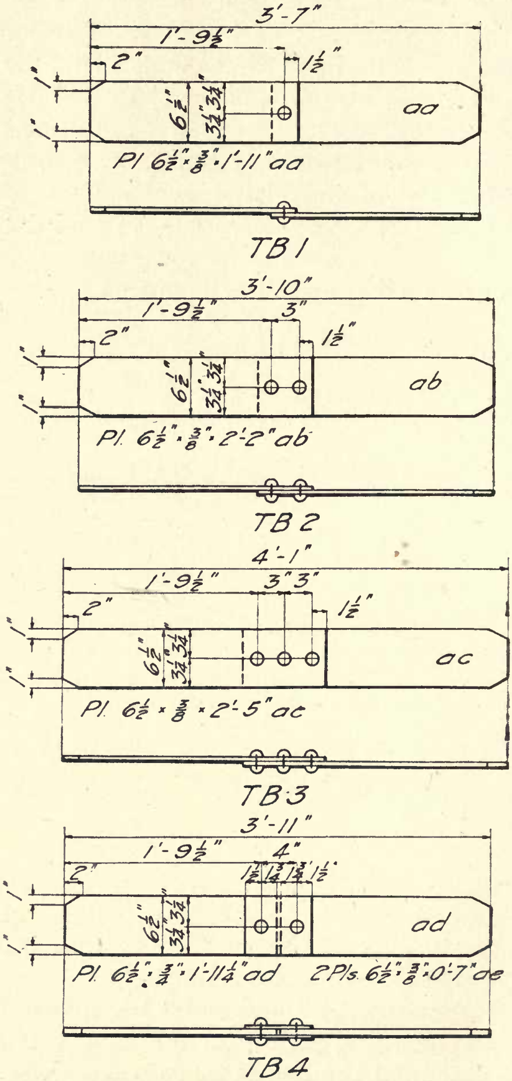

FIG. 1. RIVETED JOINT TEST PIECES.

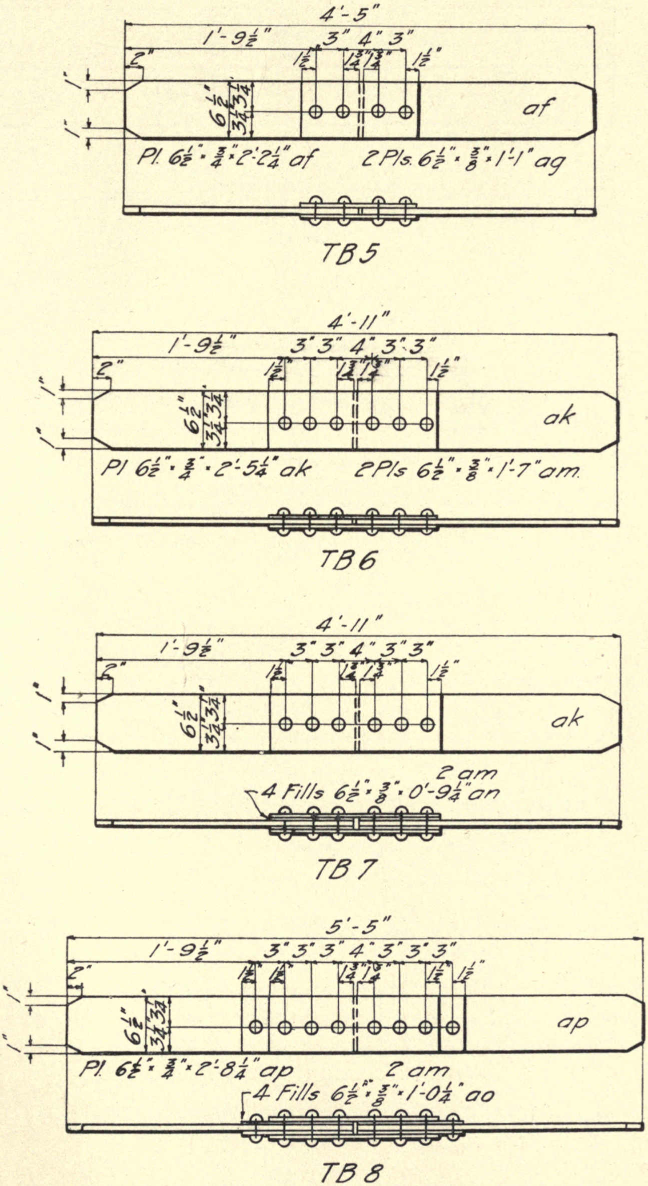

Fig. 2. Riveted Joint Test Pieces.

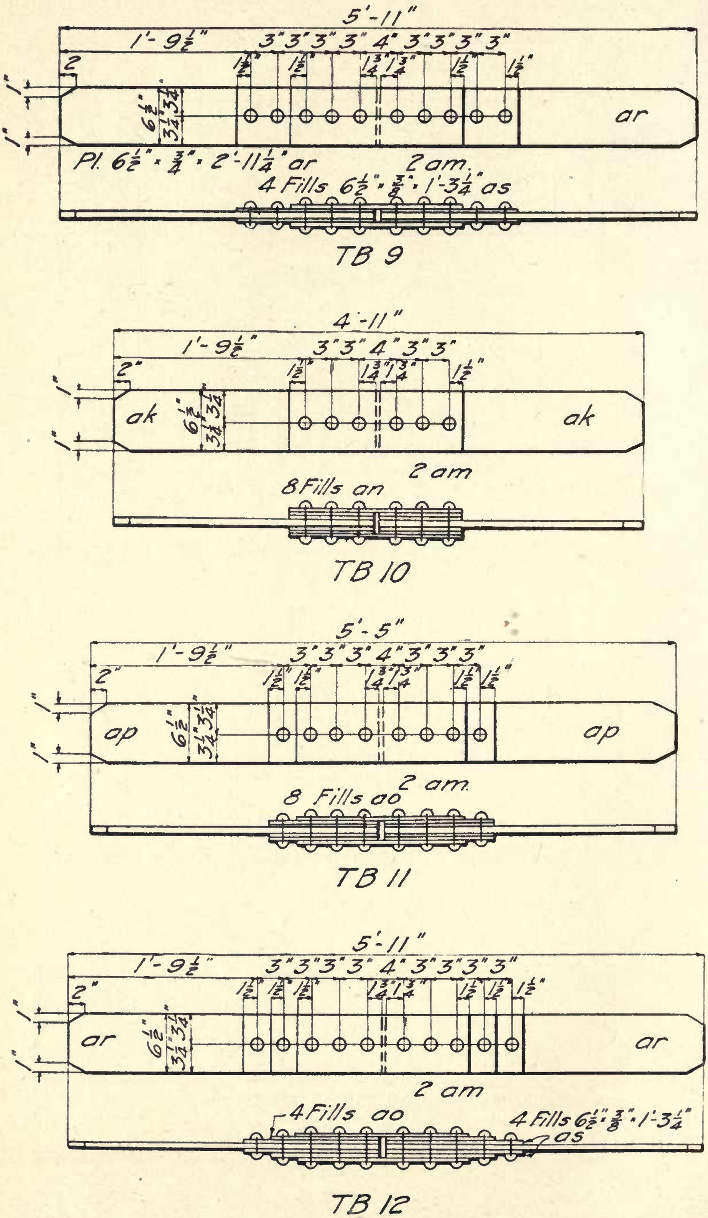

FIG. 3. RIVETED JOINT TEST PIECES.

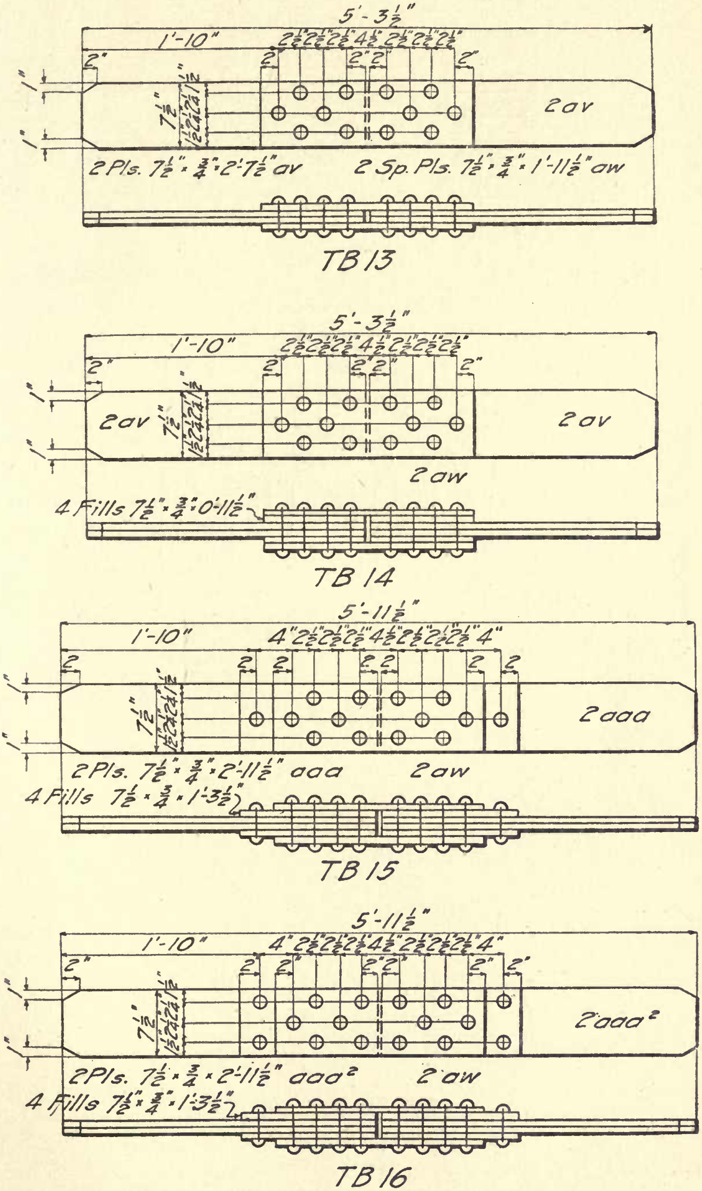

FIG. 4. RIVETED JOINT TEST PIECES.

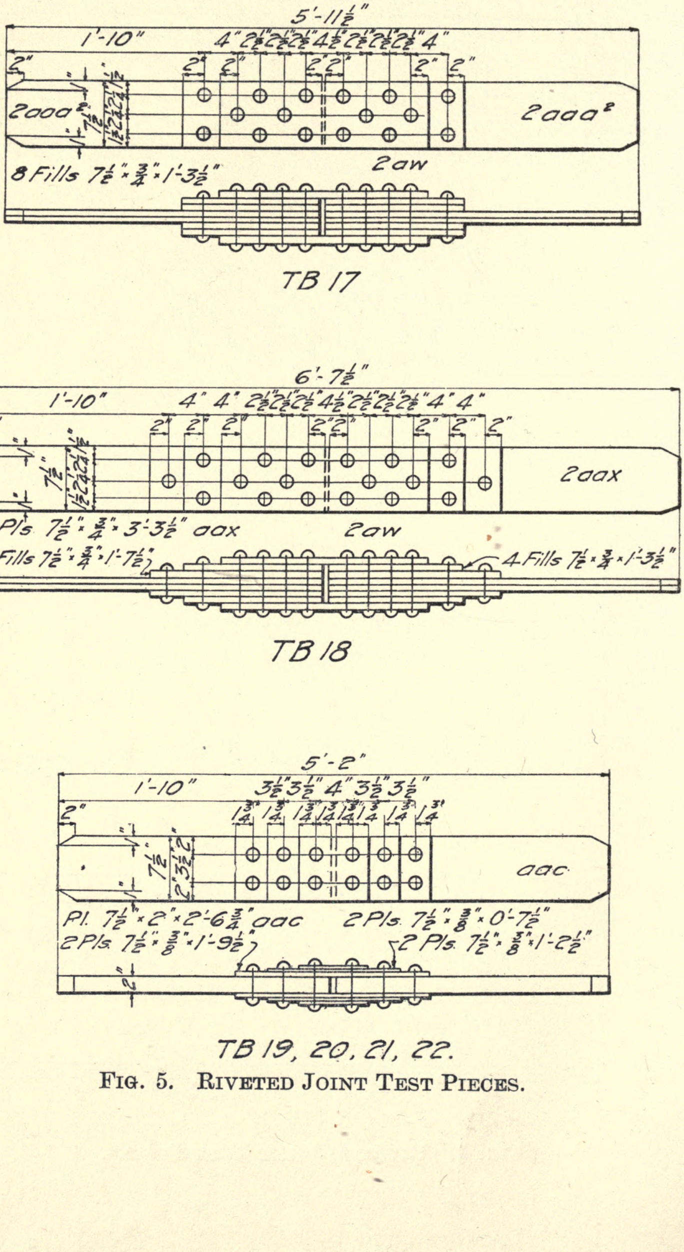

FIG. 5. RIVETED JOINT TEST PIECES.

TABLE 4.

CLASSIFICATION OF TEST JOINTS.

All rivets were ⅝ inch in diameter. All surfaces in contact were painted with one coat of graphite paint. Joints designated as shop-riveted were riveted with a hydro-pneumatic riveting machine; those designated as field-riveted joints were riveted by a hand pneumatic hammer.

Joint	Material of Plates and Rivets	Number of Joints Tested	Method of Riveting	Number of Rivets Sheared	Single or Double Shear	Cross section of Main Plates inches	Filler Plates Each Side	Remarks
TB1S	Ni. Steel	3	Shop	1	Single	6½x⅝	None	Tested in tension
TB1F	"	2	Field	1	"	"	"	"
TB1L	Cr.Ni.Steel	3	Shop	1	"	"	"	"
TB2S	Ni. Steel	3	Shop	2	Single	6½x⅝	None	Do
TB2F	"	2	Field	2	"	"	"	"
TB2L	Cr.Ni.Steel	3	Shop	2	"	"	"	"
TB3S	Ni. Steel	3	Shop	3	Single	6½x⅝	None	Do
TB3F	"	2	Field	3	"	"	"	"
TB3L	Cr.Ni.Steel	3	Shop	3	"	"	"	"
TB4S	Ni. Steel	3	Shop	1	Double	6½x¾	None	Do
TB4F	"	2	Field	1	"	"	"	"
TB4L	Cr.Ni.Steel	3	Shop	1	"	"	"	"
TB5S	Ni. Steel	3	Shop	2	Double	6½x¾	None	Do
TB5F	"	2	Field	2	"	"	"	"
TB5L	Cr.Ni.Steel	3	Shop	2	"	"	"	"
TB6S	Ni. Steel	3	Shop	3	Double	6½x¾	None	Do
TB6F	"	2	Field	3	"	"	"	"
TB6L	Cr.Ni.Steel	3	Shop	3	"	"	"	"
TB7S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Do
TB7F	"	2	Field	3	"	"	"	"
TB7L	Cr.Ni.Steel	3	Shop	3	"	"	"	"
TB8S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Tested in tension
TB8F	"	2	Field	3	"	"	"	Filler anchored
TB8L	Cr.Ni.Steel	3	Shop	3	"	"	"	with 1 rivet
TB9S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Tested in tension
TB9F	"	2	Field	3	"	"	"	Filler anchored
TB9L	Cr.Ni.Steel	3	Shop	3	"	"	"	with 2 rivets
TB10S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension
TB10F	"	2	Field	3	"	"	"	"
TB10L	Cr.Ni.Steel	3	Shop	3	"	"	"	"
TB11S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension
TB11F	"	2	Field	3	"	"	"	Fillers anchored
TB11L	Cr.Ni.Steel	3	Shop	3	"	"	"	with 1 rivet
TB12S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension
TB12F	"	2	Field	3	"	"	"	Fillers anchored
TB12L	Cr.Ni.Steel	3	Shop	3	"	"	"	with 2 rivets
TB13S	Ni. Steel	3	Shop	6	Double	7½x¾*	None	Tested in tension
TB13F	"	2	Field	6	"	" *	"	"
TB13L	Cr.Ni.Steel	3	Shop	6	"	" *	"	"
TB14S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Do
TB14F	"	2	Field	6	"	" *	"	"
TB14L	Cr.Ni.Steel	3	Shop	6	"	" *	"	"
TB15S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Tested in tension
TB15F	"	2	Field	6	"	" *	"	Fillers anchored
TB15L	Cr.Ni.Steel	3	Shop	6	"	" *	"	with 1 rivet
TB16S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Tested in tension
TB16F	"	2	Field	6	"	" *	"	Fillers anchored
TB16L	Cr.Ni.Steel	3	Shop	6	"	" *	"	with 2 rivets

* Double plates.

TABLE 4.—(*Continued.*)

Joint	Material of Plates and Rivets	Number of Joints Tested	Method of Riveting	Number of Rivets Sheared	Single or Double Shear	Cross Section of Main Plates inches	Filler Plates Each Side	Remarks
TB17S	Ni. Steel	3	Shop	6	Double	7½x¾*	Two	Tested in tension
TB17F	"	2	Field	6	"	" *	"	Fillers anchored
TB17L	Cr.Ni.Steel	3	Shop	6	"	" *	"	with 2 rivets
TB18S	Ni. Steel	3	Shop	6	Double	7½x¾*	Two	Tested in tension
TB18F	"	2	Field	6	"	" *	"	Fillers anchored
TB18L	Cr.Ni.Steel	3	Shop	6	"	" *	"	with 3 rivets
TB19S	Ni. Steel	2	Shop	6	Double	7½x2	None	For tests in alternate tension
TB20S	"	2	"	6	"	"	"	and
TB21S	"	2	"	6	"	"	"	compression
TB22S	"	2	"	6	"	"	"	
TB19F	Ni. Steel	2	Field	6	Double	7½x2	None	Do.
TB20F	"	2	"	6	"	"	"	"
TB21F	"	2	"	6	"	"	"	"
TB22F	"	2	"	6	"	"	"	"
TB19L	Cr.Ni.Steel	4	Shop	6	Double	7½x2	None	Do.
TB20L	"	4	"	6	"	"	"	"
TB21L	"	4	"	6	"	"	"	"
TB22L	"	4	"	6	"	"	"	"

* Double plates.

Table 4 gives a classification of the test joints with a tabulation of their principal dimensions. In all 176 joints were tested. For the nickel-steel joints five or more specimens of each type were tested and of each type some were riveted with a hydro-pneumatic riveter and others were riveted with a hand pneumatic hammer. Joints riveted with the hydro-pneumatic riveter were marked S and are hereafter referred to as shop-riveted joints. Joints riveted with a hand pneumatic hammer were marked F and are hereafter referred to as field-riveted joints. All chrome-nickel-steel joints were riveted with a hydro-pneumatic riveter. They were marked L. In all test joints the surfaces in contact had been given one coat of graphite paint.

Only one type of joint was tested under alternate tension and compression (see Fig. 5). There were thirty-two joints of this type.

7. *Testing Machine and Its Arrangement.*—The tension tests were made in the 600 000-lb. screw-power Riehle testing machine of the Laboratory of Applied Mechanics of the University of Illinois. The ends of the specimens were held in the heads of the machine by wedge-shaped grips. In testing, the load was applied at a speed of head of machine of 0.4 in. per min.

The thirty-two joints designed to withstand alternate tension and compression were also tested in the 600 000-lb. testing machine. In the tests in alternate tension and compression, the machine was fitted with an auxiliary cross-head and with two auxiliary nuts on the screws. Fig. 6 shows in diagram the arrangement of apparatus, and Fig. 7 shows the general appearance of the machine fitted with the auxiliary apparatus.

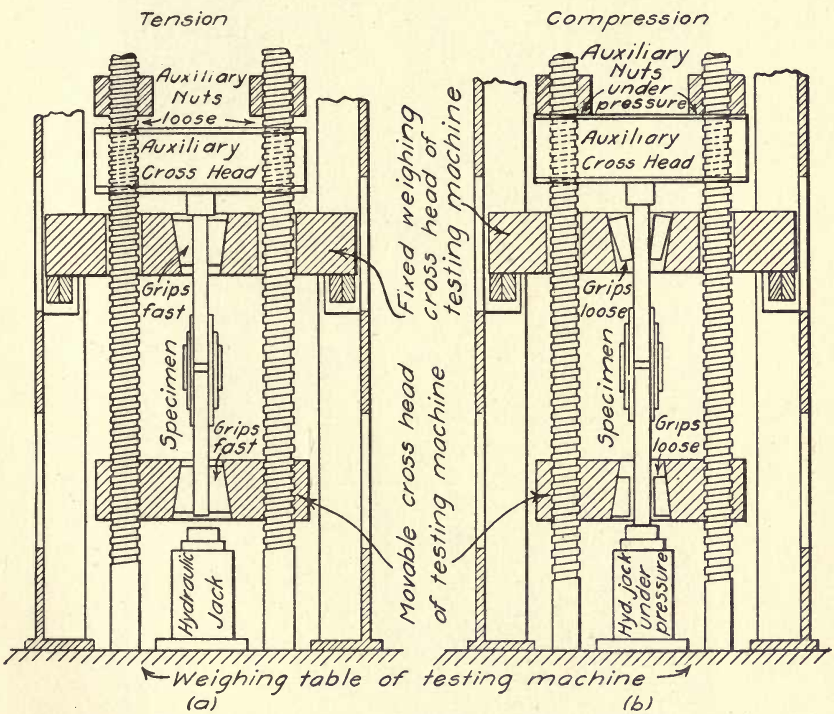

FIG. 6. AUXILIARY APPARATUS FOR TESTS IN ALTERNATE TENSION AND COMPRESSION.

Tension and compression were applied alternately as follows: To put the specimen in tension the load was applied through the screws of the machine and weighed in the usual manner. During this part of the test the auxiliary cross-head above the weighing head of the testing machine rested on the top of the specimen, and the auxiliary nuts were clear of the auxiliary cross-head and turned with the screws. (See Fig. 6 (a)). The specimen, of course, was held by the wedge grips. The tension load was next released, after which the lower grips loosened themselves from the specimen. The hydraulic jack under the specimen was then pumped up, and its rising plunger carried the specimen and the auxiliary cross-head upward until the auxiliary cross-head was forced against the auxiliary nuts and the specimen put in compression. Fig. 6 (b) shows this condition. The reaction of the hydraulic jack on the weighing table was weighed by balancing

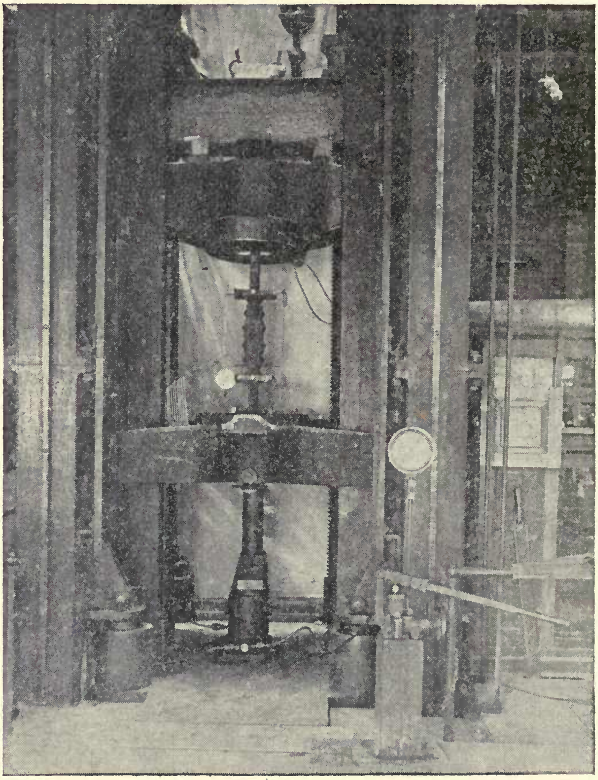

FIG. 7. VIEW OF TESTING MACHINE WITH AUXILIARY APPARATUS FOR TESTS IN ALTERNATE TENSION AND COMPRESSION.

the beam of the testing machine, and, of course, was equal to the compression load on the specimen. The pressure was next released from the jack, the weight of the auxiliary cross-head acted to tighten the grips in the weighing head of the machine, the lower grips were tightened by hand, and another tension load was applied. It will be seen that the load in compression was as accurately determined as that in tension.

8. *Measurement of Deformation.*—In the tension tests the elongation of the specimen was measured by means of the apparatus shown in Fig. 8. This instrument consists of two frames AA_1 which are fastened to the specimen by pointed screws SS_1, these screws being symmetrically placed with respect to the longitudinal axis of the specimen. As the specimen stretches, the frames tend to separate, but at the right hand side (as shown in the figure) they are held at a constant distance apart by means of the rod R, whose ends receive the pivots FF, and by the springs XX. At the left hand side the lower frame carries a dial D around which rotates a pointer. On the axle of this pointer is a small sheave one inch in circumference, which is driven by a fine insu-

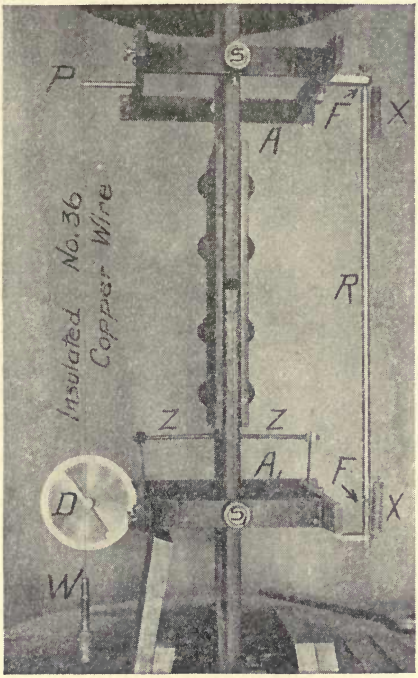

Fig. 8. View of Extensometer Attached to Test Piece.

lated copper wire wrapped around it. This wire, which is kept taut by the weight W, is attached at its upper end to the pin P which is carried at the left hand side of the upper frame. This wire and the axis of the rod R are equidistant from the axis of the specimen, and thus as the specimen stretches, the pin P and the dial D separate by twice the stretch of the specimen, and this double stretch is indicated by the pointer on the dial. The dial was graduated to measure the stretch of the piece to one ten-thousandth of an inch. Before making tests with this apparatus, the dial wrapped with wire was tested in comparison with a screw micrometer, and it was found under repeated reversals to be free from slip of wire over drum and free from appreciable error. The apparatus behaved with entire satisfaction during the test and, it is believed, gave thoroughly trustworthy results.

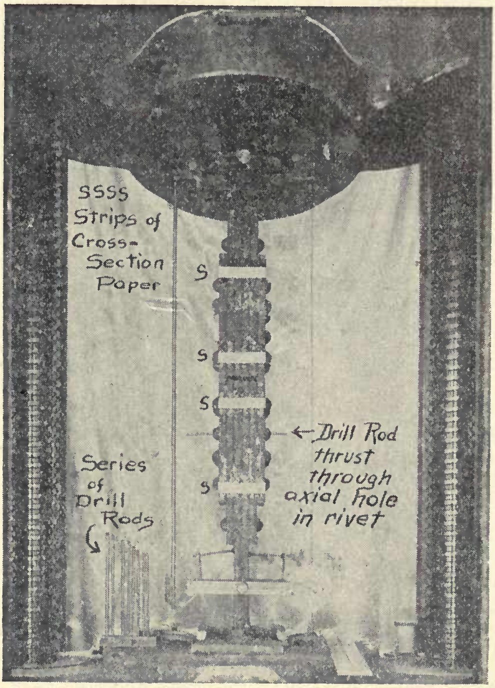

FIG. 9. VIEW OF TENSION TEST PIECE WITH AUXILIARY APPARATUS FOR MEASURING DEFORMATION.

For the purpose of measuring the movement of the several plates of a joint, strips of cross-section paper were glued across the narrow sides of the plates before testing the joints, and after the glue had hardened, these strips were cut into pieces along the edges of the plates, leaving a piece attached to each plate. As the plates slipped over each other the amount of slip was read directly from the cross-section paper. Fig. 9 and 10 show this arrangement.

In the tests in alternate tension and compression the same apparatus was used to measure the deformation of the joints as was used in the tension tests.

In one or more joints of each type the bending of the rivets was investigated. The apparatus used for detecting the bending

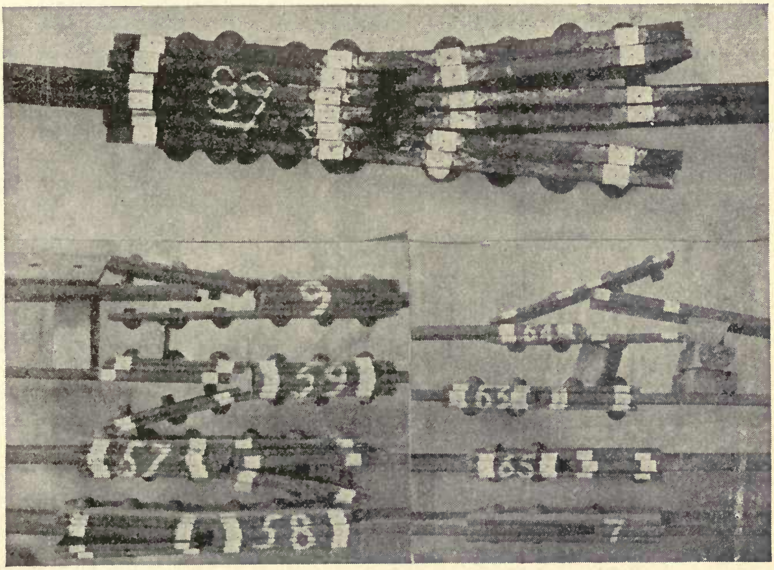

Fig. 10. View of Fractured Test Pieces showing Movement of Plates.

of rivets is shown in Fig. 9 and 11. Holes 0.204 inch in diameter were drilled through all rivets of the joint as nearly axially as possible. A series of Stubs' steel drill rods varying in diameter from 0.180 inch to 0.204 inch by steps of about 0.003 inch was provided, and under the initial load the largest drill rod which could be thrust through the hole was determined by trial. This arrangement is illustrated in Fig. 11 (a) where d_1 is the diameter of this drill rod. Under any other load on the joint, if appreciable bending of the rivet had occurred, this drill rod could not be thrus through the hole in the rivet, and the maximum size of rod which would pass the hole was of smaller diameter (d_2), as illustrated in Fig. 11 (b). $d_1 - d_2$ gives the total amount of bending and detrusion under the given load.

9. *Procedure of Tests.*—In the tension tests an initial load of 1000 lb. was first applied, and the dial of the extensometer set to zero; the first desired load was then applied and the dial read; the load was then reduced to the initial load of 1000 lb. and the dial again read; the next higher load was then applied, and the load again reduced to the initial load. This process was repeated until a load equal to about three-quarters of the estimated breaking load had been applied. At this point the measuring instrument was removed, and in the further test the load was progressively

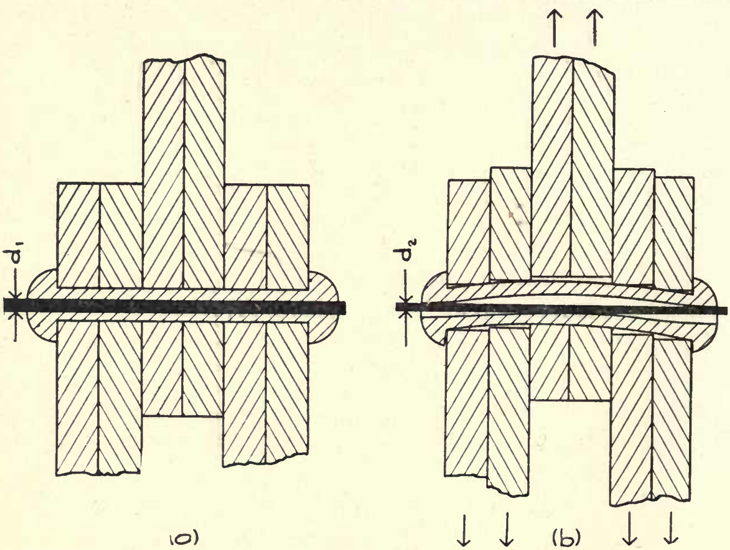

FIG. 11. DIAGRAM SHOWING METHOD OF MEASURING BENDING OF RIVETS.

applied to failure, the reading of the cross-section paper being taken at intervals throughout the entire test.

In the tests of the joints designed to withstand alternate tension and compression (sixteen joints of nickel-steel and sixteen joints of chrome-nickel-steel of the form and dimensions shown in Fig. 5), the following schedule was carried out:

(a) Six specimens tested in tension, with release of load and observation of deformation and set as the load was progressively increased. (Joints TB20L, TB21L, TB20L, TB20S, TB21S, and TB22F).

(b) Six specimens tested in compression, with release of load and observations of deformation and set as the load was progressively increased. (Joints TB19L, TB20L, TB22L, TB22S, TB20F, and TB22F).

(c) Six specimens tested in alternate tension and compression, a tension load being first applied followed by an equal load in compression, then an increased load applied in tension followed by an equal load in compression, etc., the joint being finally broken in tension. (Joints TB22L, TB22L, TB22L, TB20F, TB21S, and TB19S).

(d) Four specimens tested as in (c), and in addition the bending of the rivets was investigated by the aid of holes drilled through them. (Joints TB21L, TB20L, TB21F, TB19F).

(e) Four specimens tested as in (c), except that the compression load applied was only one-half of the preceding tension load. (Joints TB19L, TB19L, TB20S, and TB22S).

(f) Two specimens tested as in (c), except that in all but the higher loads the cycle of tension and compression for any given load was repeated five times before the next larger load was applied. (Joints TB19L and TB20S).

(g) Four specimens tested by repeatedly applying alternately in tension and compression a load producing a rivet shear of about 10 000 lb. per sq. in., and occasionally interjecting a single application of a higher load. (Joints TB21L, TB21L, TB19F, and TB21F).

During the application and release of a load, throughout the above schedule, observations of deformation were taken at several loads, in order that the stress-deformation diagram of the specimen might be plotted during the application of tension, the release of tension, the application of compression, and the release of compression, i. e., throughout the complete cycle of stress.

In all tests in the second series except tests 69, 70, 105 and 106 the increment of load was 25 000 lb. In nearly all cases the maximum load applied before removing the measuring instruments was 300 000 lb. After the removal of the instruments a higher load was applied and the piece was broken. In tests 69, 70, 105 and 106 ((g) in the schedule of tests) the method of procedure was as follows: The specimen was subjected to ten cycles of alternated loading, the load both in tension and compression being such as to produce a shearing stress of about 10 000 lb. per sq. in.

in the rivets. The specimen was then subjected to one cycle of stress at loads which gave a shearing stress of about 15 000 lb. per sq. in. in rivets. Then followed ten cycles with 10 000 lb. per sq. in. shear in rivets, then one cycle with 20 000 lb. per sq. in., then ten cycles with 10 000 lb. per sq. in., then one cycle with 25 000 lb. per sq. in., and finally one cycle with 10 000 lb. per sq. in. After this the piece was broken in tension.

III. Data and Discussion.

10. *Sample Data of Tension Tests.*—Table 5, page 25, gives the data of a sample tension test of the riveted joints, (Joint TB10S, Test 83). In this particular test the bending of the rivets was investigated by means of the device already described. The data are self-explanatory. Fig. 12 shows the plotted data of this test. The lines drawn solid show deformation under stress and the lines drawn broken show permanent set after removal of stress. Complete data for all tests and curves for each test piece are on file in the Laboratory of Applied Mechanics of the University of Illinois, but in general only summarized data will be given in this bulletin.

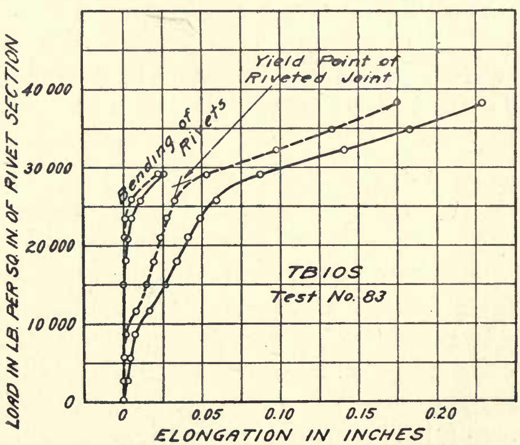

Fig. 12. Diagram of Test No. 83.

11. *Sample Data of Tension and Compression Tests.*—Table 6, page 27, shows the data of a sample test of a riveted joint under alternate tension and compression, (Joint TB21F, Test 94). In this test the bending of the rivets was investigated. Fig. 13 has been plotted from the data. In this test loads in tension were

followed by equal loads in compression. Fig. 14 shows the plotted results of a test in which loads in tension were followed by half as great loads in compression. Fig. 15 (Joint TB21L) shows the plotted results of a test under stress in tension only; a diagram of a test in compression only would be quite similar in appearance.

TABLE 5.

Sample Data of Tension Test of Riveted Joint.

Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—$\frac{7}{8}$ inch.

Specimen TB10S. Test No. 83.

Load pounds	Shear per square in. of rivet pounds	Extensometer Gauge Length 30 in.		Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter.					
		Elongation inches	Set inches						
1 000	290		0.0000	8	7	8	8	8	8
9 600	2 810	.0025		8	7	8	8	8	8
1 000	290		.0000	8	7	8	8	8	8
19 500	5 710	.0042		8	7	8	8	8	8
1 000	290		.0005	8	7	8	8	8	8
30 200	8 820	.0075		8	7	8	8	8	8
1 000	290		.0015	8	7	8	8	8	8
40 000	11 720	.0168		8	7	8	8	8	8
1 000	290		.0079	8	7	8	8	8	8
51 200	15 000	.0260		8	7	8	8	8	8
1 000	290		.0146	8	7	8	8	8	8
61 500	18 000	.0337		8	8	8	8	8	8
1 000	290		.0192	8	7	8	8	8	8
71 800	21 040	.0409		9	8	8	8	8	8
1 000	290		.0234	8	8	8	8	8	8
80 400	23 550	.0495		9	8	9	9	8	9
1 000	290		.0272	8	8	8	8	8	8
87 700	25 680	.0588		11	11	11	9	9	11
1 000	290		.0325	9	9	9	8	8	9
99 600	29 160	.0875					13	12	14
1 000	290		.0531	14	13	14	11	11	12
109 800	32 150	.1410							
1 000	290		.0978						
119 400	34 920	.1823							
1 000	290		.1335						
128 800	37 700	.2286							
1 000	290		.1750						
182 200	53 320	Maximum load							

Upper rivets on north side sheared between second filler and main plate.

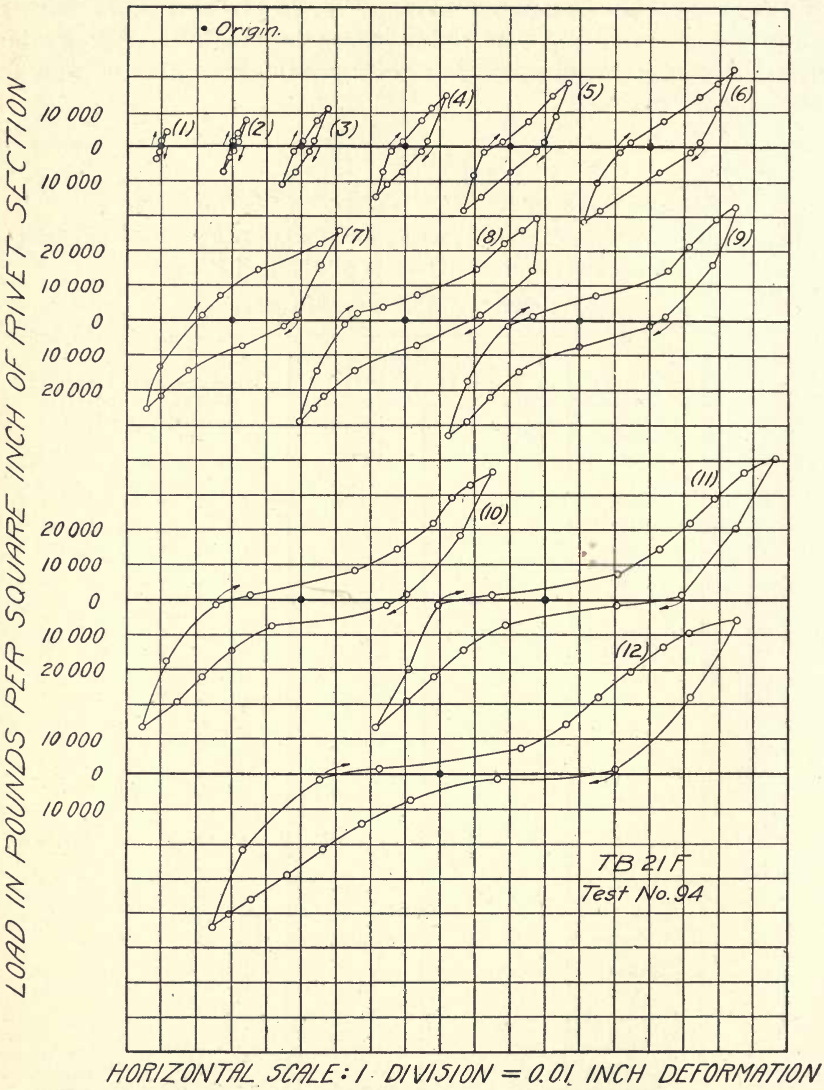

FIG. 13. DIAGRAM OF TENSION AND COMPRESSION TEST NO. 94.

TABLE 6.

Sample Data of Test of Riveted Joints in Alternate Tension and Compression.

T denotes load in tension; C, load in compression. Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—⅞ inch.

Specimen TB21F. Test No. 94.

	Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter
T	7 000	1 025	+.0000	6 6 6 6 6 6
T	28 000	4 100	+.0014	6 6 6 6 6 6
T	7 000	1 025	+.0007	
C	10 000	1 465	—.0007	
C	25 000	3 665	—.0014	
C	10 000	1 465	—.0007	
T	7 000	1 025	+.0003	
T	25 000	3 665	+.0016	
T	50 000	7 330	+.0041	6 6 6 6 6 6
T	7 000	1 025	+.0020	
C	10 000	1 465	+.0005	
C	25 000	3 665	—.0005	
C	50 000	7 330	—.0025	6 6 6 6 6 6
C	10 000	1 465	—.0009	
T	7 000	1 025	+.0004	
T	50 000	7 330	+.0044	
T	75 000	10 990	+.0075	
T	7 000	1 025	+.0037	
C	10 000	1 465	+.0021	
C	50 000	7 330	—.0016	
C	75 000	10 990	—.0054	6 6 6 6 6 6
C	10 000	1 465	—.0023	
T	7 000	1 025	—.0008	
T	50 000	7 330	+.0047	
T	75 000	10 990	+.0075	
T	100 000	14 650	+.0118	6 6 6 6 6 6
T	7 000	1 025	+.0062	
C	10 000	1 465	+.0044	
C	50 000	7 330	—.0010	
C	75 000	10 990	—.0052	
C	100 000	14 650	—.0088	6 6 6 6 6 6
C	51 000	7 475	—.0068	
C	10 000	1 465	—.0042	
T	7 000	1 025	—.0026	
T	50 000	7 330	+.0050	
T	100 000	14 650	+.0120	
T	124 500	18 230	+.0167	6 6 6 6 6 6
T	60 000	8 790	+.0130	
T	7 000	1 025	+.0094	
C	10 000	1 465	+.0072	
C	50 000	7 330	—.0002	
C	100 000	14 650	—.0089	
C	125 000	17 320	—.0140	6 6 6 6 6 6
C	57 000	8 355	—.0108	
C	10 000	1 465	—.0078	
T	7 000	1 025	—.0058	
T	50 000	7 330	+.0038	
T	100 000	14 650	+.0142	
T	125 000	18 320	+.0195	
T	152 500	22 350	+.0242	6 6 6 6 6 6
T	75 000	10 990	+.0194	
T	7 000	1 025	+.0141	
C	10 000	1 465	+.0115	
C	50 000	7 330	+.0024	
C	100 000	14 650	—.0112	
C	125 000	18 320	—.0147	
C	150 000	21 980	—.0192	6 6 6 6 6 6
C	70 000	10 260	—.0155	
C	10 000	1 465	—.0109	
	0 000	0 000	—.0080	

	Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter
T	7 000	1 025	—.0087	
T	50 000	7 330	+.0035	
T	100 000	14 650	+.0075	
T	150 000	21 980	+.0250	
T	176 000	25 785	+.0307	6 6 6 6 6 6
T	108 000	15 830	+.0255	
T	7 000	1 025	+.0179	
C	10 000	1 465	+.0148	
C	50 000	7 330	+.0029	
C	100 000	14 650	—.0125	
C	150 000	21 980	—.0202	
C	175 000	25 640	—.0246	6 6 6 6 6 6
C	91 000	13 340	—.0210	
T	10 000	1 465	—.0143	
T	25 000	3 665	—.0065	
T	50 000	7 330	+.0035	
T	100 000	14 650	+.0202	
T	150 000	21 980	+.0283	
T	175 000	25 640	+.0235	
T	200 500	29 370	+.0374	6 6 7 7 7 6
T	100 000	14 650	+.0309	
T	7 000	1 025	+.0213	6 6 6 6 6 6
C	10 000	1 465	+.0178	
C	50 000	7 330	+.0032	
C	100 000	14 650	—.0148	
C	150 000	21 980	—.0237	
C	175 000	25 640	—.0262	
C	200 000	29 300	—.0303	7 6 7 7 7 7
C	101 000	14 800	—.0256	
C	10 000	1 465	—.0173	6 6 6 6 6 6
T	7 000	1 025	—.0132	
T	50 000	7 330	—.0048	
T	100 000	14 650	—.0245	
T	150 000	21 980	—.0319	
T	200 000	29 300	—.0395	
T	224 000	32 820	—.0450	6 7 8 8 8 8
T	110 000	16 120	—.0385	
T	7 000	1 025	+.0248	
C	10 000	1 465	+.0205	
C	50 000	7 330	+.0000	
C	100 000	14 650	—.0174	
C	150 000	21 980	—.0253	
C	200 000	29 300	—.0322	
C	225 000	32 960	—.0372	7 6 7 7 7 7
C	120 000	17 580	—.0321	
C	10 000	1 465	—.0206	7 6 7 6 6 6
T	7 000	1 025	—.0147	
T	50 000	7 330	+.0152	
T	100 000	14 650	+.0278	
T	150 000	21 980	+.0380	
T	200 000	29 300	+.0432	
T	225 000	32 960	+.0488	
T	251 000	36 770	+.0552	6 8 9 9 8 8
T	125 000	18 320	+.0458	
T	7 000	1 025	+.0302	6 7 8 8 7 7
C	10 000	1 465	+.0248	
C	50 000	7 330	—.0085	
C	100 000	14 650	—.0198	

TABLE 6. (*Continued.*)

SAMPLE OF DATA OF TEST OF RIVETED JOINTS IN ALTERNATE TENSION AND COMPRESSION.

T denotes load in tension; C, load in compression. Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—$\frac{7}{8}$ inch.

Specimen TB21F. Test No. 94.

Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter	Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter
C 150 000*	21 980	−.0283		C 10 000	1 465	−.0308	8 8 8 8 8 8
C 200 000	29 300	−.0352		T 7 000	1 025	−.0175	
C 250 000	36 630	−.0393		T 50 000	7 330	+.0235	
C 250 000	36 630	−.0455	8 7 8 8 8 8	T 100 000	14 650	+.0362	
C 121 000	17 730	−.0386		T 150 000	21 980	+.0458	
C 10 000	1 465	−.0243	7 7 7 7 7 7	T 200 000	29 300	+.0548	
T 0 000	0 000	−.0152		T 250 000	36 630	+.0642	
T 50 000	7 330	+.0208		T 275 000	40 300	+.0720	
T 100 000	14 650	+.0330		T 300 000	43 960	+.0852	8 12 13 13 13 12
T 150 000	21 980	+.0415		T 150 000	21 980	+.0722	
T 200 000	29 300	+.0489		T 7 000	1 025	+.0502	7 9 11 11 11 9
T 250 000	36 630	+.0575		C 10 000	1 465	+.0168	
T 275 000	40 300	+.0666	7 9 11 9 11 9	C 50 000	7 330	−.0085	
T 140 000	20 500	+.0550		C 100 000	14 650	−.0225	
T 7 000	1 025	+.0392	6 8 8 8 7 7	C 150 000	21 980	−.0338	
C 10 000	1 465	+.0208		C 200 000	29 300	−.0437	
C 50 000	7 330	−.0112		C 250 000	36 630	−.0542	
C 100 000	14 650	−.0235		C 275 000	40 300	−.0605	
C 150 000	21 980	−.0320		C 300 000	43 960	−.0747	12 11 14 13 14 11
C 200 000	29 300	−.0398		C 150 000	21 980	−.0667	
C 250 000	36 630	−.0588		C 10 000	1 465	−.0441	11 9 11 9 11 8
C 275 000	40 300	−.0572	9 8 11 9 11 8	T 392 800	57 550		
C 137 000	20 070	−.0492					

Failed by shearing 6 upper rivets on both sides.

*Slipped about .0100.

In four tests an effort was made to study the behavior of the test pieces under several reversals of a load which gave a shearing stress of about 10 000 lb. per sq. in. of rivet area. In Fig. 16, page 38, in the test of each riveted joint the diagram marked (1) shows the deformation of the specimen under the first cycle of load (i.e., during the application of tension, the release of tension, the application of compression, and the release of compression); diagram marked (10) shows the deformation during the tenth cycle of load; (11) shows the deformation during a cycle in which the rivet shear was increased to 15 000 lb. per sq. in.; (12) shows the next cycle which was for a load of 10 000 lb. per sq. in. rivet shear, etc.

12. *Tables and Diagrams of Results.*—Table 7 gives the shearing stress in the rivets (stated in lb. per sq. in. of the shearing area of the rivet) at which the first noticeable slip of the riveted

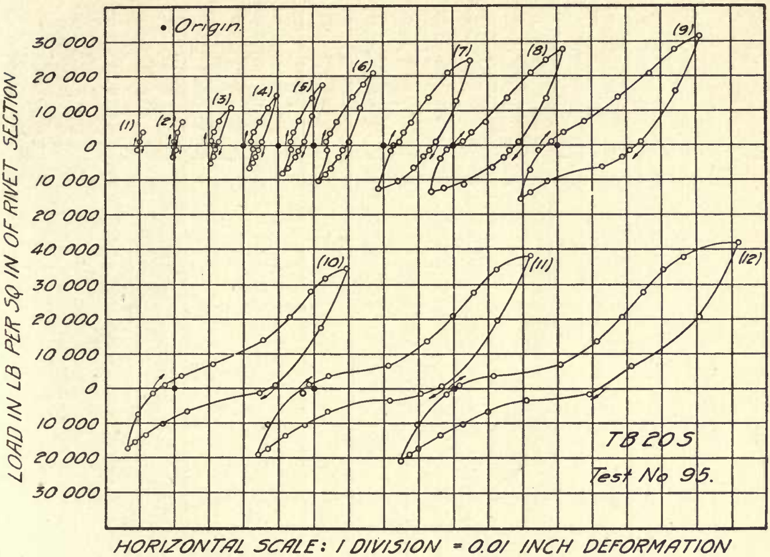

FIG. 14. DIAGRAM OF TENSION AND COMPRESSION TEST NO. 95.

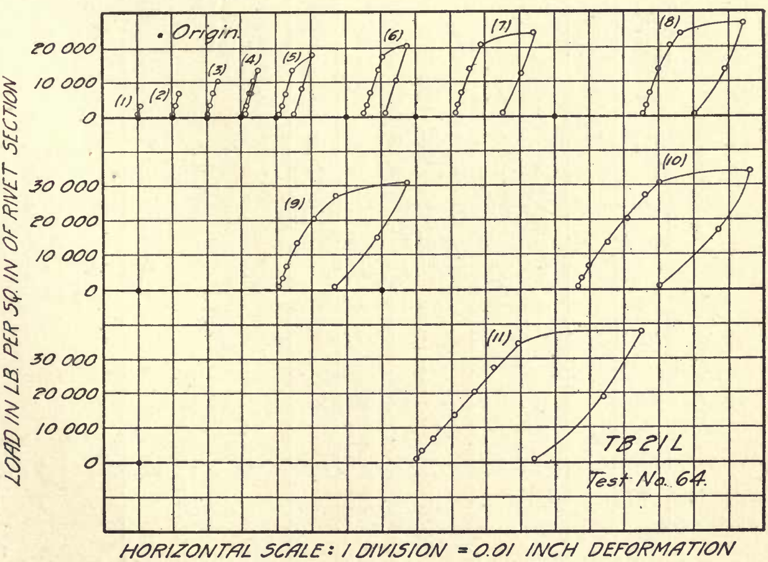

FIG. 15. DIAGRAM OF TENSION TEST NO. 64.

TABLE 7.

FIRST NOTICEABLE SLIP OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints.																		
Shop riveted	8 900	10 500	8 200	7 500	6 100	6 000	10 000	9 500	11 600	12 500	11 500	13 000	9 500	11 500	15 000	11 000	14 000	15 500
	10 500	6 300	5 600	6 900	8 000	6 000	9 000	10 000	12 200	9 000	12 500	14 000	12 000	10 000	11 000	17 500	14 500	18 000
	11 000	11 000	15 000	7 600		5 900	8 800	10 500	10 500	11 800	13 000	12 500	8 600	10 500	14 100	13 000	12 500	10 500
Field riveted	10 500	17 500	15 000	5 200	5 500	5 600	8 000	6 600	8 800	8 600	9 100	8 500	11 100	12 500	11 400	9 500	13 000	15 000
	17 000	13 000	10 500	10 000	5 800	5 600	7 500	9 700	7 500	7 500	9 000	7 500	8 400	8 500	11 000	9 500	11 000	14 000
Av. shop riveted	10 130	9 270	9 600	7 330	7 050	5 970	9 270	10 000	11 430	11 100	12 330	13 000	10 030	10 670	13 370	13 830	13 800	14 670
Av. field riveted	10 750	15 250	12 750	7 605	5 650	5 600	7 750	8 150	8 150	8 050	9 050	8 000	9 750	10 500	11 200	9 500	12 000	14 500
Av. shop and field riveted	10 380	11 660	10 860	7 440	6 350	5 820	8 660	9 260	10 120	9 880	11 020	11 100	9 920	10 600	12 500	12 080	13 080	14 600
General average 10 300																		
Chrome-nickel-steel Riveted Joints.																		
	13 000	13 000	11 000	11 500	12 000	10 500	12 000	14 500	14 000	13 500	16 500	16 500	16 500	15 000	16 000	15 000	15 000	16 500
	15 000	14 000	13 500	10 000	12 000	11 500	12 000	14 000	13 000	13 500	14 000	15 000	16 500	16 500	18 000	15 000	13 500	16 500
	15 000	13 500	11 000	10 000	13 000	10 000		13 500	11 500	11 500	14 000	15 000	14 000	12 500	10 000	16 000	19 000	13 500
Average	14 330	13 500	11 830	10 500	12 330	10 670	12 000	14 000	12 830	12 830	14 830	15 500	15 670	14 670	14 670	15 330	15 830	15 500
General average 13 690																		
Carbon-steel Riveted Joints. (Maintenance of Way Association Tests).																		
	27 000	13 000	8 000	16 000	14 000	6 500	6 500		12 000	6 000	6 000	8 000	9 000	6 000	8 500	6 500	5 000	5 500
	17 000	14 000	13 500	15 000	12 500	7 000	6 500	7 500	13 500	8 000	6 000	10 000	8 500	6 500	5 500	6 500	4 500	6 000
	18 000	14 500	10 500	11 500	7 500	7 500	7 500	8 000	12 000	7 000	9 000	11 000	9 000	7 000	6 000	4 000	5 000	7 000
	20 000	16 500	12 500	11 500	7 000	5 500	7 000	7 000	11 000	6 000	10 500	13 500	10 000	7 000	6 000	8 500	6 500	5 500
	19 000	13 000	12 500	12 500	11 500	5 500	7 500	7 000	9 000	7 500	9 500	11 000	8 000	7 500	5 000	6 000	6 000	6 500
Average	20 200	14 200	11 400	13 300	10 500	6 400	7 000	7 380	11 500	6 900	8 200	10 700	8 900	6 800	6 200	6 300	5 400	6 100
General average 9 310																		

joint occurred in the tension tests. In all cases in computing the area of a rivet the nominal diameter of the rivet was used. The shearing stress is taken at the load at which the total apparent movement amounted to about 0.0025 in. The determination of this point involves the use of some judgment, but as the same method was used in all cases the results are considered to be comparable with each other.

Table 8, page 32, gives the yield point of the nickel-steel and the chrome-nickel-steel riveted joints stated in terms of the shearing stress on the rivets.

In Fig. 17 and 18 (at the end of the text) permanent set is plotted for the nickel-steel riveted joints, the chrome-nickel-steel riveted joints, and the carbon-steel riveted joints. In each case the results given are the average for the test pieces of the set. A general comparison may be made by eye.

Table 9, page 34, gives the ultimate strength of the nickel-steel and of the chrome-nickel-steel riveted joints stated in lb. per sq. in. of the shearing area of the rivets. In computing rivet area the nominal diameter was used. The ultimate strength of the carbon-steel joints reported by the Maintenance of Way Association is also given.

Table 10 gives the ultimate shearing strength and Table 11, the yield point of riveted joints tested in alternate tension and compression.

Fig. 19 to 22 (at the end of the text) show graphically the total deformation produced by different intensities of stress. In the direct tension and direct compression tests, the set is also plotted, and in the other tests except tests 69, 70, 105, and 106, both the total range of deformation and the deformation under tension are given. Table 11 gives the yield point of the joints tested in alternate tension and compression.

13. *Slip in Tension Tests.*—By the use of delicate extensometers slip of the rivets in a test joint can be detected and measured under small loads. An inspection of Fig. 17 and 18 shows that the plates began to slip at loads as low as the usual working loads, the amount of slip increasing regularly until the yield point of the joint was reached. The first noticeable slip of the riveted joint given in Table 7 is taken when the total apparent movement amounted to 0.0025 inch. The slip of joint in the Maintenance of Way tests of carbon-steel riveted joints is also included in Table 7.

TABLE 8.

Yield Point of Riveted Joints.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test Piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints																		
Shop riveted	37 800	36 200	30 600	35 000	30 100	31 600	31 400	36 200	36 800	29 900	34 900	40 100	35 000	28 900	32 300	34 000	28 800	31 800
	35 500	35 500	32 100	34 100	35 100	37 000	32 700	35 500	37 700	29 200	37 600	37 500	35 000	28 300	31 900	35 600	27 600	32 500
	36 600*	34 500*	35 500*	34 900*	34 100*	33 300*	31 400*	35 700*	38 300*	27 800*	36 200	38 200*	34 300*	27 500*	33 700	35 200	27 000	30 000
Field riveted	37 000	35 800	34 300	37 000	34 000	35 700	34 000	36 800	36 200	30 200	35 300	36 800	40 000	29 200	34 100	34 500	27 000	31 700
	35 500	38 000	34 000	34 500	36 800	35 100	32 500	37 000	37 200	30 000	34 200*	37 000	36 100	31 300	32 700*	35 000	28 000	29 800
Av. shop riveted	36 630	35 400	32 730	34 670	33 100	33 970	31 830	35 800	37 600	28 970	36 230	38 600	34 770	28 230	32 630	34 930	27 800	31 430
Av. field riveted	36 250	36 900	34 150	35 750	35 400	35 400	33 250	36 900	36 700	30 100	34 750	36 900	38 050	30 250	33 400	34 750	27 500	30 750
Average shop and field riveted	36 480	36 000	33 300	35 100	34 020	34 540	32 400	36 240	37 240	29 420	35 640	37 920	36 080	29 040	32 940	34 860	27 680	31 160
Yield point of rivet in bending	38 600	32 400	32 500	35 000	32 600	29 000	31 000	32 700	37 400	23 500	35 600	32 100	31 500	22 000	28 100			
Chrome-nickel-steel Riveted Joints.																		
	34 500	36 800	36 500	35 000	32 000	36 000	31 300	34 000	37 000	24 500	29 500	34 500	32 300	25 500	28 100	31 000	23 400	27 800
	37 200	34 000	34 500	36 000	36 000	34 700	29 800	33 800	35 700	24 000	30 200	30 900	30 600	25 000	30 500	32 200	24 100	27 500
	38 000	37 500	35 500	39 200	36 200	37 300	32 000	31 300	34 600	24 400	28 700	31 100	30 600	25 000	28 000	30 000	25 000	27 000
Average	36 570	36 100	35 500	36 730	34 730	36 000	31 030	33 030	35 770	24 300	29 470	32 170	31 170	25 170	28 870	31 070	24 170	27 430
Yield point of rivet in bending	36 300	36 000	33 600	38 000	35 000	36 700	30 900	32 000	35 200	24 400	29 000	32 800	30 600	25 500	29 100	31 500	24 200	27 100

* Joint with hole drilled through rivet.

TABLE 8.—(*Continued.*)

YIELD POINT OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test Piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Carbon-nickel-steel Riveted Joints—(Maintenance of Way Association Tests).																		
	28 000	24 900	26 100	28 800	29 600	24 700	20 100	26 600	26 100	19 400	25 000	29 500	28 500	18 600	20 700	21 200	15 800	17 600
	31 400	27 100	26 400	27 000	27 600	23 000	19 300	25 000	25 800	19 500	23 300	27 500	28 000	20 600	19 800	17 700	16 000	16 800
	29 900	25 500	27 100	28 000	25 100	23 000	19 400	27 400	23 800	19 300	25 100	26 000	27 800	18 900	19 600	21 500	15 400	17 600
	31 000	27 000	25 200	27 700	26 800	21 600	21 900	26 200	27 800	19 400	19 800	27 800	28 900	18 700	21 700	22 300	16 000	16 600
	32 800	26 300	24 100	26 000	29 300	24 100	22 800	28 000	27 900	19 400	22 300	26 000	27 900	18 800	20 000	22 000	16 000	17 000
Average	30 620	26 160	25 780	27 500	27 680	23 280	20 700	26 640	26 280	19 400	23 100	27 360	28 220	19 120	20 360	20 940	15 840	17 120
Excess of nickel steel over carbon steel, per cent	19.2	37.6	29.6	27.6	23.0	48.4	56.6	36.4	41.8	51.8	54.4	38.7	27.9	52.0	61.9	66.5	75.0	82.0
Excess of chrome nickel steel over carbon steel, per cent	19.4	37.7	37.6	33.5	25.5	54.7	50.0	24.0	36.1	25.4	27.6	17.6	10.3	31.6	41.8	43.3	53.0	60.2

TABLE 9.

Ultimate Shearing Strength of Riveted Joints.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints.																		
Shop riveted	63 900 58 900 60 600*	58 600 58 080 58 300*	55 000 55 600 57 500*	57 700 56 700 55 800*	46 950 56 600 55 800*	56 500 56 700 54 800*	55 900 56 100 55 500*	57 700 58 900 58 200*	57 700 57 600 58 400*	55 100 54 300 53 300*	55 200 58 000 57 600	59 700 56 400 57 500*	55 700 56 600 57 800*	51 400 53 000 52 300*	53 700 54 200 55 000	53 700 55 300 56 900	55 000 56 600 54 500	56 000 55 400 55 300
Field riveted	60 000 57 300	56 900 58 500	56 300 56 200	59 400 59 000	58 300 58 000	58 400 58 400	57 200 57 600	59 300 59 300	58 100 57 600	55 000 56 100	57 700 57 300*	59 700 57 700	57 500 57 400	52 400 53 100	57 200 56 600*	56 700 56 700	56 200 53 400	55 300 54 600
Av. shop riveted	61 130	58 300	56 030	56 730°	53 100	56 000	55 830	58 270	57 900	54 230	56 930	57 870	56 700	52 230	54 300	55 300	55 400	55 570
Av. field riveted	58 650	57 700	56 250	59 200	58 150	58 400	57 400	59 300	57 850	55 550	57 500	58 700	57 450	52 750	56 900	56 700	54 400	54 950
Av. shop and field riveted	60 140	58 080	56 120	57 720	55 120	56 960	56 460	58 460	57 880	54 760	57 160	58 200	57 000	52 440	55 340	55 860	55 140	55 320
Max. tensile stress in plate (lb. per sq. in.)	18 150	33 300	48 950	16 850	33 100	49 700	49 100	49 600	49 700	47 800	49 400	50 800	48 400	45 300	47 900	47 600	47 400	46 800
Chrome-nickel-steel Riveted Joints.																		
	53 350 56 400 56 900	57 100 54 250 57 650	55 700 53 850 55 750	54 550 57 300 58 100	52 700 55 650 56 550	53 940 54 500 56 300	51 300 51 450 53 100	55 000 53 250 51 600	53 950 55 200 53 620	48 900 48 150 47 530	51 550 53 420 50 600	54 800 51 520 50 720	52 450 53 000 52 050	48 400 48 300 49 000	51 350 51 550 50 450	51 950 52 800 51 280	51 150 49 620 50 650	51 320 50 900 50 920
Average	55 550	56 330	55 100	56 650	54 970	54 910	51 950	53 280	54 260	48 190	51 860	52 350	52 500	48 570	51 120	52 010	50 470	51 050
Max. tensile stress in plate (lb. per sq. in.)	16 170	32 750	49 500°	16 510	32 200	48 000°	45 250°	16 840°	45 950°	41 650°	45 550°	46 650°	44 350	41 000	43 150	44 180	42 800	42 950

* Joints with hole drilled through rivets. ° Plate after rupture showed "stress lines" indicating that the yield point of the plate material had been passed.

TABLE 9.—(*Continued.*)

ULTIMATE SHEARING STRENGTH OF RIVET JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Carbon-steel Riveted Joints (Maintenance of Way Association Tests).																		
	53 200	47 600	45 700	53 500	50 100	48 500	50 000	48 800	48 800	46 300	48 800	53 900	48 800	46 900	49 200	48 400	45 400	45 500
	36 600	48 400	44 900	50 700	50 400	45 300	47 800	48 900	48 900	50 800	44 000	48 400	54 700	46 600	48 000	45 000	44 600	46 300
	54 900	48 200	45 500	52 100	50 600	47 400	45 700	49 500	48 800	45 000	50 100	51 400	49 200	44 000	46 800	45 900	44 300	47 300
	54 500	48 100	47 120	52 400	50 900	47 900	50 900	50 400	50 400	52 100	51 400	48 200	48 500	47 700	48 100	50 000	45 500	46 300
	55 700	49 100	45 700	51 600	52 400	45 500	49 200	49 900	56 800	47 500	50 800	47 600	51 500	45 100	46 800	48 500	44 900	46 200
Average..............	50 980	48 280	45 780	52 060	50 880	46 920	48 720	49 500	50 740	48 340	49 020	49 900	50 540	46 060	47 780	47 760	44 940	46 320
Max. tensile stress in plate (lb. per sq. in.)................	15 800	27 900	40 100	15 190	29 800	41 300	43 300	42 900	48 400	44 300	43 700	45 900	45 800	39 900	41 200	41 800	37 100	39 600
Excess of nickel-steel over carbon steel in shearing stress (per cent)..	17.2	20.4	22.7	10.9	8.4	21.4	13.9	18.2	13.2	13.3	16.5	16.7	12.9	14.0	15.9	17.2	22.6	19.4
General average....	16.4																	
Excess of chrome-nickel-steel over carbon steel (per cent)...............	9.1	16.6	20.5	8.9	8.2	17.1	6.6	7.7	7.0	—1.5	5.6	5.1	4.0	5.3	7.0	9.1	12.5	10.4
General average....	8.85																	

TABLE 10.

ALTERNATE TENSION AND COMPRESSION TESTS.
ULTIMATE SHEARING STRENGTH OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Nickel-steel Riveted Joints			Chrome-nickel-steel Riveted Joints		
Joint	Load at Failure lb. per sq. in.	Remarks	Joint	Load at Failure lb. per sq. in.	Remarks
Riveted Joints Subjected to Tension only.					
TB20S	56 700		TB20L	52 400	
TB21S	58 100		TB20L	49 800	
TB22F	58 800		TB21L	49 800	
Av.	57 870		Av.	50 670	
Riveted Joints Subjected to Compression only.					
TB20F TB22S TB22F	55 600	End of plates butted. Rivets sheared. Joint buckled.	TB19L TB20L TB22L		Joints buckled. Plates butted.
Riveted Joints Subjected to Tension followed by Half as Great Compression.					
TB20S	57 400		TB19L	50 200	
TB22S	55 200		TB19L	49 700	
Av.	56 300			49 950	
Riveted Joints Subjected to Tension followed by Equal Compression.					
TB19S	56 200		TB19L	49 500	
TB20S	56 600		TB20L*	49 300	
TB21S	55 820		TB21L*	51 700	
			TB21L°	50 800	
Av. shop riveted	56 200		TB21L°	51 600	
			TB22L	51 600	
			TB22L	52 000	
TB19F*	58 260		TB22L	51 700	
TB19F°	57 500				
TB20F	57 700		Av.	51 020	
TB21F*	57 550				
TB21F°	60 250				
Av. field riveted	58 230				
Av. field and shop riveted	57 480				

* Riveted joints with holes drilled through rivets.

° Riveted joints subjected to cycles of reversed load causing a shearing stress in the rivets of 10 000 lb. per sq. in.

TABLE 11.

Alternate Tension and Compression Tests.
Yield Point of Riveted Joints.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Nickel-steel Riveted Joints				Chrome-nickel-steel Riveted Joints			
Joint	Load at Yield Point lb. per sq. in.	Range of Deformation at Yield Point		Joint	Load at Yield Point lb. per sq. in	Range of Deformation at Yield Point	
		Under Load inches	Set inches			Under Load inches	Set inches
Riveted Joints Subjected to Tension only.							
TB20S	34 000	0.050	0.030	TB20L	29 500*	0.067	0.047
TB21S	34 600	0.045	0.028	TB20L	32 000	0 027	0.020
TB22F	36 100	0.041	0.028	TB21L	23 000*	0.040	0.027
Av.	34 900	0.045	0.029	Av.	28 170	0.045	0.032
Riveted Joints Subjected to Compression only.							
TB20F	37 000	0.035	0.020	TB19L	18 000*		
TB22S	33 700	0.045	0.030	TB20L	30 500	0.040	0.030
TB22F	36 200	0.035	0 020	TB22L	31 200	0.035	0.025
Av.	35 630	0.038	0.023	Av.	30 850§	0.037	0.027
Riveted Joints Subjected to Tension followed by Half as Great Compression.							
TB20S	39 000	0.079		TB19L	20 700*	0.015	
TB22S	38 900	0.095		TB19L	24 300*	0.017	
Av.	38 950	0.087		Av.	22 500	0.016	
Riveted Joints Subjected to Tension followed by Equal Compression.							
TB19S	33 800	0.089		TB19L	17 200*	0.015	
TB19F†	36 600	0.085		TB20L†	15 700*	0.017	
TB20F	36 400	0.092		TB21L†	15 300*	0.013	
TB20S	34 800	0.095		TB22L	19 500*	0.027	
TB21S	31 800	0.088		TB22L	16 000*	0.015	
TB21F†	36 500	0.100		TB22L	15 000*	0.015	
Av.	34 970	0.091		Av.	16 450	0.017	
Riveted Joints Subjected to Cycles of Reversed Load Causing a Shearing Stress in the Rivets of 10 000 lb. per sq. in.							
TB19F	30 300	0.045‡		TB21L	24 100	0.050‡	
TB21F	32 700	0.052‡		TB21L	25 900	0.055‡	
Av.	31 500	0.049		Av.	25 000	0.052	

* Yield point not well defined.

† Riveted joints with holes drilled through rivets.

‡ Range in deformation in tension.

§ TB19L omitted in taking average.

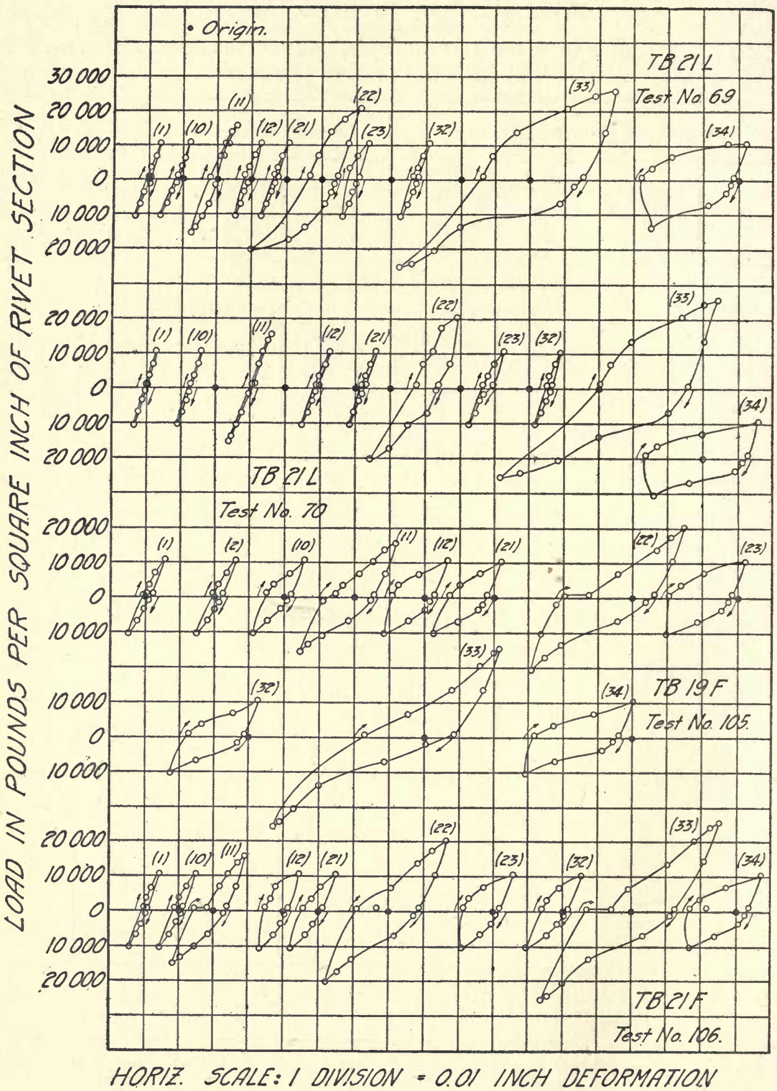

FIG. 16. DIAGRAM OF TENSION AND COMPRESSION TESTS UNDER ALTERNATIONS OF LOW STRESSES.

In general, the nickel-steel riveted joints showed first noticeable slip under a slightly higher load than that producing first noticeable slip in the carbon-steel joints of the Maintenance of Way Association. It may be doubted whether a comparison of the general averages would be significant. If the first slip of the joint is caused by the overcoming of the friction of the rivet heads and plates, no reason is apparent for expecting a higher load at first slip in nickel-steel riveted joints than in carbon-steel riveted joints, and the higher resistance of the nickel-steel riveted joints as compared with the carbon-steel riveted joints may be due to differences in fabrication.

In the tests of chrome-nickel-steel riveted joints, both plates and rivets were made up of steel softer and weaker than that used in the nickel-steel riveted joints, but the first noticeable slip took place at a load considerably higher than the load causing first slip in either the nickel-steel joints or the carbon-steel joints, indicating that the strength of material has very little effect on the stress at first slip of joint.

14. *Yield Point in Tension Tests.*—The term "yield point of riveted joints" will be used to designate the point at which a marked increase of yield in the riveted joint occurs and at which also a marked set of the riveted joint is found. As the loads are increased beyond the load causing a first noticeable slip, the permanent set increases regularly for several increments of load, as if the rivets were gradually seating themselves against the sides of the rivet holes; then quite suddenly the set increases markedly and the slope of the set curve becomes noticeably less. The method of determining the yield point in the tension tests is shown in Fig. 12. Some judgment must be exercised in determining this point, but it is quite definite except for the joints with long rivets. The increased deformation seems to be due partly to bending of the rivet and partly to shearing detrusion. Before the yield point is reached, a considerable movement of the riveted joint as a whole has taken place, and, of course, beyond the yield point the deformation increases rapidly. As measured by the displacement of the paper strips, the amount of slip up to the yield point in the riveted joints with short rivets and without filler plates was about 0.025 in., and after rupture the slip of the unbroken end was about 0.20 in. After the yield

point of the joint had been passed, the movement was due in greater part to the shearing detrusion of the rivet. In the joints with long rivets, a greater movement occurred, as much as 0.05 in. before the yield point was reached, and after rupture as much as 0.40 in. in the unbroken end of several of the riveted joints.

15. *Ultimate Strength in Tension Tests.*—All the riveted joints tested, both nickel-steel and chrome-nickel-steel, finally failed by shearing of rivets. The ultimate shearing stress in the rivets is given in Table 9. Whether a riveted joint will fail by shear of rivets or otherwise depends upon the design of the joint and the relative strength of the rivet and plate material. A fact not always recognized is that the stress at which a rivet will break under shear depends not only upon the quality of the rivet material but also on the relative hardness of the rivet and of the plate on which the rivet bears. The rivet material used in the nickel-steel riveted joints was about 16 per cent stronger in tension than that used in the chrome-nickel-steel riveted joints; the plate material of the nickel-steel riveted joints was considerably stronger and harder than the rivet material, while in the chrome-nickel-steel riveted joints the plate material was not much stronger than the rivet material; the result was the shearing strength of the nickel-steel riveted joints was only 7 per cent greater than that of the chrome-nickel-steel riveted joints, about half of the gain which might be expected from a comparison of the tests of rivet material.

Comparing the ultimate strength of the Maintenance of Way Association tests of carbon-steel riveted joints, the apparent gain in ultimate strength is only about 16 per cent for the nickel steel and about 9 per cent for the chrome nickel steel. However, the carbon-steel riveted joints were designed so as to have nearly the same strength in shear of rivets and in tension in plates; this is shown by the fact that some failed by shear of rivets and some by tension in plates. The tensile stresses in the plates forming the riveted joints, developed at the ultimate load, are given in Table 9. In the case of the nickel-steel riveted joints it will be noted by reference to the strength of the specimens cut from the plates (see Table 2) that even in the riveted joints in which three or six rivets were sheared the tensile stress in the plate at rupture of the riveted joint was in no case as great as the yield point of the material of the plates. The nickel-steel and the chrome-nickel-steel riveted joints were made with the same dimensions as the Maintenance of Way Association riveted joints and as they all failed by shear of rivets and as no scaling or other indication of exceeding the yield point of the plates was observed in the nickel-steel riveted joints, and no chrome-nickel-steel riveted joints failed in the plates, (though many of the plates in the chrome-nickel-steel riveted joints were stressed beyond the yield points as was shown by "scaling" and by the appearance of characteristic "stress lines",) it is evident that the efficiency of joint was less than in the carbon-steel joints, and that a larger gain could have been shown for the nickel-steel and chrome-nickel-steel riveted joints had they been proportioned so as to have as high joint efficiencies as had the Maintenance of Way Association carbon-steel joints. The tests, therefore, may not be used to compare the full strength of riveted joints of the three classes of materials.

In connection with this topic the results of the tests made by Preuss at Darmstadt are of interest (see foot note on page 5). In the test joints of that series nearly all the rivets were of nickel steel. The plate material was not specified, and Dr. Preuss writes that its nature is not known; it probably was ordinary structural steel. At any rate, judging from the rivet material, it seems probable that the rivets of the joints were of stronger and harder material than were the plates. Comparing the butt joints in Preuss' tests with those most nearly similar in the University of Illinois tests, the ultimate shearing stress in the rivets of Preuss' test joints was about 19 per cent greater than the ultimate shearing stress in the rivets of the corresponding Illinois test joints. In view of the fact that in the University of Illinois tests the plate material was stronger and harder than the rivet material, while in Preuss' tests the reverse is true, the difference in shearing strength does not seem excessive. Making similar comparisons for lap joints in the two series of tests, Preuss' results for ultimate shearing stress in rivets are about 39 per cent higher than those found at Illinois. This great difference in ultimate strength may be due in part to the fact that the riveted ends of the lap joints in Preuss' tests were bent during fabrication to make the center of the rivet come in the direct line of the pull on the joint.

16. *Slip in Alternate Tension and Compression Tests.*—The slip of the riveted joints in the alternate tension and compression tests is shown by the diagrams in Fig. 13 to 16. The most striking feature in the tests under alternate tension and compression is the very large slip which may take place under comparatively low loads. Especially is there danger of a large amount of slip if at any time a riveted joint has been subjected to a single load considerably beyond the ordinary working load. In Fig. 16, if cycle (1) is compared with cycle (12) there is seen a marked increase in the amount of slip under loads below ordinary working loads; this slip occurred in the joint after a single application of an unusually high load.

17. *Yield Point in Alternate Tension and Compression Tests.*—In the tension tests the yield point of the riveted joints was in general determined from the set curve (see Fig. 12); but in tests in alternate tension and compression there is very little set at the end of a cycle of stress and the amount of this is not significant. In these tests the yield point has been located by J. B. Johnson's method which consists in finding a point on the stress deformation curve where the rate of change of deformation is 50 per cent greater than during the early part of the test. The average yield point obtained in this way does not differ much from that obtained by taking the first marked change in direction of the stress-deformation curve. Where bending of rivet was directly examined, the first noticeable set of rivet took place at a stress not widely differing from the yield point as determined by the above method. From the results of the tests it would seem that the riveted joints tested under alternate tension and compression showed yield points about as high as those tested under stress in one direction only. Attention is called to the lower yield points found in Tests 69, 70, 105, and 106, in which the joints had been subjected to repeated applications of the load.

18. *Ultimate Strength in Alternate Tension and Compression Tests.*—Of the series of riveted joints for alternate tension and compression loads, six were tested in direct tension and six in direct compression. This was done to furnish a basis of comparison for the alternate tension and compression tests. Every joint of the series failed by shear of rivets, except that in nearly all of the direct compression tests the main plates finally came in di-

rect contact and the joints buckled noticeably, thus preventing the completion of the shearing action. In the one compression test in which the rivets were sheared to failure, the joint buckled noticeably and the failure was on the concave side of the joint. In the tension failures, in some cases rivets sheared on both sides of the main plates and in other cases on one side only. The joints failed suddenly with a loud report, the load falling off slightly just before failure. In no case was there any indication that either the main plates or the cover plates had reached their elastic limit when the ultimate load was applied.

The comparatively few alternations of load to which the nickel-steel and the chrome-nickel-steel riveted joints were subjected apparently had very little effect on the ultimate strength, as may be seen by comparing the ultimate strengths with those of the joints tested in tension. It is entirely probable, however, that a large number of reversals of load would cause failure under lower loads. Reversed load tests involving a large number of loadings on full-sized riveted joints have never been made, so far as is known. Such tests would be very expensive and would require a long time. In the absence of such tests it may be assumed that riveted joints under repeated reversals of load would be in danger of failure at loads very much lower than under steady tension loads.

19. *Bending of Rivets.*—It has long been recognized that in riveted joints the rivets are subjected to bending stresses, and attempts have been made to calculate these stresses. A mathematical analysis of the bending of a rivet is subject to many uncertainties: the ends of the rivets are partially restrained; the compression and detrusion of the rivet and plate modify the bending action and render uncertain the position of the point of application of the resulting pressure; and in various ways the conditions of beam action are indeterminate. The investigation of bending of rivets made in these tests is novel, so far as known. It shows to what extent bending takes place in such joints. The first marked bending of the rivets was found to be closely coincident with the yield point of the joint. It is seen also that the longer the rivet the greater the relative importance of the resistance to bending. It will be noted that in those joints having long rivets (TB14 to TB18) the nickel-steel riveted joints have their yield point at a stress considerably higher than do the carbon-

steel riveted joints, and that the yield point of the chrome-nickel-steel riveted joints is between the two.

In the alternate tension and compression tests, the load at which actual appreciable bending of the rivets first takes place (also generally coincident with the yield point of the joint) seems to be slightly lowered by a few applications of alternate tension and compression.

20. *Action of Riveted Joints under Steady, Repeated, and Alternated Loads.*—The tests indicate in a general way the behavior which may be expected in a riveted joint of a structure under various kinds of loading. Under a steady load in one direction, a slight slip may be expected under ordinary working loads, and the deformation of the structure will be greater than if it contained no riveted joints. Under ordinary loads the deformation due to slip of rivets will not be at all serious. If the joint were subjected to repeated applications of working load in the same direction, probably the deformation due to slip would increase but little after the first few applications of the load; in this case there would be a small permanent deformation of the structure, which would not be large enough to cause trouble, and which would increase but very little under successive loads. If the joint were subjected to ordinary working loads acting first in one direction and then in the other, the slip of rivets would doubtless be much greater than under a steady load or a repeated one-direction load of maximum amount equal to the maximum value of the alternated load. Under such stresses as are sometimes used in practice, this slip might increase under repetition of load, the joint working loose until the frictional hold of the rivet heads was greatly lessened and perhaps reduced to zero. Moreover, a single application of an overload, from accidental or other causes, might greatly increase this slip under succeeding working loads. The resulting deformation in the structure might become so great as to seriously impair its usefulness.

If a riveted joint in any structure be loaded beyond the yield point, the resulting deformation in the structure may be large enough to seriously injure it. If a riveted joint is stressed beyond the yield point under a long continued load, it might eventually fail, though data on this point are lacking. If a riveted joint is repeatedly stressed beyond the yield point by loads always acting in the same direction, the probability is that it would eventually fail. If a riveted joint is repeatedly stressed beyond the yield point by loads acting first in one direction and then in the other, the probability of failure would be great.

21. *The Basis for Design of Riveted Joints.*—It has been held that riveted joints should be designed on the basis that there will be no slip of plates at working loads and that the friction between the plates will be sufficient to sustain ordinary working loads and to prevent bearing stresses on the rivets. The experimental evidence of these tests, and of other tests already referred to shows that it would be futile to attempt to design riveted joints which shall have zero slip, whether the rivets be of carbon steel or of nickel steel. Slip must be expected below the ordinary working stresses, and if for any reason the assumed stresses are exceeded the slip of the joint will increase rapidly. It seems evident that with ordinary workmanship, the frictional hold of the plates is not an available asset of strength.

If the ultimate shearing strength of the rivets and the ultimate tensile strength of the plate are used as the basis of design, it will be important to know the shearing strength of the rivet material when used with the plate material of the riveted joints. The results of tests of shearing strength of rivet material which have been made in hardened steel dies are not directly applicable. If the shearing strength of rivet steel tested in connection with plates of the same degree of hardness be considered to be 0.80 of the tensile strength of the rivet material, it may be expected that with harder plates the ratio of shearing strength of rivet to tensile strength of rivet will be less, reaching three-quarters or even two-thirds; the ratio of shearing strength of rivet to tensile strength of plate will, of course, be still smaller. On the other hand, if the plate is softer than the rivet, the shearing strength of the rivet will be greater than otherwise. In designing riveted joints on the basis of ultimate strength, then, the shearing strength of the rivet material when used with the plate material of the riveted joint should be known. With the stronger plate material, such as nickel steel, the relatively low strength of rivet material is something of a handicap, though the higher the strength of the rivets the less this is.

Another basis which might be used is the yield point of the joint, the point at which a marked increase of yield in the riveted joint occurs. This point in the tests described seems to be coincident with the first marked increase of set of the riveted joint and generally also with the first marked bending of the rivets. In designing, this yield point of the riveted joint could be coordinated with the yield point of the plate material. The average yield point of the nickel-steel riveted joints was about 35 000 lb. per sq. in. of rivet section. The yield point of the nickel-steel plate material was 51 700 lb. per sq. in. The ratio of the yield point of riveted joint to ultimate shearing strength of riveted joint in both series of tests was about the same as the ratio of the yield point of the plate material in tension to the ultimate tensile strength of the plate material. A design of joint might be made giving equal strength for yield point of joint and yield point of net section of plate in tension. With this basis of design, it would be important to know more definitely the cause of the increase of the movement of the joint at the yield point. If it is mainly a distortion and shearing detrusion of the rivet, the hardness of the rivet material will be a governing consideration. If the bending of the rivet is of importance, the greater bending strength of the nickel-steel rivet will be of service. This feature of the action of riveted joints is worthy of further investigation.

The foregoing applies to riveted joints with the load applied in one direction only. For alternated loads, the first slip is of more importance, repetitions increase the movement, and an occasional overload makes still greater increase. Although the ultimate strength and the yield point do not seem to be seriously affected by a few alternations of load, it seems wise to keep the shearing stresses in riveted joints subjected to alternated loading so low that slip of joint will be small. For such conditions the advantage in the use of nickel-steel rivets is open to question especially if it is found, as has been claimed, that it is difficult to drive nickel-steel rivets in such way as to give effective grip on the plates they hold together.

22. *Summary.*—The following review is given:

1. A total of 90 nickel-steel riveted joints and of 54 chrome-nickel-steel riveted joints were tested in tension. These riveted joints duplicated in dimensions the series of carbon-steel riveted joints reported by the American Railway Engineering and Maintenance of Way Association. Sixteen nickel-steel riveted joints and sixteen chrome-nickel steel riveted joints were tested in tension, compression and alternate tension and compression. Stretch,

slip, and set of riveted joints were observed, and the bending of rivet was determined by means of holes drilled axially through the rivets.

2. In the tests there was a noticeable slip of joint generally at loads within ordinary working shearing stress of rivet. The movement of the joint increased fairly regularly to a load averaging about 35 000 lb. per sq. in. of rivet shear for the nickel-steel riveted joints, when a marked increase of movement was found. This increase was closely coincident with a marked set of the joint and with a marked bending of the rivet. All the riveted joints failed by shear of rivets, as was to be expected, at ultimate shearing stresses which ran fairly uniform in both the nickel-steel series and the chrome-nickel-steel series for all the types of joint tested.

3. The experimental evidence indicates that the resistance of the joint to first noticeable slip of rivet depends more upon the workmanship of the riveting than upon the quality of the rivet material, though the contractile and gripping properties of the rivets have an influence.*

4. The yield point of a riveted joint, taken as the load at which a marked increase of yield occurs, seemingly indicates a definite property of the riveted joint. This phenomenon is worthy of further investigation. The first marked bending of the rivets was found to be closely coincident with the yield point of the joint. It was found that the longer the rivet the greater the relative importance of the resistance to bending. In the alternate tension and compression tests the first appreciable bending of the rivet seemed to be slightly lowered by a few applications of load.

5. In the alternated load tests the most striking feature was the relatively large slip which took place at comparatively low loads. The amount of this slip was especially large when a riveted joint had been subjected to a single load considerably beyond the ordinary load.

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*To determine the effect of painting the contact surfaces of riveted joints upon the load to give first noticeable slip, a phase of the subject brought out in correspondence with Mr. Albert Kingsbury, of Pittsburgh, Pennsylvania, tests for this purpose have been made since this bulletin was put in type. Joints resembling TB5 were riveted up, one set being unpainted, one set painted with graphite paint, and one set painted with red lead. All the riveted joints showed evidence of slip at loads within ordinary working shearing stress of rivets. Those painted with graphite paint gave noticeable slip at loads somewhat lower than those painted with red lead, and the unpainted test joints slipped at loads still a little higher, the differences in the three types of test joints being not large.

6. The ultimate shearing strength of riveted joints depends on the shearing strength of rivet material, and this is influenced by the relative hardness of rivets and plates.

7. The ratio of the yield point of riveted joint to ultimate shearing strength of riveted joint in the tests was about the same as the ratio of the yield point of the plate material in tension to the ultimate tensile strength of the plate material.

8. In riveted joints designed on the basis of ultimate strength, strength of rivet material and of plate material are of prime importance and the use of special steels of great strength may be of advantage.

9. In riveted joints designed on the basis of frictional hold of rivets without reference to the bending of rivets there is little advantage in using rivets of special steels of great strength since joints with such rivets show about the same resistance to first noticeable slip as do joints with ordinary carbon-steel rivets.

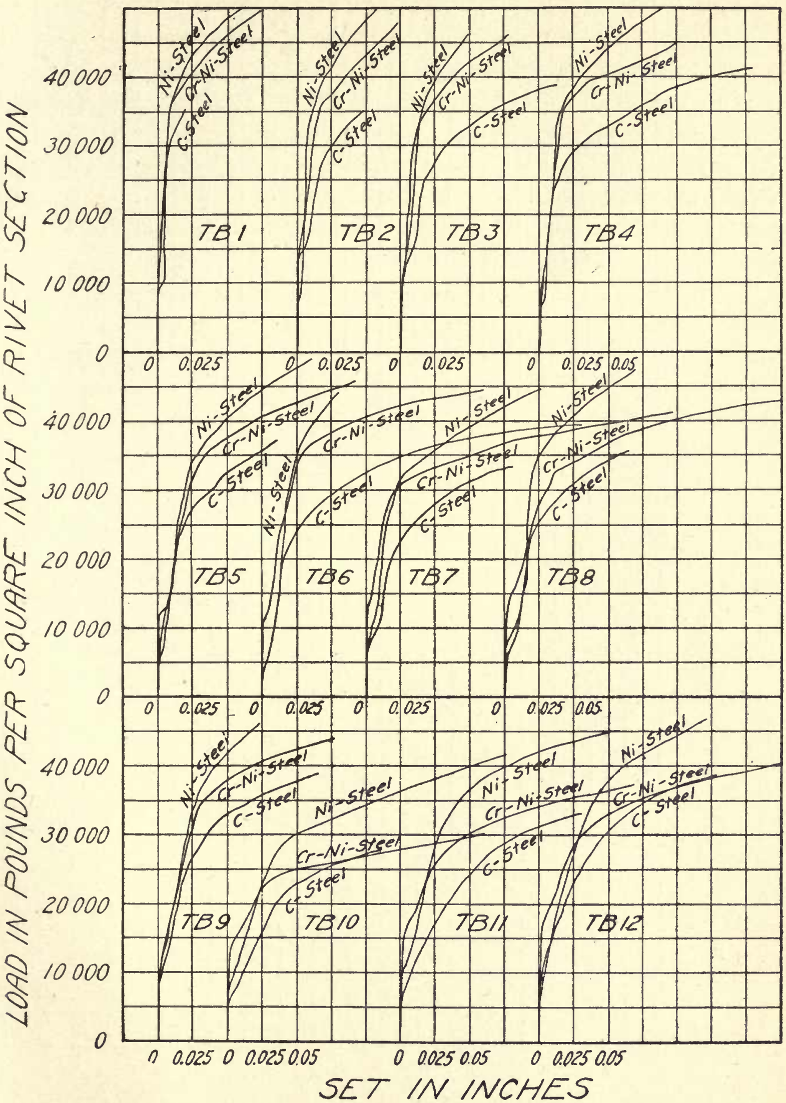

FIG. 17. DIAGRAM SHOWING PERMANENT SET IN TENSION TESTS.

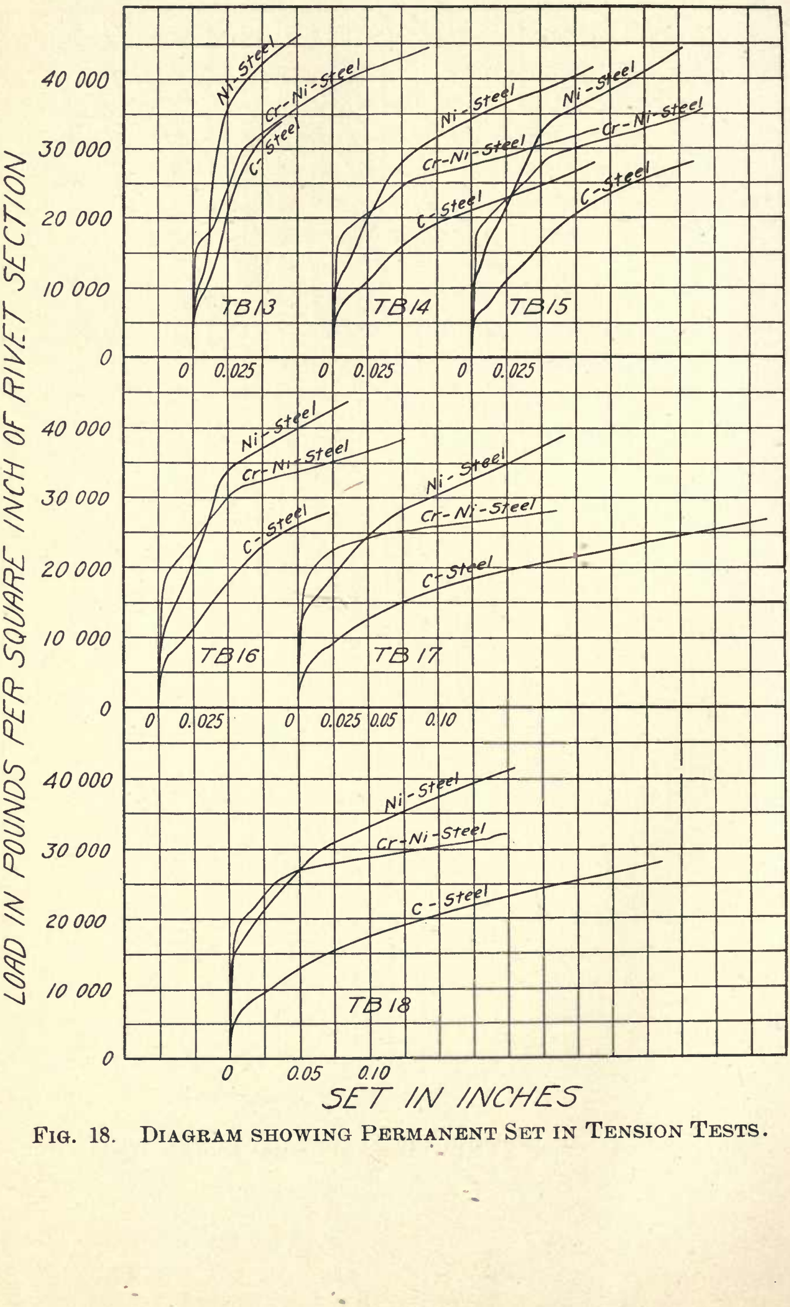

FIG. 18. DIAGRAM SHOWING PERMANENT SET IN TENSION TESTS.

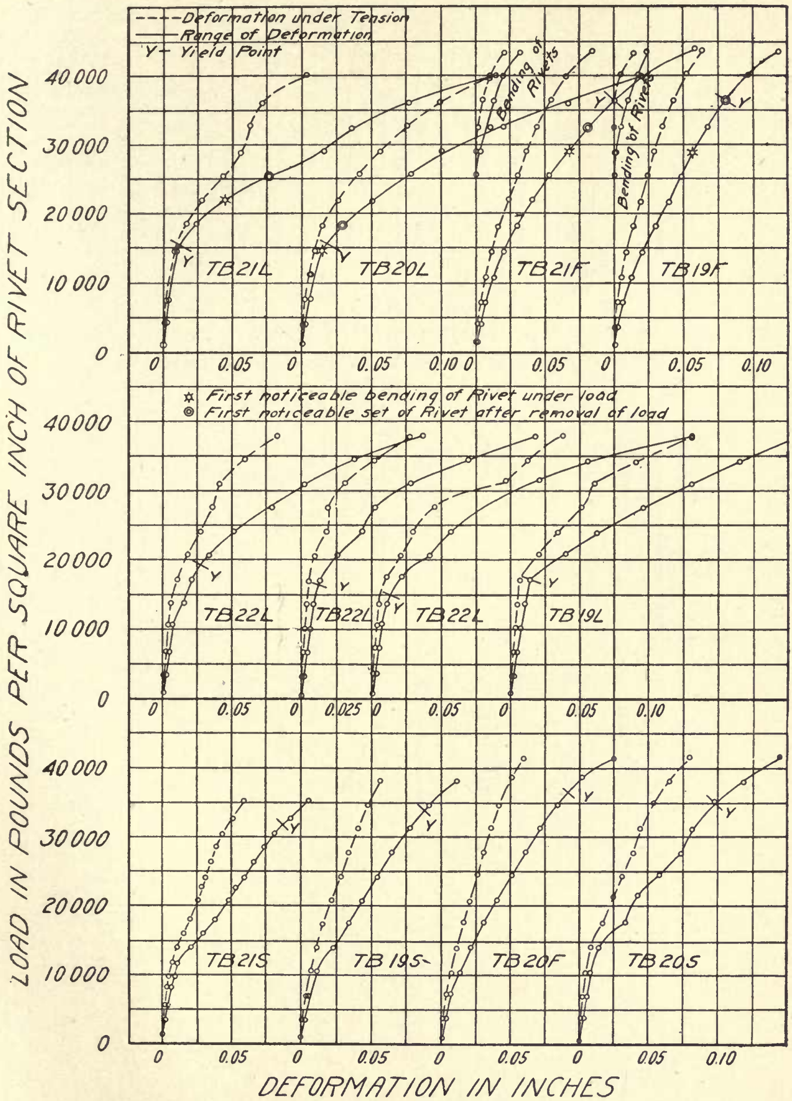

FIG. 19. DIAGRAM SHOWING DEFORMATION IN TESTS IN TENSION FOLLOWED BY EQUAL COMPRESSION.

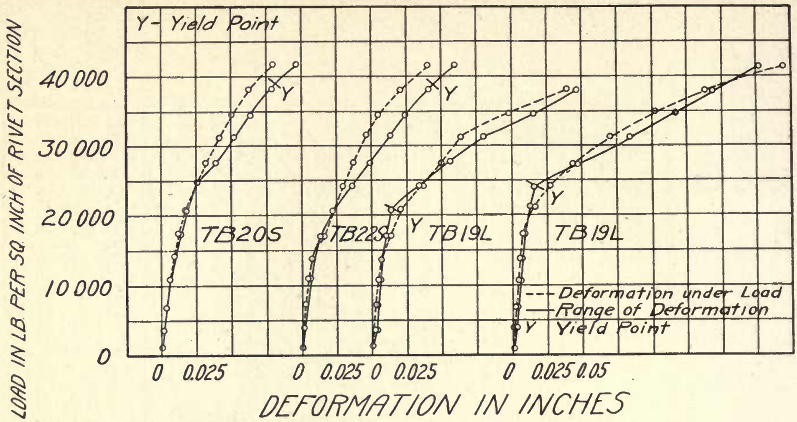

FIG. 20. DIAGRAM SHOWING DEFORMATION IN TESTS IN SIMPLE TENSION AND SIMPLE COMPRESSION OF RIVETED JOINTS DESIGNED FOR ALTERNATED LOADS.

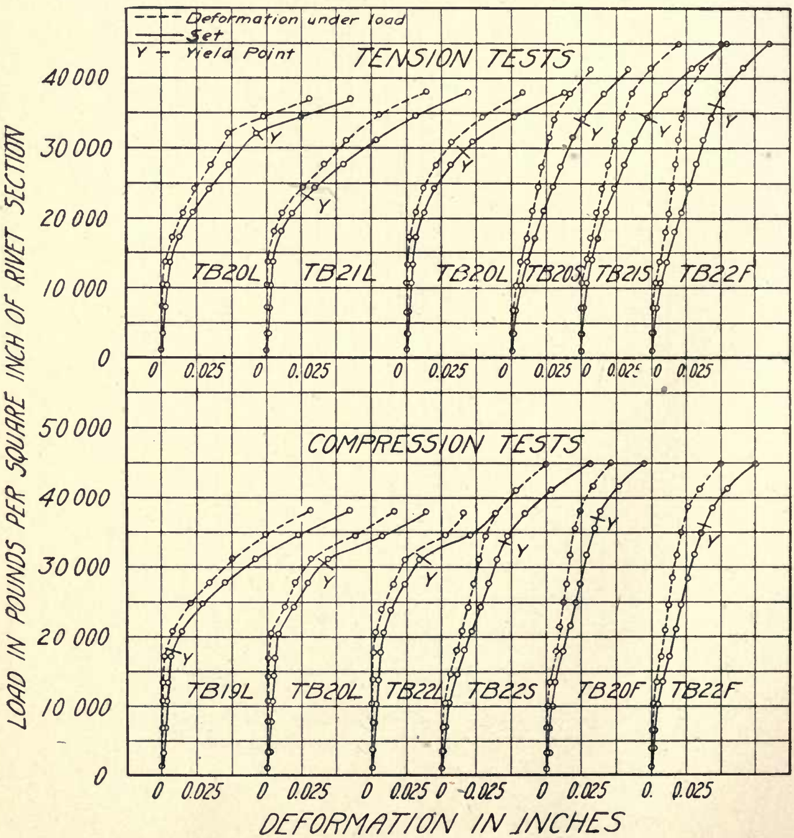

FIG. 21. DIAGRAM SHOWING DEFORMATION IN TESTS IN TENSION FOLLOWED BY HALF AS GREAT COMPRESSION.

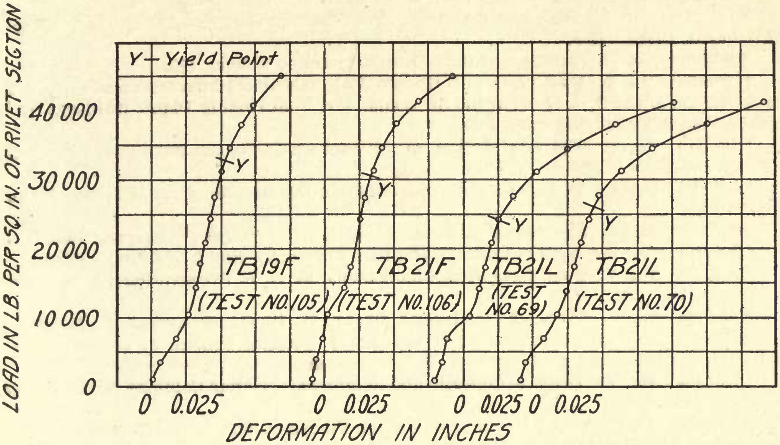

FIG. 22. DIAGRAM SHOWING DEFORMATION OF RIVETED JOINTS TESTED UNDER ALTERNATIONS OF LOW LOADS.

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