PART II.

AN EXPERIMENTAL INVESTIGATION OF THE STRAINS IN UNSYMMETRICAL RIVETED JOINTS.

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17. *Introductory.*— In this second part of the Paper an account is given of the experimental investigations which were carried out with the object of confirming, or otherwise, the view taken of the causes of the two boiler failures discussed in the foregoing pages, and of obtaining additional data as to the behaviour of unsymmetrical connections in boilers.

The work was divided into the following series of experiments :—

(a) Experiments to determine the magnitude of the extreme fibre stresses in the plates of typical lap joints, so designed as to be readily placed in a testing machine.

(b) Application of similar methods of measurement to the determination of the extreme fibre stresses in the plates of actual boilers fitted with lap joints. This enquiry was extended to include the determination of extreme fibre stresses in the vicinity of the flanged parts of a boiler.

During the course of these two series of experiments the apparatus and methods of measurement were naturally considerably improved and a final series was therefore carried out.

(c) Confirmatory tests on lap joints, on boiler drums, and on the dished ends of boilers.

The tests will be found set out in the following pages in these three series.

18. *Details of Experimental Joints.*— For the purpose of experimentally determining the magnitude of the extreme fibre stresses in the plates of typical lap joints, special joints were constructed as shewn in Fig. 16.

It will be noticed in each case that the width of one plate forming the joint was greater than that of the other plate to which it was fastened—this was necessary in order that the surface of one of the plates at least, might be available for experimental observation throughout its entire length. Of course there still remains a portion which is not get-at-able, but preliminary experiments showed that it was

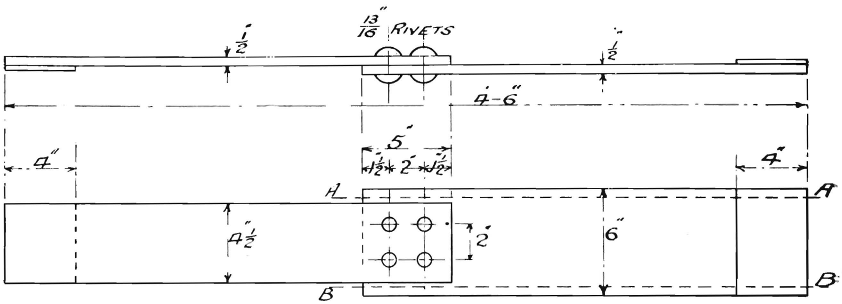


FIG. 16A. LAP JOINT WITH STRAIGHT PLATES.

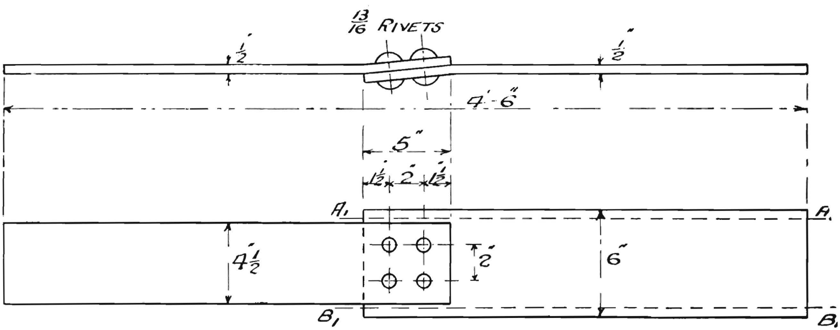


FIG. 16 B.

LAP JOINT WITH JOGGLED PLATES

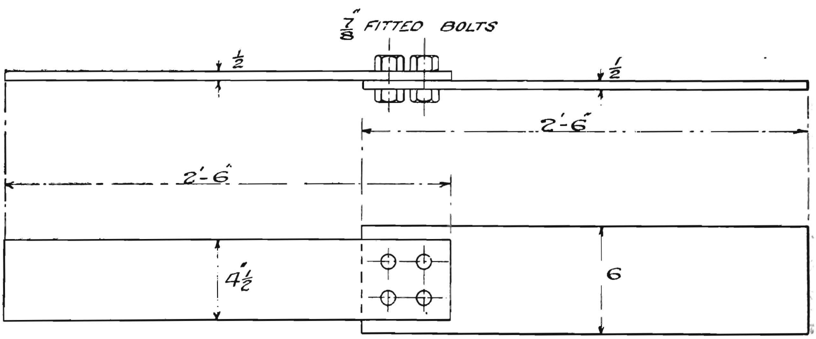


FIG. 16 C.

FIG. 16.—Experimental Lap Joints.

sufficient to determine the extreme fibre stress at a single point along a line at right angles to the direction of the applied load, as the stress is sensibly uniform in value at all points along that line. The extreme fibre stress, so determined, along any surface line such as A.A., would then represent the stress which would exist along any other parallel line upon the same surface of that plate.

In the case of the joints with straight plates, packing strips were attached at the ends of the plates, where they

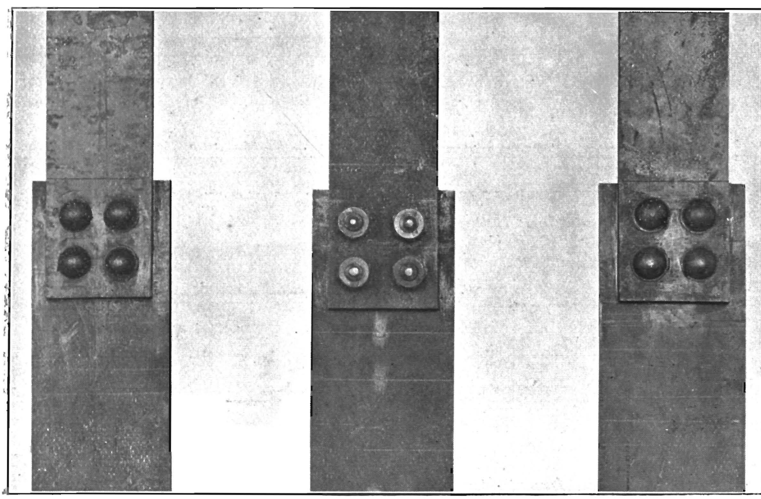
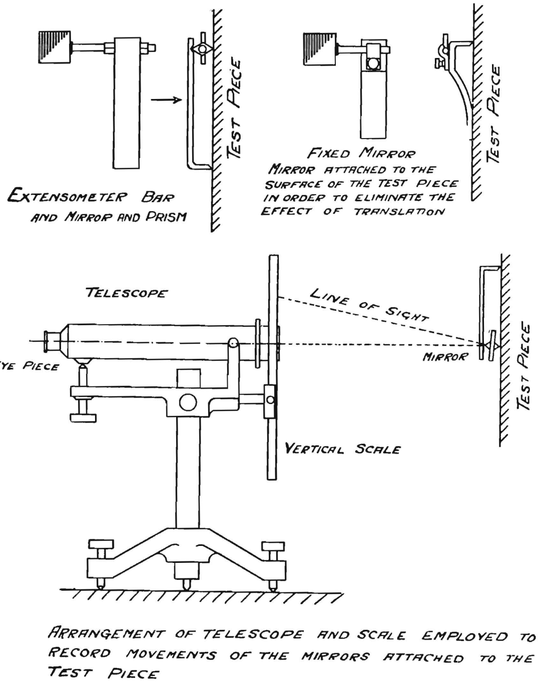


FIG 16D.—Photograph of Experimental Joints.

were gripped by the clamps of the testing machine, in order that the pull upon the joint might be more direct; later experiments, however, showed that such strips were not necessary.

For convenience the diameter and pitch of the rivets were made to correspond with the dimensions of the lap joint which failed upon the N.S.W.G. Locomotive No. 163 near Thornton, N.S. Wales, and similar dimensions were employed in the case of the lap joint with joggled plates, so that a direct comparison might be made between these two types of joint.

19. *First Method of Measurement—Martens' Mirror Extensometer.** —The magnitude of the extreme fibre stresses at any point upon the surface of the plates forming the joint, could not be obtained by any direct method, but as strains are proportional to their corresponding stresses



MARTENS MIRROR EXTENSOMETER AS ORIGINALLY EMPLOYED

FIG. 17

(within the elastic limit of the material), the determination of relative strains was sufficient.

The ordinary form of Martens' mirror extensometer was employed for the direct measurement of the extreme fibre

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* A detailed description of the construction of this form of measuring instrument may be seen by referring to the Proceedings of the Royal Society of N.S.W., Volume XXXI (1896), where its theory and application are treated in detail.

strains. The various parts of this extensometer are shown in Fig. 17 which also indicates how the reflected scale readings are observed with the aid of a telescope.

The extensometer bar is pressed with one end against the surface of the test piece, and the other against a prism which is also bearing on the test piece. A rubber band is frequently employed to press the extensometer bar against the surface of the material under test, but for these experiments a special form of clamping arrangement was devised

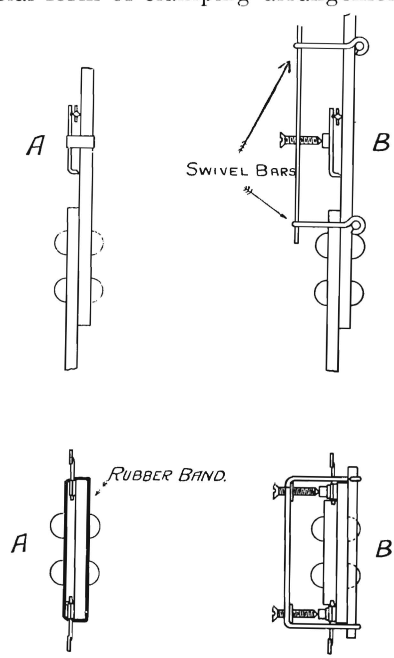

FIG. 18.—Methods of Pressing the Extensometer Against the Test Piece.

'A'—With Rubber Band (discarded in this case)
'B'—Method Actually Employed.

(see Fig. 18), as it was found that the use of a rubber band tended to produce unreliable results.

Martens' mirror extensometers are usually employed for the measurement of extreme fibre strains in test pieces which are subject only to direct loading; in this case, however, an additional complication is presented, for not only are the plates of the joint subject to direct loading, but also to the effects of a bending moment which causes the value of the extreme fibre strains to increase to a maximum in the vicinity of the joint.

When the extensometer is employed upon a test piece subject only to direct loading, the elongation of that portion of the surface between its points of contact with the extensometer bar and the prism, causes the prism, and also its attached mirror, to rotate. When the mirror is so arranged as to reflect the scale reading into the telescope, then the rotation of the mirror is observed as a difference in the "mirrored" scale reading—but, since a test piece may move bodily when subjected to a varying load, it is necessary to eliminate any translational motion from the "mirrored" scale differences obtained from the extensometer mirror, in order that its simple rotation, and hence the strain in the extreme fibre may be measured. This is effected by the attachment of an additional mirror, hereinafter termed the "fixed mirror," to a suitable spot upon the test piece, so that the variation in the mirrored scale reading caused by the motion of the test piece as a whole may be directly measured. The difference between the change of mirrored scale readings given by the extensometer mirror and by the fixed mirror is then a direct measure of the rotation of the extensometer mirror caused by the surface strain in that portion of the plate under consideration. This difference is therefore a measure of the strain.

The elimination of the effect of all movements of those portions of the plate surface carrying extensometers proved difficult, in this case, as the surface of the plate when under load suffers not only a translational movement, but also a local rotation, due to the bending of the plates of the joint. A sufficient degree of accuracy was attained in the first series of tests by placing a fixed mirror so as to give a reading, showing approximately the rotational movement of that portion of the plate upon which the prism of the extensometer was resting. Greater accuracy was obtained in the modification of the apparatus used later in the third series of tests.

FIRST SERIES OF TESTS.

20. *Test Lines.*— Experimental work was first carried out upon the joint with straight plates, and from what has been said previously, it was sufficient that the determination of the strain should be made along one line only, such as the line A.A. Fig. 16A. However, since sufficient mirrors were available, observations were taken along the two lines A.A. and B.B. in order that one set of readings might be used as a check against the other. The two lines A.A. and B.B. constitute what are hereinafter known as "test lines;" that is, they are lines on the surface of the specimen along which a sufficient number of observations was taken for the determination of the strain at all points along that line.

21. *Relative Positions of Extensometer and Fixed Mirrors.*— For the purpose of determining a suitable position for one or more fixed mirrors, so as to eliminate the effect of any general movement of the surface of the test piece upon which the extensometers were placed, a series of preliminary experiments was carried out, from which it was ascertained that the mirrored scale differences obtained from fixed mirrors situated upon any line at right angles to the line of action of the applied load, were similar under similar conditions of loading. This fact simplified matters very much, as a single fixed mirror was sufficient to eliminate the effect of the general movement of the surface under consideration from the "mirrored" scale differences obtained from two extensometers which were so arranged that a line passing through their points of contact with the surface of the specimen contained the point to which the fixed mirror was attached, and was at right angles to the direction of the applied load. (See Fig 19.)

22. *Method of Recording Observations.*— Seven series of observations were made from mirrors situated at various positions along the surface of the plates of the joint, the relative positions of both the extensometer and fixed mirrors being shown for each of the seven series of observations in Fig. 19. The prisms of the two extensometers and the point of attachment of the corresponding fixed mirror (which were together employed for a single set

of observations) were in the same straight line, which was at right angles to the direction of the applied load. The loads upon the joint varied for each set of observations, from an initial load of 0.2 tons to a maximum gross load of 3 tons, and readings of the three mirrors were taken for every increase and decrease of load by 0.2 tons, the maximum load of 3 tons being twice applied. The initial load of

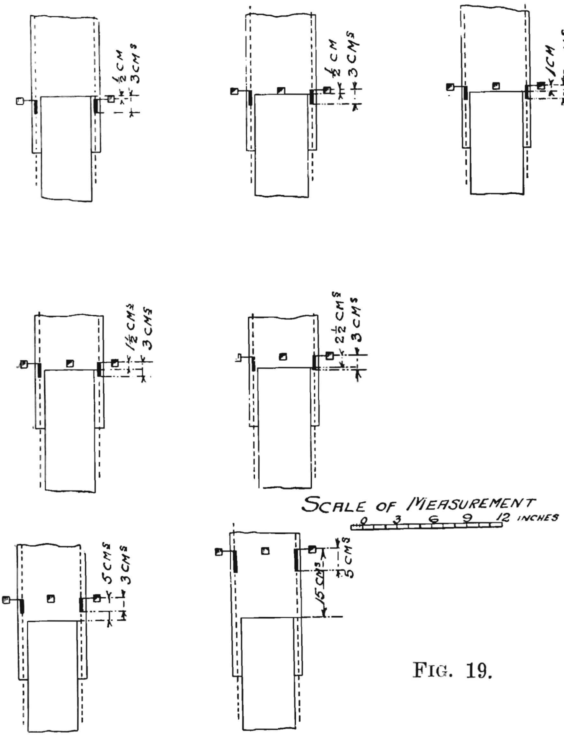

FIG. 19.

0.2 tons was necessary to retain the grip on the test piece in the clamps of the testing machine.

The "mirrored" scale differences obtained from each mirror were then plotted against the loads which caused them, and a fair curve drawn through the points so obtained. The typical treatment of the results from a single mirror is shown in Fig. 20. From the "fair" curves of observed results obtained in this way, the "mirrored" scale difference corresponding to any particular load was more accurate when thus derived than the experimental observations themselves, as by the use of such a curve small errors of observation are eliminated.

23. *Curves of Extreme Fibre Strains.*—Using the results of the seven series of observations obtained from the mirrors arranged upon the surface of the plates as shown in Fig. 19, and taking the mirrored scale difference

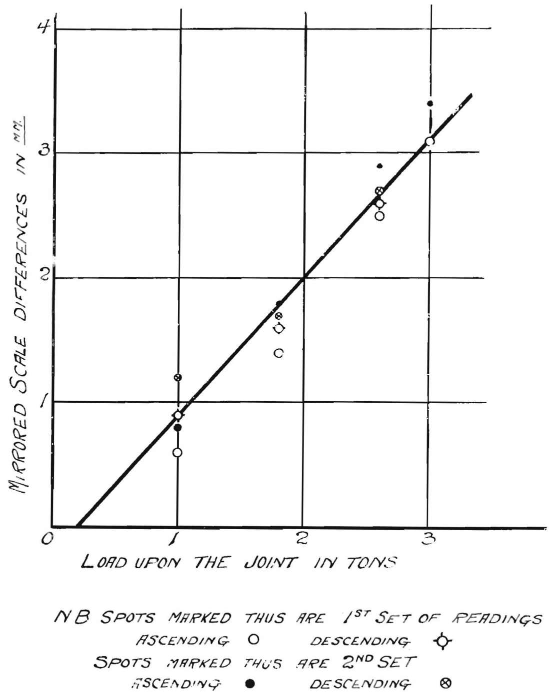

FIG. 20

that would be obtained from the fair curves of observed results for a load of three tons, the curves of strain shown in Fig. 21 have been drawn for the surface of the plate under test. These curves of strain have been obtained in the following manner:—A base line O.A. was taken, along which the relative positions of the surface points along the test line A.A. might be represented. Upon this line were drawn rectangles with their bases corresponding to the length and relative position of the extensometer bar employed, and with their heights proportional to the average strain per centimetre over a length equal to that of the extensometer bar (the strain being measured in terms of "mirrored" scale differences). The strain was reduced to represent the strain per unit of length, for by referring to Fig. 19 it may be seen that the lengths of the extensometer bars were not the same for each series of observations. A continuous curve, drawn so that the areas bounded by the

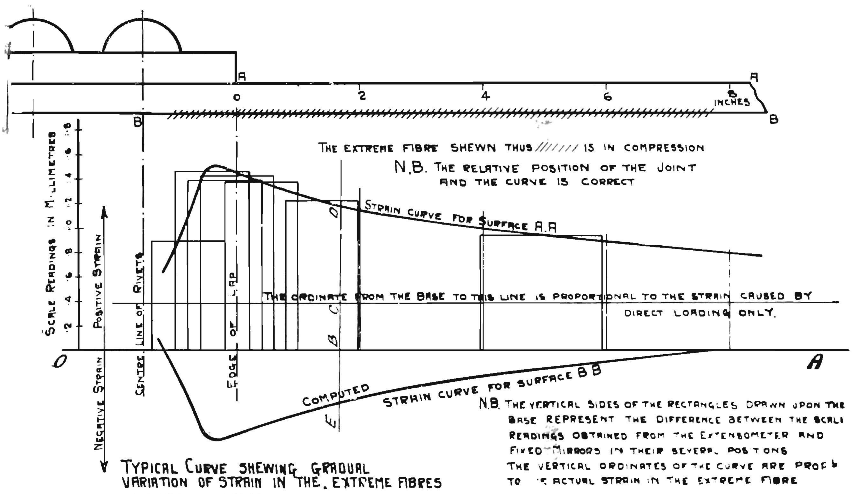

FIG. 21.—Strain Curves for Lap Joints.

curve, the sides, and the base of the rectangles, were respectively equal to the areas of the rectangles themselves, is the locus of the extremities of vertical ordinates which are proportional to the strain per centimetre in the extreme fibres of the plate, at every point along the test line A.A. produced by a gross load of 3 tons. Reference to this curve shows very clearly that the strain increases to a maximum near the edge of the landing of the joint, indicating an increase in the bending moment at that place.

24. *Significance of the Results.*—Experiment showed that the Modulus of Elasticity of the material forming the joint was 29,100,000lbs. per square inch. It is

thus possible to calculate the constant value of the "mirrored" scale differences which would have been obtained from the same extensometers placed along the line A.A. if the plates had been subjected to a direct load only of the same magnitude as that for which the strain curve has been drawn. The strain curve which would have been produced by a direct load of 3 tons is shown in Fig. 21, and is a line parallel to the base O.A. The ratio between the ordinates of these two curves, at any point, represents the number of times the extreme fibre stresses which are actually present when there is a load of 3 tons upon the joint, are increased beyond the magnitude which they would possess if the eccentric effect of the joint were absent.

The maximum value of this ratio is 3.9, and this agrees with the theoretical deduction, that the maximum extreme fibre stress in the plates of a straight plate lap joint is nearly four times what it would have been under the same load if no bending moment had existed. (See §5.).

The experimental results thus obtained indicate that this ratio is a maximum in a position which corresponds to that in which typical lap joint fractures occur.

25. *Computation of Strain Curve for Other Surface of Plate.*—Having thus obtained a measure of the strain in the extreme fibres of one surface of the plate, the computation of the strain at corresponding points upon the opposite side is readily performed, for it is known that in the case of a beam subject to a bending moment only, the algebraic sum of the extreme fibre stresses (and hence the strains) on the upper and the lower surfaces is zero; also if, in addition to being acted upon by a bending moment, a beam is subjected to a direct pull then the algebraic sum of the extreme fibre strains in the upper and lower surfaces of the beam is equal to twice the fibre strain produced by the direct load only. Hence if, through any point "B" on the horizontal axis OA, a line $EBCD$ be drawn at right angles to OA such that $BD-BE=2\ BC$, the point "E" will be a point upon the strain curve for the surface B.B. of the plate. Proceeding in this manner, the strain curve for the surface B.B. is drawn as indicated in Fig. 21.

The curve for the surface B.B. shows the existence of compressive stresses in the extreme fibres for a considerable distance along the surface of the plate; it also shows that the maximum value of the extreme fibre stress on the surface B.B. is about twice what the extreme fibre stress would have been for a direct load of the same magnitude,

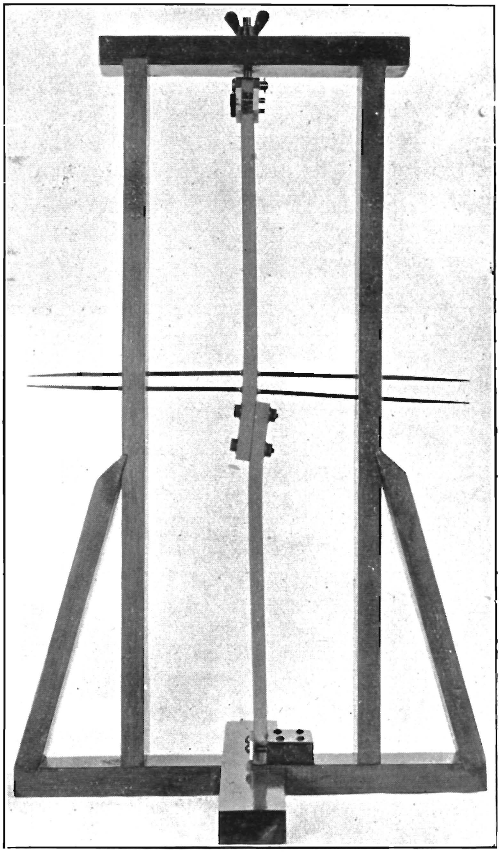

FIG. 21A.—Lap Joint made of Rubber Strips bolted together. Pointers attached to demonstrate the tension and compression.

but it is of opposite sign. A rubber model of a lap joint (see Fig. 21A) affords an interesting illustration of this action.

26. *Experiments on Lap Joint with Joggled Plates.*— Experiments were carried out upon a lap joint,