BOILER EXPLOSIONS AS AFFECTED BY UNSYMMETRICAL RIVETED JOINTS.

PART I.

TYPICAL LAP JOINT BOILER EXPLOSIONS.

By S. H. Barraclough and A. J. Gibson.

PART II.

AN EXPERIMENTAL INVESTIGATION OF THE STRAINS IN UNSYMMETRICAL RIVETED JOINTS.

By S. H. Barraclough, A. J. Gibson, H. W. May and E. P. Norman.

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PART I.

TYPICAL LAP JOINT BOILER EXPLOSIONS.

By S. H. BARRACLOUGH and A. J. GIBSON.

1. *Scope of the Paper.*—Some few years ago, the authors had occasion, in the course of their professional work, to investigate the causes of two explosions of boilers of the locomotive type. During the prosecution of these enquiries, several questions arose in regard to the actual stresses that occur in boiler shells and especially in the neighbourhood of riveted joints of unsymmetrical design, such as ordinary lap joints. In order to elucidate these matters, and to determine with some precision, what are, in fact, the maximum stresses met with in boiler shells, the authors subsequently undertook a series of investigations in the Mechanical Engineering Laboratory at the University of Sydney. These have been proceeding at intervals during the last five years, and, as some fairly definite conclusions have been come to, it seems a fitting opportunity to place a summary of them before the Members of the Engineering Association.

The paper thus naturally divides itself into two parts. In the present one is given a short account of the two boiler explosions that led up to the experimental work above referred to.* The conditions surrounding each explosion, and the technical questions to which they give rise are in themselves of considerable professional interest, and repay careful

*In carrying out these investigations the authors had the advantage of the assistance of Messrs. H. W. May, G. F. Davidson, and E. P. Norman, who were, at the time of doing the experiments, Senior Students in Mechanical Engineering, and carried on the work in their respective years under the authors' direction. Messrs. May and Norman have collaborated with us as joint authors of Part II. of the Paper.

study. In fact, so typical are the illustrations of the accidents to the two boilers that they would serve as they stand for text-book illustrations of boiler explosions due to the causes herein described.

In the second part of the Paper, a concise account is given of the more important of the questions that were the subject of definite laboratory investigation. The results will be found to in general confirm the views arrived at when reporting upon the boiler failures, and they also throw considerable light upon the unusual stresses obtaining in those parts of a boiler which are commonly treated by purely empirical methods of design, such as man-hole fittings, dished ends, etc.

2. *General description of the Thornton Locomotive Boiler Explosion.*—The first of the two boiler failures referred to occurred near Thornton, N.S.W., on December 5th, 1905, while the engine was running in ordinary service between Maitland and Newcastle. The accident occurred on a down grade when the speed of the train was approximately 40 miles an hour. All the evidence points to the fact that there was no unusual circumstance about the running of the engine prior to the accident. The boiler was carrying its normal pressure of 140 lbs. per square inch, and the safety valves were blowing freely. Subsequent to the accident, the steam gauge and the safety valves were removed from the locomotive and tested, and were all found to be correct and in good order.

The general character of the failure will be seen by reference to the accompanying illustrations (Fig. 1 and Plates I. and II.) The side plate of the furnace fractured without any warning almost along its whole length at the seam on the right hand side of the fire box, causing a large rent just under the landing of the joint. The steam escaped through the fracture and was deflected by the lagging into the cab of the locomotive, scalding the driver fatally, and the fireman very severely.* In its details the fracture shows somewhat

*Although possibly outside the immediate scope of this paper, the authors feel that they should not let the opportunity pass of recording the very courageous action of the fireman W. H. Pearce, who, although terribly injured, crawled along to the front of the locomotive and opened the brake cock, thus stopping the train.

unique characteristics. The authors have not come across any record of a fracture of such a length (about 40 inches) so straight that it might almost have been marked out with a rule, and the edges so clean as to suggest the operation of shearing rather than an explosive action. This point is of special interest when comparing the fracture in this plate with the remarkable state of affairs subsequently found to have occurred in a corresponding position on the opposite side plate of the furnace (see § 8). A reference to Fig. 1, which shows a cross section of the fractured plate, will make

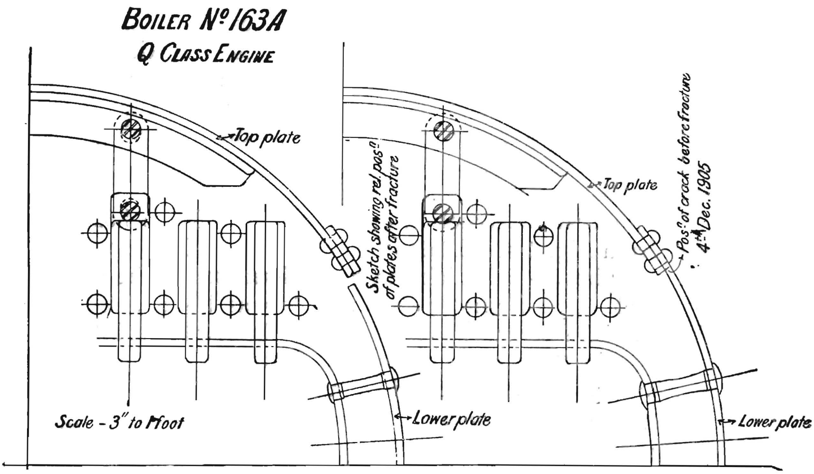

FIG. 1.

clear that the crack began on the inner surface of the outer plate just underneath the landing of the inner plate.

3. *Construction and history of the Boiler.*—The boiler under consideration (No. 163A on Engine 163 "Q" class) was one of two boilers made of iron plates constructed by Messrs. Beyer, Peacock & Co., of Manchester, England, and imported in 1890. It was put into service in June, 1891, and went without important repairs till July, 1901, at which date it had run practically 200,000 miles. It was then taken out of the engine frame and thoroughly repaired in the Eveleigh workshops, the repairs being completed in Novem-

ber, 1902.* The boiler was then allowed to stand out of the engine frame until November, 1904, when it was again fitted to Engine 163, being thus out of service three years and four months. The boiler worked ordinarily at a pressure of 140 lbs. per square inch, and before leaving the sheds in November, 1904, was tested by hydraulic pressure (warm) to 175 lbs. per square inch. It will be seen that, from the time of its thorough repair until the mishap occurred, it was in use between twelve and thirteen months, and during that time the engine had run an additional 17,000 miles. There can be little doubt but that the crack was already well developed at the time of this thorough overhaul, and the possibility of such flaws developing and escaping detection, even in the case of boilers subject to such rigid scrutiny as was the case here, emphasises the unusual difficulties that beset those responsible for the inspection of boilers having this type of riveted joint; and it should be remembered that even to-day, probably the majority of boilers possess such joints.

The general construction of the boiler and fire box can be seen from Fig. 1 and Plates I and II. The boiler was made of Lowmoor iron 9-16″ thick, its mean diameter at the crown being 4 feet. The diameter of the rivets was 13-16″, and the pitch $2\frac{3}{8}$″. The percentage strength of the riveted joint was approximately 66, and the nominal factor of safety as ordinarily computed was about five and a half.

4. *Examination of the fractured plate, and results of tests.*—The boiler was taken to the Eveleigh workshops.

*"All tubes, longitudinal stays, foundation bar and copper fire box were taken out. Sides and crown and back plate of copper fire box cleaned and straightened and new copper front plate fitted. Crown stay bars cleaned and re-fitted; new bolts and ferrules fitted on same. Bad parts of iron casing around fire box at foundation bar taken out and new pieces fitted to sides and front and back plate. New sheathing pieces fitted on top and sides of stay holes on water side on left and right-hand side of fire box and fastened with $\frac{5}{8}$-inch studs. New pieces fitted on both left and right sides of corners of throat plate, and fastened with $\frac{5}{8}$-inch studs. New foundation bar made and fitted. New throat plate brackets fitted, and new bronze stays for same, 25 $1\frac{1}{8}$in., 59 1 1-16in., and 1 1 3-16in. new copper stays fitted to fire box. Bottom of barrel sheathed on water side all along with $\frac{3}{8}$in. plate and riveted. New front iron tube plate made and fitted. Hanging links and pins cleaned and re-fitted, and new cotters for same. Longitudinal stays cleaned and re-fitted with seven new heads and two new points, and all new copper washers for same. A new steel liner fitted around fire-hole ring on water side, 5-16in. thick."

and the fractured plate removed and sent to the University where it was carefully examined as a whole, and the position and nature of the requisite test pieces decided upon. It was apparent on examining the plate in this condition that the actual fracture was not the only crack in the plate, but that there were a few other small ones which had been hidden by the lap and could not be seen by an examination of the plate in situ. The position of these cracks and groovings is shown in Fig. 2, Plate III., from which it will be seen that the main ones form a continuation of the actual fracture, and occur at the edge of the landing. To develop more fully the nature of these defects, the corners of the plate were bent over in an hydraulic press. These cracks and groovings were found to be serious defects, evidently of considerable age, and helped materially to determine the true cause of the failure. The test pieces were chosen, as shown on the diagram, Fig. 2, Plate III. They were marked off for identification and cut out at the Eveleigh workshops and tested at the University. The pieces were selected with a view to arriving at the average quality of the plate, regard being paid to the fact that near the fracture the material might show some evidence of change. The railway authorities also selected specimens adjacent to those taken by the University, their test pieces being lettered from A to H, while the University test pieces were numbered 1 to 13 (see Fig. 2 (Plate III.) and 2A). The corner pieces, marked 11 and 12 in the diagram, were taken for minute examination of the nature of the cracks and grooving developed in them.

The general results of the tests are given in the accompanying table (see Appendix I). They show the plate to be of good average quality, of normal ductility, and to exhibit no marked defect of structure. Fractures of the broken specimen show a clean fibrous structure with slight lamination, but the latter not of such a character as to render the plate unsuitable for high-class boiler construction. The plate was such that it would have been accepted for use on the results of these tests, even if it had been a new one.

The question was raised by some of the witnesses at a preliminary enquiry into the cause of the explosion, as to whether the plate had been worked into the boiler in the right direction, that is, with the grain of the material running parallel to the circumferential seams. It was suggested that if this were not the case, it might have contributed in some degree to the accident. Tests were made by means of bending and twisting a few of the specimens cut from the plate, which definitely settled this point, and showed the grain of the plate to be running in the right direction.

The tests all point to the fact that there was no original flaw or defect in the plate when it was put into the boiler. It must also be remembered that the boiler was made by a highly reputable firm, with the customary inspection and

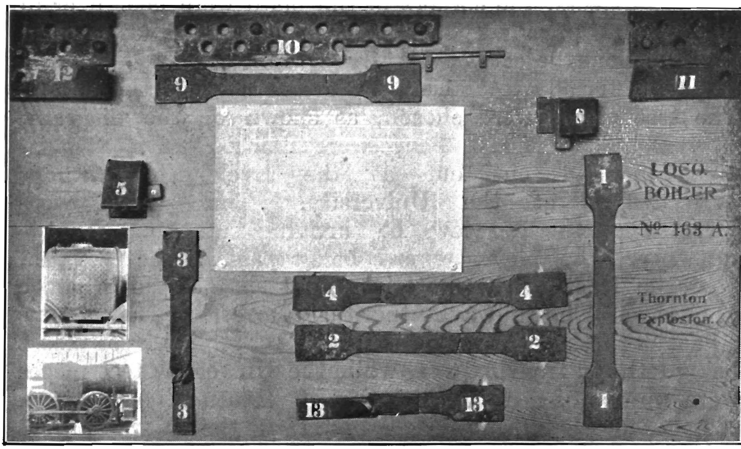

Fig. 2A—Board of Exhibits, Boiler No 163A.

good workmanship. It is, perhaps, worth pointing out that, as a matter of probability, it is extremely unlikely that in an otherwise good plate, one individual flaw of a nature to cause such an even deterioration of the plate for so great a distance, would have occurred precisely at the line marked on the inner surface of the outer side plate by the edge of the inner crown plate.

The authors came to the conclusion that the failure was entirely due to what is commonly termed "lap joint action," and further, that the essential circumstance in this action is the extremely high stress set up in the surface fibres of the metal in the neighbourhood of such riveted joints.

5. *Stresses in Lap Joints.*—It will be as well at this stage to investigate the large stresses which must occur in the plates composing a lap joint, and to make evident that the ordinary method of calculating the strength of such joints does not cover the condition of maximum stress.

For the sake of precision, consider the case of a joint occurring in two flat plates (Fig. 3), and assume that we can find places equidistant on either side of the joint where no bending exists, i.e., where we have only an axial pull. This condition of axial pull is found, for instance, in an ordinary testing machine between the two main pin connections. The method of jointing the plates cannot affect the bending moment imposed so long as the joint is rigid; we can, therefore, consider that the two plates are all one piece,* allowing for inefficiency of the joint and such disturbing factors as curvature of the plates, etc., in the final statement of stresses.

To eliminate all possibility of bending at the places where we intend to exert the pull, we should insert pin joints and pull on these with a force P (Fig. 3). Now it is obvious that the system cannot remain stationary under the influence of forces P and P. Forces Q and Q, will be called into play sufficient to balance the turning couple Pt, i.e., $Q=\frac{Pt}{l}$ and the resultant of P and Q, i.e., R will now be the pulling force, and since RR is a straight line, the joint is in equilibrium.

We can now apply the ordinary methods of finding the Bending Moment at any spot, working, of course, from points on the neutral axes (drawn in heavy lines, see Figs. 3 and 4).

$$\text{At } A \text{ the Bending Moment} = O$$
$$\text{At point } x \text{ from } A = Qx$$
$$\text{At } B = \frac{Ql}{2} \text{ (max.)}$$
$$\text{At } O = \frac{Ql}{2} - \frac{Pt}{2} = O$$
$$\text{At } C = \frac{Ql}{2} - Pt = -\frac{Pt}{2} = -\frac{Ql}{2} \text{ (max.)}$$
$$\text{At } D = Ql - Pt = O$$

*In Part II. Fig. 16C. will be seen a lap joint in which bolts are used instead of rivets. The stresses developed were almost identical with those in the riveted joints; moreover, the stresses were the same whether the bolts were just tight or "hard up."

Such a curve of Bending Moments is shown in Fig. 4.

The stress produced in the extreme fibres will depend not only on the Bending Moment, but also on the Moment of Resistance of the section; the latter is constant at all sections outside the joint, but, in the joint itself, we have twice the depth of section and, consequently, a much greater Moment of Resistance with a correspondingly diminished fibre stress. Here we see the advantage of double and triple riveting over single riveting owing to more of the region of high Bending Moment being covered by stronger sections (see Fig. 4).

The point of highest stress in any one plate will, therefore, be at the point nearest to the joint where the plate just ceases to receive assistance. We are, therefore, quite safe in saying that the Bending Moment which a single plate is called upon to bear is not greater than $\frac{1}{2}$ Pt, although with single riveting this value may be very nearly reached.

Taking the maximum of $\frac{1}{2}$ Pt the stress in the extreme fibres would then be f where

$$\frac{fI}{y} = \frac{Pt}{2} \quad or \quad f = \frac{Pt}{2} \div \frac{I}{y}$$

Assuming b to be width of plate

$$f = \frac{Pt}{2} \times \frac{\frac{t}{2}}{\frac{bt^3}{12}} = 3\frac{P}{bt}$$

per sq. inch, tension on one side, and compression on the other.

But there is already a direct pull on the plate causing a tensile stress on both sides of magnitude $F = \frac{P}{bt}$ lbs. per square inch.

The algebraic sum of these gives the actual fibre stress, viz,—

$$F \pm f = \frac{P}{bt} (1 \pm 3)$$

that is a tension of four times the direct stress on the inner side of each plate, and a compression of twice the direct stress on the outer side of each plate.

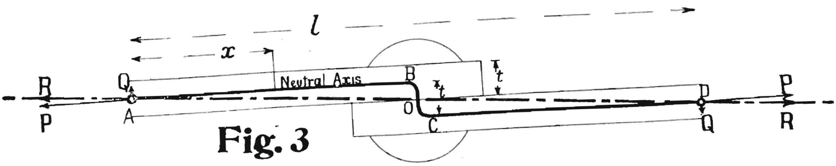

Fig. 3

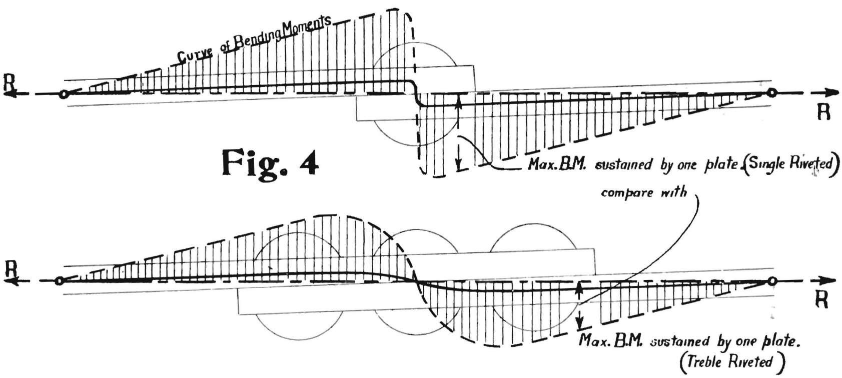

Fig. 4

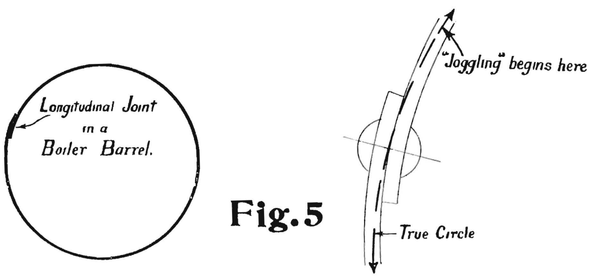

Fig. 5

Fig. 6

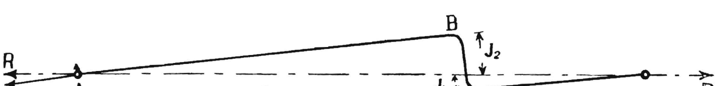

Fig. 7