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“Experiments on the Strength and Fatigue Properties of
Welded Joints in Iron and Steel.”

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(*Communicated from the National Physical Laboratory.*)

AT the suggestion of Sir John Wolfe Barry research experiments on the subject of welded joints were commenced at the National Physical Laboratory in 1908. Considerable interest in the question of the reliability of such joints had been excited by the failure of the roof of Charing Cross Station in 1906, which appeared to be due to a defective weld in the main tie; and this had some influence in determining the lines of the research. It was felt that an investigation was needed on the liability of the occurrence of an unsound joint among a fairly large number of joints made by recognized satisfactory methods. In order, therefore, that some estimate of the general reliability and efficiency of modern welding processes might be arrived at, the research had for its object a comparison of the strength and fatigue properties of welded joints in iron and steel, made by different processes and by different makers, with the corresponding properties of the unwelded material from which the joints were made.

PREVIOUS WORK.

A Paper¹ read before The Institution in 1890 by the late Sir Frederick Bramwell gives considerable information as to the efficiency attained in electrical welding by the Thomson process. In

¹ “The Application of Electricity to Welding, Stamping, and other Cognate Purposes.” *Minutes of Proceedings Inst. C.E.*, vol. cii, p. 1.

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that Paper are included the results of a series of tensile tests on a large number of joints made by the two processes of hand-welding and electric welding. In the case of fifteen electrically welded iron joints the mean maximum stress was 91·9 per cent. of that of the unwelded material, whereas for nineteen hand-welded joints of the same material the mean maximum stress was 89·3 per cent. Previous to this, three important investigations on the efficiency of welded joints in iron and steel had been carried out: (1) in 1882, by Dr. Böhme¹ at the Royal Prussian Testing Institute, Berlin; (2) in 1883, by Mr. W. Hupfeld² at Prevali, in Austria; and (3) in 1885, by Professor Bauschinger³ in the Mechanical Laboratory of the Technical High School at Munich. The comparison of the Berlin and Prevali investigations is interesting on account of the contradictory nature of the conclusions drawn from them. Thus, the conclusion drawn from the Berlin tests was that perfectly good welds were the exception, and that therefore all welding of ingot iron should be avoided; whereas the exactly opposite conclusion was arrived at from the Prevali tests, in which the welds on Bessemer steel were remarkably perfect, as regards both the tensile strength of the welded material and its elongation. This will be seen from the following Table, which gives the mean results of the investigations.

RESULTS OF TESTS MADE IN 1882 AND 1883.

Material.	Treatment.	Carbon Content.	Maximum Stress.	Elongation on 7·88 in.	Contraction of Area at Fracture.	Remarks.
		Per Cent.	Tons per Sq. In.	Per Cent.	Per Cent.	Mean of
<i>Tests made at Berlin.</i>						
Siemens-Martin steel	Unwelded	0·21	32·2	20·8	34·9	6 tests.
" " "	Welded .	0·21	18·7	3·2	4·5	9 "
" " "	Unwelded	0·11	28·8	25·1	44·7	6 "
" " "	Welded .	0·11	20·4	5·1	10·5	9 "
Wrought iron . .	Unwelded	0·05	25·8	22·2	39·5	6 "
" " . .	Welded .	0·05	21·0	7·7	14·0	9 "
<i>Tests made at Prevali in Austria.</i>						
Bessemer steel . .	Unwelded	0·21	35·1	18·8	57·5	22 "
" " . .	Welded .	0·21	34·7	19·1	55·4	27 "

¹ Verhandlungen des Vereins für Beförderung des Gewerbflusses, 1883, p. 146.² Oesterreichische Zeitschrift für Berg- und Hüttenwesen, vol. 32 (1884), p. 105.³ Mittheilungen aus dem Mechanisch-technischen Laboratorium der Kgl. tech. Hochschule in München, Pt. 12 (1885), p. 31.

A comparison of the results given in this Table shows that in the Berlin tests the tensile strength of the welded joints varied from 58 per cent. to 82 per cent. of that of the unwelded material according to the carbon content of the specimens, and that in all cases the elongation and contraction of area at fracture were a small fraction of the original value before welding. In the Prevali tests the mean tensile strength of a large number of welded joints was 99 per cent. of that of the original material, and the elongation and contraction of area were practically equal to their original values. Of the twenty-seven welded joints tested the lowest tensile strength obtained was 89 per cent. of the mean tensile strength of the unwelded materials. The reason for the abnormal weakness of the joints tested at Berlin is not easy to explain, as very little information was published on the manner in which the welds were made. All that is said is that the welds were made with extraordinary care in Messrs. Borsig's works at Moabit and by the same experienced workman, under as far as possible the same conditions, but taking into consideration the most suitable degree of heating for each kind of iron as already determined from preliminary tests.

In Mr. Hupfeld's opinion the unsatisfactory behaviour of the joints at Berlin was due to insufficient practical experience on the part of the smiths who prepared the samples.

On the other hand, the high efficiency obtained in the Prevali tests is equally remarkable, not so much with respect to the high percentage of tensile strength obtained, but as to the elongation and contraction of area at fracture, which were practically equal to those of the original material.

In these tests it is stated that "fracture (of the welded joints) was always accompanied by a very considerable local contraction with a convex head corresponding to a deep cavity in the other part. The external appearance of the unwelded and welded bars was the same both before and after fracture. It was not possible to observe weld-seams either before or during testing, not even at the fractured surface, which never had a crystalline appearance but a dull velvety grey aspect."

These characteristics are in marked contrast with those observed in normal testing practice, in which, although a high percentage of strength can usually be obtained, the elongation and contraction of area at fracture are invariably considerably less than for the unwelded material. As an instance of this it may be mentioned that in the present work an elongation of over 90 per cent. of that of the original material has been extremely rare, and this was also the experience of Professor Bauschinger, who carried out an

elaborate series of tests at the Technical High School in Munich to discover the most satisfactory method of welding mild steel. There can be no doubt, however, that the large amount of mechanical work put on the joints after welding at Prevali is largely responsible for the high efficiency obtained, as it is stated that the original dimensions of the welded bars were $1\frac{3}{8}$ inch by $1\frac{3}{8}$ inch, and that after welding they were reheated and forged down (presumably under a steam-hammer) to less than $\frac{3}{4}$ inch by $\frac{3}{4}$ inch. It is therefore hardly fair to compare results obtained with this treatment with tests made on joints in which the original area of the bars is the same as that of the finished weld, but even allowing for such an improvement due to mechanical working the results of the Prevali tests are still remarkably good.

Professor Bauschinger's experiments were made with the object of determining the possibility of producing a welded joint in mild-steel bars, which should be as reliable as one made from the best wrought iron. He accordingly undertook a careful experimental study of the effect of the strength of the fire, the nature of the flux, and the rapidity and extent of the mechanical working, on the strength and elongation properties of welded joints in both wrought iron and mild steel. Professor Bauschinger's conclusions were that joints in mild steel could be made as reliable as joints in wrought iron if the conditions laid down by him were carefully observed.¹

MATERIALS USED.

In accordance with the objects of the research, and to obtain material for the work, a circular letter was sent from the laboratory to various engineers in England inviting them to submit specimens of welded joints for testing. Sixteen firms responded to this invitation, and the total number of welded joints received was 167.

The method of welding and treatment of the specimens was left

¹ For the welding of mild steel, in addition to keeping the welding heat moderate (i.e., at the transition from bright red to incandescence—at the very most at the commencement of incandescence), there is another rule to be followed, namely, a good fire, so that it is not necessary for the pieces to remain long in it, and strong blows in rapid succession, that is to say, rapid working during the actual operation of welding, in order that the pieces, which are not so hot to start with as are wrought-iron pieces, do not become too cold. The more these directions are followed the more certainly will the mild steel welds attain the same quality as those of wrought iron. (Mittheilungen aus dem Mech.-tech. Laboratorium der Kgl. techn. Hochschule in München, Pt. 12, p. 35.)

entirely to the makers, the only condition being the important one suggested by a comparison of the Berlin and Prevali tests, namely, that all specimens should be made from bars $1\frac{1}{4}$ inch in diameter.¹ The makers were asked to supply information as to the method of welding and the subsequent treatment of the joints.

The details of the material submitted and the methods employed are as follows :—

Maker A.

Ten joints of wrought iron, hand-welded.

” ” ” ” ” electrically welded.

” ” ” mild steel, hand-welded.

” ” ” ” ” electrically welded.

Unwelded material to correspond.

Note by Maker.—The hand-welded iron and steel bars were scarfed after slightly thickening up the ends, heated in a blacksmith's coke fire and welded. No flux was used, except a little shore sand sprinkled on the bars. None of these samples were annealed in any way after rolling or welding.

The electric welding was done by the Thomson system. When the metal has reached the welding temperature, the hand feed comes into operation, forcing the bars together as the heat increases; this causes an enlarged diameter, or irregular area; it is then withdrawn from the machine, and hammered to its proper form under a small steam-hammer. The weld is of the butt type and has proved very satisfactory, especially iron to iron, hard steel not being so satisfactory, on account of local wasting during the process.

Maker B.

Four joints from A quality steel bloom (Carbon, trace).

” ” ” B ” ” ” (Carbon 0·22 per cent.).

” ” ” C ” ” ” (Carbon 0·57 ”).

” ” of $1\frac{1}{2}$ -inch chain-iron.

” pieces of untreated material to correspond.

All these joints were made from material $1\frac{1}{2}$ inch in diameter, and then turned down to $1\frac{1}{4}$ inch diameter.

Note by Maker.—The rod-ends were all prepared by scarfing before welding. The A and B steels were welded without flux, but with the C quality a small quantity of silver sand was used.

¹ It will be seen from the detailed statement of the material submitted that in the case of Maker B this condition was not complied with.

Maker C.

Six hand-welded rivet steel bars (Carbon 0·006 per cent.).

„ electrically welded rivet steel bars (Carbon 0·006 per cent.).

Unwelded material to correspond.

Note by Maker.—The hand-welding is done at either a coal or a coke fire, the ends of the pieces to be welded having been first scarfed. The welded piece is afterwards annealed in an annealing furnace.

The electric welding is effected by the Thomson resistance method, the weld being thoroughly hammered under a power-hammer. The piece being welded is always put back into the machine a second time and heated again to welding heat. The weld is afterwards jumped up by end pressure and again hammered down. The welded pieces then undergo the same annealing operation as in the case of welds made by hand. This, of course, is to reduce the large structure of the steel due to the high temperature of welding.

We consider the electrical method of welding superior, as the temperature is entirely under control, and there is less oxidation and no possibility of foreign matter getting between the surfaces of the weld.

Maker D.

Six hand-welded joints of wrought iron.

„ „ „ „ mild steel (Carbon 0·217 per cent.).

Unwelded material to correspond.

Note by Maker.—The bars were cut in the middle, and the ends to be welded were made hot and scarfed for about 2 inches. These scarfed ends were then raised in a smith's fire to a welding-heat, placed together and hammered until the welding was complete. They were then reheated to a “wash heat,”¹ hammered a second time, and the bars finally worked in semi-circular tools. They were then heated to 850° C., packed in ashes, and allowed to cool slowly. No flux was used, although in the case of welding larger pieces a little sand is sprinkled over the portions to be welded together in order to flux the scale.

Maker E.

Three hand-welded joints of wrought iron.

„ „ „ „ mild steel bar (Carbon 0·171 per cent.).

Unwelded material to correspond.

Note by Maker.—The steel bars were annealed for 2 hours at approximately 730° C. after completing the joint.

¹ A term used by blacksmiths to denote the next stage above white heat.

Maker F.

Six hand-welded joints of wrought iron.

" " " " steel (Carbon 0·175 per cent.).

Unwelded material to correspond.

Note by Maker.—The two pieces of material it was proposed to weld were selected at random from our works' stock, and heated in a common smith's fire, scarfed and slightly staved at the ends. They were then reheated to a white heat, and the two pieces welded into one by hand-hammering, after which the finished specimen was annealed by heating it to a red heat and leaving it to cool slowly.

Maker G.

Three hand-welded joints of wrought iron.

" " " " steel (Carbon 0·222 per cent.).

Unwelded material to correspond.

Note by Maker.—These welds were ordinary scarf welds made in the usual way by a blacksmith.

Maker H.

Six hand-welded joints of steel (Carbon 0·204 per cent.).

Unwelded material to correspond.

Note by Maker.—These joints were all made by a competent smith and were carefully inspected after welding. In our opinion such welded joints are uncertain, as there is no means of determining absolutely whether the joint is perfect or not. In our own practice we permit no welding of steel whatever in engine-work.

Maker J.

Six hand-welded joints of wrought iron.

Unwelded material to correspond.

Note by Maker.—The welds were made in the ordinary manner by scarfing the two ends, and heating them in an ordinary smith's fire with gas coke; the operation was performed by a smith and one mate, the weld being made on the anvil.

Maker K.

Six electrically welded joints of mild steel (Carbon 0·056 per cent.).

Unwelded material to correspond.

Note by Maker.—We made these joints on our Standard No. 7 welder as nearly as possible under ordinary manufacturing conditions without special preparations, i.e., the bars were sheared off (not turned or sawn), the ends were left unprepared, and the rust covering the bars was not cleaned off.

Maker L.

Five acetylene-welded joints of wrought iron.

Unwelded material to correspond.

Note by Maker.—The samples were welded with a mild-steel wire employed as a feeder for the additional metal required. The specimens were slightly hammered after welding, and were subsequently annealed.

Comparatively heavy welding of this description is not the class of work on which the oxy-acetylene process shows up best. Our own view is that $1\frac{1}{4}$ -inch bar welding favours the electric and ordinary forge-welding processes, whilst work on sections up to $\frac{1}{2}$ inch would show oxy-acetylene welding at its best.

Maker M.

Six acetylene-welded joints of steel (Carbon 0·207 per cent.).

Unwelded material to correspond.

Maker N.

Six hand-welded joints of wrought iron.

” ” ” ” steel (Carbon 0·158 per cent.).

Unwelded material to correspond.

Note by Maker.—Each piece was heated and stamped at one end to get the proper amount of material required for welding. The pieces were then scarfed to an angle of about 30° ready for welding, and were heated in an ordinary smith's fire using smithy charcoal as fuel. The welding was done under a 7-cwt. steam hammer, and the welded part was at first formed square and then finished round to the required size. All the welded pieces were then heated in a furnace to a temperature of about 900° C. and allowed to cool in the atmosphere.

Maker O.

Six hand-welded joints of best chain-iron.

Two electrically welded joints of best chain-iron.

Unwelded material to correspond.

Maker P.

Three hand-welded joints of Yorkshire wrought iron.

” ” ” ” Staffordshire wrought iron.

Unwelded material to correspond.

Maker Q.

Six hand-welded joints of wrought iron.

Unwelded material to correspond.

NATURE OF THE TESTS TO WHICH THE JOINTS WERE SUBJECTED.

The joints were subjected to a tensile test, and in the majority of cases to a fatigue test. The former included the determination of the elastic limit by means of the Ewing extensometer, the yield-point determined by the drop of the beam of the testing-machine, the maximum stress, the total elongation of an 8-inch length, including the weld, the local extension near the fracture, and the general extension outside the region of the weld. No attempt was made to determine the contraction of area at fracture, as this quantity is almost impossible to measure with any degree of accuracy in any welded specimens which break at the weld, owing to the unequal drawing out of the material at opposite sides of the fracture and also the occasional splitting of the specimen. For this reason it was considered that the measurement of the local extension near the fracture would be a much better indication of the satisfactory character of the weld.

In the determination of this general and local extension the method adopted was that of Dr. Unwin,¹ President Inst. C.E., which is as follows:—The total elongation e for bars of the same material and cross section is given by

$$e = a + b l,$$

where l is the length of the specimen, and a and b are constants. The first term on the right is the local and the second term the general extension. To determine these values the total length of the specimen (*Fig. 1*) was divided up into 1-inch lengths by means of centre dots. After the fracture of the specimen the distances

Fig. 1.

between these dots were carefully measured and plotted as in *Fig. 2*. The resulting curve is seen to consist of two parallel branches connected by an S curve, and it will be evident from the equation that the vertical distance between the two parallel branches is the local extension. This curve was plotted for all the specimens tested and the results were tabulated.

As regards the nature of the fatigue test to be employed, some method whereby the specimen could have been subjected to reversals

¹ W. C. Unwin, "Testing of Materials of Construction," 3rd ed., p. 96. London, 1910. Also Minutes of Proceedings Inst. C.E., vol. clv, p. 178.

of direct stress from tension to compression would have been preferable, but as the machine working on this method at the National Physical Laboratory was only capable of testing specimens up to a diameter of $\frac{3}{8}$ inch, it was not considered advisable to reduce the welded joints to such an extent, and finally recourse was had to the well-known alternate-bending method of Wöhler, in which one end of the specimen is fixed in a revolving chuck and the other end carries a loaded bearing. A consideration of the ordinary working of machines on this method soon demonstrated, however, that, with the number of tests required for the present purpose, the time required for their completion would be very considerable, and therefore some more rapid means of making the tests than those usually employed was essential. Some preliminary experiments were accordingly made to test the possibility of using Wöhler's

Fig. 2.

method at speeds of the order of 2,000 alternations per minute. For this purpose the chuck-spindle was connected directly to an electric motor running at 2,200 revolutions per minute, and the hanger carrying the load was attached to a ball-bearing at the end of the specimen; to prevent vibration at this high speed the spindle of the hanger was extended and provided with a piston working in an oil dash-pot. After some modifications this arrangement was found to work quite satisfactorily, and there only remained the investigation of the effects of the high speed on the fatigue strength of the specimens, in order to bring the results into line with those of previous experimenters. The effect of this speed of alternation on fatigue strength was expected to be considerable from a study of Messrs. Reynolds and Smith's experiments, since these authors, working with a steam-engine mechanism for producing alternations of direct stress, found that in mild steel at 2,000 reversals¹ per minute, the range of stress necessary to produce fracture after one million

¹ As to the sense in which "reversals" is used in this Paper, see the Authors' reply to the Correspondence, *post*, p. 76.—SEC. INST. C.E.

reversals was only 55 per cent. of the corresponding stress when the number of reversals was one hundred per minute.

To investigate this effect for the present work the motor and chuck-spindle were disconnected, and the latter was driven through a countershaft, reducing the speed of rotation to 200 revolutions per minute. As the results of the first experiments at the low speed showed no appreciable divergence from those obtained at the high speed, the matter was gone into carefully in the case of three materials, a moderately high-carbon spindle-steel, an axle-steel of average quality and a Swedish iron. The following Table gives the results on these materials at the high and low speeds:—

EFFECT OF SPEED OF ALTERNATION.

Material.	Reversals Per Minute.	Range of Stress.	Number of Re- versals for Fracture.
		Tons per Sq. Inch.	
Spindle-steel	2,200	48·1	235,000
" " 	2,200	46·6	1,415,450
" " 	2,200	43·2	{ 3,071,600
" " 	200	46·8	{ (not broken)
" " 	200	46·0	553,000
			849,000
Axle-steel	2,200	36·3	2,028,000
" " 	2,200	34·2	{ 4,953,000
" " 	200	36·3	{ (not broken)
" " 	200	35·6	996,000
			1,961,900
Swedish iron	2,200	23·3	582,000
" " 	2,200	21·6	1,610,000
" " 	200	22·4	1,446,300

From an examination of these results it will be seen that there is no evidence at all of any reduction in fatigue strength due to the high rate of alternation of stress. In view of other corroborations of these experiments which have been published recently, it seems probable that the reduction in fatigue strength noted by Messrs. Reynolds and Smith as due to high rate of alternations is a characteristic of the particular mechanism used for their experiments.

On the conclusion of this investigation it was considered that the high-speed method described was quite satisfactory; and a larger machine, capable of testing specimens up to $1\frac{1}{4}$ inch in diameter, was designed and constructed in the workshop. The general arrangement of this machine is shown in *Figs. 3*, and the details of the chuck and dash-pot in *Figs. 4*.

Figs. 3.

was experienced in ensuring that the section at which the stress

Figs. 4.

DETAIL OF LOADING-APPARATUS.

was a maximum should always be a section of the weld. In the case of the hand-welded specimens of iron and steel and the electrically welded iron specimens, the position of the weld was easily found on taking a light cut over the specimen in the lathe, but with the electrically-welded steel bars it was difficult to discover, as the distortion of the structure at the joint was not easy to detect. It is believed, however, that in all the specimens tested the position of the weld was accurately determined. In the preparation of the specimens, the position of the weld having been marked, the machining was done (*Fig. 5*) so that the shoulder of the specimen should coincide with the centre of the weld.

In carrying out these fatigue tests the main object was, of course, to determine as quickly and accurately as possible the maximum range of stress which the joints would bear indefinitely without fracture. In the case of specimens under reversals of direct stress from tension to compression, the determination is more rapidly performed than in the case of specimens subject to alternate bending, in which only the outer fibres are subject to the maximum stress and consequently the fatigue of the material proceeds much more slowly. As an illustration of this, it may be assumed in nearly all cases that, if a specimen under reversals of direct stress bears without fracture a million reversals, the range of stress to which it is subject is below the limiting or safe range. This assumption cannot be made for specimens under alternate bending stresses, as it frequently happens that a specimen which has safely borne two or three million reversals will eventually break after five, ten, or twenty million additional repetitions. An example of this will be seen in the following record of a test of a welded joint:—

Materials.	Reversals per Minute.	Range of Stress.	Total Reversals.	Remarks.
	No.	Tons per Square Inch.	No.	
Hand-welded iron	2,200	19·64	1,000,000	{ Slight crack, visible on outer surface. Crack slightly longer. Specimen broken.
„ „	2,200	19·64	3,000,000	
„ „	2,200	19·64	5,616,000	

It was clear, therefore, that unless some method could be devised for approaching the limiting range more rapidly than is here apparent, very few fatigue tests could be made. After some

consideration the device was adopted of boring the specimen in the manner shown in *Fig. 5* so that the material tested was in the form of a hollow cylinder. It was found that by doing this, the limiting range was much more rapidly approached, and in all the remaining tests the inner core of metal was removed in this way. The Authors fully realize that objections may be raised to the application of this method to a welded bar, but in reply to these it may be urged that the main object of the tests was comparative, and this condition was fully met by the fact that all the specimens were all of precisely the same dimensions, and also that any lack of precision in the determination of the fatigue strength of the whole joint is compensated for by the rapidity with which the work can be carried out. Another feature in the present experiments which involved some difficulty was the prediction of the limiting range of stress for fracture after an unlimited number

Fig. 5.

TEST-SPECIMEN.

of reversals from a test on a single specimen which had broken after a moderate number of reversals. The method adopted was to make a considerable number of experiments, at different ranges of stress, on a material whose strength properties did not vary greatly from those of the material of which only one specimen was available. The plotting of these results gave a standard curve, and in order to predict the limiting range of stress required for a single specimen it was assumed that the ratio of this range to the experimentally determined range of the standard material was the same as the ratio at the corresponding number of reversals at which the single specimen had broken. Fortunately, in the case of the present experiments the materials—both iron and steel—were so much alike in their fatigue properties that a single standard curve was sufficient for all the tests. This is shown in *Fig. 6*. The results of the experiments made for the purpose of plotting the standard curve are given in Table III of the Appendix.

RESULTS OF THE TESTS.

The results of the tensile tests and the reductions from these are given in Table I of the Appendix, and the results of the fatigue tests in Table II. For purposes of rapid comparison a diagram-

matic view of the results has been plotted in *Fig. 7*, the quantities shown being the three chief characteristics of the joints, namely:—

(1) The tensile strength of each joint expressed as a percentage of that of the original material.

(2) The local elongation obtained by Dr. Unwin's method, expressed as a percentage of that in the original material.

(3) The fatigue strength of the hollow specimens prepared from the curve in *Fig. 6*, and also expressed as a percentage of the fatigue strength of a specimen of the original material.

From an inspection of *Fig. 7*, there can be no doubt, in the Authors' opinion, that the approximation of the material in the weld to the precise condition of the original material is best shown by the percentage of local elongation attained. High values of this

Fig. 6.

STANDARD CURVE FOR PREDICTION OF FATIGUE STRENGTH.

percentage have been very uncommon throughout the work, as there were only six cases (four in iron and two in steel) in which, although the specimen undoubtedly broke at the weld, the strength and local elongation, as well as the appearance of the fracture, were fully as good as the corresponding characteristics of the original material. In the majority of cases of welds, however, it appears that, as pointed out by Professor Bauschinger,¹ the material in the region of the weld is in quite a different condition from that of the original material, and this may be the case even when annealing has taken

¹ By the operation of welding the material becomes non-uniform, harder and more brittle in the region of the weld. . . . The contraction of area is therefore always smaller in such fractures than in the case of unwelded material, and this applies equally to wrought iron and mild steel.—(Mittheilungen aus dem Lab. der Kgl. tech. Hochschule in München, Pt. 12, p. 36.)

PROPERTIES OF WELDED JOINTS IN TERMS OF THOSE OF THE ORIGINAL MATERIAL.

(NOTE.—In the three cases indicated thus * the ordinary visual evidence of welding was not apparent before or after the test.)

place after welding. On the other hand, it may be pointed out that the fact of the local elongation of a welded joint being considerably below that of the original material does not necessarily imply that the weld is in a dangerously brittle condition: this is shown by the results of the fatigue experiments on the steel joints of maker A, in which the endurance of the welded specimens was nearly equal to that of the original material, whereas the local extension was in nearly all cases extremely small. It appears, therefore, that the characteristic non-uniformity (*Ungleichartigkeit*) of the material in the region of a welded joint, referred to by Professor Bauschinger, and which is indicated by the smaller reduction of area at fracture, is not fatal to the resistance of the joint to alternations of stress many times repeated; and this is the most important evidence afforded by the fatigue tests, a definite failure having in all cases been traced to a place in the joint where actual welding has not taken place. As regards the tensile strength of the welds, the mean results of the tests, expressed as a percentage of the tensile strength of the material from which the welds were made, together with those obtained by other experimenters, are given in the following Table:—

TENSILE STRENGTH: PER CENT.

Berlin Tests.		Prevall Tests.	Sir Frederick Bramwell's Tests.		National Physical Laboratory Tests.				Mr. Kirkaldy's Tests. ¹			
Hand-welded Iron.	Hand-welded Steel.	Hand-welded Steel.	Hand-welded Iron.	Electrically-welded Iron.	Hand-welded Iron.	Hand-welded Steel.	Electrically-welded Iron.	Electrically-welded Steel.	Hand-welded Iron.	Electrically-welded Iron.	Hand-welded Steel.	Electrically-welded Steel.
Mean of 9 Tests.	Mean of 18 Tests.	Mean of 27 Tests.	Mean of 19 Tests.	Mean of 15 Tests.	Mean of 24 Tests.	Mean of 21 Tests.	Mean of 7 Tests.	Mean of 8 Tests.	Mean of 30 Tests.	Mean of 150 Tests.	Mean of 20 Tests.	Mean of 60 Tests.
81	65	99	89·3	91·9	89·3	81·6	89·2	93·4	84·3	85·7	75·7	80·8

In comparing the figures in this Table it must, of course, be borne in mind that the National Physical Laboratory mean results are from specimens by different makers, which is not the case in the other investigations. Thus the mean result for electrically-welded iron in the N.P.L. tests is below that attained in Sir Frederick Bramwell's tests, but a reference to Table I will show that in the case of several makers the results were above this value.

¹ These results, which are the means of those handed in by Mr. Kirkaldy (see *post*, p. 42), were added after the reading of the Paper.—T. F. S.

If a percentage strength of less than 70 per cent. be taken as evidence of a bad weld, the results show that the number of bad welds was 5 in 21 hand-welded steel joints, 2 in 24 hand-welded iron tests, 1 in 8 electrically-welded steel joints, and 0 in 7 electrically-welded iron joints. It would appear, therefore, that even at the present time the hand-welding of mild steel has not been brought to the same state of perfection as that of wrought iron.

As regards the acetylene-welded joints, which were supplied by two makers, in no case does it appear that a joint was made which could be looked upon as equally as good as one made by the hand-welding or electric-welding process.

With reference to the respective merits of hand- and electrical-welding, the tests show, as would be expected, that more uniform results are obtained by the electrical method, although the number of tests made is not sufficient to point to a definite conclusion. As regards the resistance to alternations of stress, there appears to be some evidence, from the tests of the steel joints of maker A, that joints made by the electrical method are weaker than those which are hand-welded. Thus, the five hand-welded joints gave a fatigue strength of 92 per cent. of that of the original material, whereas that of the electrically-welded joints was 86 per cent. This feature, however, may be due to the particular method adopted, and may not apply to the general process.

The broad conclusion of the investigation is that in important work, where the failure of any particular welded joint may involve serious damage to the structure, the subjection of each joint to a proof-load is still desirable. Further, there appears to be no evidence that the want of uniformity in the material, which is usual in the region of a welded joint, is liable to cause failure of the joint under repeated applications of the load, provided the weld be originally sound.

The Authors desire to express their indebtedness to the various engineering firms who have kindly presented the specimens of welded joints, and also wish to thank their colleagues, Messrs. L. Bairstow, R. G. C. Batson, Assoc. M. Inst. C.E., A. Bailey, M.Sc., and J. H. Hyde, Stud. Inst. C.E., for assistance in carrying out the work.

The Paper is accompanied by four drawings, from which the figures in the text have been prepared; also by the following Appendix.

[APPENDIX.

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APPENDIX.

TABLE I.—TENSILE TESTS.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.		General Extension on 8 inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.		Actual.	In Terms of Original Material.		
				Tons per Sq. In.	Tons per Sq. In.	Tons per Sq. In.	Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.	
A	103	Iron	Unwelded	8.5	16.5	23.61	..	28.9	0.39	..	..	{ Broke probably across end of weld; no sign of weld after fracture.
A	098	"	Hand-weld	10.5	13.5	23.53	99.5	20.2	0.26	66.6	3½	{ Broke at weld; ⅔ of fracture crystalline.
A	100	"	Elec. Weld	9.5	13.6	23.05	97.6	15.75	0.05	12.8	butt	{ Broke across weld. Broke away from weld and outside marks; slight second neck at weld.
A	118	"	Hand-weld	11.0	14.0	23.22	98.4	25.9	0.55	141.0	3½	{ Broke at weld; ⅔ of fracture crystalline.
A	119	"	"	11.0	13.8	23.08	97.7	19.9	0.57	145.0	3	{ Broke at weld; ⅔ of fracture crystalline.
A	120	"	"	9.0	14.0	23.11	97.9	15.1	0.10	25.6	3	{ Broke at weld. Broke at weld; ⅔ of fracture crystalline.
A	121	"	"	11.0	14.0	23.10	97.8	14.2	0.11	28.2	3½	{ Broke at weld; ⅔ of fracture crystalline.
A	122	"	Elec. Weld	11.5	14.1	22.42	95.0	11.5	0.06	15.4	butt	{ Broke at weld. Broke at weld; crystalline patch.
A	123	"	"	11.0	13.0	22.97	97.3	15.75	0.15	38.5	"	{ Broke at weld; crystalline patch.
A	124	"	"	11.0	13.5	20.43	85.8	6.75	0.10	25.6	"	{ Broke along weld.
A	125	"	"	10.5	13.8	22.08	93.4	11.1	0.15	38.5	"	{ Broke along weld.

1 Estimated.

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.			General Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.	
						Actual.	In Terms of Original Material.			Actual.	In Terms of Original Material.			
							Per Cent.	Per Cent.			Per Cent.			Per Cent.
				Tons per Sq. In.	Tons per Sq. In.	Tons per Sq. In.	Per Cent.	Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.		
A	102	Steel	Unwelded	11.0	15.5	27.82	..	31.5	26.1	0.57	..	..	Broke across weld.	
A	099	"	Hand-weld	12.0	15.0	27.64	99.4	13.5	12.0	0.08	14.0	3½	{ No sign of weld before or after fracture.	
A	101	"	Electric weld	11.5	15.6	27.67	99.5	23.2	16.1	0.56	98.3	butt ?	{ Broke along weld.	
A	106	"	"	9.0	14.5	19.18	68.8	1.2	0 and 0.25	0.03	5.3	butt	{ Broke along weld.	
A	107	"	"	13.5	15.6	27.27	98.0	12.9	12.0	0.06	10.5	½	{ Partly crystalline ; shows a marked core.	
A	127	"	Hand-weld	15.0	16.0	25.53	91.7	7.9	7.5	0.0	0.0	3½	{ Broke along weld.	
A	128	"	"	12.5	15.0	27.80	99.9	14.0	14.0	0.0	0.0	4½	{ Broke partly along weld.	
A	129	"	"	14.0	15.5	24.30	87.4	6.4	6.3	0.07	12.3	3½	{ Broke mainly along weld.	
A	130	"	"	9.5	14.5	15.64	56.2	0.0	0.0	0.0	0.0	3½	{ Broke along weld ; dirty fracture ; crack opened at 11 tons.	
A	131	"	Electric weld	17.5	18.5	27.35	98.3	13.6	13.4	0.05	6.8	½	{ Broke at weld ; fracture fine crystalline.	
A	132	"	"	14.5	17.3	25.70	92.4	8.4	7.5	0.03	5.3	1½	{ Broke at weld ; fracture fine crystalline.	
¹ B	092	" A	Unwelded	11.5	15.2	24.73	..	33.2	27.5	0.64	..	..	{ Broke along weld ; fracture shows oxide.	
B	089	" A	Hand-weld	9.5	12.6	19.62	79.3	6.4	5.0	0.12	18.8	2½		

¹ All maker B specimens turned down from 1½ inch diameter.

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.		Total Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.		In Terms of Original Material.	Per Cent.		
				Tons per Sq. In.	Tons per Sq. In.	Tons per Sq. In.	Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.	
B	136	Steel A	Hand-weld	7.5	12.7	16.59	67.1	4.25	2.5	0.13	16.1	{ Broke along weld ; only welded at edges ; dirty fracture.
B	093	" B	Unwelded	12.5	15.5	26.28	..	24.1	19.0	0.46	..	{ Broke along weld ; fracture dirty.
B	090	" B	Hand-weld	7.5	12.74	18.51	70.5	3.1	2.5	0.06	13.0	{ Broke along weld.
B	138	" B	"	8.0	13.0	14.96	57.0	1.75	1.0	0.07	15.2	{ Broke along weld.
B	094	" C	Unwelded	11.0	22.9	47.12	..	13.8	10.8	0.24	..	{ Broke at weld with extensionometer on ; fracture crystalline.
B	091	"	Hand-weld	..	..	19.5	41.4	0.0	0.0	0.0	2½	{ Broke partly along weld.
B	095	Iron	Unwelded	11.5	14.0	23.21	..	28.8	25.6	0.28	..	{ Broke along weld ; dirty patches in fracture.
B	088	"	Hand-weld	7.0	10.5	20.83	89.9	11.6	11.5	0.07	25.0	{ Broke across weld ; crystalline fracture.
B	137	"	"	6.0	11.7	20.19	86.9	9.4	8.0	0.08	28.6	{ Broke along weld ; fracture dirty.
C	004	{ Rivet Steel }	Unwelded	13.0	18.5	25.54	..	26.0	18.8	0.65	..	{ No signs of weld.
C	005	"	Hand-weld	17.5	18.0	25.45	99.7	5.9	10.6	0.00	0.0	{ Weld not visible before or after fracture.
C	068	"	"	9.5	15.0	16.41	64.2	0.8	0.0	0.06	9.2	
C	006	"	Elec. weld	13.0	14.5	21.08	94.4	18.9	13.8	0.40	61.5	
C	069	"	"	12.0	14.5	24.43	95.6	23.0	13.6	0.79	121.5	

TABLE I.—TENSILE TESTS—*continued*.

Maker	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.		General Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.		Actual.	In Terms of Original Material.		
				Tons per Sq. In.	Tons per Sq. In.	Tons per Sq. In.	Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.	
C	144	{ Rivet } steel	Hand-weld	11.5	14.5	21.75	85.2	7.0	0.05	7.7	1½	{ Broke partly along weld; crystalline fracture.
D	001	Iron	Unwelded	5.0	8.5	19.75	..	28.1	0.60	..	..	{ Small hole at side of fracture.
D	002	"	Hand-weld	9.0	12.0	19.42	98.5	21.9	0.80	133.0	9 or 10	{ Extension on one side only; split along weld. Broke 1½ inch along weld; surface split.
D	064	"	"	8.0	10.0	18.84	95.4	17.1	0.66	110.0	9 or 10	{ Broke 1½ inch along weld; surface split.
D	145	"	"	6.5	10.7	17.19	87.0	9.0	0.29	48.3	9 or 10	{ Irregular extension.
D	003	{ Mild } steel	Unwelded	12.5	19.0	31.90	..	23.2	0.55	..	..	"
D	012	"	Hand-weld	8.5	17.0	31.03	97.5	21.9	0.25	45.4	about 9	"
D	065	"	"	20.0	20.5	31.90	100	11.3	0.72	131.0	" 11	"
E	079	Steel	Unwelded	20.0	20.5	29.63	..	29.8	0.62	..	..	{ Broke mainly along weld. Dirty fracture.
E	081	"	Hand-weld	8.0	16.0	24.24	81.8	4.0	0.12	19.2	3	{ Broke at weld; crystal- line patch.
E	080	Iron	Unwelded	5.0	14.0	21.56	..	21.6	0.34	..	..	{ Broke away from weld. Broke outside gauge marks.
E	082	"	Hand-weld	6.5	13.1	21.57	99.9	12.8	0.10	29.4	2½	
F	075	"	Unwelded	11.5	15.5	23.43	..	28.0	0.24	..	..	
F	108	"	Hand-weld	12.5	16.0	22.13	94.3	8.0	0.07	29.2	1½	
F	077	"	"	11.0	14.5	22.98	97.9	11.7	0.25	104.1	3	

1 Estimated.

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.		Total Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.		Actual.	In Terms of Original Material.		
				Tons per Sq. In.	Tons per Sq. In.		Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.	
F	083	Iron	Hand-weld	7.0	15.3	23.40	99.7	14.9	0.16 ¹	66.7	3	Broke away from weld —in first inch.
F	076	Steel	Unwelded	16.0	16.5	27.42	..	29.2	0.33	..	..	
F	078	"	Hand-weld	15.5	15.0	24.89	90.6	8.6	0.25	75.7	4	Broke partly along weld.
F	134	"	"	12.5	15.5	21.12	77.0	4.0	0.03	9.1	4½	Broke partly along weld.
F	133	"	"	15.5	16.0	25.90	94.5	12.25	0.18	54.6	4	Broke across weld.
G	084	"	Unwelded	9.5	16.3	29.49	..	28.7	0.53	..	..	Broke partly along weld; two small crystalline patches.
G	086	"	Hand-weld	10.0	15.0	20.84	70.8	2.75	0.05	9.4	3	
G	085	Iron	Unwelded	8.0	14.0	22.75	..	33.6	0.60	..	..	Broke partly along weld; slightly crystalline.
G	087	"	Hand-weld	7.0	14.0	20.58	90.3	6.6	0.12	20.0	2	
H	072	Steel	Unwelded	17.0	17.5	29.34	..	23.5	0.60	..	..	Broke across weld.
H	074	"	Hand-weld	8.5	13.5	14.99	51.1	0.6	0.04	6.7	3½	Broke at weld; fracture crystalline (where not along weld).
H	139	"	"	11.0	15.8	27.10	92.3	5.4	0.05	8.3	4½	
J	071	Iron	Unwelded	12.5	14.0	22.87	..	22.6	0.51	..	..	Broke partly along weld; dirty fracture.
J	073	"	Hand-weld	13.4	13.4	19.03	83.2	5.1	0.06	11.8	2	

¹ Estimated.

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.			General Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.	Total Extension on 8 Inches.		Actual.	In Terms of Original Material.		
				Tons per Sq. In.	Tons per Sq. In.	Tons per Sq. In.	Per Cent.	Per Cent.	Per Cent.	Inch.	Per Cent.	Inches.	
K	096	Steel	Unwelded	12.5	16.2	23.87	..	36.0	25.25	0.63	..	..	{ Fracture coarsely crystalline.
K	097	"	Electric weld	12.5	16.8	23.96	100.2	18.2	17.0	0.0	0	butt	
L	105	"	Unwelded	..	16.4	24.44	..	35.0	14.25	0.80 ¹	..	..	
L	104	"	Acet. weld	5.5	13.4	19.82	80.2	6.9	5.5	0.12	15.0	1½	{ Broke at weld; fracture crystalline.
M	109	"	Unwelded	10.0	14.3	22.05	..	32.8	29.0	0.55	..	..	
M	110	"	Acet. weld	9.5	13.6	14.77	67.0	1.2	0.0	0.04	7.3	{ Region 1¼	{ Broke along weld; conical scarf; patches of oxide.
M	114	"	"	5.0	..	10.72	48.6	0.25	0.0	0.02	3.6	{ Region 1	{ Broke along weld; conical scarf; patches of oxide.
M	135	"	"	6.5	..	13.80	60.3	1.0	0.0	0.06	10.9	{ Region 1½	{ Pulled out along weld in two opposite cones.
N	022	Iron	Unwelded	12.5	13.5	21.53	..	29.9	17.5	0.90	..	..	
N	024	"	Hand-weld	8.0	12.5	22.22	103.0	28.7	20.0	0.75	83.3	3½	{ Broke at end of specimen and away from weld.
N	115	"	"	8.0	14.3	23.0	106.8	26.4	20.5	0.28	31.1	4	{ Broke away from weld.
N	067	"	"	9.5	13.0	22.0	102.0	25.0	18.0	0.55	61.0	5	{ No sign of weld after fracture.

¹ Test made on a similar specimen, i.e., 0.798 in. diam., gauge-marks every ½ in. to 5 inches. Local extension given on 1 inch diameter.

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.			General Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.	Per Cent.		Inch.	Per Cent.		
N	017	Steel	Unwelded	Tons per Sq. In. 5.5	Tons per Sq. In. 12.0(?)	26.18	..	28.2	Per Cent. 20.6	Inch. 0.55	..	Inches.	
N	015	"	Hand-weld	11.0	16.0	26.76	102.2	26.7	20.0	0.60	109.0	5½	Broke across weld.
N	066	"	"	13.5	16.0	23.90	91.4	12.5	6.5	0.47	85.4	5	Broke partly along weld; extension on one side only.
N	116	"	"	16.5	17.0	26.52	101.5	27.0	22.5	0.60	109.0	4½	Broke away from weld.
O	011	Best chain iron	Unwelded	10.5	13.5	21.16	..	27.6	21.9	0.30	..	..	Broke along weld; fracture coarsely crystalline.
O	019	"	Hand-weld	9.5	13.0	22.89	108.3	13.5	13.8	0.00	0.00	¼	Broke at weld; fracture coarsely crystalline.
O	025	"	"	10.0	13.0	22.60	106.9	12.2	12.4	0.00	0.00	¼	Broke along weld.
O	020	"	"	10.0	12.5	16.23	76.7	2.0	2.0	0.00	0.00	1½	"
O	016	"	"	10.0	13.0	19.42	91.9	5.3	3.8	0.10	33.3	1½	"
O	018	"	"	10.0	14.0	21.90	103.5	7.1	6.3	0.10	33.3	1	"
O	021	"	"	9.5	13.0	20.92	98.9	7.9	6.9	0.10	33.3	1½	"
O	023	"	Electric weld	9.0	13.0	15.80	74.8	2.6	1.2	0.10	33.3	¼	"
O	126	"	"	9.0	13.4	17.15	81.1	3.4	2.0	0.11	24.4	butt	"

TABLE I.—TENSILE TESTS—continued.

Maker.	Test No.	Material.	Treatment.	Elastic Limit.	Yield Stress.	Maximum Stress.		General Extension on 8 Inches.	Local Extension.		Approximate Length of Weld.	Remarks.
						Actual.	In Terms of Original Material.		Inch. Actual.	Per Cent. of Material.		
P	007	{ Staffs. } iron	Unwelded	Tons per Sq. In. 13·0	Tons per Sq. In. 15·0	24·08	Per Cent. ..	Per Cent. 25·0	Per Cent. 17·5	Per Cent. 0·60	Inches. ..	{ Broke with extensometer on bad weld ; fracture dirty. Broke along weld ; centre of fracture dirty.
P	008	"	Hand-weld	9·5	..	13·50	56·1	1·0	0·0	0·08	13·3	
P	143	"	"	10·0	14·7	16·44	68·3	2·1	1·0	0·09	15·0	2½
P	009	{ Yorks. } iron	Unwelded	12·0	12·5	22·18	..	22·9	13·8	0·70	..	{ Bad weld ; centre of fracture dirty. Broke along weld ; centre of fracture dirty.
P	010	"	Hand-weld	9·0	11·0	16·21	73·0	3·9	2·5	0·10	14·3	
P	142	"	"	10·0	13·9	16·70	75·3	4·0	3·4	0·07	10·0	2½
Q	014	Iron	Unwelded	11·5	15·5	24·06	..	24·2	22·5	0·15	..	{ Surface cracked ; crystalline band in fracture. Fracture through weld ; partly crystalline.
Q	013	"	Hand-weld	7·5	12·5	20·67	85·8	7·1	5·6	0·10	66·7	1½
Q	070	"	"	9·5	14·5	21·53	89·5	9·1	6·4	0·17	113·2	1½
Q	140	"	"	10·0	14·4	21·74	90·4	11·6	11·0	0·08	53·4	1½
Q	141	"	"	10·5	15·3	21·76	90·5	9·1	7·8	0·10	63·7	2

TABLE II.—RESULTS OF FATIGUE TESTS MADE ON WÖHLER TYPE MACHINE
AT 2,200 REVERSALS PER MINUTE.

Maker.	Test No.	Material.	Treatment.	Maximum Stress Applied.	Range of Stress.	Number of Reversals of Stress to Fracture.	Calculated Fatigue Strength in Terms of Original Material.
				Tons per Sq. In.	Tons per Sq. In.		Per Cent.
A	36	Iron	Unwelded	14·04	28·08	431,000	
A	33	"	Hand-weld	14·04	28·08	461,000	100
A	97	"	"	14·04	28·08	376,000	99
A	75	"	"	13·91	27·82	282,000	97
A	80	"	"	14·04	28·08	284,000	98
A	98	"	"	14·04	28·08	36,800	84
A	34	"	Electric weld	13·05	26·10	348,000	92
A	94	"	"	12·93	25·86	145,000	86
A	95	"	"	12·93	25·86	489,000	93
A	76	"	"	12·93	25·86	433,000	92
A	79	"	"	13·90	27·80	491,000	100
A	37	Steel	Unwelded	13·90	27·80	532,000	
A	32	"	Hand-weld	13·90	27·80	398,000	98
A	73	"	"	13·90	27·80	387,000	98
A	85	"	"	12·93	25·86	99,100	83
A	91	"	"	13·90	27·80	209,000	95
A	92	"	"	13·90	27·80	62,600	88
A	31	"	Electric weld	11·95	23·90	392,000	84
A	47	"	"	11·95	23·90	577,000	87
A	74	"	"	11·95	23·90	352,000	84
A	93	"	"	12·93	25·86	244,000	89
A	96	"	"	11·95	23·90	508,000	86
B	46	Steel A	Unwelded	11·95	23·90	513,000	
B	28	"	Hand-weld	11·95	23·90	165,000	94
B	66	"	"	11·95	23·90	472,000	99
B	48	Steel B	Unwelded	11·95	23·90	45,500	
B	27	"	Hand-weld	10·97	21·94	191,000	87
B	67	"	"	10·97	21·94	278,000	90
B	49	Steel C	Unwelded	15·86	31·78	462,000	
B	26	"	Hand-weld	10·00	20·00	91,000	57
B	38	"	"	8·03	16·06	382,000	50
B	84	"	"	6·08	12·16	338,000	37

TABLE II.—FATIGUE TESTS—*continued.*

Maker.	Test No.	Material.	Treatment.	Maximum Stress. Applied.	Range of Stress.	Number of Reversals of Stress to Fracture.	Calculated Fatigue Strength in Terms of Original Material.
				Tons per Sq. In.	Tons per Sq. In.		Per Cent.
B	45	Wrought iron	Unwelded	13·10	26·20	865,000	
B	21		Hand-weld	10·97	21·94	1,000,000	85
B	65	"	"	12·93	25·86	91,000	86
C	4	Steel	Unwelded	13·70	27·40	434,000	
C	6		Hand-weld	12·80	25·60	41,000	78
C	7	"	"	3·33	6·66	2,700	20
C	8	"	Electric weld	12·72	25·44	494,000	94
C	9	"	"	11·75	23·50	138,000	80
C	11	"	"	12·93	25·86	210,000	90
D	1	Wrought iron	Unwelded	10·00	20·00	1,320,000	
D	2		Hand-weld	10·00	20·00	1,830,000	102
D	13	"	"	9·14	18·28	87,000	78
D	3	Steel	Unwelded	14·70	29·40	76,000	
D	5		Hand-weld	13·70	27·40	40,000	87
D	12	"	"	13·91	27·82	966,000	112
E	14	Wrought iron	Unwelded	11·15	22·30	260,000	
E	17		Hand-weld	11·93	23·86	76,000	97
E	71	"	"	10·97	21·94	423,000	100
E	15	Steel	Unwelded	14·70	29·40	942,000	
E	16		Hand-weld	12·93	25·86	459,000	85
E	18	"	"	4·90	9·80	1,010,000	33
F	68	Wrought iron	Unwelded	11·95	23·90	821,000	
F	20		Hand-weld	14·36	28·72	64,000	102
F	29	"	"	12·07	24·14	2,140,000	106
F	90	"	"	13·90	27·80	538,000	114
F	70	Steel	Unwelded	12·93	25·86	496,000	
F	24		Hand-weld	11·95	23·90	560,000	90
F	30	"	"	11·95	23·90	368,000	86
F	69	"	"	10·00	20·00	173,000	72
G	53	Wrought iron	Unwelded	13·06	26·12	186,000	
G	22		Hand-weld	14·03	28·06	185,000	107
G	72	"	"	12·93	25·86	358,000	103

TABLE II.—FATIGUE TESTS—*continued*.

Maker.	Test No.	Material.	Treatment.	Maximum Stress Applied.	Range of Stress.	Number of Reversals of Stress to Fracture.	Calculated Fatigue Strength in Terms of Original Material.
				Tons per Sq. In.	Tons per Sq. In.		Per-Cent.
G	52	Steel	Unwelded	13·90	27·80	92,000	
G	23	"	Hand-weld	4·90	9·80	200,000	37
G	51	"	"	10·97	21·94	244,000	84
H	44	"	Unwelded	14·88	29·76	296,000	
H	25	"	Hand-weld	10·97	21·94	1,080,000	80
H	63	"	"	11·95	23·90	192,000	78
H	64	"	"	11·95	23·90	361,000	81
J	50	Wrought iron	Unwelded	12·08	24·16	319,000	
J	19		Hand-weld	12·40	24·80	213,000	100
J	61		"	10·97	21·94	454,000	92
J	62		"	12·92	25·84	154,000	102
K	35	Steel	Unwelded	13·90	27·80	179,000	
K	42	"	Electric weld	13·90	27·80	471,000	106
K	43	"	"	10·00	20·00	464,000	76
K	54	"	"	10·00	20·00	157,000	71
K	55	"	"	12·93	25·86	439,000	98
L	40	Wrought iron	Unwelded	14·88	29·76	297,000	
L	41		Acet. weld	8·04	16·08	699,000	56
L	39		"	10·00	20·00	22,000	59
L	56		"	9·01	18·02	313,000	60
L	57	"	"	6·08	12·16	1,450,000	45
M	59	Steel	Unwelded	11·95	23·90	444,000	
M	58	"	Acet. weld	5·09	10·18	71,500	38
M	60	"	"	7·05	14·10	40,300	49
M	99	"	"	4·11	8·22	451,000	34
N	81	Wrought iron	Unwelded	12·41	24·82	102,000	
N	87		Hand-weld	12·93	25·86	40,000	95
N	88		"	12·93	25·86	305,000	103
N	78	Steel	Unwelded	13·90	27·80	367,000	
N	82	"	Hand-weld	13·90	27·80	211,000	97
N	83	"	"	13·90	27·80	284,000	99

TABLE III.—FATIGUE EXPERIMENTS MADE FOR PLOTTING STANDARD CURVE.

Test No.	Maximum Stress.	Range of Stress.	Number of Reversals of Stress to Fracture.
	Tons per Sq. In.	Tons per Sq. In.	
111	16·3	32·6	49,800
114	15·0	30·0	163,700
116	14·0	28·0	481,000
119	13·7	27·4	878,100
117	13·4	26·8	1,393,500
123	13·4	26·8	1,264,000
122	13·1	26·2	1,684,400
115	12·75	25·0	2,629,500
124	12·81	25·62	4,536,700
125	12·70	25·40	{ 10,000,000 (not broken)