

(*Students' Paper, No. 159.*)

**"On Iron and Steel in Tension, Compression, Bending,  
Torsion, and Shear."<sup>1</sup>**

By PERCY VAVASSEUR APPLEBY, Stud. Inst. C.E.

THERE is so much valuable information relative to experiments on iron and steel that further investigation may appear unnecessary; but the Author has not seen records of experiments and tests of specimens of iron and steel, cut from the same bar, or cast from the same ladle, under each of the five conditions mentioned in the title. This has led him, in his course of three years as a student at University College, London, to make a large number of tests, the results of which are embodied in the present Paper.

Before proceeding to describe the tests in detail, it may be well to mention that the term iron includes both cast and wrought iron, and the term steel refers to open-hearth steel in castings and forgings, crucible-steel in castings and forgings, and Bessemer steel forgings. As regards the materials for the specimens, an identical note was written to several manufacturers, stating the purpose for which the materials would be employed.

The testing-apparatus used was that in the Engineering Laboratory, University College, London, of which the machines have been fully described,<sup>2</sup> and are generally well-known.

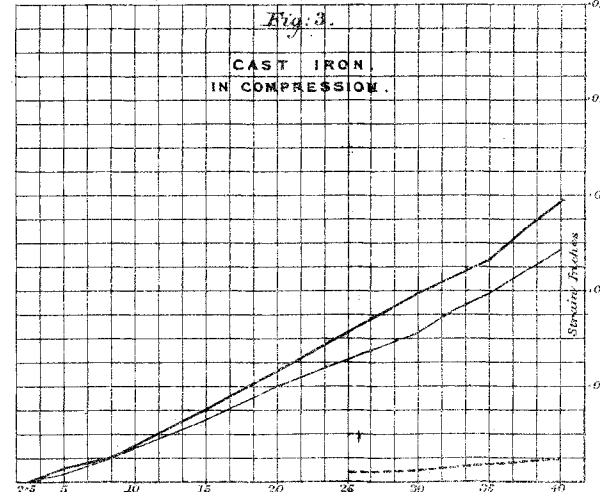
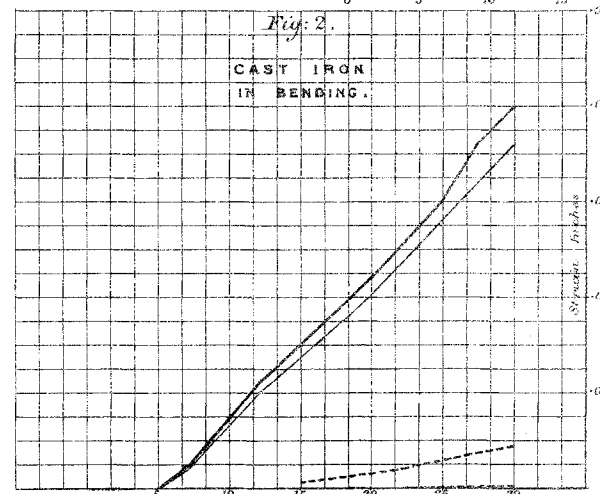
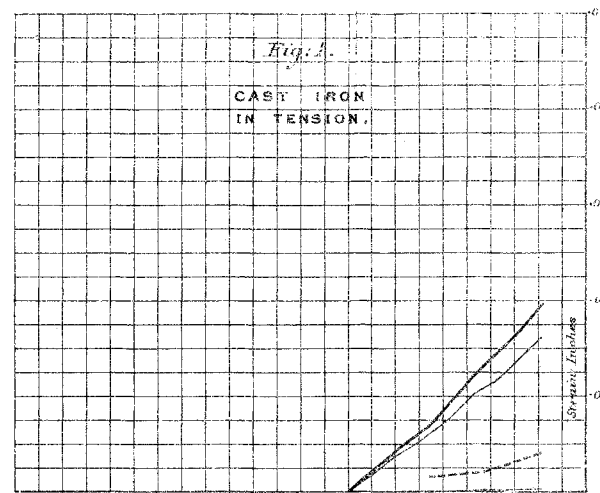
The shear-apparatus, however, is new; this is shown in Plate 15, Figs. 17 and 18. It will be seen that the specimens are under double shear, the two grooves being turned so as to avoid the possibility of any cutting action. The apparatus for holding the torsion-specimens is also shown in Figs. 19; the carriers, which are fixed on each end of the test-piece, are arranged in such a way, that the more the piece is twisted, the tighter it is gripped by the eccentric steel arm K.

With the exception of the specimens in shear, measurements of the strains were taken on all pieces tested, and a modulus of elasticity (direct or transverse), has been calculated from each

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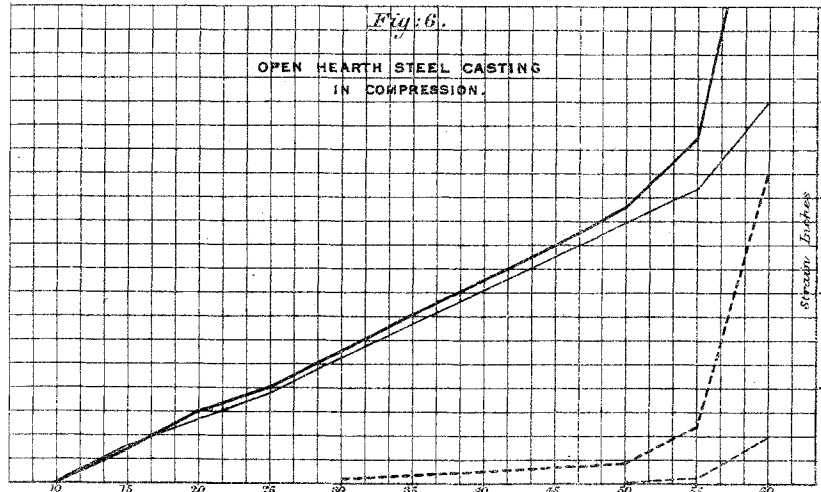
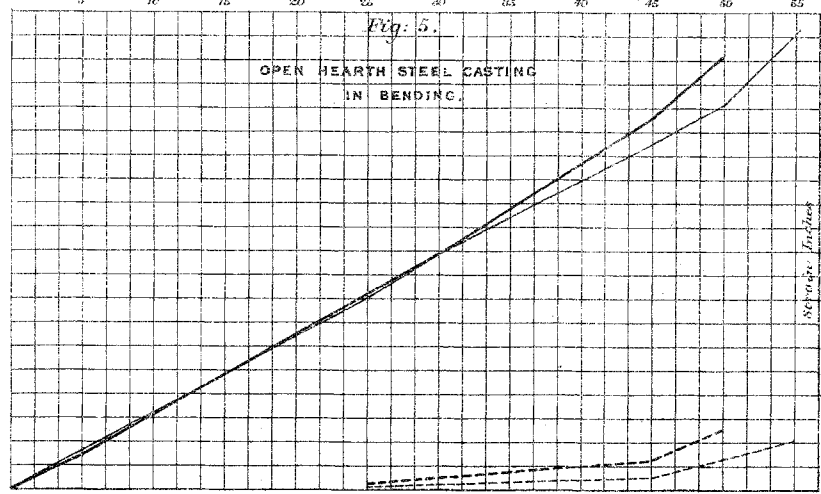
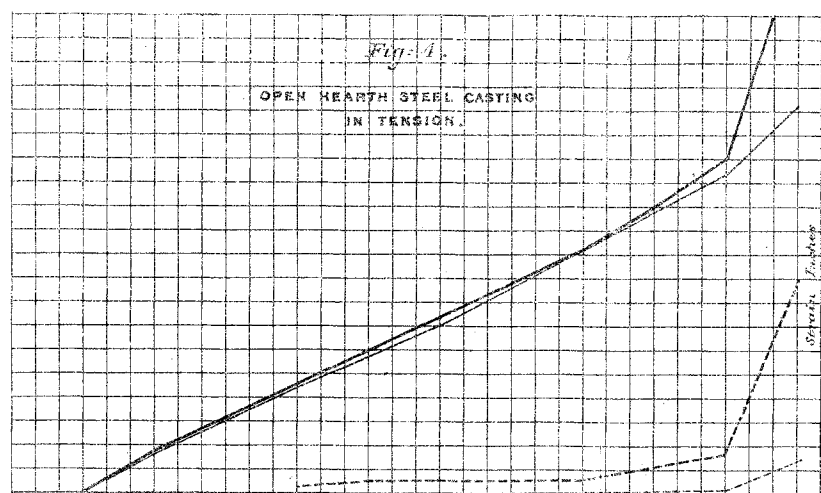
<sup>1</sup> This communication was read and discussed at a Meeting of the Students on the 9th of March, 1883, and has been awarded a Miller Prize.

<sup>2</sup> "Engineering," Sept. 26, 1879, and Jan. 21, 1881; also "The Engineer," Feb. 25, 1881.

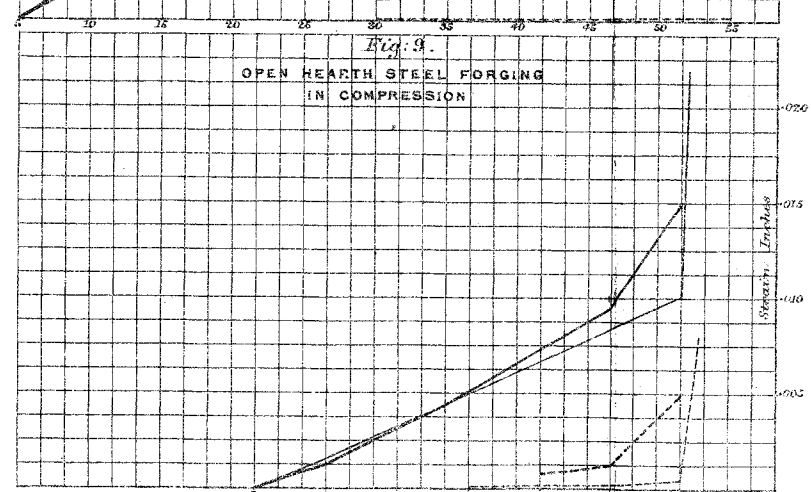
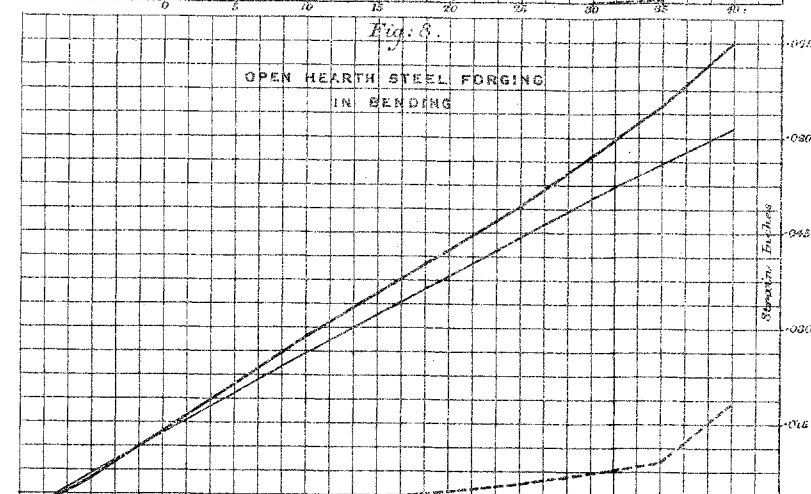
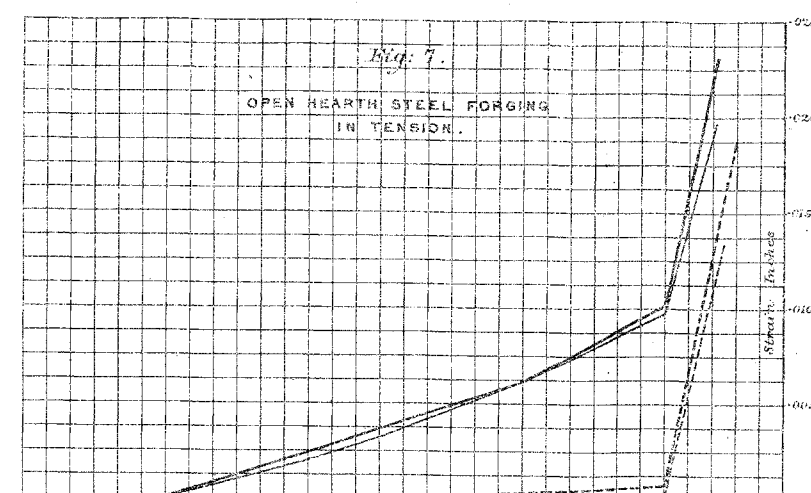


Thousand lbs. per Square Inch Stress.

P. V. APPELBY, DEL.

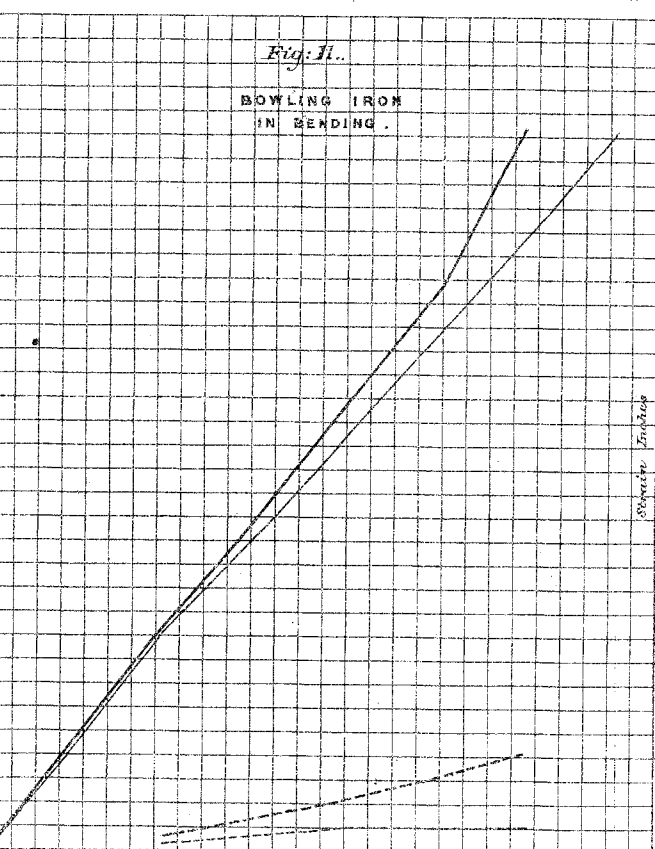
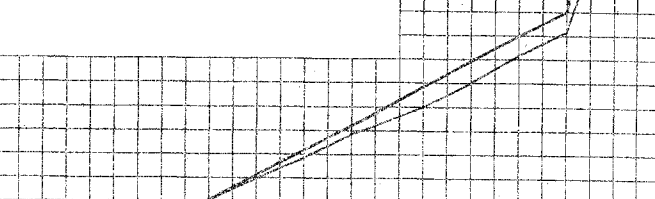
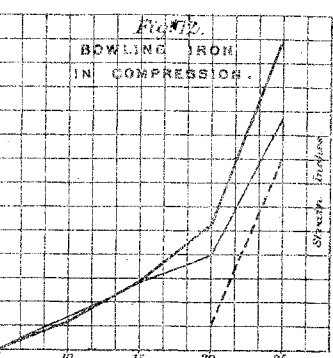


Thousand lbs. per Square Inch Stress.

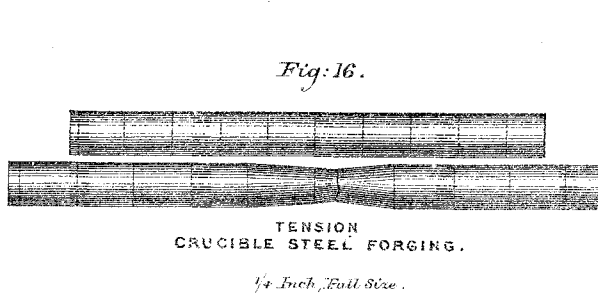
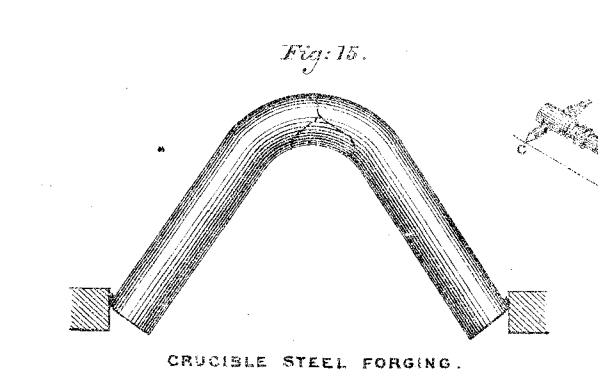
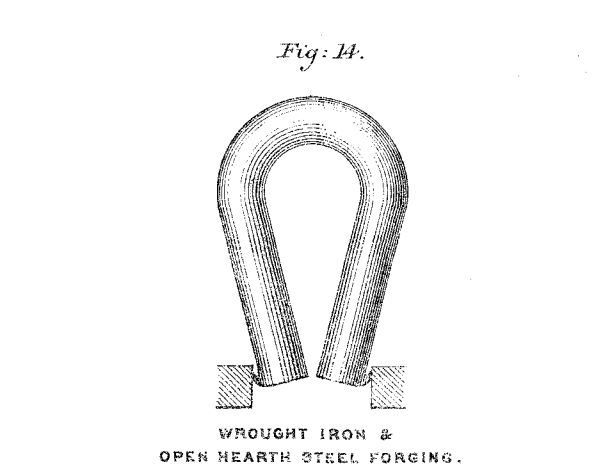
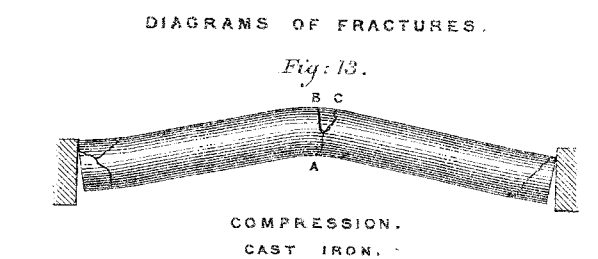


Thousand lbs. per Square Inch Stress.

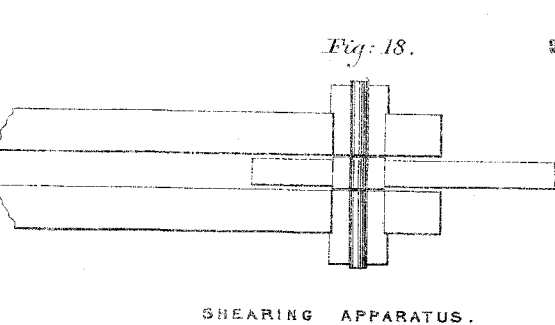
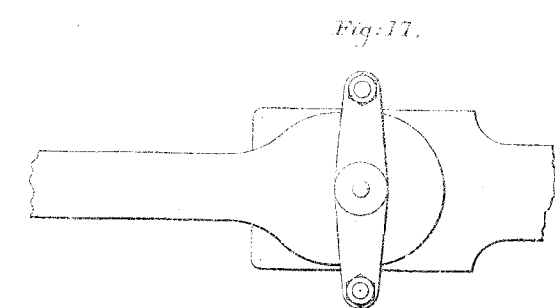
# IRON AND STEEL IN TENSION, BENDING, COMPRESSION, TORSION, & SHEAR.



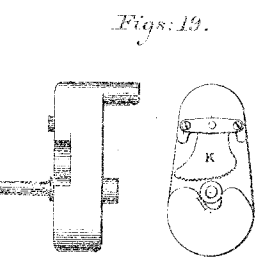
Thousand lbs. per Square Inch Stress.



1/2 Inch, Full Size.



1/2 Inch, Full Scale.



1/2 Inch, Full Scale.

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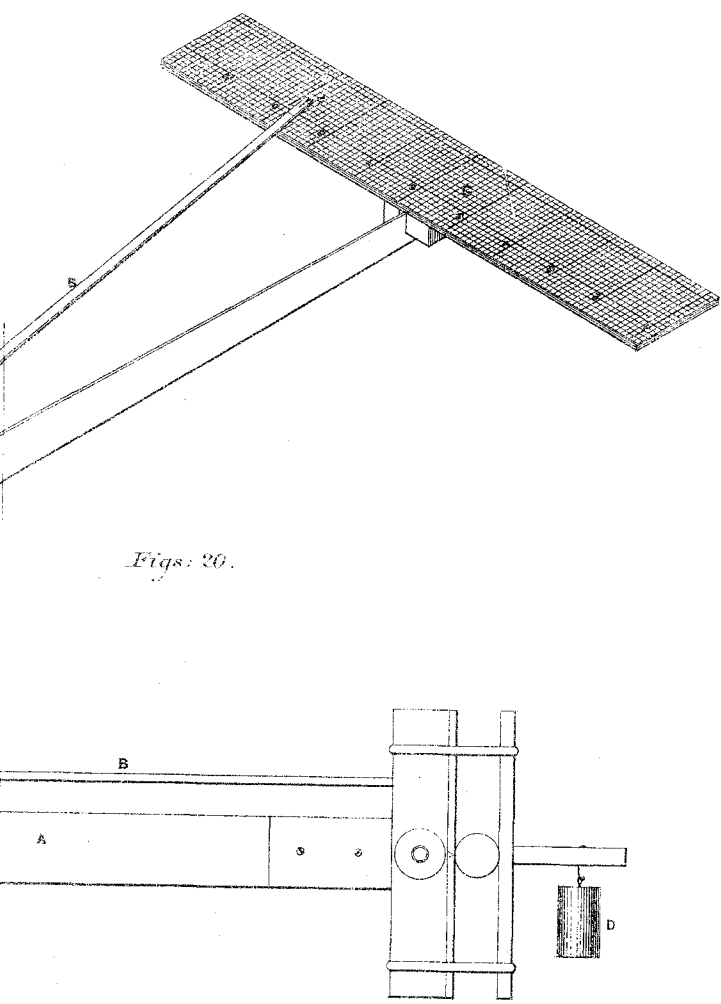
1/2 Inch, Full Scale.

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1/2 Inch, Full Scale.



STRAIN-MEASURING APPARATUS.

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piece. The actual readings on each piece are not given, because a detailed account of the tests of over one hundred and forty pieces would occupy too much space. But curves connecting the stresses and strains of each piece tested have been drawn, and from these the typical curves for each material under each kind of test have been selected (Plate 15, Figs. 1 to 12).

The strains in tension, compression, and bending, were measured by the apparatus shown in Figs. 20. This consists of a light frame A, carrying a simple lever B. The two steel points, C C, are 10 inches apart; these are placed in centre punch-marks on the specimen, the apparatus being held in position by elastic bands, and the weight D serving to preserve the balance. The lever B turns on the two set-screws E E, and at one end is a pointer F, moving on the sectional paper G. As the piece extends, the steel points, C C, are moved apart, and their motion is communicated to the pointer F. The leverage is 100 to 1, and has been corrected by actual measurement on vernier callipers; by this apparatus, the effects of strains are measured to  $\frac{1}{10,000}$  inch.

In the torsion-tests, a large cardboard protractor was fixed on one end of the test-piece, and a cardboard circle of the same size, with a sector cut out of it, was attached to the other end; both being so arranged that they could turn only as the piece twisted. Readings to one edge of the sector were taken on the application of each different stress by the aid of a telescope fixed 10 yards distant in line with the test-piece.

In the first left-hand column in the table of tests is given the test-marks of the pieces, and in the next a brief description of the materials.

The term "specific extension" in the tension-tests, is merely a convenient quantity for the comparison of the rates of extension of different materials within the limit of elasticity, the ordinary units of 1 lb. and 1 inch used to express the specific extension as "The extension in inches produced by 1 lb. stress on 1 inch length," gives quantities inconveniently small for comparison. For this reason, the "specific extension" is defined as "the average extension measured in  $\frac{1}{1,000}$  inch, produced by 1,000 lbs. per square inch stress on a length of 10 inches within the limit of elasticity." This quantity was first introduced by Professor Kennedy, M. Inst. C.E., and is defined in his Paper on "The Results of Experiments on Riveted Joints made for the Institution of Mechanical Engineers."<sup>1</sup>

<sup>1</sup> Proceedings, 1881, p. 205.

As is well known, the "modulus of elasticity," is the ratio of the stress per square inch to the extension or compression which it produces, on 1 inch length within the limit of elasticity. Thus, if  $x$  is the extension in inches produced on a length  $l$  by the stress  $s$ , then the modulus of elasticity  $E = \frac{s}{\frac{x}{l}} = \frac{sl}{x}$ .

In this expression, if  $x$  could equal  $l$ , then  $E = s$ , thus obtaining a further definition of the modulus of elasticity, viz., "That ideal stress which would stretch a perfectly elastic bar to double its original length." In the expression  $E = \frac{sl}{x}$ , if the specific extension ( $\epsilon$ ) be substituted for  $x$ , and  $s$  and  $l$  replaced by their corresponding values, then  $E = \frac{1,000 \times 10}{\epsilon} = \frac{10^7}{\epsilon}$  which gives the relation

$$\frac{1,000}{\epsilon}$$

between the specific extension and the modulus of elasticity. It is worthy of note, that the specific extension is always the observed quantity, and the modulus of elasticity is derived from it by calculation.

Where bending- and torsional-stresses are given per square inch, the maximum stress per square inch on the outermost fibre is referred to.

The "limit of elasticity" is the stress at which the ratio  $\frac{\text{strain}}{\text{stress}}$  ceases to be a constant quantity, the strain increasing in a higher ratio than the stress; this is clearly shown in Figs. 4 and 7, by the line of strains; which was straight up to this point, commencing to curve upwards.

The "steelyard drop" may be regarded as the commercial limit of elasticity; at this stress the material seems to break down, and it extends without increase of load, generally about ten times as much as the whole extension up to this point. Mr. Tweddell, M. Inst. C.E., has suggested that this period in the elastic life of a piece should be termed "the limit of fatigue."

The "specific compression" (values of which are given in the second column of the compression tests), corresponds exactly with the specific extension, being the average compression in  $\frac{1}{1,000}$  inch produced by 1,000 lbs. per square inch stress, on a length of 10 inches, within the limit of elasticity. The modulus of elasticity is calculated from it by the formula  $E = \frac{10^7}{\epsilon}$ .

In the bending-tests, the modulus of elasticity is obtained by the formula  $E = \frac{1}{12} \cdot \frac{s l^2}{y d}$ ,  $d$  being the average deflection in inches produced within the limit of elasticity by the stress  $s$ , on a beam of span  $L$  and half-depth  $y$ .

The modulus of transverse elasticity is obtained from the torsion-tests; this quantity is the ratio of the stress to the proportional strain on a piece in torsion. The strain being measured by the tangent of the angle of distortion,  $C = \frac{\text{stress}}{\tan \angle \text{of distortion}} = \frac{2 s l}{t d}$ , where  $t$  is the average twist in circular measure produced within the limit of elasticity, on a piece of length  $l$  and diameter  $d$  by the stress  $s$ .

*Cast Iron.*—The specimens A and B were cast by the Tyne Foundry Company, at Deptford, from the following mixture of metals:—

A. Half Gartsherrie and half machine-scrap.

B. Half cold-blast iron and half machine-scrap. Each set of specimens was cast from the same ladle.

It will be observed that the B specimens have a greater strength in tension and bending than the A specimens.

A tendency was shown in all cases for the compression-specimens to break in the manner shown in Fig. 13. This seems to be explained by considering that as the piece buckles, a shearing-stress is set up in the planes A B, A C, and the piece gives way by shearing in these planes as soon as the maximum shearing resistance is reached; at the same time the ends, which are in shear, give way.

The ratio  $\frac{\text{length}}{\text{diameter}}$  was 8·6 for specimens A and 11·5 for specimens B. A small piece for which the ratio  $\frac{\text{length}}{\text{diameter}}$  was 1·57 broke into fragments at 46·4 tons on the square inch, by shearing. Another piece, for which the ratio  $\frac{\text{length}}{\text{diameter}}$  was 3·63, broke at 41·4 tons by shearing at one end. In the cast-iron bending tests, special care was taken to make the pressure vertical with the length of the beam.

The shearing-stress for the B specimens was 12·3 tons, and the torsional-strength was 18·9 tons per square inch for the turned pieces. The breaking-stress of the unturned torsion-specimens was rather low, as the three pieces tested were slightly unsound.

Of all the specimens tested, those alone which are marked C

were not supplied as test-pieces. The material was wrought-iron plate, of a quality frequently used for girders and shipbuilding; the low tenacity, small extension, and small reduction of area, were remarkable. The fractures were laminated, with about 60 per cent. crystalline, and the welding was indifferent. In bending, specimens of  $\frac{1}{2}$ -inch plate, 1 inch deep, broke before they had bent through  $30^\circ$ .

The fourteen specimens D were made at the Stanners Closes Steel-works by the Attwood open-hearth process, and all were cast from the same ladle. The material was ordinary steel-casting, which will not bend much when cold, but when heated it can be bent to any shape, or when drawn out under the hammer hot (into a chisel) it can be hardened and tempered in the ordinary way. As is usual in steel castings, some of the specimens were porous, and the values obtained from the tests of the porous pieces have been withheld in taking the average. The torsion-pieces were especially troublesome; but this is no doubt greatly due to the difficulty in making sound castings of such small dimensions. The tension-specimens broke, with a finely crystalline fracture, under a strain averaging 29.06 tons per square inch, the final extension being imperceptible. The three compression-specimens were all unsound, two breaking at blowholes, and one specimen at a black cinder; so probably the values for the limit of elasticity, &c., will in practice exceed those given in the tables. In bending, the fractures were largely crystalline, the piece always breaking diagonally across. The deflection previous to fracture was very small.

Of the five torsion-specimens, the only sound one had a limit of 20.09 tons and breaking-stress of 39.29 tons per square inch. This is a high value as compared with most other materials. The piece did not twist 1 turn in a length of 30 diameters, showing great resistance to strain in torsion. Its fracture closely resembles that of the cast-iron torsion pieces. In shear, this material has also a high resistance, namely, 29.7 tons per square inch. The specimens broke like cast iron, and not in the grooves.

The fifteen specimens E were from the Stanners Closes Steel-works, and were forgings made from an open-hearth steel furnace. In tension, the tenacity was about 30 per cent. greater than the castings, and the extension 17 per cent. on 10 inches, the reduction of area being 36.3 per cent. The fractures were in two cases cup-shaped. The compression-pieces had a somewhat lower limit than the castings D, but they bent double without sign of cracking (Fig. 14). The bending-specimens were not broken at 66.4 tons per square inch, having then bent through a right angle. In tor-

sion the limit was reached at about one-half the load of the cast-steel specimens D. Fracture occurred at 29·6 tons per square inch, the specimen having then twisted on an average 7·14 turns on a length of 30 diameters. In shear, the average breaking-stress was 25·9 tons per square inch.

The next material, F, was wrought iron of the well-known "B. B. H." brand, and the results obtained were :—

Commercial limit, 17 tons per square inch; breaking-stress, 25·4 tons per square inch; extension on 10 inches, 22·3 per cent.; reduction of area, 23·9 per cent.

The fracture was fine, silky, and non-crystalline, and the welding was sound. In compression the specimens doubled up without sign of cracking (Fig. 14), and they were bent to a right angle without breaking. In torsion, the limit was 8·9 tons, and breaking-stress 26 tons per square inch, the total twist being 10·56 turns on a length of 30 diameters.

The specimens G were of the "S" quality of Landore-Siemens steel, which is used for ship- and boiler-plates where not exposed to flame, and the specimens H were of the "S. M." quality, which is used for forgings. The tabulated tests of these two materials show that H is a tougher material throughout. The fractures of the G tension-specimens were silky, with little white spots caused by the presence of small cones, due to irregularities in ductility. The specimens H had uniform, silky, cup-shaped fractures. Both materials doubled up without breaking in compression; but in bending, they broke after deflecting through nearly a right angle. Comparing these results with those of the open-hearth steel forgings E, the latter seems a still tougher material than either G or H.

The specimens K were wrought iron made by Messrs. Fry, Ianson and Co. of Darlington, and the results obtained were :—

Commercial limit, 15·16 tons per square inch; breaking-stress, 22·46 tons per square inch; extension on 10 inches, 14 per cent.; reduction of area, 19 per cent.

The fracture was laminated, with 10 per cent. crystalline, and the welding was fair. The bending-specimens were deflected through a right angle without cracking. The limit of elasticity in torsion was 8·9 tons, and breaking-stress 22·3 tons per square inch, with a total twist of 3·2 turns on a length of 30 diameters. The piece was much distressed and bent before it broke.

The material L was Bessemer-steel bar made by Messrs. John Brown and Co. of Sheffield, and was described by them as a medium-temper steel, such as is usually supplied in steel forgings.

It bore a close resemblance in all its tests to the open-hearth steel forgings E. The fractures had a uniform silky appearance, those in tension being cup-shaped. The 10-inch length on which strains were measured, is shown for one of the tension-specimens in its final and extended form in Fig. 16. The bending-specimens were deflected through a right angle before fracture. This feature is important as showing where the strain was smallest, namely, in a plane through the axis of symmetry of the cross-section parallel to the edge of the beam.

The scaling was observed to take place soon after the limit was reached, and long before the ultimate load was put on. The same phenomenon was observed in many of the wrought-steel and iron beams, but was specially marked in the instance mentioned.

The specimens M were of Bowling iron, and the results obtained were :—

Commercial limit, 14·4 tons per square inch; breaking-stress, 20·9 tons per square inch; extension on 10 inches, 19·8 per cent.; reduction of area, 29·8 per cent.

The fractures were uniform and silky, and the welding sound. The test across the fibre in tension is also given. In compression, the pieces were doubled up; and in bending, they were deflected through a right angle without breaking. In torsion, two bars were tested, also a square piece of  $\frac{1}{2}$ -inch plate; the latter had a limit of elasticity of 8·9 tons, and breaking-stress of 20·099 tons per square inch, twisting 3 turns before fracture.

After having been tested up to 25 tons per square inch stress, and twisted 10 turns on a length of 30 diameters, one of the torsion-specimens was subjected to a tensile-test. It was found that the limit of elasticity had been increased to 20·34 tons, the breaking-stress being 22·47 tons per square inch. The extension on 20 inches was only 0·25 per cent., the fracture being very finely crystalline, and the twisting of the fibres quite perceptible.

The specimens N were Bowling crucible-steel casting, taken from an ordinary heat for castings such as forge-hammers and mill pinions. The values of the tensile-test are probably somewhat lower than would be obtained in practice, because the two specimens tested broke at blowholes; the fractures were finely crystalline. The shear-specimens were somewhat unsound. The material throughout was very tenacious, but non-ductile, and in these respects it resembled the open-hearth castings D.

The specimens O were of crucible-steel rolled bar, and the results obtained were :—

Commercial limit, 25 tons per square inch; breaking-stress, 47

tons per square inch; extension on 10 inches, 9·5 per cent.; reduction of area, 25 per cent.; the fractures were finely granular and uniform. One of the tension-specimens drew down considerably in two places just before fracture, and then broke at the larger diameter. The compression-specimens broke as shown in Fig. 15. In bending, the limit of elasticity was 64·3 tons, and the breaking-stress 121·2 tons on the square inch, though the deflection was not very great. In torsion, the limit of elasticity was 18·5 tons, and the breaking-stress 44·6 tons per square inch (a high value), the total twist being only 1 turn on a length of 30 diameters.

The specimens P were from very hard steel, specially made for turning-tools to work without hardening in water. The tension-specimens were so hard that they could not be turned, but one of them was forged to such a shape that it might be held in the testing-machine. This piece broke at 36·25 tons, but not at the smaller sectional area, indicating that the material was injured by forging; the fracture had a vitreous appearance. In compression, the limit of elasticity was not reached at 45 tons; but the steel-yard drop was observed at 51·3 tons per square inch. These pieces stood the whole load of the machine, a stress of 52·05 tons per square inch, without buckling perceptibly. In bending, the breaking-stress was 57·4 tons per square inch, no limit or steel-yard drop being perceptible. The total deflection just before fracture was not more than  $\frac{1}{8}$  inch. Similar fractures of tool-steel have been obtained by Mr. J. J. Webster, Assoc. M. Inst. C.E., under a monkey-test.<sup>1</sup> A piece of this steel was tested in torsion up to 20 tons per square inch stress, and there was no sign of a "limit" or of fracture.

Specimens Q and R show the relative values of crucible-steel forging and casting. The commercial limits were respectively 18·3 and 20·2 tons per square inch; the extension of the forging, however, was 26·5 per cent., and its reduction of area 65·4 per cent., while those for the casting were 1·8 per cent. and 7·7 per cent. respectively.

The experiments recorded in this Paper seem to lead to the following general conclusions:—

The values of the specific extension and of the modulus of elasticity for wrought iron and steel are nearly the same, but the tests indicate that, as a rule, the softer and purer the iron or steel, the higher is the modulus; whilst the harder steels, in

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<sup>1</sup> Minutes of Proceedings Inst. C.E., vol. lx., p. 161.

which a greater percentage of carbon is present, have a lower modulus of elasticity. Thus:—

	Inches.	Per Cent.	$\epsilon$	E
E Soft forged steel with extension on 10 = 17·0	has	0·309		32,474,300
G Soft open-hearth steel . . . . .	21·6	„ 0·316		31,688,300
F B.B.H. wrought iron . . . . .	22·3	„ 0·323		30,950,700
M Bowling iron . . . . .	19·8	„ 0·333		30,027,800
L Bessemer steel . . . . .	19·7	„ 0·336		29,759,500
H Harder open-hearth steel . . . . .	20·2	„ 0·337		29,722,000
N Cast crucible steel . . . . .	nil	„ 0·349		28,796,000
O Crucible steel bar . . . . .	9·5	„ 0·350		28,546,000
D Cast open-hearth steel . . . . .	nil	„ 0·383		26,089,000

showing clearly that the modulus of elasticity decreases as the hardness of the material increases.

Cast iron, which is furthest removed from pure iron, has a modulus varying between 11,250,000 and 16,500,000 lbs. From other experiments made by the Author, its average value seems to be about 12,500,000 lbs.

The values given for the modulus of transverse elasticity do not show the peculiarities just referred to in so marked a manner, though its values for the crucible-steel specimens O and P are low, and for cast iron far lower. It will be noticed that the modulus of elasticity varies for each material in the tension, compression, and bending-experiments. The difference between the moduli in tension and compression does not, as a rule, exceed 10 per cent. This is no doubt in part due to variations in the quality of the material in different specimens. The difference between the moduli in tension and bending generally exceeds 10 per cent. This, too, may to some extent be attributed to the cause above mentioned; but probably the internal conditions of a beam under stress are not yet entirely understood.

Attention is directed to the fact that, in all cases, the ultimate strength of each material is greater in the form of a beam than in that of a tie. This anomaly has given rise to considerable discussion, and the fraction  $\frac{\text{ultimate strength in bending}}{\text{ultimate strength in tension}}$ , which in all cases is greater than unity, is denoted by  $\phi$ . Mr. B. Baker, M. Inst. C.E., in his work on “The Strength of Beams, Columns, and Arches,” has used the symbol  $\phi$  in a somewhat different sense, namely, as the ‘difference’ between the ultimate stresses as a beam and a tie; these two values are readily convertible.

Previous experiments have uniformly shown that  $\phi$  varies for beams of different section, its value being greatest when the

material is most concentrated at the centre. This has raised the question whether the usual method of calculating the stress in a beam (which is theoretically correct) gives a real value. The question seems to be answered by the fact that values of the modulus of elasticity have been calculated from the deflections of beams, agreeing closely with the values obtained in tension, in which the ordinary method of determining the stress in beams has been employed.

It has again been urged, that the apparent anomaly is accounted for by supposing that, after the material has passed the limit of elasticity as a beam, the position of the neutral axis is altered, and consequently the general method of calculating the stress no longer holds good. That this reasoning does not answer the question satisfactorily seems to be proved by the fact that a value  $\phi$  has been obtained, by comparison of the limits of elasticity in tension and bending, which agrees closely with that obtained by comparison of the ultimate stresses. Moreover the scaling of the beams before mentioned occurred after the limit of elasticity had been reached, showing that the neutral axis had not been shifted perceptibly to one side of the beam; and it can easily be proved that the neutral axis must be very much shifted to cause the difference in the bending and tensile stresses which actually occurs.

The only satisfactory way in which this ratio  $\phi$  can be explained, appears to be that set forth by Mr. Barlow, Past President Inst. C.E.,<sup>1</sup> namely, that the lateral action of the fibres tends to modify the effect of the unequal strains and opposite forces, thus diminishing the amount of extension and compression which would otherwise arise, and constituting an element of strength which Mr. Barlow has named the resistance of flexure.

A similar anomaly appears in connection with torsion and shear; the ultimate strength in torsion being in all cases greater than in shear. The ordinary method of calculating the stress in a shaft is proved to be correct, because the modulus of transverse elasticity (C), in determining which the values of the stress obtained by using ordinary formulas have been used, agrees closely with values for C obtained in shear.

For reference, the ratio  $\frac{\text{breaking stress in shear}}{\text{breaking stress in tension}}$  is calculated for each material; with the exception of the cast-steel D, this ratio is a proper fraction.

Referring to Plate 15, Figs. 1 to 9, the stresses are set off as

<sup>1</sup> Philosophical Transactions, 1855 to 1857.

abscissas, and the corresponding strains as ordinates. The four lines on each diagram, represent the two sets of readings of the actual strains, and of the permanent strains or "sets;" the full lines refer to the total strains, and the dotted lines to the permanent strains.

The strains and sets in the first trial are always greater than in the second. This, as is well known, is due to the presence of initial strain in the piece, which is not present after the first trial. In the tests under all of the four conditions, the elastic line is very nearly straight up to the limit of elasticity; but it then begins to curve upwards rapidly. In testing cast iron, no "limit" is reached, the elastic line curving slowly upwards from the commencement of the test.

A special point, demonstrated in these diagrams, is that the "elastic strain," or the strain in excess of the permanent strain, is the same in both trials, so that the strain for a given stress in the first trial exceeds that for the same stress in the second trial by an amount nearly equal to the "set" in the first trial. This holds good for all the materials tested, and in whatever manner. A similar result has been observed by Professor Kennedy, and was referred to by him in the discussion on his Paper on "Riveted Joints."<sup>1</sup> In testing a specimen to obtain its modulus, it would seem best to strain it to about three-quarters of the limit before commencing to record the readings. The initial strain is thus taken out of the piece, and the readings would be substantially the same as those shown as the second curve in Figs. 1 to 9.

It may be well to mention that the construction of the torsion-machine is such as to allow freedom to the piece under test to lengthen or shorten. In these experiments it was found that the tendency under twist was to lengthen, but only to a small extent, never exceeding 0.25 inch on a length of 30 inches, and observable only in the softer materials.

The order in which the limit of elasticity was successively reached was practically the same throughout, and cast iron was always strained to a much greater extent for a given stress than any other material within the limit of elasticity.

The ratio of the modulus of transverse elasticity to the modulus of direct elasticity =  $\frac{C}{E}$ , and designated by the symbol  $\mu$ , varied, cast iron being excluded, from 0.375 to 0.486, its average value

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<sup>1</sup> Institution of Mechanical Engineers. Proceedings, 1881, p. 288.

TABULATED RESULTS OF TESTS.

TEST MARK.	MATERIAL, ETC.	TENSION-TESTS.								COMPRESSION-TESTS.						BENDING-TESTS.					TORSION-TESTS.					SHEAR-TESTS.		I ATIOS.						
		Number of Experiments in average.	Specific Ex-tension. (e)	Modulus of Elasticity. (E)	Limit of Elasticity by Diagram.	Steelyard Drop.	Breaking Stress.	Extension on 10 inches after Fracture.	Reduction of Area after Fracture.	Number of Experiments in average.	Specific Compression. (e)	Modulus of Elasticity. (E)	Limit of Elasticity by Diagram.	Steelyard Drop.	Crushing Stress.	Ratio. length diam.	Number of Experiments in average.	Modulus of Elasticity. (E)	Limit of Elasticity by Diagram.	Steelyard Drop.	Breaking Stress.	Number of Experiments in average.	Modulus of Transverse Elasticity. (C)	Limit of Elasticity by Diagram.	Breaking Stress.	Twist after Fracture on a length of 30 dias.	Number of Experiments in average.	Shearing Stress.	Test Mark.	Bending stress Tensile stress $\phi$	Limit in bending Limit in tension $\phi_1$	Torsile stress Shearing stress $\Phi$	Shearing stress Tensile stress	$\frac{e}{E} = \mu$ (E in tension).
A	Cast iron, turned . . . .	2	0·889	11,623,000	Tons per sq. inch. ..	Tons per sq. inch. ..	Tons per sq. inch. 10·750	Per cent. ..	Per cent. ..	2	0·584	17,169,000	Tons per sq. inch. ..	Tons per sq. inch. ..	Tons per sq. inch. 57·955	8·64	..	..	Tons per sq. inch. ..	Tons per sq. inch. ..	Tons per sq. inch. ..	..	..	Tons per sq. inch. ..	Tons per sq. inch. ..	No. of turns. ..	..	Tons per sq. inch. ..	A	..	..	..	..	..
A	„ unturned . . . .	1	0·704	14,204,000	..	..	9·006	..	..	2	0·581	17,234,000	..	..	36·920	8·60	2	15,263,800	..	..	17·262	..	..	..	..	..	..	..	A	1·9167	..	..	..	..
B	„ turned . . . .	2	0·610	16,404,500	..	..	12·517	..	..	2	0·626	16,024,500	..	..	28·458	11·60	..	..	..	..	..	3	5,514,740	..	14·471	0·04	2	12·338	B	..	..	1·1729	0·9857	0·3362
B	„ unturned . . . .	2	0·604	16,552,500	..	..	9·728	..	..	2	0·632	15,814,000	..	..	28·580	11·33	2	15,777,000	..	..	19·713	3	6,066,920	..	18·913	0·08	..	..	B	2·0265	..	..	..	0·3665
C	Wrought iron plate . . . .	2	0·320	31,252,000	..	11·325	19·125	1·5	4·3	..	..	..	..	..	..	..	2	25,847,000	..	34·825	36·225	..	..	..	..	..	..	C	1·8941	..	..	..	..	
D	{Stanners Closes open-hearth} steel casting . . . .	2	0·383	26,089,600	22·233	..	29·060	Nil	Nil	3	0·344	29,071,000	17·562	22·938	23·131	12·92	3	26,292,700	26·786	31·122	39·495	1	12,138,500	20·094	39·286	0·90	2	29·700	D	1·3591	1·2048	1·3228	1·0220	0·4653
E	{Stanners Closes open-hearth} steel forging . . . .	3	0·309	32,474,300	20·093	25·297	38·950	17·06	36·3	3	0·330	30,328,700	17·113	20·880	..	12·94	3	26,806,700	29·020	32·197	..	6	12,612,800	10·977	29·635	7·14	2	25·903	E	..	1·4443	1·1441	0·6650	0·3884
F	Barrow B.B.H. wrought iron .	3	0·323	30,950,700	14·509	17·075	25·410	22·3	23·9	3	0·352	28,409,000	14·137	16·475	..	13·73	3	27,777,700	22·325	25·803	..	3	12,696,700	8·928	26·042	10·56	2	22·436	F	..	1·5386	1·1607	0·8830	0·4019
G	Landore - Siemens "S" forged steel . . . .	3	0·316	31,688,300	15·625	18·310	28·415	21·6	34·0	3	0·324	30,946,600	15·625	17·857	..	13·67	3	27,318,500	24·550	26·877	51·351	3	12,917,800	11·163	30·878	7·64	2	24·663	G	..	1·5712	1·2520	0·8679	0·4077
H	{Landore-Siemens "S.M." forged} steel . . . .	3	0·337	29,722,000	17·113	19·033	31·962	20·2	42·1	3	0·347	28,837,700	18·601	20·201	..	13·58	3	27,443,000	26·786	30·587	57·229	3	13,124,800	11·807	32·865	7·75	2	26·655	H	..	1·5653	1·2330	0·8340	0·4217
K	Fry Ianson & Co.'s wrought iron	1	0·324	30,826,000	11·161	15·165	22·461	14·0	19·0	1	0·391	25,569,000	13·265	15·625	..	13·52	1	22,704,000	22·322	24·266	..	1	11,570,700	8·929	22·323	3·20	2	19·507	K	..	2·0000	1·1444	0·8685	0·3754
L	{John Brown & Co.'s Bessemer} steel . . . .	2	0·336	29,759,500	22·322	23·051	34·465	19·75	52·75	..	..	..	..	..	..	..	2	27,709,500	34·250	34·269	66·267	2	14,413,450	17·857	38·231	16·03	..	..	L	..	1·4000	..	..	0·4859
M	Bowling } along fibre . .	3	0·333	30,027,600	12·649	14·446	20·954	19·8	29·8	2	0·362	27,693,000	8·929	12·436	..	13·71	3	27,196,400	19·759	22·035	..	2	12,715,150	7·812	27·232	14·48	2	18·933	M	..	1·5621	1·4384	0·9035	0·4416
M	Wrought iron } across „ . .	1	0·383	26,089,600	11·161	14·353	18·433	7·5	9·6	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	M	..	..	..	..	..	
N	Bowling crucible-steel casting	2	0·349	28,796,000	20·099	..	22·517	Nil	Nil	2	0·374	26,729,000	22·322	24·432	26·751	13·61	2	27,157,000	31·250	35·159	42·704	1	13,048,300	19·643	29·576	0·25	2	18·903	N	1·8965	1·5548	1·5616	0·8395	0·4081
O	Jessop crucible-steel forging .	2	0·350	28,546,000	24·554	25·102	47·048	9·5	25·0	2	0·352	28,370,500	22·322	31·563	36·605	11·71	2	28,441,000	..	64·369	121·20	2	11,729,000	18·528	44·687	1·00	2	33·134	O	2·5761	2·0400	..	0·7043	0·4109
P	„ tool steel . . . .	..	..	..	..	..	..	..	..	2	0·376	26,618,000	..	51·339	..	11·43	2	29,716,000	..	..	57·397	1	11,588,000	..	..	..	..	..	P	..	..	..	..	0·4314
Q	„ soft forged crucible-steel	1	0·321	31,153,000	17·857	18·303	26·529	26·5	65·4	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Q	..	..	..	..	..	
R	„ crucible-steel casting .	1	0·313	29,154,000	16·964	20·218	34·654	1·8	7·7	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	R	..	..	..	..	..	

being 0.4271 apparently increasing in proportion to the hardness of the material. It has been proved that for a perfectly elastic material,  $\mu \left( = \frac{C}{E} \right) = 0.4$ . For most of the materials tested  $\mu$  was greater than this; but the average value was not much in excess of the theoretical value. For cast iron, this ratio had a value about 12 per cent. below that of a perfectly elastic body.

The question as to the relative commercial value of iron and steel has been so fully discussed, that the Author feels it unnecessary here to express an opinion; but, the above experiments clearly show that steel is a more uniform and tenacious material than iron, and being, at least, equally ductile, it is to be preferred for constructive purposes.

In conclusion, the Author wishes to express his obligations to the manufacturers mentioned in the Table of Tests; also to Professor Kennedy for the facilities he has so kindly afforded during the experiments, and to Mr. G. W. Butchard, Stud. Inst. C.E., his fellow-student at University College, for valuable co-operation in the work of testing.

The Paper is illustrated by numerous drawings, from which Plate 15 has been compiled.

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