Thesis for the degree of Doctor of Philosophy

on

THE BENDING OF STEEL, ANNEALED AND OVERSTRAINED
(and additional papers)

by DAVID BINNIE B.Sc., A.I.C.

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The experiments described in this thesis were undertaken with the object of determining the effect which tensile overstrain has on the resistance of mild steel to compression. The investigation was conducted by means of bending tests for, when a beam is bent tensile stress exists on the convex side and compressive stress exists on the concave side of the stressed beam. Since the effect of tensile overstrain on the resistance of steel to tension is known, the compressional resistance offered might be inferred from the behaviour of the bent tensile overstrained beam. As the research developed it was soon found that the interpretation of the bending of steel in the annealed condition, that is, free from overstrain, was not so simple as presupposed, also, since the bending of steel initially overstrained is really an extension of the annealed steel problem, the subject is conveniently divided into two sections; the bending of annealed steel, and the bending of steel overstrained by tension.

Part One:- THE BENDING OF ANNEALED STEEL.

The material used for the tests consisted, first of all, of different lots of half-inch mild steel rod of carbon content about 0.1 per cent. The material was always carefully annealed by heating in an electric furnace for half an hour at 900°C. followed by slow cooling in the furnace. Most of the pieces for the tensile tests required in conjunction with the bending tests were prepared by turning down the annealed rod to about 0.44 inch diameter and screwed ends were used for taking the load, an eight-inch Ewing extensometer measured the strain. The beams for the bending tests were prepared by machining the annealed rods, of length about two feet, into a rectangular shape and a smooth finish was given by grinding over the central nine inches or so of the beams. The finished dimensions of the beams were of the order, total depth 0.25 inch, total breadth 0.40 inch. The

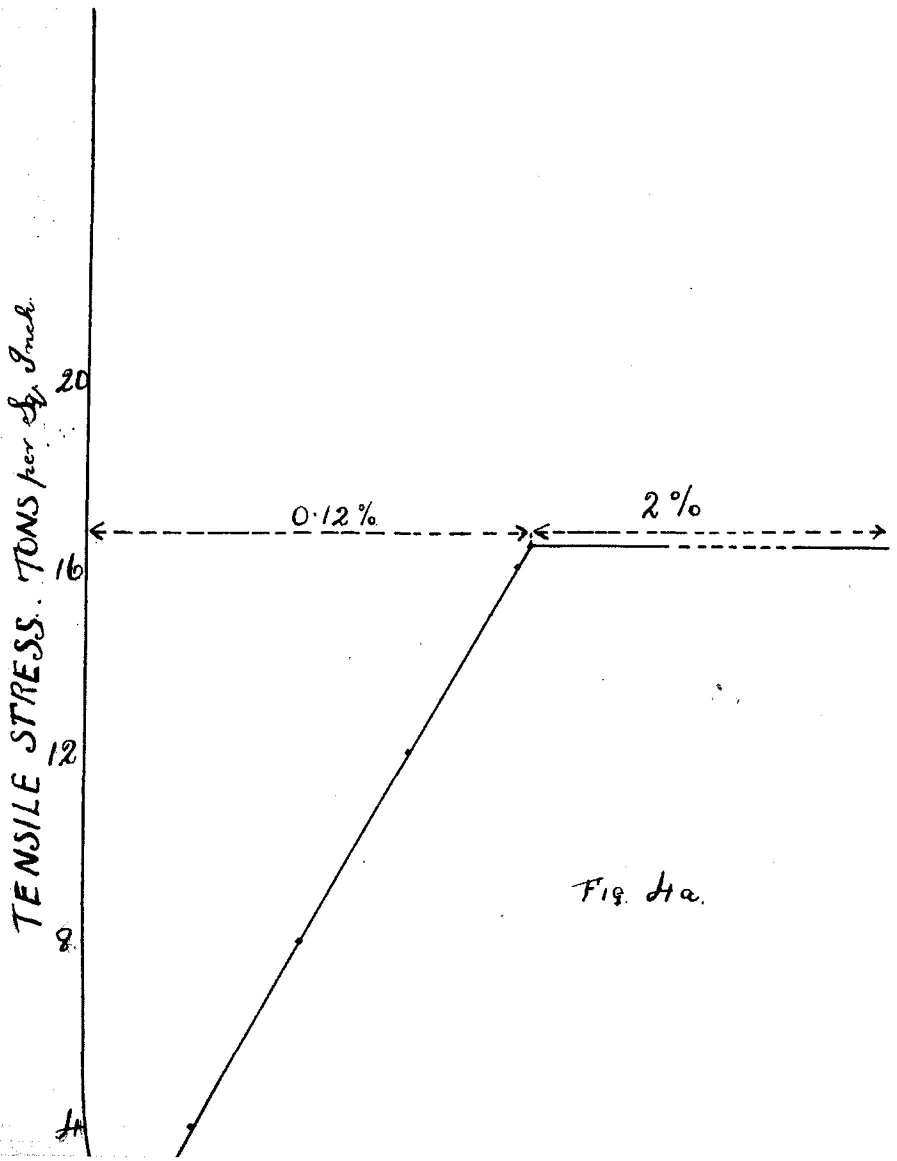

TENSILE STRESS. TONS per Sq. Inch
20
16
12
8
4
0·12%
2%

Fig. 4a.

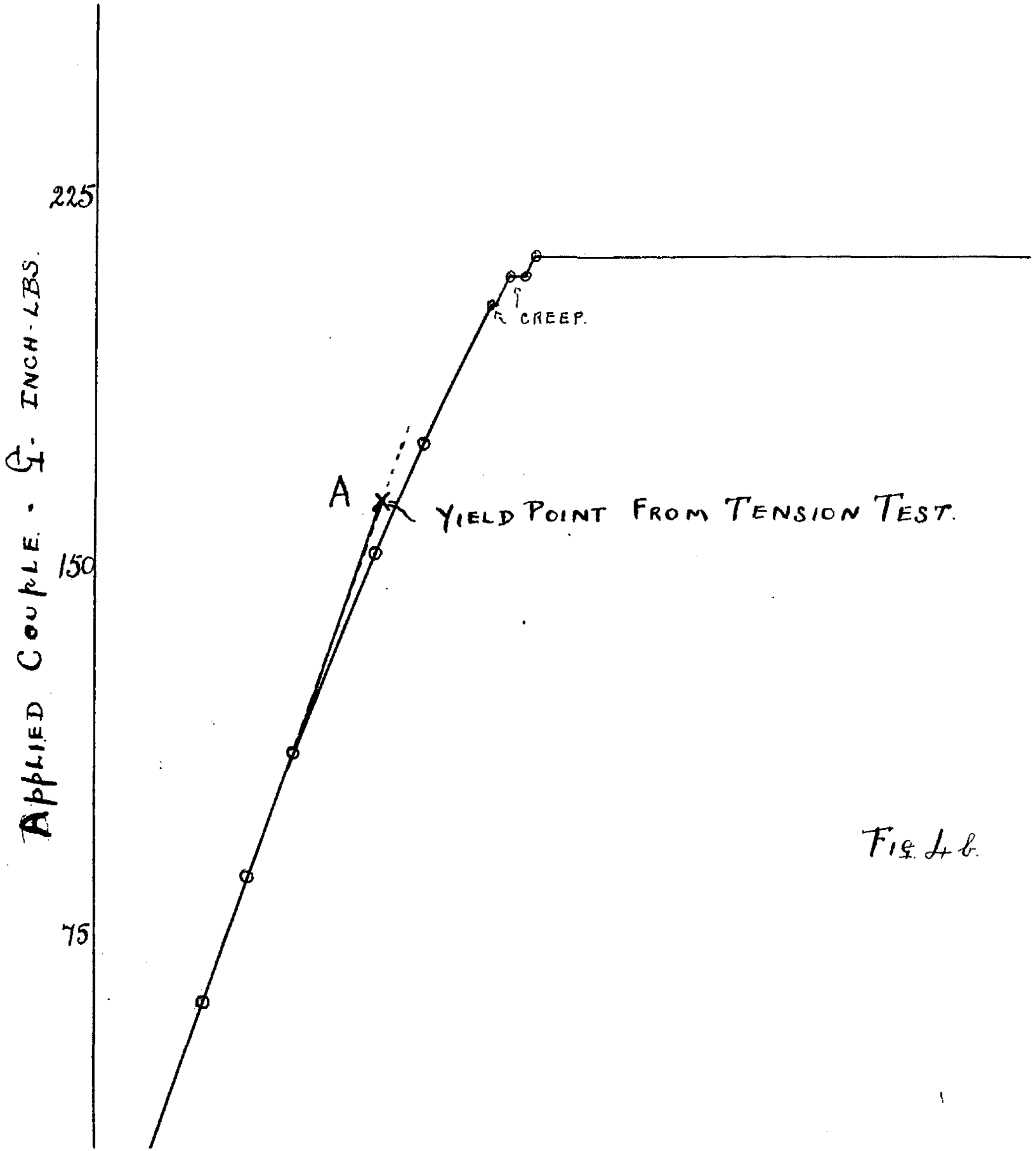
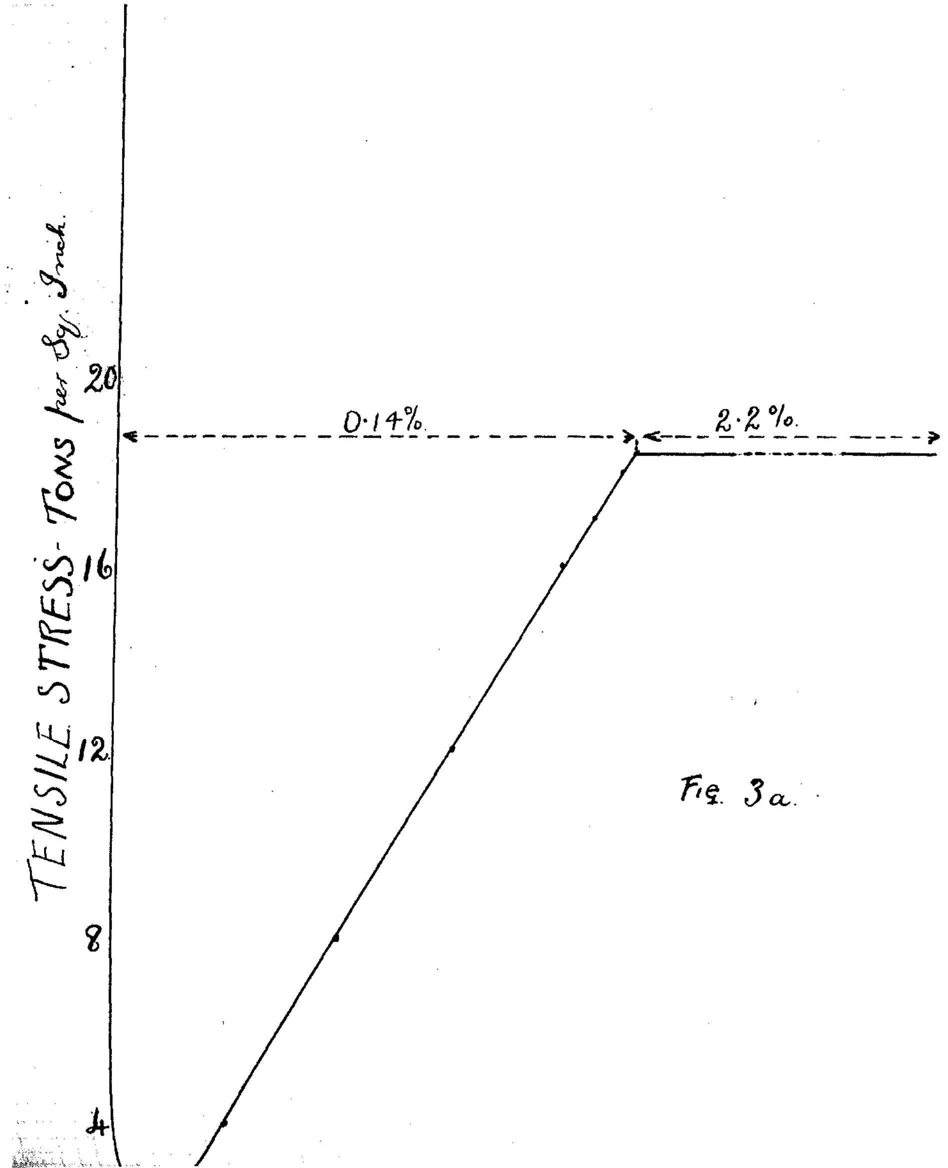
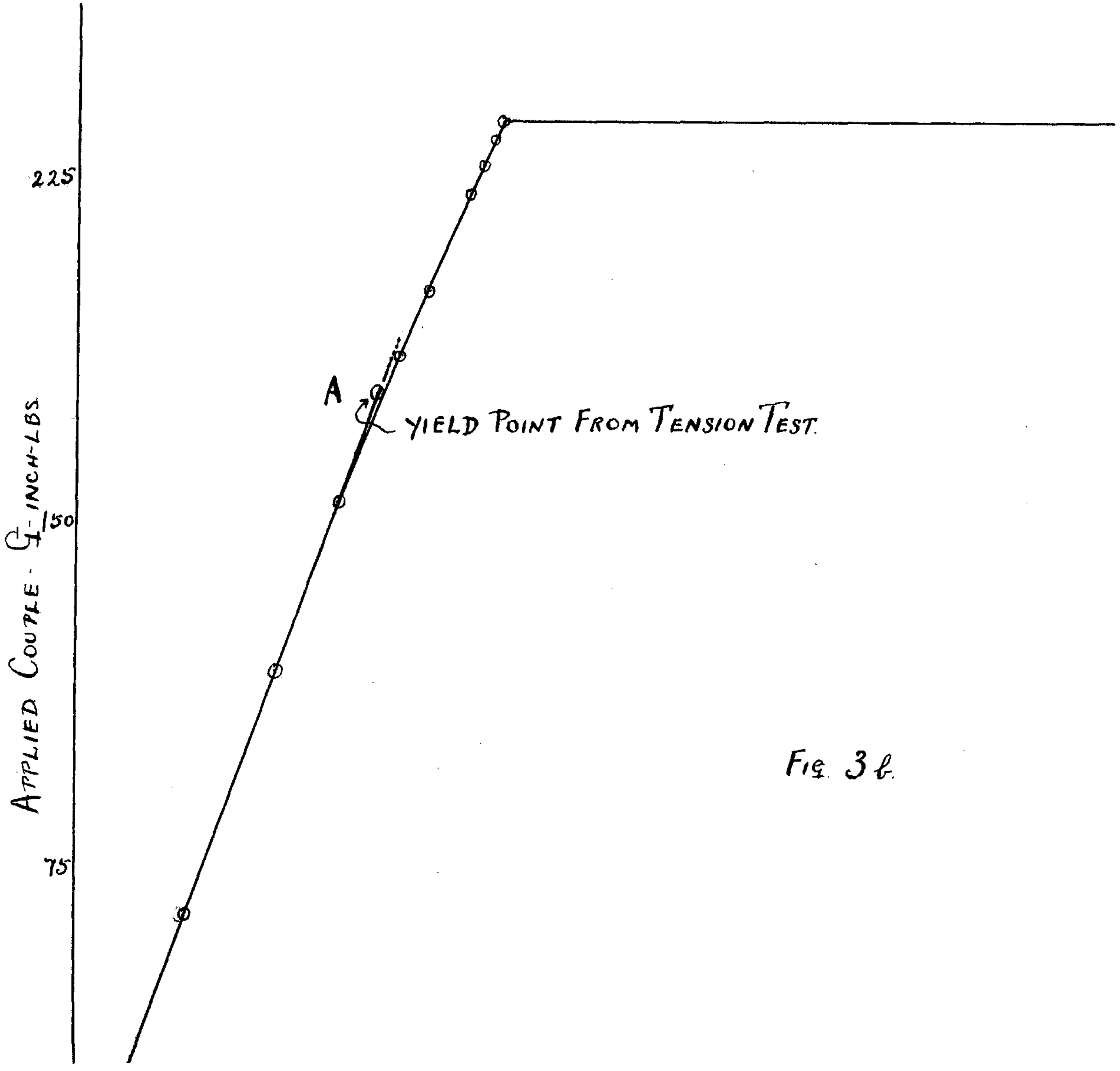

APPLIED COUPLE · G · INCH-LBS.
225
150
75
CREEP.
A
YIELD POINT FROM TENSION TEST.

Fig. 4b.



TENSILE STRESS - TONS per Sq. Inch.
20
16
12
8
4
0·14%
2·2%

Fig. 3a.



APPLIED COUPLE - G - INCH-LBS
225
150
75
A
YIELD POINT FROM TENSION TEST

Fig. 3b.

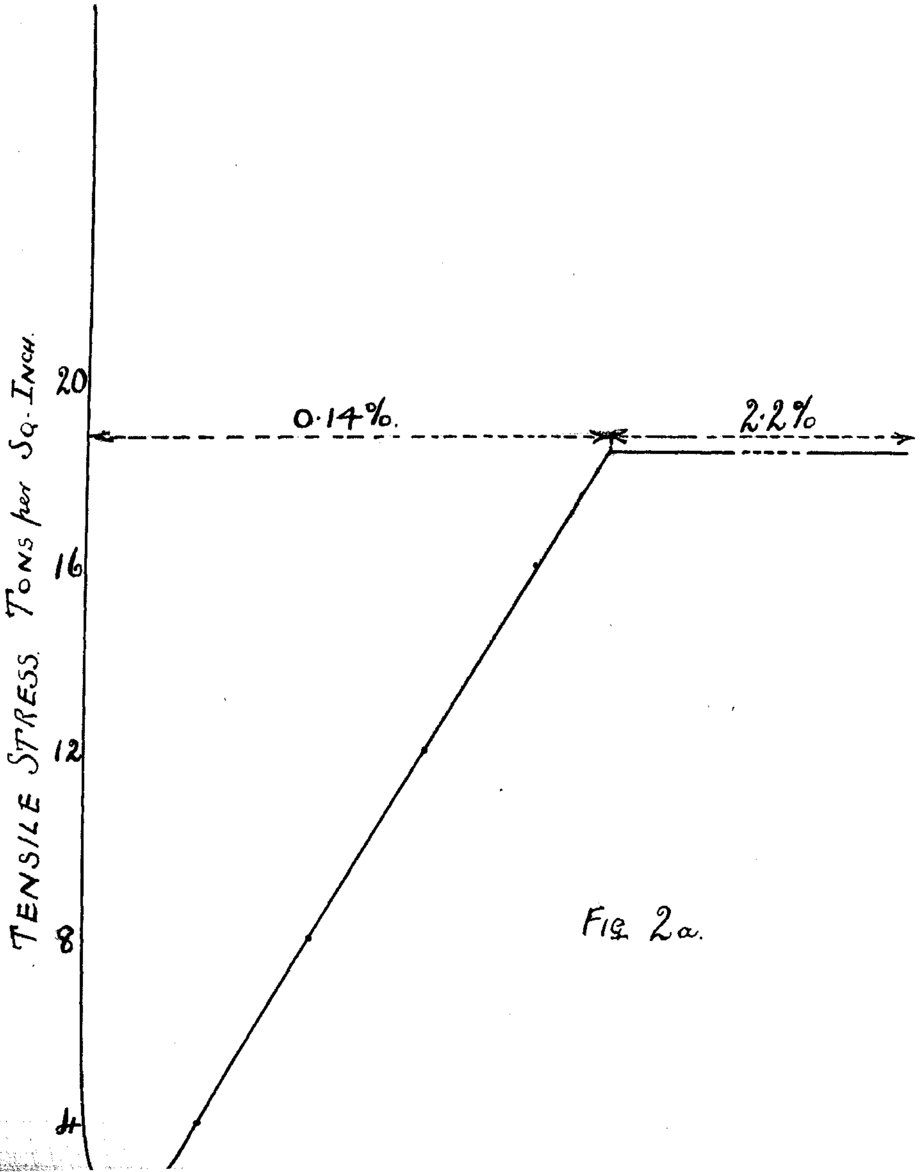

Tensile Stress Tons per Sq. Inch
20
16
12
8
4
0.14%.
2.2%

Fig. 2a.

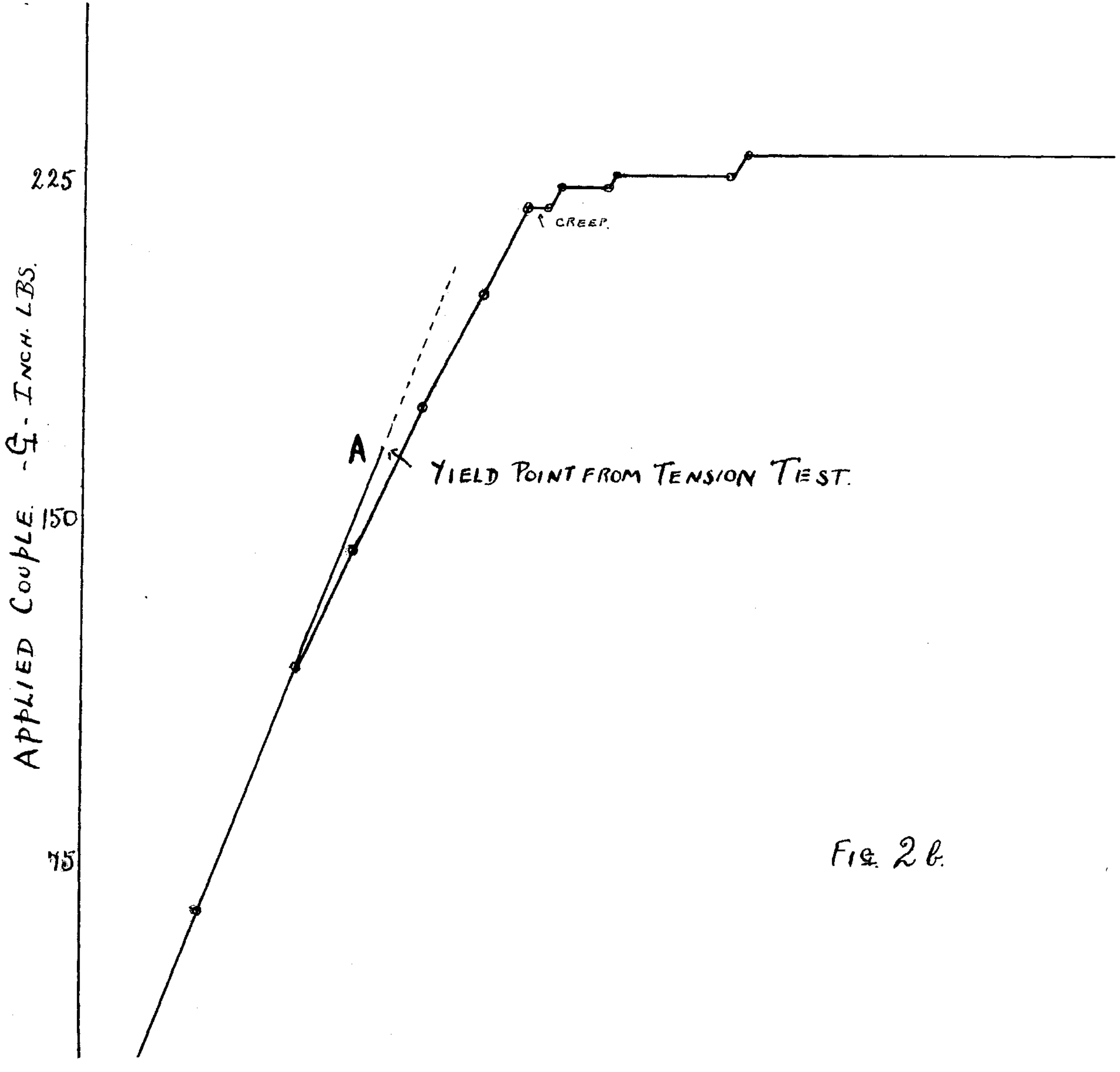

Applied Couple -G- Inch. LBS.
225
150
75
creep.
A
Yield Point from Tension Test.

Fig. 2b.

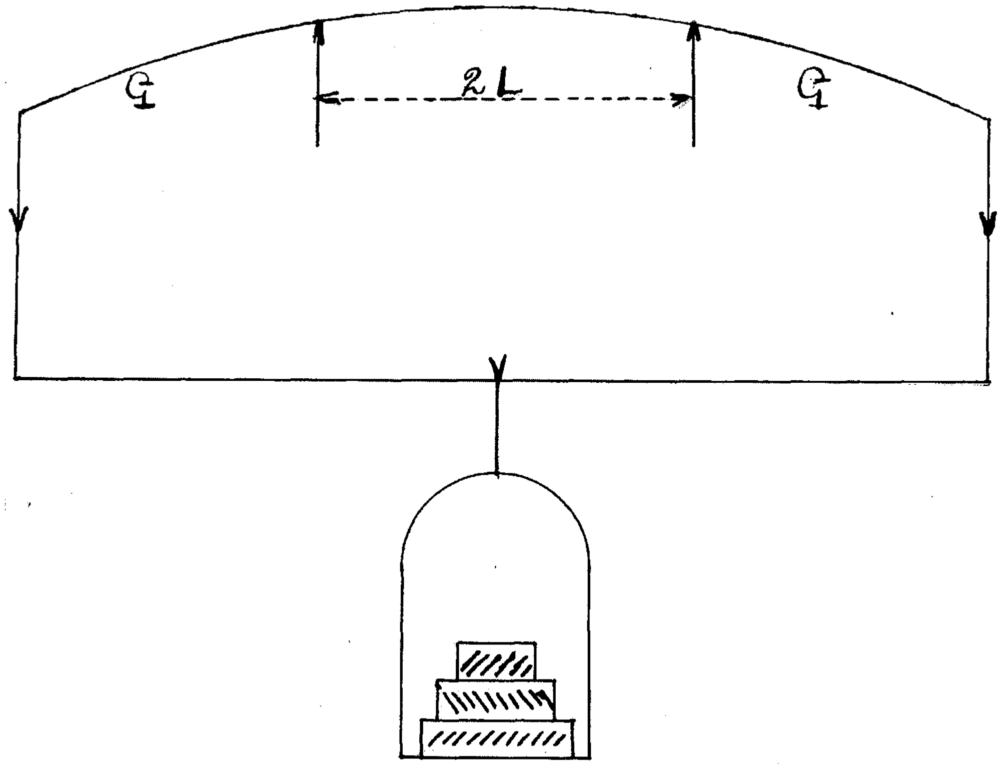


Fig 1.

bending tests were carried out in the manner illustrated by Fig.1. The beam was placed on supports five or eight inches apart and a couple G was applied as shown. Great care was taken in the applying of load to the pan when the beams were in a highly stressed condition. The method used was to lower the weights on with a spring balance attached to a kathetometer, thus very small increments of couple could be given to the beams if desired, also the load was put on much more gently than could have been done by hand. The rounded knife edges were lubricated and the deflections produced by increasing couples were measured in earlier tests by means of a telescope reading on to a scale placed mid-way between knife edges. One scale division was 0.01 inch and this was subdivided into 40 by means of a scale placed in the eyepiece of the telescope. One eyepiece scale division was thus equivalent to 0.00025 inch.

Fig. 2a represents a tensile test carried out on the material, strained up to the completion of the yield-point and no more. The material showed almost perfect elasticity up to a stress of f= 18.5 tons when the strain was 56.0 extensometer divisions on an eight inch length or 0.14 per cent. At this stress the material yielded sharply giving a permanent set of 0.17 inch or 2.2 per cent, that is, 16 times the elastic extension at the yield-point. The modulus of elasticity for the steel was 29.9×10^6 lbs. per square inch. A prepared beam of the same material was now subjected to the pure couple bending, the curve obtained by plotting couple against deflection is shown in Fig. 2b. The dotted line is the modulus line, calculated from the tensile modulus of elasticity and the accurate dimensions of the beam, total depth 2d = 0.2481 inch, total breadth 2b = 0.3933 inch. From the ordinary elastic theory of bending, the couple required to produce yield-point stress in the outermost fibres is $\frac{4fbd^2}{3}$ and the deflection Δ is then $\frac{fL^2}{2Ed}$.

These values are shown in Fig. 2b as the point A. Figs. 3 and 4 represent similarly tension and bending tests carried out on different lots of material. It is quite evident from the curves shown that the beams do not show a yield-point when the outermost fibres have attained yield-point stress, also under a larger bending moment the beams show a yielding, or more truly a buckling, which, however, is not necessarily sharp but is anticipated by much creeping. Another observation made was that the beams always showed an elastic limit lower than the elastic limit in direct tension and also it was noticed that the curvature of the highly stressed beams did not conform to the true circular arc. The portion of the beams between knife edges, just before buckling took place, could be seen to have a greater curvature at one part than at another, the effect being a sort of whale-backed appearance.

At this point of the research attention was directed to a paper published by Sir. Alex. B.W. Kennedy F.R.S.(1) in which reference is made to experiments performed 35 years earlier and new experiments are described showing how the calculated maximum stress at the yield-point observed in a bending test depends on the cross section of the steel beams used. If the maximum stress in the material, when a yield-point is observed in bending, be calculated from the applied bending moment, using the ordinary theory of bending, a much higher value is obtained than that given by the material when subjected to a simple tensile or compressive test. For example, the ratio of the yield-point stress, calculated from a bending test, to the yield-point stress found from a simple tension test is given as 1.98 for a bar of square section placed on edge, and 1.55 for a certain rectangular bar. This exaltation of the yield-point is accounted for in a general way (in the paper referred to) by supposing the less stressed material near the neutral axis to give support to the more stressed. It will be shown, however, in what follows, that this increase in yield-point is merely apparent; some material in the outside fibres of a bent beam yields when the stress, as

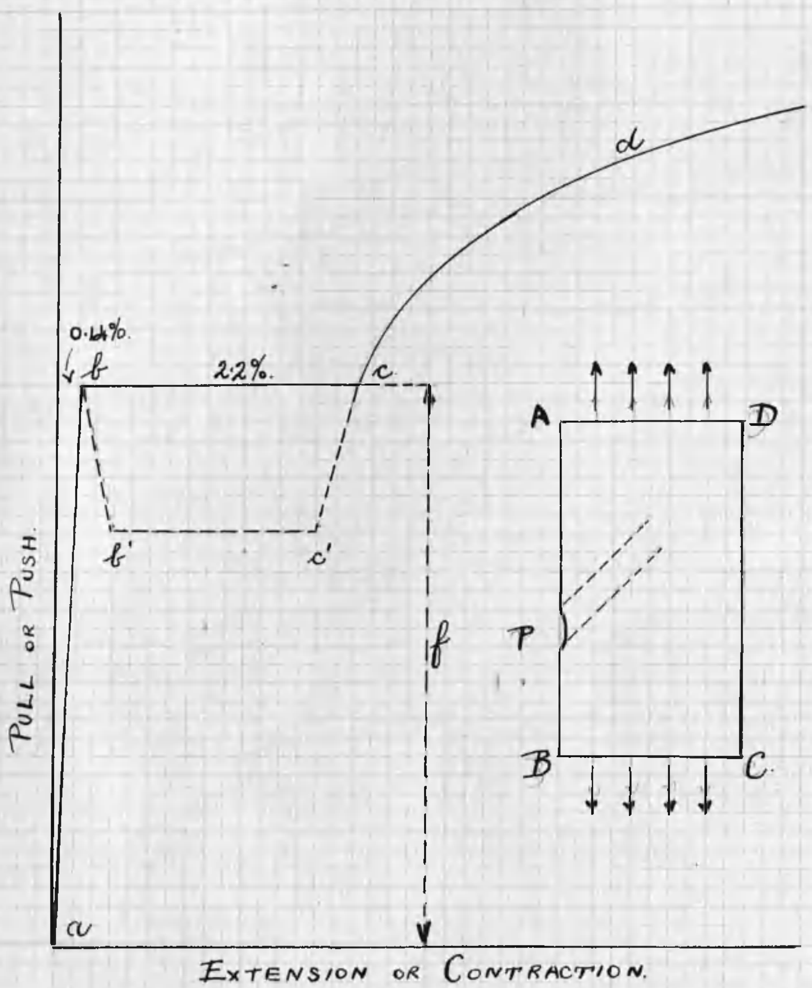


Fig 5.

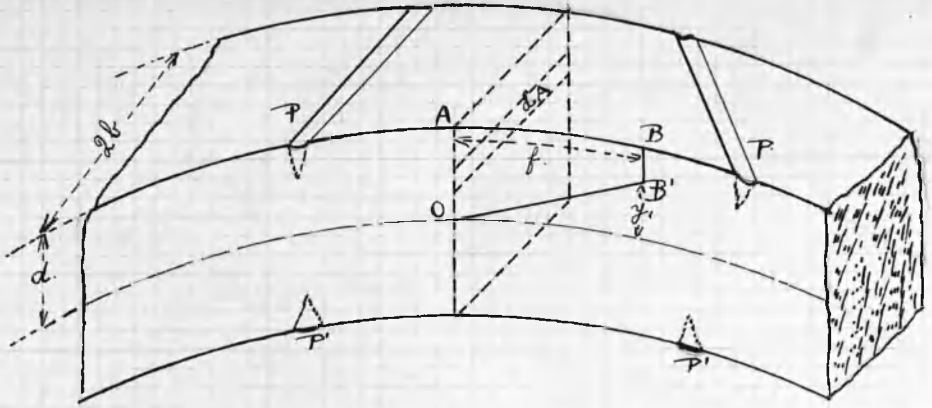


Fig 6.

Fig 7.

calculated by the elementary theory of bending, reaches the yield-point stress as given by a simple tension test, but there is then a new distribution of stress which necessitates modification of the elementary theory and masks the initial yielding of the beam.

The properties of annealed mild steel as revealed by a simple tension test will first be considered and the test used for Fig. 2a will be taken as an example. As has already been mentioned the material yielded at a stress of 18.5 tons per sq. inch when the elastic extension was 0.14 per cent, and the extension at the yield-point was 2.2 per cent or about 16 times the elastic extension. Now under compression the material would give a yield-point, as well defined as the tension yield-point, at the same stress of 18.5 tons, and it would also similarly contract 2.2 per cent. at that stress.(2) Also the modulus of elasticity would be the same in compression as in tension. It is important to remember the manner in which yield takes place at the yield-point. Suppose ABCD (Fig. 5) represents a slice of material subjected to yield-point stress f, and suppose yielding starts at some point P. A very small portion of material at P becomes incapable of withstanding the stress f until it has stretched 2.2 per cent (as the result of shearing along planes at, say, 45 degrees.) A very tiny portion of material at P will first yield by 2.2 per cent, the long fibres AP, BP, contracting elastically by amounts so small that no appreciable change results in the stress f along AB. The yielding at P will, however, cause a redistribution of stress in the material surrounding P, such that particles adjoining P will temporarily be subjected to rather greater stress than f, so these adjoining particles will yield, by 2.2 per cent, and the action will be transmitted piecemeal throughout the material.

Reference may be made here to a paper on the 'Transition from the Elastic to the Plastic State in Mild Steel' by Messrs. Robertson and Cook which was transmitted to the Royal Society by Professor J.E. Petavel F.R.S.(3) In this paper experiments are described, in which the pull applied to a tension specimen was automatically reduced as the specimen yielded, with the result that a reduction of about 25 per cent. (17 to 36 per cent.) was found possible in the total pull applied, without stopping the yield which had started at the yield point. This was interpreted by the authors to mean that a stress 25 per cent below the yield-point stress was required to keep the material yielding, when in the transition state between b and c Fig. 5, but the piecemeal character of the yielding must be remembered. At any instant of time during yield the amount of material in the transition stage must be negligibly small, the material is either in the original elastic condition or in the fully 2.2 per cent. stretched condition; and it is not difficult to picture a 25 per cent reduction in the total load giving a varying distribution of stress with a peak value equal to f, at points where the material is yielding, provided allowance be made for the fact that both material which has stretched its 2.2 per cent., and material in the original elastic condition, may be under less stress than f.

Now consider a rectangular rod subjected to the bending produced by a pure couple. The couple may be increased until the outer layers of material are subjected to yield-point stress f, then at some point P or P', Fig.6, a tiny portion of material yields 2.2 per cent., an extension on the convex side and a contraction on the concave side. This yielding will spread piecemeal across the surface and inwards towards the centre of the beam. Now the beams which had been used in the bending tests had been given a bright finish by the final grinding in their preparation and inspection revealed that the upper and lower surfaces had a network of wrinkles which could be seen to be concave on the upper or convex side and convex on the lower or concave side also inspection of the sides of the beams revealed that the wrinkles diminished in size as the neutral axis was approached, giving rise to a wedge like appearance. The next beam to be tested was then given a highly polished finish by rubbing with very fine emery paper and then when it had been bent even a small way beyond yield-point stress in the outer fibres, the formation of wrinkles and wedges could be watched. As the couple was increased the wrinkles became more numerous also the wedges became deeper. In the earlier stages of the overstrain the large central depth of still elastic material compelled the beam to retain its circular shape, the overstrained material, (the wrinkles), was regularly distributed across the whole length of the outer fibres between the points of support. But for great overstrain the overstrained material grew more at one part than at another, giving a greater curvature to that part, the shape of the beam then assumed the whale-backed appearance, and finally the beam yielded, or rather buckled, at the highest portion of the whale-backed curve. A photograph of these wrinkles, which should perhaps be described as Luders' lines produced by bending, is shown in Fig.7.

With very great overstrain, the wrinkles, except on the vertical sides of the beam disappear, the surface becoming smooth again as all the material there is then in the overstrained condition.

A rough estimate of the amount of overstrained material present at any stage during overstrain may be made as follows. Suppose the applied couple has been increased until some material has become overstrained in all layers beyond y_1, Fig.6. The distribution of stress across the section may be as illustrated by OABB' (with a similar figure for compression below.) The strain at y_1 may be taken to be the elastic strain at the yield-point, (all the material up to y_1 is elastic, - 0.14 per cent according to Fig. 5), while outside y_1 the strain is partly 2.2 per cent and partly 0.14 per cent. Now take the case when $y_1 = d/2$ and say the average strain at the outside fibre is double the yield-point strain at y_1 viz., 0.28 per cent. If L_1 is the length of elastic material in the outermost fibre and L_2 the length of material there which has stretched 2.2 per cent. then

$$L_1\left(1+\frac{0.14}{100}\right)+L_2\left(1+\frac{2.2}{100}\right)=\left(L_1+L_2\right)\left(1+\frac{0.28}{100}\right)$$

giving L_2 about 1/14th. of the total length between supports.

Coming in from the outermost fibres of material, smaller and smaller proportions of overstrained material will exist, until at $y_1 = d/2$ from the neutral axis the material is entirely elastic. Even with the large amount of overstrain assumed there is only about 1/28th. of the beam in the overstrained condition and the whole central half of the beam is entirely elastic. Even in a beam which has completely yielded there is a large amount of unstrained elastic material in all layers of the beam.

In the experiments described in Sir. Alex. Kennedy's paper the stress in the outer fibres is calculated in that paper by the ordinary formula for the bending of beams, viz. (see Fig. 6)

$$G = 2\int_0^d \frac{f'}{d}\,y.\,dA.\,y = f'\frac{I}{d} \qquad \text{(A)}$$

where f' is the stress in the outermost fibres (assumed elastic) and I is the second moment of the cross section area. But if the applied couple G is larger than required to bring the outer fibres to yield-point stress f, then this formula must be replaced by

$$G = 2\int_0^{y_1} \frac{f}{y_1}\,y.\,dA\,y. + 2\int_{y_1}^{d} f.\,dA\,y. \qquad \text{(B)}$$

For the case of a rectangular beam (2b x 2d) equation A becomes $G = \frac{4}{3}f'bd^2$.

and equation B becomes $$G = 2fb\left(d^2 - \frac{y_1^2}{3}\right)$$

If we assume that the yield-point observed in a bending test occurs when the couple G is large enough to make y_1 very small, then, neglecting $\frac{y_1^2}{3}$ the yielding stress f' calculated by the wrong formula is 1.5 times the actual yield-point stress f. Sir. Alex. Kennedy finds by experiments with rectangular bars, 1.37 to 1.58 for this ratio. Similarly for the case of his beam of square section placed on edge, equations A and B give the ratio f'/f = 2, which agrees well with the 1.98 ratio got by experiment. In the case of a beam of circular cross section the ratio f'/f is $16/3\pi$ or 1.70. These ratios, 1.5, 2, 1.70 for square on side, square on edge and circle respectively, were given by W.H. Thorpe in a letter to 'Engineering' of date June 29th. 1923, but Thorpe's assumption that the material is stressed well beyond the yield-point in tension and compression right up to the neutral axis is unnecessary. A beam has yielded largely when the overstrained material represented by the little wedges at P and P', in Fig. 6, has reached the neutral axis; and this occurs while there is still a large amount of material in the original unstrained elastic condition, the remainder of the material being stressed just beyond the yield-point and no more.

It would not be easy to develop an accurate theory which would give the deflection of a beam subjected to an overstraining couple, owing to the casual manner in which the overstrained material represented by the little wedges P and P' of Fig. 6 will form and grow. The distribution of strain in the neighbourhood of a wedge can hardly be taken as linear, and it is not even necessary that the stress distribution should remain of the form illustrated by OABB' in Fig. 6. Under a given couple a wedge might grow deeper than it ought to, B' being lowered; in which case the stress in the outermost fibres would be reduced, B going closer to A. In order to get some comparison between theory and experiment, the stress distribution

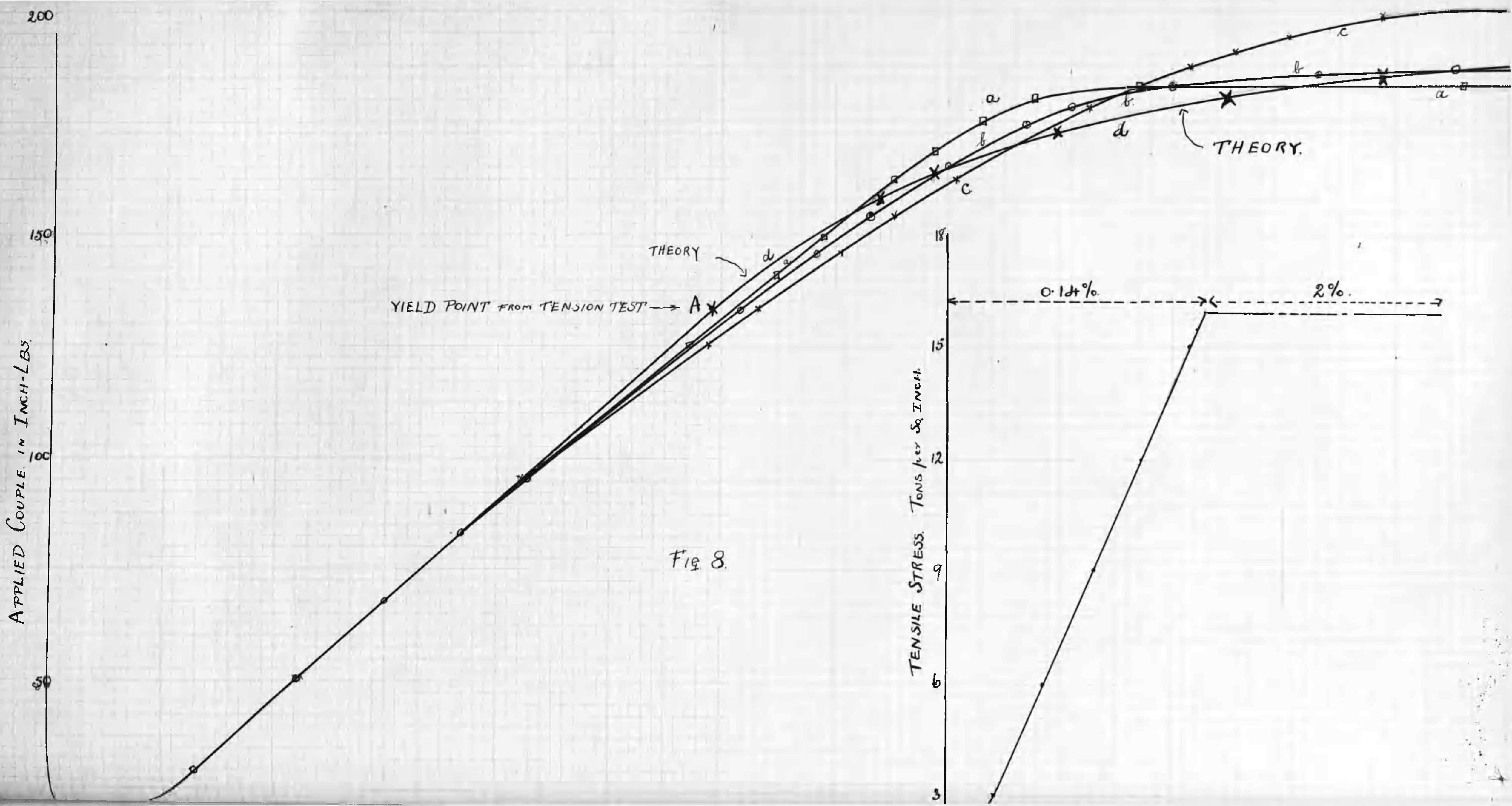

APPLIED COUPLE IN INCH-LBS.
200
150
100
50
YIELD POINT FROM TENSION TEST → A
THEORY
THEORY.
a
b
c
d
TENSILE STRESS. TONS per SQ INCH.
18
15
12
9
6
3
0·14%
2%

Fig. 8.

may be supposed to remain in accordance with OABB' [that is, the applied overstraining couple G may be taken to be $2fb\left(d^2 - \frac{y_1^2}{3}\right)$ for the case of a rectangular beam], and deflections can be calculated for an entirely elastic beam of depth $2y_1$, with stress f on its outermost fibres. The actual deflections of the whole beam (depth 2d), due to the constraint of the mixture of elastic and overstrained material will be less than these calculated values.

The theory may now be applied to the curves already recorded, Figs. 2, 3 and 4, but a new series of curves were taken which will illustrate the point fully. A test piece of annealed mild steel, carbon content 0.19 per cent., 1½ inches in diameter and 22 inches long, was cut up by very careful milling and grinding into six beams. Four of the beams had for finished dimensions, total depth = 0.250 inch, total breadth = 0.350 inch. The beams were placed on supports five inches apart and a couple G was applied. The curvature of the stressed beams was now measured by observing , with telescope and scale, the tilt of two little mirrors placed one inch inside the knife edges. The scales were placed 200 and 207.5 cms. from their respective mirrors. This provided a more sensitive method of measuring the curvature and also since the curvature of the central three inches alone was measured, any effect on the beams, due to the reaction of the knife edges, was obviated. From the curvature the deflection of the mid-point was calculated. The deflection of the mid-point against applied couple is plotted in Fig. 8. Curves a,b,c, Fig. 8 were obtained from three of the beams. Curve d, Fig. 8 was obtained entirely by calculation. A simple tensile test of the material employed gave a well defined yield-point at a stress f of 16.5 tons, with a permanent extension at the yield-point of 2 per cent. and a value for Young's modulus E = 31.1×10^6 lbs. per square inch. From the ordinary elastic theory of bending, the couple required to produce yield-point stress in the outermost fibres is $G = \frac{4fbd^2}{3}$ and the deflection

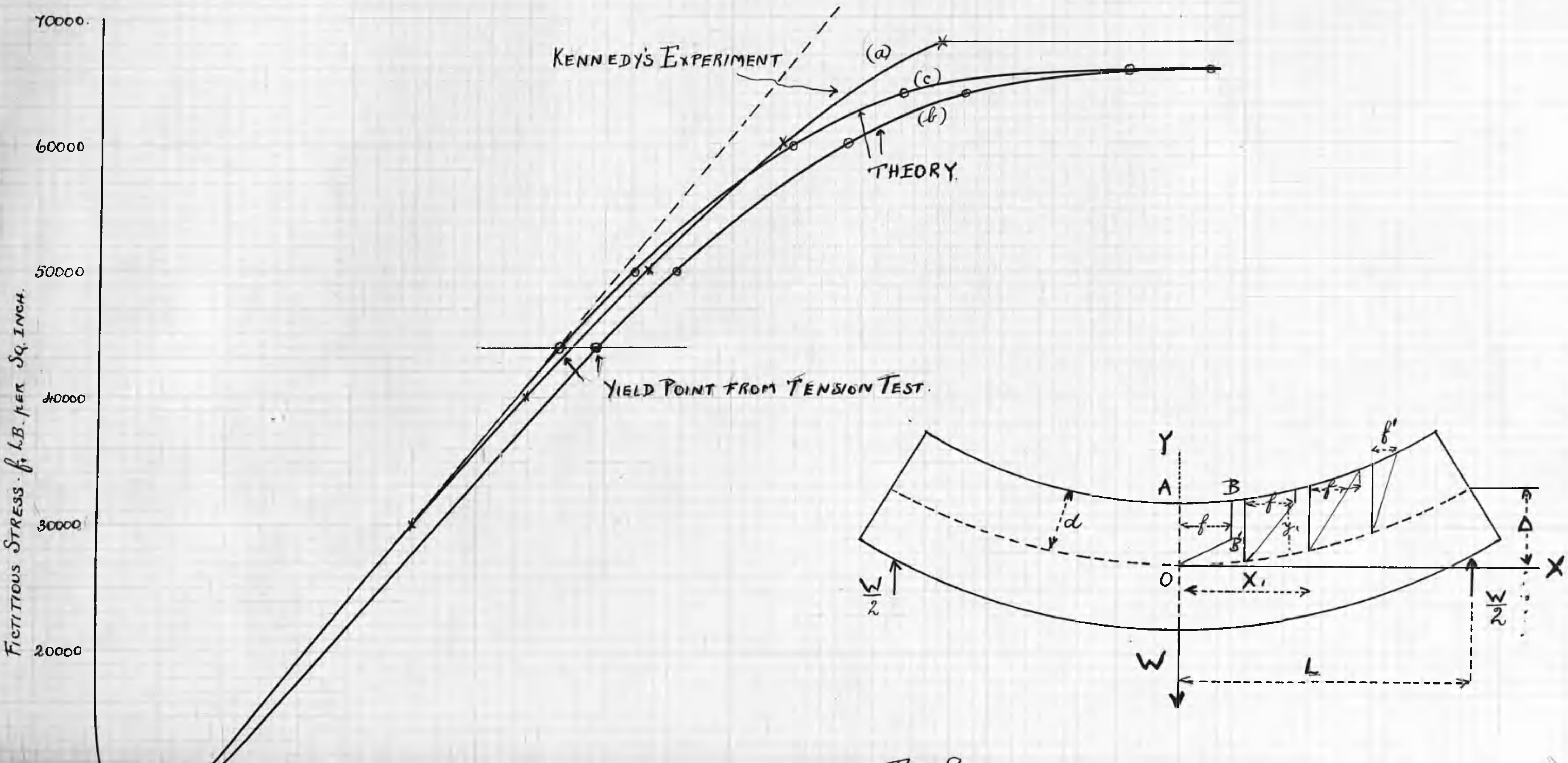

70000.
60000
50000
40000
30000
20000
10000
Fictitious Stress. f, LB. per Sq. Inch.
Kennedy's Experiment
(a)
(c)
(b)
Theory.
Yield Point from Tension Test.
Y
A
B
f
f'
d
O
X
X,
W
L
W/2
Δ

Fig 9.

is then $\Delta = \frac{fL^2}{2Ed}$. These values give point A of curve d, Fig. 8. The other points of this curve are obtained by substituting various values for y_1 in the equations

$$Q = 2fb\left(d^2 - \frac{y_1^2}{3}\right) \quad ; \quad \Delta = \frac{fL^2}{2Ey_1}$$

The agreement between theory and experiment is satisfactory; the experimental deflections are rather less than the calculated ones, in accordance with expectations. The value for the modulus of elasticity given by the bending experiments agrees with the value given by the tension test, but, as has already been stated, the bending curves always showed a decided departure from Hooke's law before the yield-point of the material was reached in the outer fibres, but, however it is scarcely to be expected that the assumptions made in the elementary theory of elastic bending, with regard to the freedom of longitudinal filaments to contract laterally, the anti-clastic curvature of the beam being neglected, and with regard to the application of imaginary 'body forces', should hold right up to the yield-point of the material.

The theory may be extended to meet the case of a centrally loaded beam and since an experimental curve of a centrally loaded beam was reproduced in Sir. Alex. Kennedy's paper, together with sufficient data, the theoretical curve can be calculated and compared with the experimental one.

The curve given was for the case of a rectangular beam, depth 2d = 1¾ inches, breadth 2b = ¾ inch placed on supports 24 inches apart. The bending moment varied along the length of the bar, the distribution of stress being as illustrated by the various figures such as OABB' on the inset diagram of Fig. 9. The beam may thus be considered in two parts, a central portion where some overstrained material exists in the outer layers, and the end portions which consist of entirely elastic material. The deflection due to the central portion will be somewhat less than Δ_1 obtained by assuming that the curvature at any point is fixed by the interior entirely elastic material (of depth $2y_1$). The deflection Δ_2 due to the elastic ends of the beam may be got from the ordinary elastic theory of bending. Details of the mathematics which are of some length, need not be given. The result is as follows:-

$$\Delta_1 = \frac{64 f^3 b^2 d^3}{27 E W^2}\left[1 - \frac{3}{2}\left(\frac{3WL}{4fbd^2} - 2\right)\sqrt{3 - \frac{3WL}{4fbd^2}} - \left(3 - \frac{3WL}{4fbd^2}\right)^{\frac{3}{2}}\right]$$

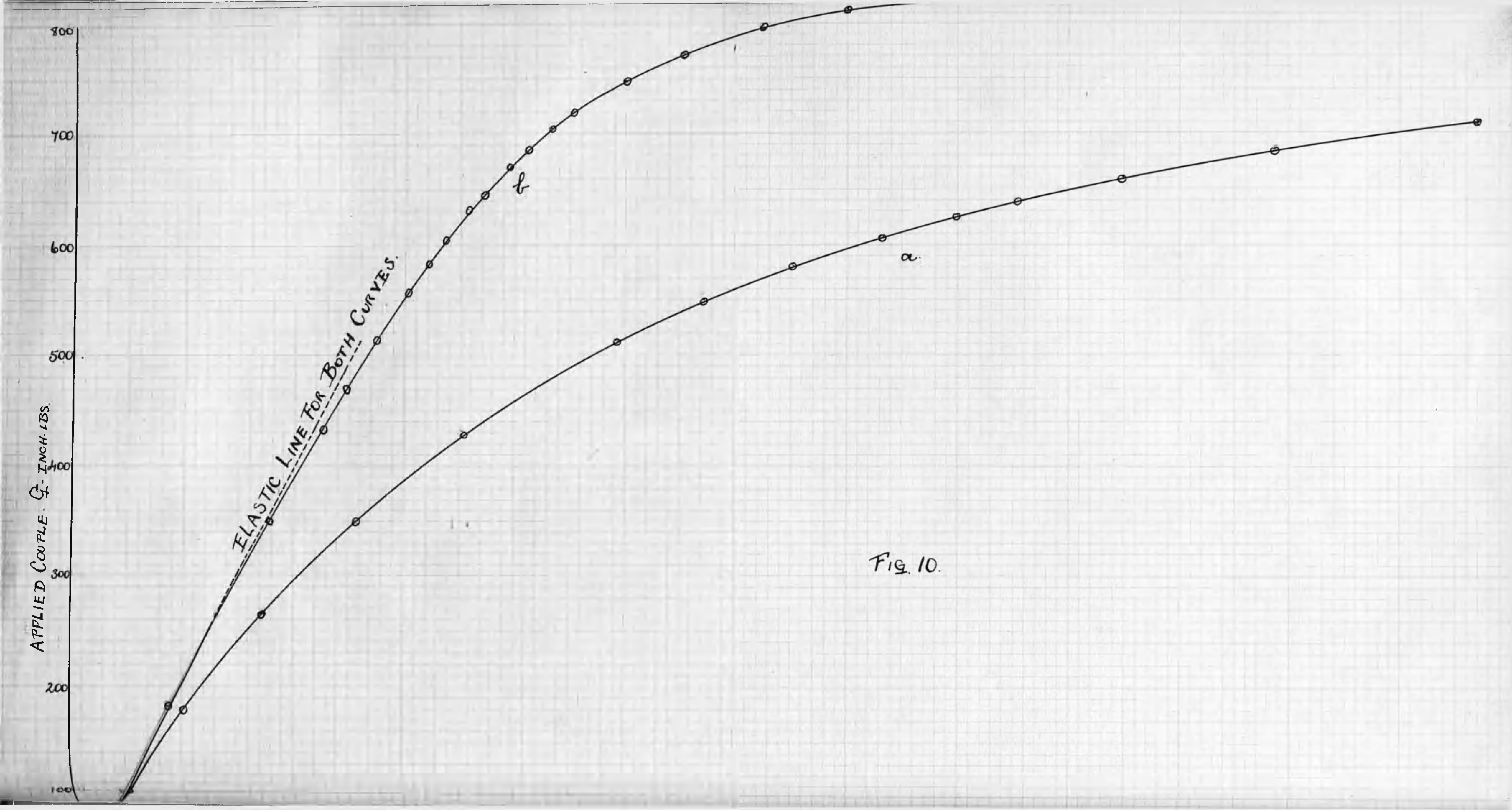
$$\Delta_2 = \frac{64 f^3 b^2 d^3}{27 E W^2}\left[4 - 3\sqrt{3 - \frac{3WL}{4fbd^2}}\right]$$

But Sir. Alex. Kennedy plots deflection against a fictitious stress (say f_1) in the outermost fibre, got by applying the ordinary elastic theory of bending. This stress f_1 is equal to $\frac{3WL}{8bd^2}$, hence

$$\Delta_1 = \frac{f^3 L^2}{3 E d f_1^2}\left[1 - 3\left(\frac{f_1}{f} - 1\right)\sqrt{3 - \frac{2f_1}{f}} - \left(3 - \frac{2f_1}{f}\right)^{\frac{3}{2}}\right]$$

$$\Delta_2 = \frac{f^3 L^2}{3 E d f_1^2}\left(4 - 3\sqrt{3 - 2\frac{f_1}{f}}\right)$$

Taking the approximate dimensions given above for the rectangular beam used and the values $f = 44,000$ lbs. per square inch, found by direct tension experiments, values for $\Delta = \Delta_1 + \Delta_2$ were calculated from the above equations for various values of f_1, and the results plotted to give curve b of Fig. 9. Curve a of Fig. 9 has been copied from the figure in "Engineering" showing the experimental curve. The marked increase in the modulus of elasticity shown by the bending experiment is difficult to account for except perhaps it may be due to the accurate dimensions of the beam not having been given. Curve c Fig. 9 is the theoretical curve taking for the modulus of elasticity the value shown by the bending experiment, 32.5×10^6 lbs. per square inch. The agreement between the calculated and experimental curves is very good, but of course it must be remembered that in the case of central loading, the mixture of elastic and overstrained material only affects the part Δ_1 of the total deflection plotted in curves b and c of Fig. 9.



APPLIED COUPLE. G - INCH. LBS.
800
700
600
500
400
300
200
100
ELASTIC LINE FOR BOTH CURVES.
b
a

Fig. 10.

Part Two: THE BENDING OF STEEL OVERSTRAINED BY TENSION.

The preliminary experiments in this work were carried out on different lots of half inch annealed mild steel rod, similar in kind to the material used in part one.

A tension test on a two foot length of rod showed a sharp yield-point at a stress of 17.5 tons, with a permanent extension of 2.5 per cent. This test piece, now in the freshly overstrained condition, would not obey Hooke's law in tension nor in compression and a bending test carried out immediately after the tensile overstraining showed the poor elasticity of the freshly overstrained material. The rod was placed on supports eight inches apart. The deflection of the mid-point of the rod was measured with telescope and scale. The curve obtained is plotted in Fig. 10a. Creeping was detected from the beginning and time was allowed for the creep to slow down before increasing the bending moment. Another length of annealed rod was taken and a tensile test on it showed a sharp yield-point at a stress of 18.5 tons with an extension of 2.5 per cent. Recovery from overstrain was effected by boiling the rod in water for ten minutes and a bending test was performed on this recovered overstrained material. The curve obtained is plotted in Fig. 10b. It is seen at once that the recovery from overstrain has distinctly hardened the material also creeping could not be detected until the beam was highly stressed. Another length of annealed material was subjected to tensile stress and a sharp yield-point was obtained at a stress of 18.7 tons. The material was boiled in water to effect recovery from overstrain and was returned to the testing machine when a new sharp yield-point was obtained at a stress of 23.2 tons. The test-piece was again boiled in water and another tensile test was performed.

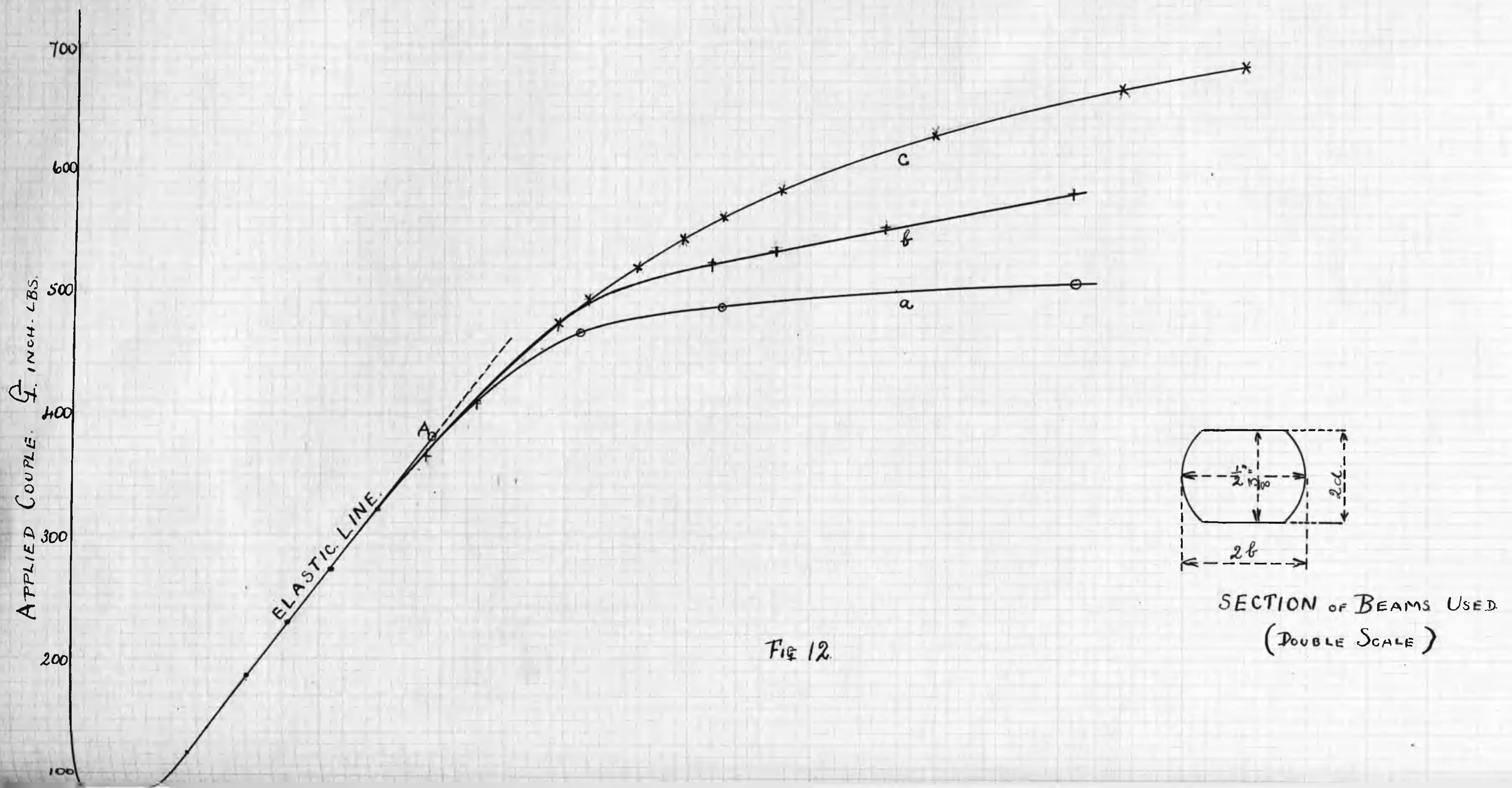
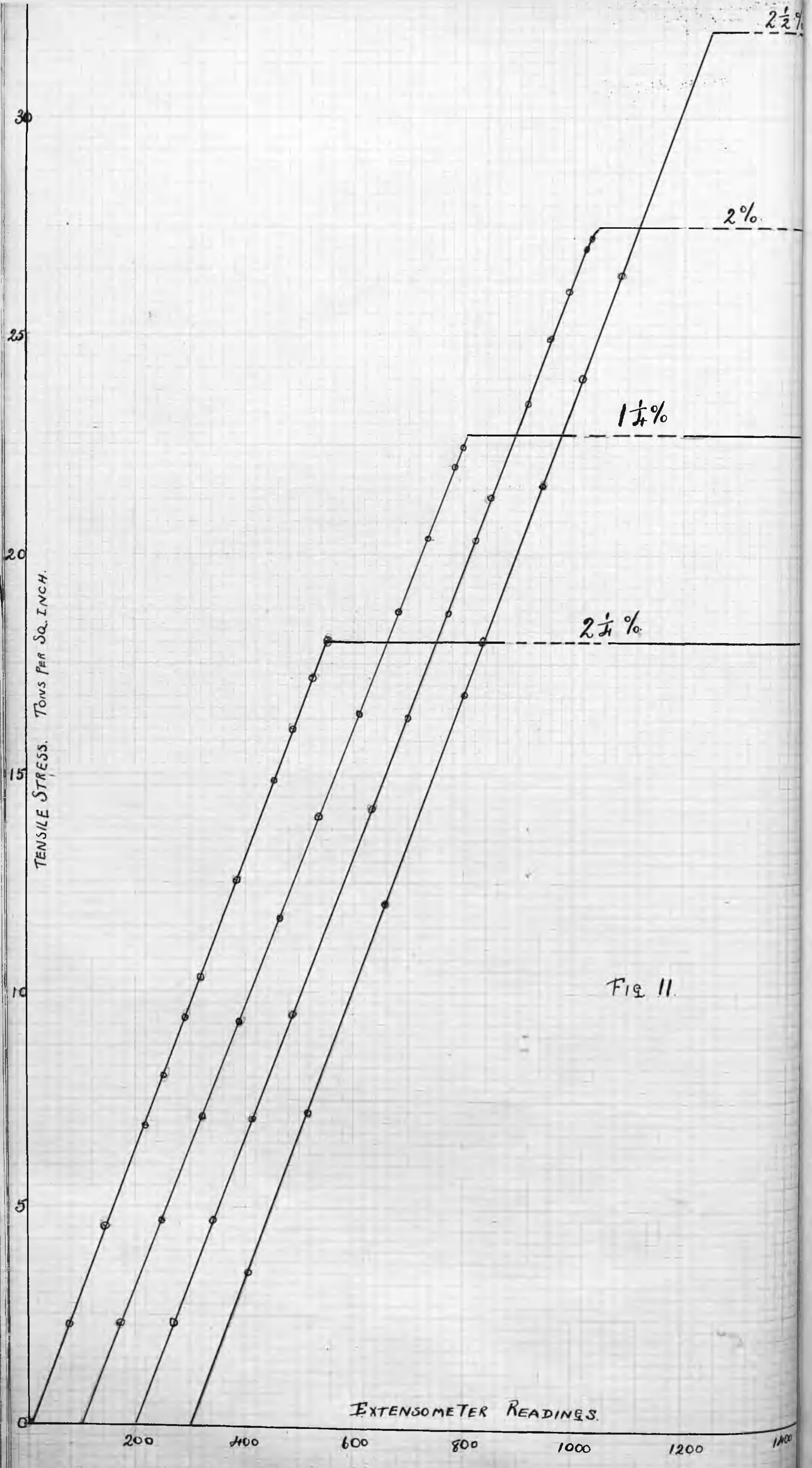

Applied Couple. G. inch. lbs.
700
600
500
400
300
200
100
Elastic Line.
A
a
b
c
2b
2d
Section of Beams Used
(Double Scale)

Fig 12.

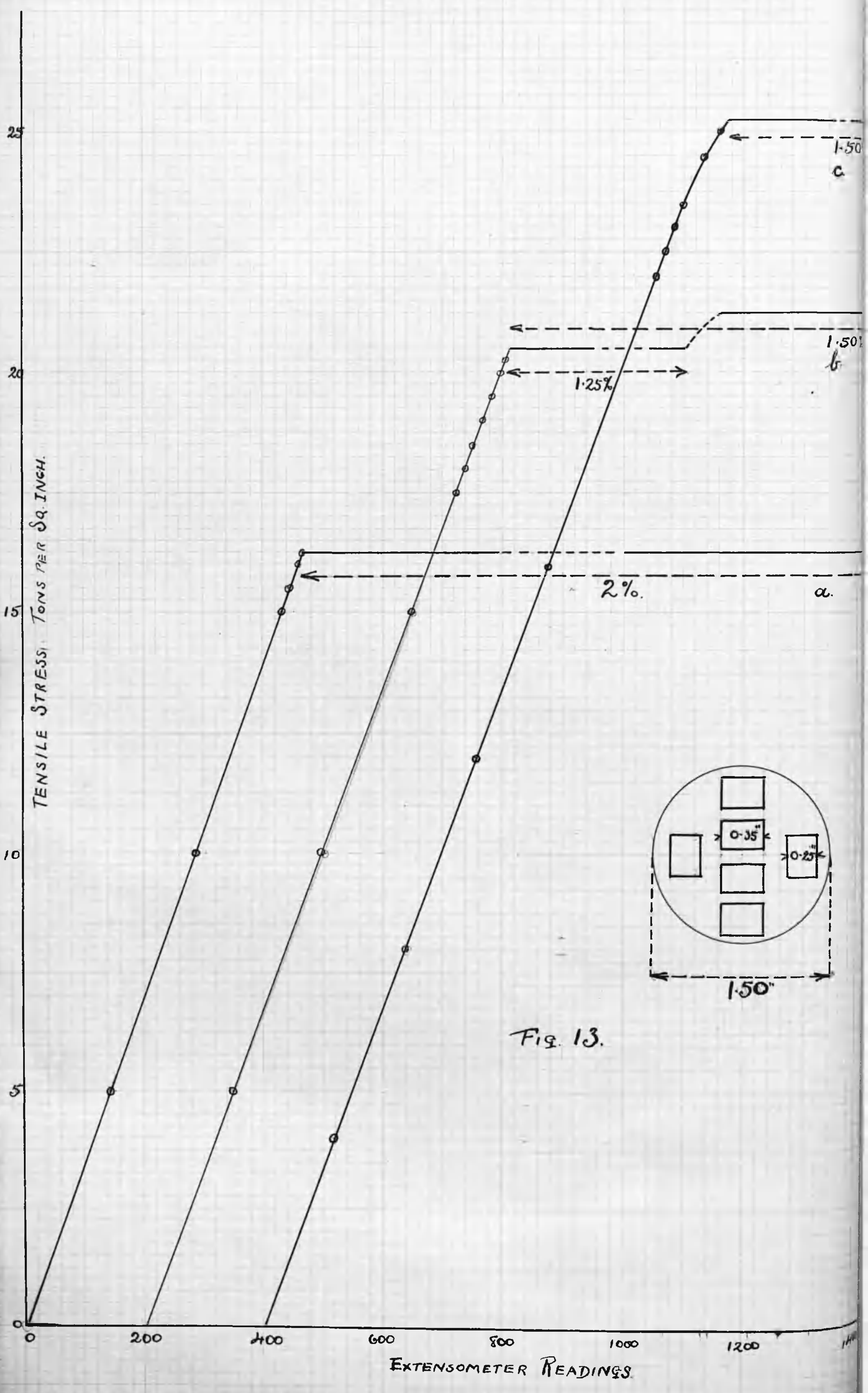


2½%
2%
1¼%
2¼%
30
25
20
15
10
5
0
TENSILE STRESS. TONS PER SQ. INCH.
EXTENSOMETER READINGS.
200
400
600
800
1000
1200
1400

FIG. 11.

A sharp yield-point now took place at a stress of 27.8 tons. The highly overstrained test-piece was again boiled in water and again returned to the testing machine. The yield-point occurred this time at a stress of 32.2 tons. These tensile curves are plotted in Fig. 11. The yield-point has been raised by steps of 4.5 or 4.6 tons and had the test-piece again been pulled after recovery, a yield-point would have occurred at a stress of (32.2 + 4.5) = 36.7 tons stress, although very likely fracture would supervene.

Now a fresh length of annealed rod was pulled and a sharp yield-point was obtained at a stress of 18.7 tons. After recovery from overstrain this material was in a condition to give a tensile yield-point at a stress of (18.7 + 4.5) = 23.2 tons stress. Another annealed rod was pulled and a yield-point was obtained at 18.0 tons stress. Recovery from overstrain was effected and on restressing a new tensile yield-point was obtained at 22.5 tons stress, (18.0 + 4.5). This test-piece, recovered from overstrain was in a condition to give a tensile yield-point at 27.0 tons stress. These two overstrained test-pieces, together with an annealed test-piece, were machined into approximately rectangular beams. The three beams were then subjected to bending tests. The three curves obtained are plotted in Fig. 12. Curve a is for the annealed material, curve b is for the material which has been given one overstrain, and curve c is for the twice overstrained material. The annealed beam whale-backed and buckled similarly to the other annealed beams but the overstrained beams in bending preserved their circular curvature even when highly stressed and the test was stopped when the curvature had become very great. The overstraining has increased the resistance of the steel to bending but the degree of overstraining, followed of course with recovery from overstrain, has not raised the elastic limit to bending.



25
20
15
10
5
0
TENSILE STRESS. TONS PER SQ. INCH.
0
200
400
600
800
1000
1200
EXTENSOMETER READINGS
1·50
c
1·50%
b
1·25%
2%.
a.
0·35"
0·25"
1·50"

Fig. 13.

Now at this point of the investigation attention was directed to a paper by W.A. Scoble B.A. (4) in which it was suggested that the outside and central portions of a permanently stretched bar might be in very different overstrained states. In order to test this matter, two large bars of carefully annealed material were obtained from Dr. Andrew McCance of the Clyde Alloy Co. Ltd. The bars were each three feet long and two inches in diameter, but they were turned down to a diameter of 1.5 inches over the central 22-inch length. The ends were cut off from one of these bars, and the central length was cut into six beams. Three of these beams, one of which was from the central portion of the large bar were used in the final tests in part one, (Fig.8). The three curves are not identical but it must be remembered that annealed steel when tested by bending ultimately fails at a more or less casual load due to the growth of wedges of overstrained material. The second bar was placed in the 100- ton testing machine of the Mechanical Engineering Department of the Royal Technical College, an 8-inch Ewing extensometer was applied, and the stress-strain curve a of Fig. 13 was obtained. A well defined yield-point is shown at a stress of 16.5 tons, the bar stretching permanently by 2.0 per cent. at that stress. The bar was now removed and recovery from overstrain was effected by heating to 100 C. for a few minutes. It was then replaced in the testing machine and a well defined yield-point was now obtained at a stress of 20.5 tons stress. The extension at this second yield-point was only 1.25 per cent. The load was increased to 21.25 tons stress when the extension was 1.50 per cent. The yield-point had thus been raised by overstrain and recovery from overstrain by a stress of 4.0 tons. The bar was again removed and recovery from overstrain was again effected by boiling in water. On restressing the bar a new tensile yield-point occurred at a stress of 25.25 tons. The yield-point had thus been raised by a second increment or step of 4.0 tons stress. No further tensile overstrain was attempted, so the material of the bar, after recovery from overstrain, was in an elastic condition which would give a yield-point in tension at 29.25, (25.25 + 4.0), tons stress. The overstrained test-piece was cut up into six beams, as illustrated by the inset diagram of Fig. 13, and it may be stated here that no difference was found in the beams cut from the central and outside portions of this test-piece.

The problem now arises as to how this overstrained material would yield under compression. Considering the large test-piece just described, the original annealed material would give a well-defined yield-point under compression at 16.5 tons stress, exactly the stress of the primary yield-point under tension, also the contraction at that compressive stress would be by 2.0 per cent,- the primary yield-point extension. (2) But would the material, hardened by tensile overstrain yield under compression at a greater or at a less stress than the primary yield-point. Possibly no well-defined yield-point might be given by material hardened by tensile overstrain. In the paper just referred to, 'On the Overstraining of Iron by Tension and Compression', the suggestion was made that, when steel is hardened by tensile overstrain, followed by recovery from overstrain, two distinct effects may be produced:-

(1) The application of an overstraining load in tension may harden the material equally as regards resistance to both tension and compression.

(2) The process of recovery from tensile overstrain, which still further strengthens the material as regards resistance to tension, (raising the yield-point by a definite step above the overstraining stress), may weaken the material as regards resistance to compression, (lowering the compression yield-point below the overstraining load by the same step).

Taking, for example, the large test-piece, at the third overstrain the material yielded at a stress of 25.25 tons, Fig. 13, with a stretch of 1.5 per cent. Now the theory just expounded states that this material in the freshly overstrained state would stand a tensile or compressive stress up to a stress of 25.25 tons without showing much further permanent set. Now on effecting recovery from overstrain, (by heating to 100° C. for a few minutes) then, as is well known, the material under tension would show practically perfect elasticity up to a stress of 29.25 (25.25 + 4) tons at which stress a definite yield-point would be obtained. The suggested theory states that under compression this material would remain elastic up to a compressive stress of 21.25, (25.25 − 4), tons stress, and at this stress a definite yield-point would be obtained. The recovery process being supposed to result in the application of an internal compressive stress of 4 tons stress. Now in the paper referred to, the experiments indicated that the suggestion was approximately correct, but the experiments were by no means conclusive. The difficulty lay in conducting satisfactory compression tests. In only one experiment, and that was with annealed material, was a really well-defined yield-point obtained. At all other yield-points in compression the stress-strain curves were rounded, and with material which had been subjected to tensile overstrain, the compression yield-points were always ill-defined. However the assumption will be made that the above suggestion is rigorously true so that the material overstrained in tension as illustrated by Fig. 13 would be in a perfectly elastic state which would give a yield-point in tension at 29.25, (25.25 + 4) tons stress, and in compression at 21.25, (25.25 − 4) tons stress.

In order to find from theory the graph which should be obtained by plotting the couple applied to a rectangular beam (2L x 2b x 2d) against the central deflection produced, for the case of material having a yield-point in tension at 29.25 tons stress and in compression at 21.25

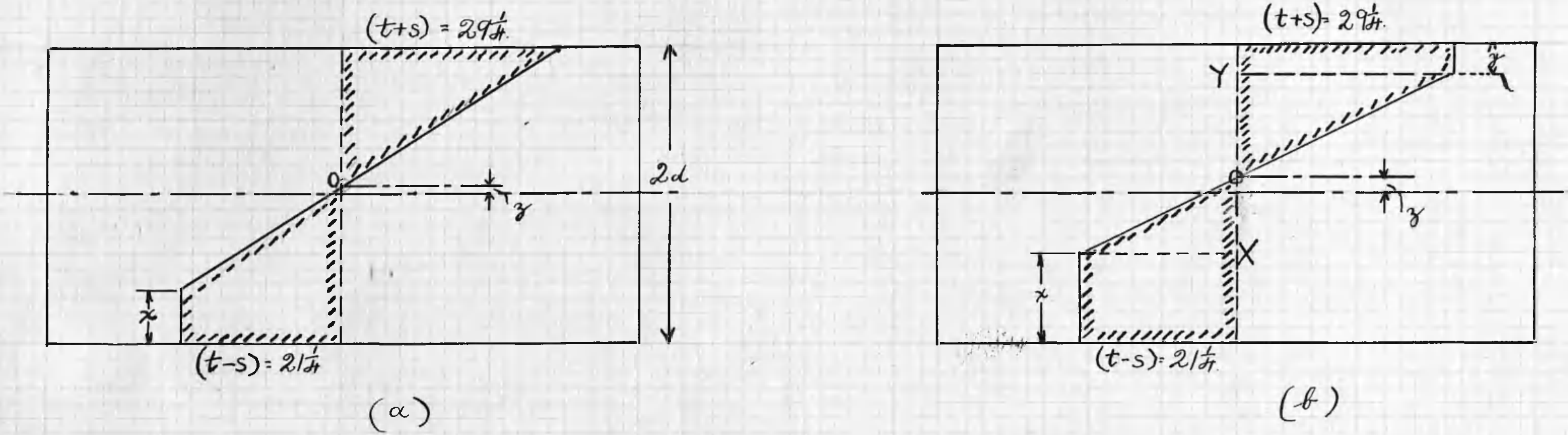


Fig 15

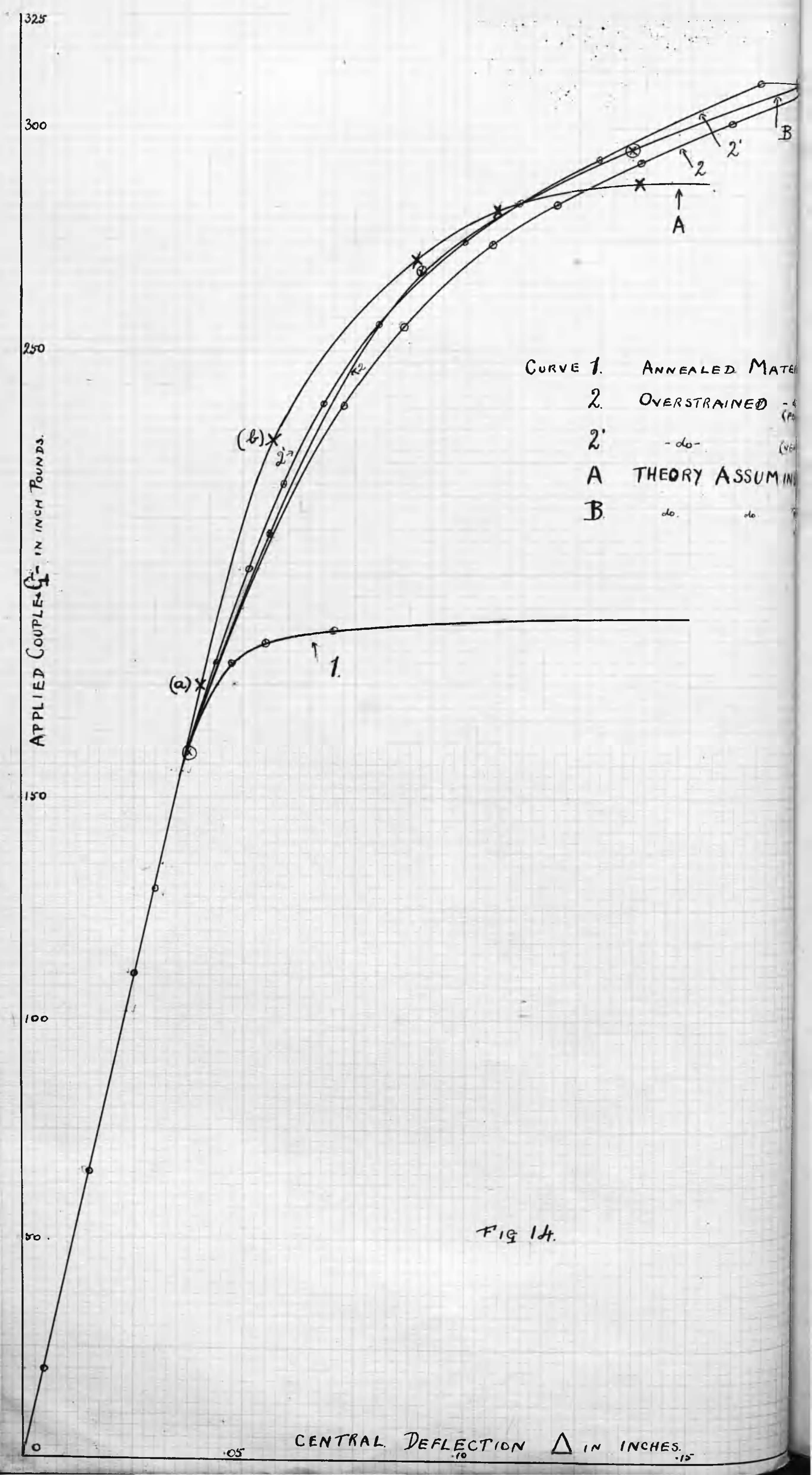

325
300
250
150
100
50
APPLIED COUPLE G_1 IN INCH POUNDS.
CENTRAL DEFLECTION Δ IN INCHES.
·05
·10
·15
CURVE 1. ANNEALED MATE
2. OVERSTRAINED
2' -do-
A THEORY ASSUMIN
B do. do.
(a)
(b)
1.
2
2'
A
B

Fig 14.

tons stress, it is desirable to take the loading in three stages. First, the graph is a straight line until the stress on both outside layers is 21.25 tons stress. During this stage the couple is given by $G = \frac{4fbd^2}{3}$ where f is the stress on the outermost fibres and the radius of curvature of the beam is given by $R = E\frac{d}{f}$ where E is Young's modulus for the material. The central deflection Δ is obtained from $2r\Delta = L^2$. The point marked (a) on Curve A Fig. 14 was obtained by substituting in these equations the values 2L = 5.00 inches, 2b = 0.350 inch, 2d = 0.250 inch, f = 21.25 x 2240 lbs. per square inch, E = 29.9 x 10^6 lbs. per square inch, the value found from Fig. 13.

During the second stage of the loading of the beam, some material has yielded in the outer fibres on the lower compression side of the beam, while the tension side remains quite elastic until the stress on the outermost tension fibres is 29.25 tons per square inch. The distribution of stress across the section of the beam will be as shown at (a) in Fig. 15. The neutral axis moves up from the centre of the beam by a distance z, which can be found from the condition that the two shaded areas must be equal, so that there may be no resultant force on the section.

Taking the end point of this stage, when the stress on the outermost fibres in tension is (t + s) say, where t is the overstraining tensile stress applied to the original bar of material (25.25 tons per square inch) and s is the step between successive yield-points (s = 4 tons per square inch), then (t − s) is the stress on a depth x of mixed overstrained and elastic material on the compressive side of the beam and $z = \frac{s^2}{t^2} \cdot d$, $x = 2\frac{s}{t} \cdot d$. The couple for this distribution of stress can be found by adding the moments about O of the two shaded areas; and the radius of curvature of the beam may be assumed reasonably to be entirely controlled by the wholly elastic upper portion of the beam, and so to be given by $E(d-z)/(t+s)$. The second point, marked (b) on curve A Fig. 14, was found in the manner just explained and represents the end of the second stage in the loading of the beam. During the third stage in the loading the stress diagram will be as illustrated at (b) Fig. 15. Other points on curve A were found by choosing any depth y for the mixture of overstrained and elastic material on the tension side of the beam, then finding O the position of the neutral axis (which gives the shaded areas equal) graphically by trial, or by calculation. The couple G is then found by taking the sum of the moments of the shaded areas about O; and the radius of curvature (and so the deflection Δ) of the beam can be got from either $r = E.OY/(t+s)$ or $r = E.OX/(t-s)$, neglecting any constraint applied by the semiplastic top and bottom layers. The theoretical curve A Fig. 14 obtained in this manner just explained, agrees only moderately well with curve 2, which was obtained from the experiments on the six beams cut from the steel rod overstrained in accordance with Fig. 13.

With regard to the experiments performed by bending the overstrained beams, the curves obtained with four out of the six beams were in almost perfect agreement, in spite of the fact that 'creeping' takes place as soon as the elastic limit in compression is passed, so that the observed deflections depend to some extent on the time taken to perform the experiment. The time taken varied, in the case of the four beams, from 30 to 65 minutes, yet the agreement was so good that only one curve No. 2 has been drawn, using observations taken at random from the four experiments. In order to test the effect of time on the curve obtained, the fifth beam was loaded at great speed, (only five minutes taken as against 30 to 65 minutes), so that ultimately, at higher loads, rapidly moving telescope scale readings had to be taken. Curve 2' Fig. 14, obtained from these rapid observations, differs appreciably from curve 2; but, the final loading soon equalled the deflection observed with slow loading, and in 15 minutes (when the

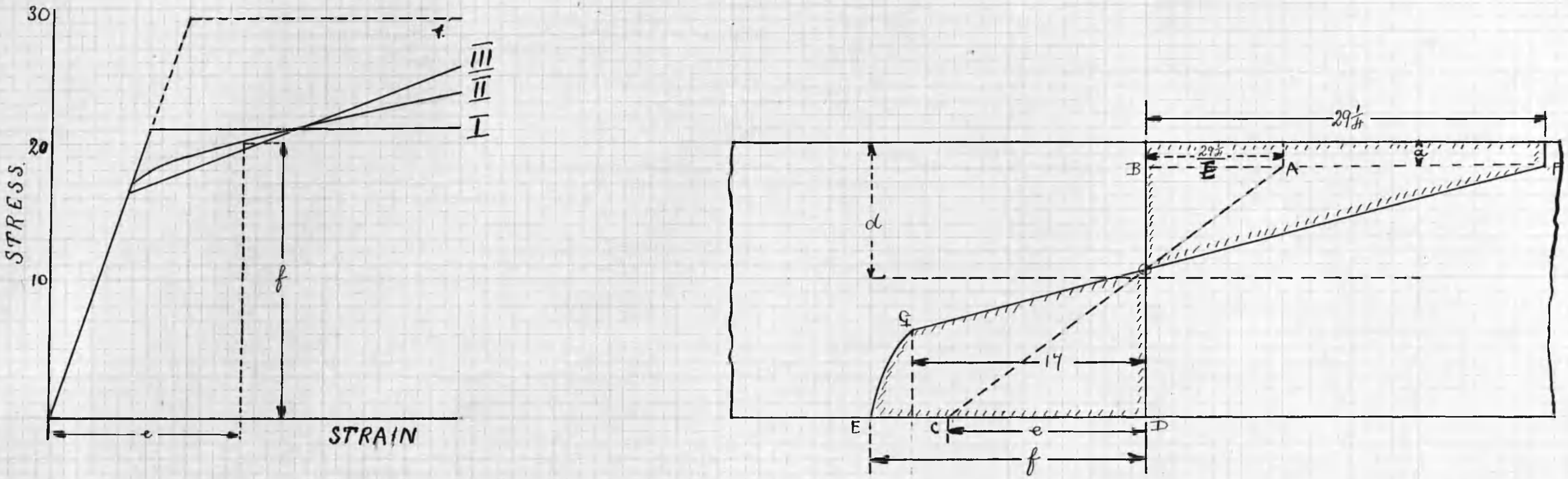


Fig 16

creeping was very slow) exceeded it. The curve obtained with one of the six beams has not been reproduced. It fell slightly below curve 2, no doubt due to faulty machining which had previously been detected when measuring the beam by micrometer screw gauge.

Since the agreement between curves 2 and A, Fig. 14, was not good enough to justify the assumption of well defined yield-points at 29.25 tons per sq. inch in tension and 21.25 tons per sq. inch in compression, and since direct compression experiments had always shown that steel overstrained in tension did not give a well-defined yield-point in compression, it was decided to try if better agreement between theory and experiment could be got by assuming a curve such as 11 Fig. 16 (instead of 1), to represent the yielding of overstrained steel under compression. Curve 11 is similar in shape to the direct compression experimental curves 3 and 4 of diagram 111 page 286 of the 'Proceedings of the Royal Society' for 1906, and it was drawn so as to leave the straight Hooke's law line at 17 tons per sq. inch, since this was just about the stress at which curve 2 Fig. 14. shows departure from perfect elastic behaviour. The theoretical curve marked B in Fig. 14 was obtained from curves 1 and 11 of Fig. 16 in a manner (illustrated by b Fig. 16) similar to that already described for finding curve A from curves 1 and 1 of Fig. 16.

A depth a for the mixture of elastic and overstrained material on the tension side of the beam was first chosen, then the point A was marked where BA is the elastic strain corresponding to the stress of 29.25 tons. Next, the position O of the neutral axis was found graphically by one or two trials, so as to make the shaded stress-diagrams areas equal. The lower area was found by drawing AOC (the strain line, plane sections being supposed to remain plane), finding the strain DC on the outermost compression fibres and from curve 11 the stress f (or DE) on these fibres.

The stress line FO was produced to G, so that the maximum elastic stress on the compression side was 17 tons per sq. inch, and the curve joining G and E was readily found from curve 11. After O had been fixed, giving the shaded areas equal, the couple was calculated by dividing the stress areas into parts and finding the sum of the moments about O. The radius of curvature of the beam was found from E.OB/BF, where E is Young's modulus, and the central deflection got from the curvature. Curve B, calculated in the manner just explained, agrees with the experimental curve No. 2, Fig. 14, much better than curve A. To get more perfect agreement still, a curve of the form indicated by 111 in Fig. 16 would require to be assumed as the compression curve for the overstrained steel, and curve 111 is still similar in shape to curves got by direct compression experiments. J.A. van den Broek's[5] work showed that the compression yield-point, obtained from recovered tensile overstrained material, was always rounded the elastic limit occurring at about the same stress as in the original annealed material.

The conclusion of the matter seems to be that mild steel overstrained in tension does not give a well-defined yield-point in compression. The bending experiments, however, give support to the suggestion, made in 1906, (as the result of direct compression experiments) that steel hardened by tensile overstrain t and recovery from overstrain yields under tension at $(t+s)$ where s is the step between successive yield-points (in tension or compression), not sharply but gradually, at about the stress $(t-s)$. Thus tensile overstrain can strengthen steel very considerably as regards resistance to tension, compression and bending, (compare curves 1 and 2 of Fig. 14. It is only when the tensile overstrain is small, less than s above the primary yield-point stress, that the material will be weakened in compression.

REFERENCES.

1. Sir. Alex. B.W. Kennedy F.R.S.
ENGINEERING, June 15th. 1923.

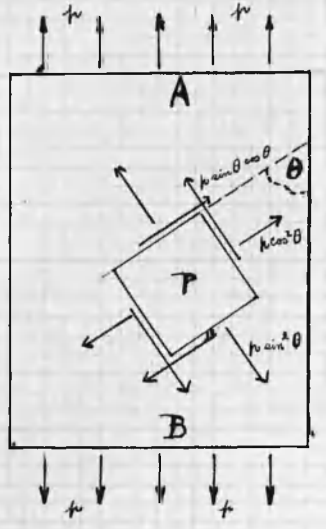
2. J. Muir. D.Sc. M.A.
'The Overstraining of Iron by Tension and Compression'.
Proc. Royal Society., vol. 77, page 280, 1906.

3. Robertson and Cook.
'The Transition from the Elastic to the Plastic State in Mild Steel.'
Proc. Royal Society, vol. 88, page 462, 1913.

4. W. A. Scoble, D.Sc.
'Eccentric Loading in Tension and Compression Tests'.
British Association Report 1919, page 479.

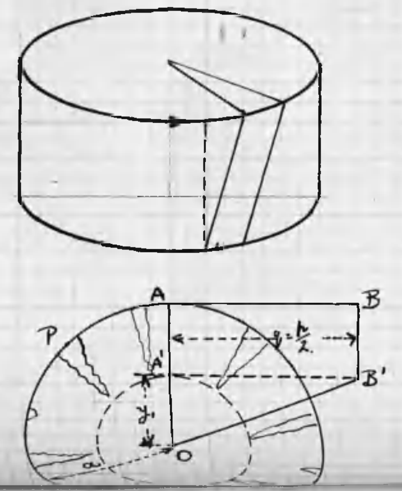
5. J. A. van den Broek.
'The Effects of Cold-Working on the Elastic Properties of Steel.'
The Iron and Steel Institute Carnegie Scholarship Memoirs, 1918.

THE OVERSTRAINING OF STEEL BY TORSION.



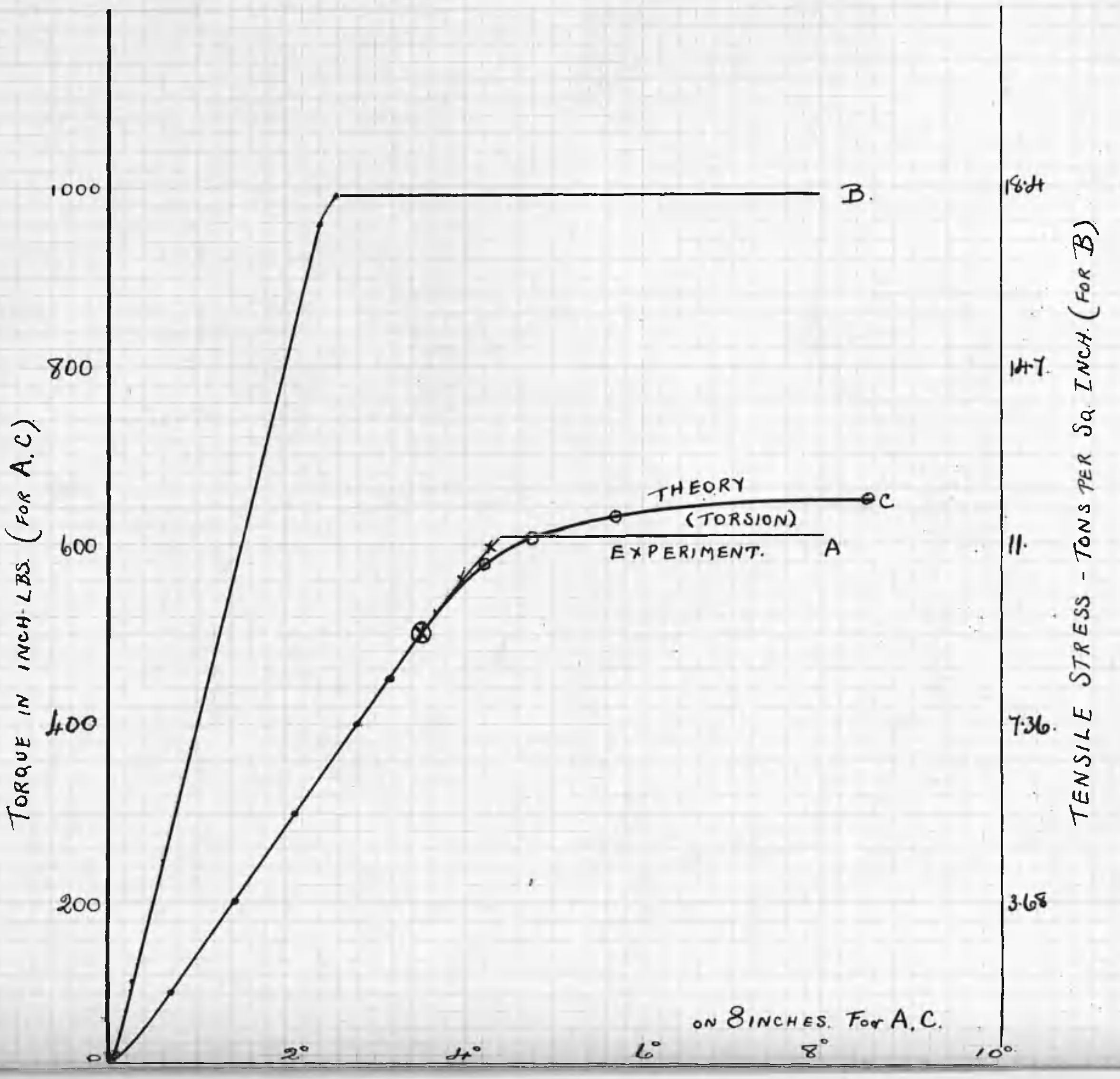
p
A
p sin θ cos θ
θ
p cos² θ
P
p sin² θ
B
p

Fig 1A.



A
B
P
A'
B'
O
α

Fig 1B.



TORQUE IN INCH-LBS. (FOR A.C)
0
200
400
600
800
1000
B.
THEORY
(TORSION)
C
EXPERIMENT.
A
TENSILE STRESS - TONS PER SQ. INCH. (FOR B)
3.68
7.36.
11.
14.7.
18.4
2°
4°
6°
8°
10°
ON 8 INCHES. FOR A.C.

When elastic material is subjected to a simple pull of intensity p, the stress on an element of material may be resolved into two normal stresses- $p\sin^2\theta$, $p\cos^2\theta$ and a shear stress $p\sin\theta.\cos\theta$, as illustrated by Fig 1a. If the pull be increased so as to overstrain the material, yielding takes place under shear and will begin along planes at 45°, for which direction the shear stress has its maximum value p/2.

If a circular rod of elastic material be subjected to torsion, the material is under a simple shear stress, varying in intensity from zero at the axis to a maximum at the surface of the rod. If the applied torque be gradually increased, yielding under torsion might be expected to take place, when the shear stress q, on the outer fibres, reached the value p/2, one-half the stress at which the material would yield under direct pull.

Fig. 2 illustrates tension and torsion tests on half-inch rods of the same well annealed steel. Curve A shows the torque applied in inch-pounds plotted against the twist produced measured in degrees on an 8-inch length; while curve B gives the tensile stress applied to another specimen, plotted against the extension produced, measured in extensometer scale divisions. The scales adopted for plotting curve B are such that the stress scale for curve B also represents in curve A the shear stress in the outer fibres of the torsion specimen, up to the elastic limit; and the strain scale is such that the tangents of the inclinations of curves A and B to the axis of strain are in the ratio of the rigidity modulus to Young's modulus for the material.

It will be noticed that the torsion test gives apparently a yield-point at a stress distinctly higher than 9.1 tons per square inch (one half the tension yield-point stress). The object of this paper is to explain this apparent discrepancy between theory and experiment; and the explanation given is an extension to the case of torsion of the theory already given for the case of bending in the submitted paper on the bending of steel.

Consider first the properties of steel revealed by the simple tension test. Curve B shows that the steel in question exhibited very perfect elasticity right up to the yield-point stress of 18.3 tons per square inch. The elastic extension at this stress was 0.14 per cent. The large permanent extension which occurred at the yield-point was 2.0 per cent. or, say, 14 times the elastic extension there.

It is important to remember the manner in which the permanent yield ate the yield-point takes place. A very small portion of material at some point P, Fig. 1a becomes incapable of withstanding the yield-point stress, until it has stretched by 2 per cent. (as the result of yield under shear at 45^{o}). This extension of the small portion of material at P will cause the long lengths of material AP, BP above and below P to contract, but the contraction will be so slight that there will be no appreciable change in the stress along AB. The yielding at P, however, will cause a redistribution of stress in the material surrounding P, such that particles adjoining P will be subjected to slightly greater stress than yield-point stress; so these adjoining particles will yield (by 2 per cent.) and the action will be transmitted piecemeal throughout the material.

Consider now a rod subjected to a torque just sufficient to subject the material, in the outermost layer, to shear stress equal to one-half the tension yield-point stress. At some point P, Fig. 1b, in the outermost layer, the material will yield by 2 per cent., and yielding will spread piecemeal along the length of the rod and inwards towards its centre. If the applied torque be gradually increased, little wedges of overstrained material will grow, in the manner roughly indicated by Fig. 1b, giving rise to Luders' lines on the surface of the bar.

In order to get an estimate of the amount of overstrained material present at any stage during overstrain, consider the torque to have been increased until some material has been overstrained in all layers beyond y_1, Fig. 1b. The distribution of stress across the section may be as illustrated by OABB'. Consider the special case $y_1 = a/2$. Had all the material remained elastic the shear strain in the outermost layer would have been double the shear strain $\underline{s}$ at y_1 from the axis. Of course, the material cannot all remain elastic and be subjected to the stress 2q necessary to produce the elastic strain $2\underline{s}$. The outer layer of the bar consists of elastic material strained by amount s and overstrained material strained by amount 14s. (The permanent extension at a yield-point in tension with the material in question was 14 times the elastic extension there; the permanent shear strain at a yield-point is also 14 times the elastic shear strain.) There will thus be only about 1/15 of the material in the outermost layer of the rod in the overstrained condition, 14/15 being still in the elastic state. For other layers down to $y_1 = a/2$ less and less material is overstrained, so about 1/30 of the outer ring between y_1 and $\underline{a}$ is overstrained and the whole of the central portion of the rod is entirely elastic.

It is probably impossible to develop a theory which would give the twist of a rod subjected to an overstraining torque, owing to the casual manner in which the overstrained material, represented by the little wedges in Fig. 1b, will form and grow. It is, perhaps not even necessary that the stress distribution should remain of the form illustrated by OABB'. Under a given torque a wedge might grow deeper than is to be expected, B' being lowered, in which case the stress in the outermost fibre would be reduced, B going closer to A.

In order, however, to get some comparison between theory and experiment, the stress distribution may be supposed to remain in accordance with OABB'; the applied overstraining torque is then given by

$$T = \int_0^{y_1} \frac{q}{y_1} r . 2\pi r . dr . r + \int_{y_1}^{a} q . 2\pi r . dr . r$$

or
$$T = \frac{2}{3}\pi q \left(a^3 - \frac{y_1^3}{4}\right) \qquad (I)$$

The twist produced may be supposed to be that of the entirely elastic portion of the rod (radius y_1) when subjected to the torque corresponding to OA'B'. This twist, in radians, is given by $\theta_1 = ql/ny_1$, where l is the length of the rod and n is the rigidity modulus of the material. But θ_1, for any y_1 is most easily calculated from

$$\theta_1 = \theta_0 \times \frac{a}{y_1} \qquad (II)$$

where θ_0 is the twist, found by experiment, when the applied torque is just sufficient to give the yield-point stress $q = p/2$ in the outermost fibres. Curve C, Fig. 2 has been plotted from values of T and θ got by taking $y_1 = a$, 0.8a, 0.6a, etc., and substituting values in equations (I) and (II). These equations, of course, only hold after the outer fibres have been raised to one-half the tension yield-point stress, and before all the material in the outermost fibres has been overstrained, and so has become capable of withstanding a greater stress than $q = p/2$ (one-half the tension yield-point stress). This last condition, however, involves enormous overstrain. A comparison of the experimental curve A and the theoretical curve C shows that, at first, the actual strains are less than the theoretical. This is what might be expected since the mixture of elastic and overstrained material, in the outer layers, will act as a constraint, and prevent the inner entirely elastic portion of the bar twisting as far as it otherwise would. On the other hand curve A shows that the material has failed more suddenly and at a lower stress than that given by theory. This probably is to be accounted for by the casual manner in which the overstrained material forms and grows from point to point in the material of the outer layers.

THE MAGNETIC PROPERTIES OF PERMALLOY.

A sample of the permalloy used in 'loading' the New York Azores cable having been obtained, it was thought that it might be of interest to have the wonderful magnetic properties of this alloy illustrated by a simple comparison with those of good soft iron. Of course, no detailed account will be given here of the remarkable properties of all the nickel-iron alloys containing more than 30 per cent. nickel. These properties were discovered and investigated in the Research Laboratories of the American Telephone and Telegraph Company and the Western Electric Company, Incorporated, New York. and it will suffice here to refer to one paper on permalloy by Arnold and Elmen, published in the Journal of the Franklin Institute, vol. 195, May 1923, in which the magnetic properties of permalloy and of annealed Armco iron are compared in detail.

The sample of permalloy whose properties are illustrated by the accompanying diagram contained practically 78.5 per cent. nickel and 21.5 per cent iron, there being said to be only traces of some inevitable impurities. The magnetic properties of the alloy may be described shortly as follows. If properly heat-treated (the treatment varying with the size and shape of the specimen) a magnetic field as low as that of the earth suffices practically to saturate the alloy to a magnetic intensity comparable with that of soft iron. The initial permeability (that is, the permeability calculated when the magnetizing force tends to zero) is claimed to be thirty times that of the best soft iron. The magnetic properties of the alloy are, however, very sensitive to strain; within the elastic limit the effect of strain disappears when the strain is removed, but permanent set causes a marked diminution of magnetic susceptibility which can only be removed by further heat treatment.

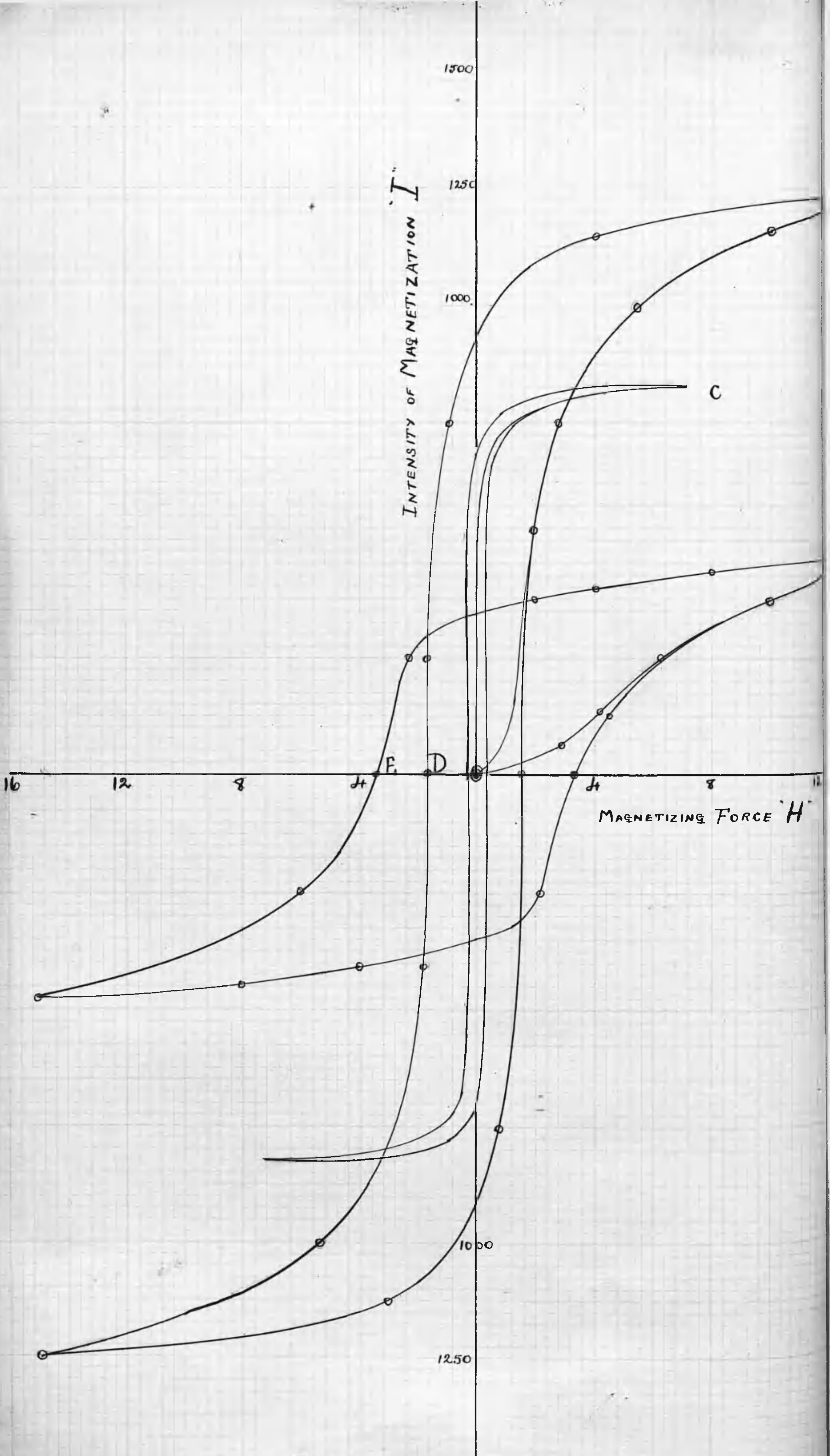


Diagram Showing Hysteresis Cycles.

The curves shown in the accompanying diagram may now be described. They are I-H curves obtained by the old single-pole magnetometric method, and they were checked by modifying the apparatus used and also by obtaining B-H curves by the ballistic method.

Curve A was obtained from a rod of very good soft iron. The saturation value of the intensity of magnetization is about I = 1250 and the coercive force (OD) about H = 1.5.

Curves B and C illustrate the properties of the permalloy. The sample was supplied in the form of a coil of thin ribbon or tape, one-eighth of an inch broad, and six-thousandths of an inch thick. To find the cross-sectional area of the sample a measured length was weighed in air and in water. The density of the material was thus found to be 8.60 grams per cubic cm., and the section area of the sample 0.00428 sq. cm. The coil was then straightened against a wooden lath, placed in the magnetizing coil and the readings obtained from which curve B has been plotted. Curve B thus shows the properties of the permalloy in the severely overstrained condition produced by coiling and straightening the specimen. The properties resemble those of steel rather than those of soft iron. Saturation was not reached even with a field H = 40, and the coercive force (OE) required to wipe out the magnetization was quite large.

The specimen was next removed from the wooden lath, annealed by simply heating it to redness by passage through a bunsen flame, and replaced on the lath; readings were then obtained from which curve C has been plotted. The simple heat-treatment had sufficed to induce the striking magnetic properties of permalloy. A field as low as that of the earth (less than H = 0.5) produces almost the saturation value for the intensity of magnetization I = 830. The permeability (which may be taken as equal to $4\pi I/H$) is seen to be very high for low fields, as compared with that of soft iron; and this high value extending down to zero field demonstrates the value of permalloy in telephonic communication.

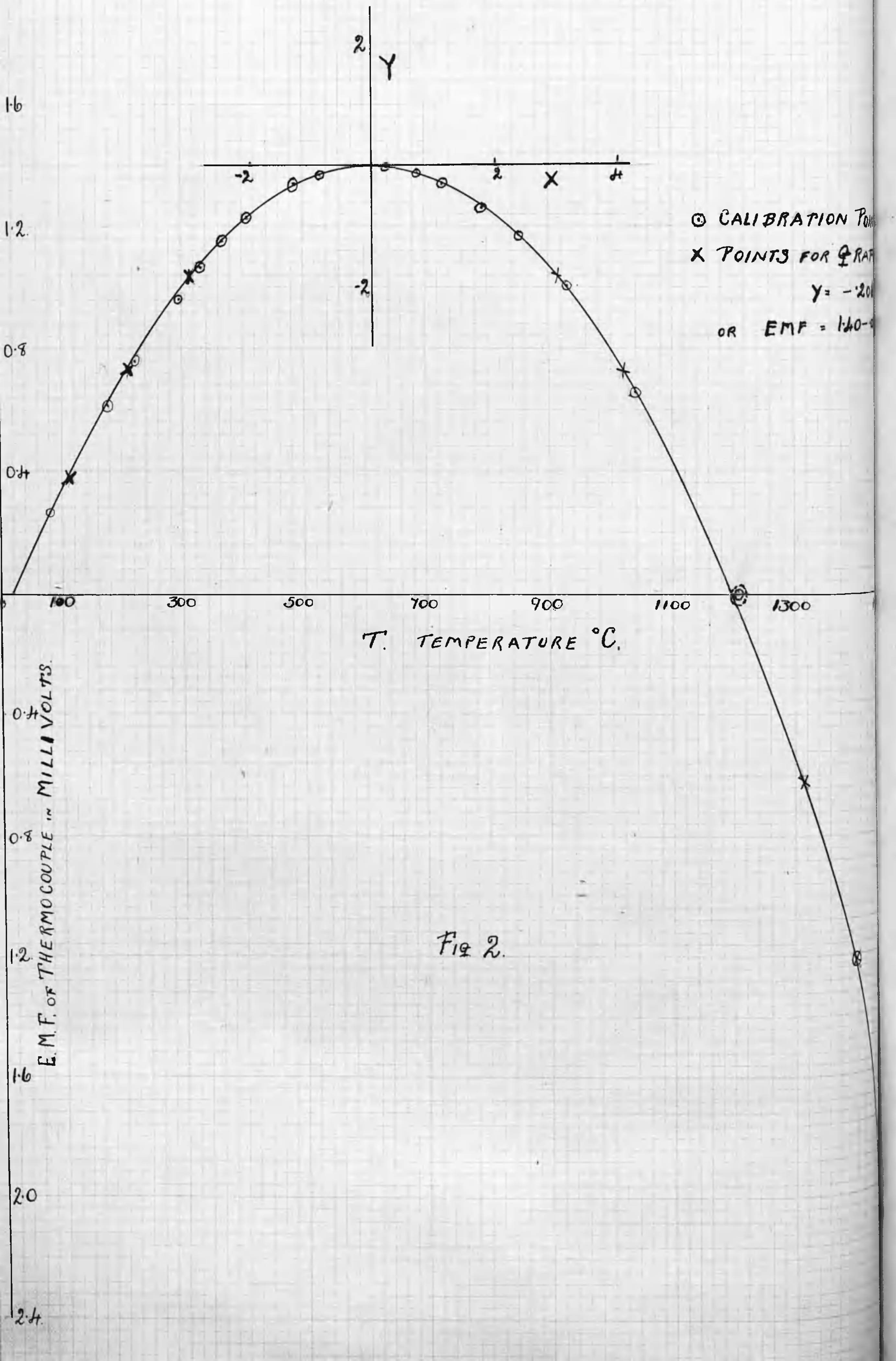
In order to verify the effect of overstrain the annealed sample was wound on a spindle of diameter one inch. This permanently bent the sample into a coil of about four inches diameter. This coil was straightened on the wooden lath and a magnetic curve for overstrained permalloy again obtained. To avoid confusion, this curve has not been reproduced, it resembled curve B but indicated rather less overstrain.

HIGH TEMPERATURE MEASUREMENT.

In the course of an investigation, which the author is at present carrying out under the supervision of Professor Andrew for the Heterogeneity Committee of the Iron and Steel Institute, into the liquidus and solidus of particular types of steel, the problem arose as to how to overcome the difficulties met with in the accurate measurement of temperatures up to 1,600°C. The furnace employed to attain high temperatures was of the ordinary wire-wound resistance type- an alundum tube wound with molybdenum wire. A reducing atmosphere was maintained both inside and outside the furnace tube by passing a stream of cracked ammonia gas, as the presence of oxygen would have caused the hot molybdenum wire to burn out immediately. The use of a platinum platinum-10% rhodium thermocouple was ruled out on account of the rapid deterioration of a thermocouple, made from these metals, when used at very high temperatures, more especially in the presence of gases.

Tungsten and molybdenum have very high melting points, the former melting at a temperature somewhat over 3,000°C,, and the latter melting in the vicinity of 2,400°C. Since these metals can be supplied economically in a very pure state, their thermo-electric properties were investigated to determine their suitability for high-temperature measurement. Alloy thermocouples are liable to change when used at high temperatures; therefore the use of pure metals was especially desirable. The reducing atmosphere used in the furnace permitted the use of tungsten and molybdenum.

Suitable lengths of these metals were procured from the Tungsten Manufacturing Co. Ltd., London, and a thermocouple was made. The junction, of course, could not be fused; the ends were merely twisted round each other and pressed tightly with pliers. This simple method gave no reason for dissatisfaction, and was always adhered to, a few inches being



2
Y
-2
2
X
4
-2
⊙ CALIBRATION POI
X POINTS FOR GRAP
Y = -·20
OR EMF = 1·40-
1·6
1·2
0·8
0·4
0·4
0·8
1·2
1·6
2·0
2·4
100
300
500
700
900
1100
1300
T. TEMPERATURE °C.
E.M.F. OF THERMOCOUPLE IN MILLI VOLTS.

Fig 2.

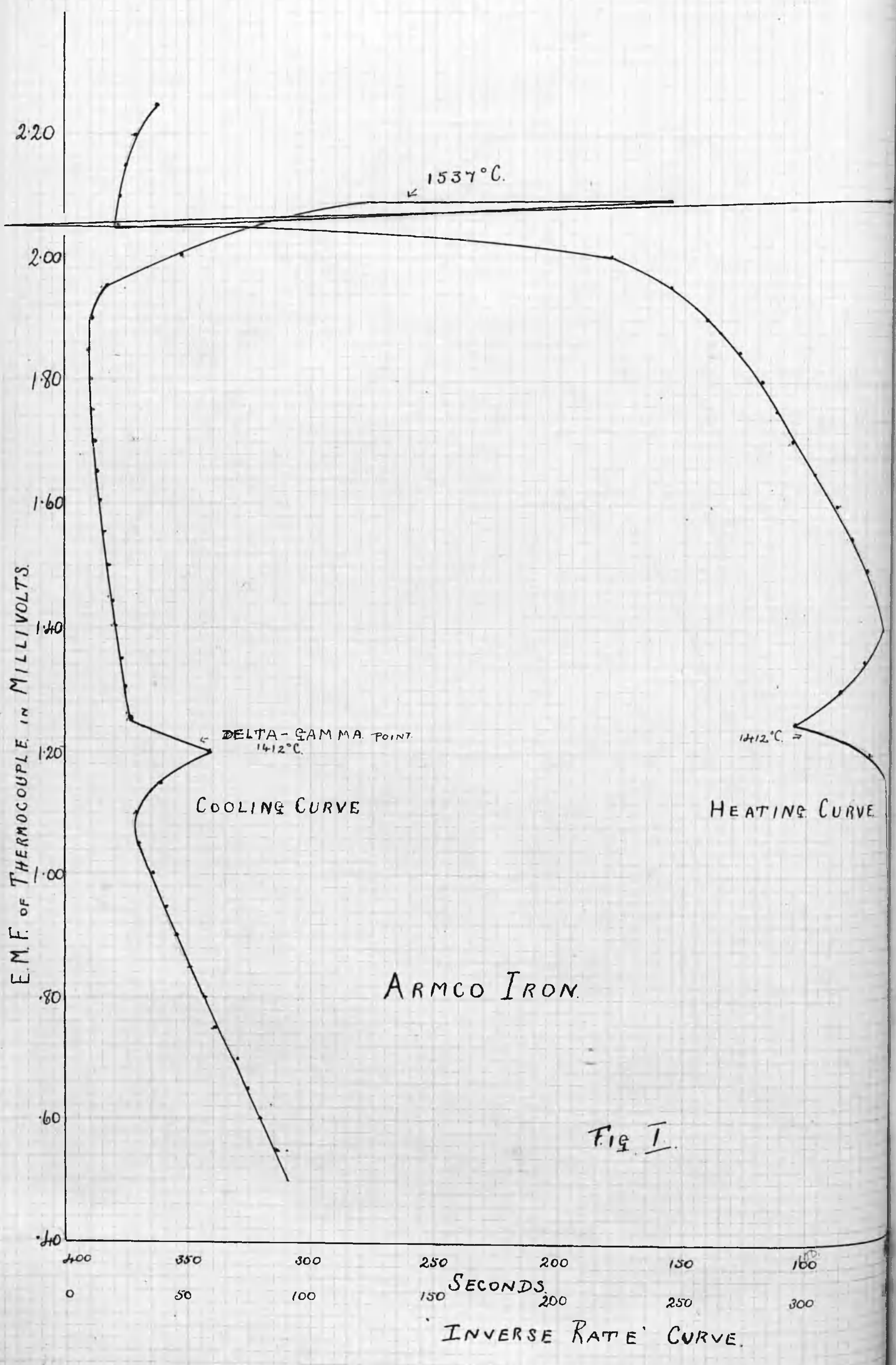
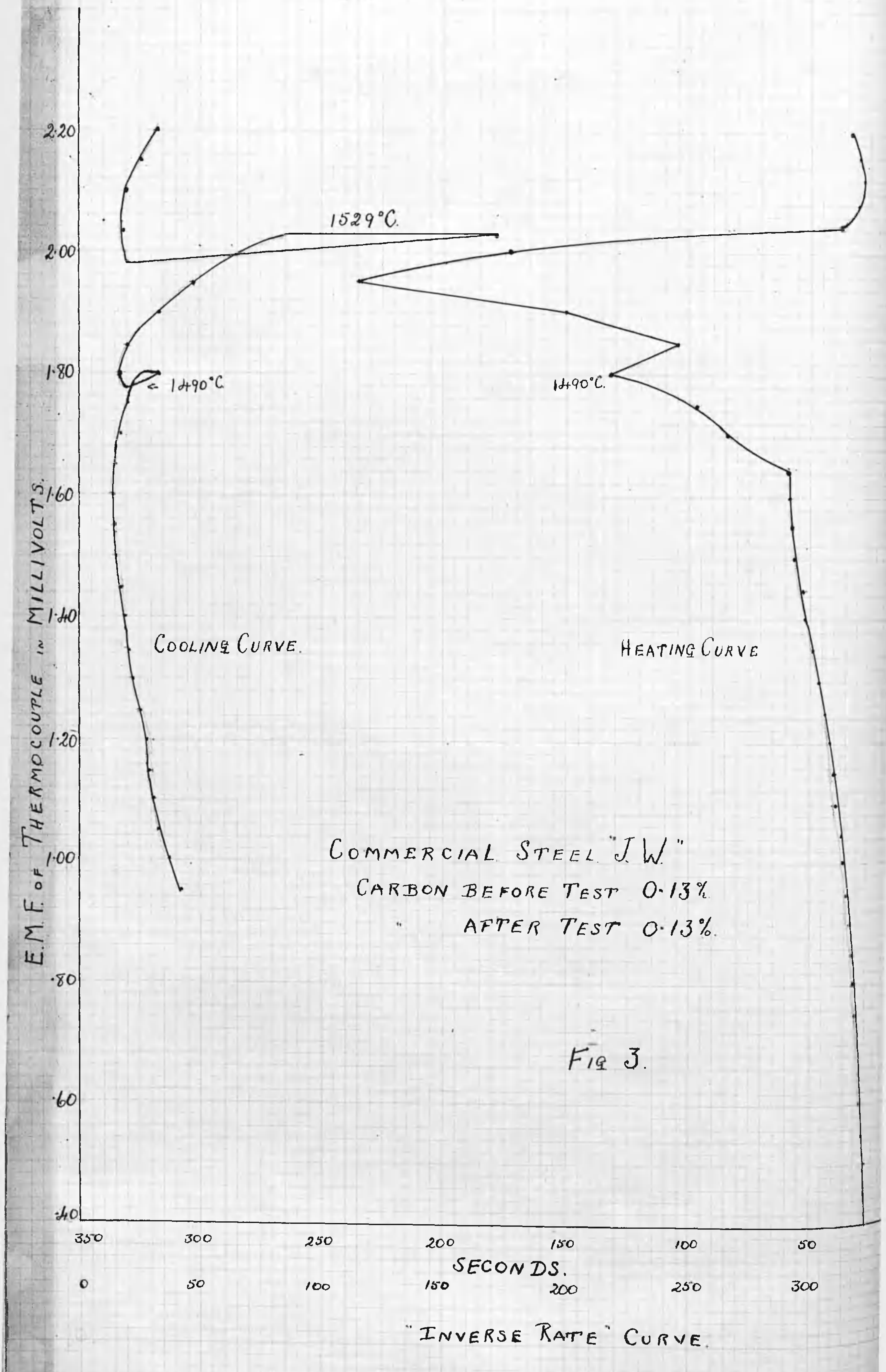

1537°C.
DELTA-GAMMA POINT
1412°C.
1412°C.
COOLING CURVE
HEATING CURVE
ARMCO IRON
E.M.F. OF THERMOCOUPLE IN MILLIVOLTS.
2.20
2.00
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
400
350
300
250
200
150
100
0
50
100
150
200
250
300
SECONDS
INVERSE RATE CURVE.

Fig I.

TABLE 1.

Temperature. °C.	E.M.F. Millivolts.	Calculated. Temperature °C.	E.M.F. Millivo [cut off] $E = 1.140 - .04$ [cut off]
83	.26		
180	.61	115 or 1115	.37
224	.75	215 or 1015	.72
296	.96	315 or 915	1.03
334	1.06		
367	1.15	1315	- .62
407	1.22	1415	- 1.24
485	1.34		
527	1.37		
586	1.40		
615	1.40		
638	1.40		
688	1.38		
730	1.34		
794	1.26		
846	1.17		
927	1.00		
1060	.64		
1412	-1.22	1412	- 1.22
1537	-2.09	1537	- 2.10

cut from the hot junction after every heat and a fresh junction made. The thermo-electric property was then determined up to a temperature of about 1,100°C., by comparison with a chromel-alumel thermocouple. Two holes were drilled in a small length of Armco iron, and the two couples were inserted side by side and then placed in an ordinary ni-chrome wire-wound electric furnace. The ends of the furnace tube were plugged with asbestos wool, and a small but steady current of hydrogen from a Kipp's apparatus was allowed to pass through the inside of the furnace to maintain a reducing atmosphere. The temperature was raised by suitable steps, the furnace being adjusted to maintain as steady a temperature as possible after each step. The respective E.M.Fs. were read off from a Tinsley vernier potentiometer. In Table 1 the temperatures obtained from the chromel-alumel thermocouple are plotted in column 1, column 2 gives the corresponding E.M.Fs. in millivolts of the tungsten-molybdenum junction. The calibration for higher temperatures was determined from heating and cooling curves of Armco iron. The difficulties involved in taking a heating curve for temperatures above 1,400°C. were very great, for apart from the breaking down of the electrical insulation of the furnace tube, there was an electronic emission from the hot furnace winding, a difficulty which was only got over by inserting the specimen and thermocouple in a flanged alundum tube along which a number of molybdenum wires were placed in the form of a grid. A heating and cooling curve of Armco iron is reproduced in Fig. 1, the delta change point occurring at 1412°C. and the melting point occurring at 1,537°C. The delta point is taken at 1,412°C since Armco iron contains about 0.03 per cent of carbon. The thermo-electric curve obtained is plotted in Fig. 2. A neutral temperature occurs about 615°C., when the E.M.F. of the junction is 1.40 millivolts; thus, with the cold junction at 18°C., the reversal point will come in at 1,212°C. For temperatures below the reversal point


E.M.F. of Thermocouple in Millivolts.
2·20
2·00
1·80
1·60
1·40
1·20
1·00
·80
·60
·40
1529°C.
1490°C.
1490°C.
Cooling Curve.
Heating Curve
Commercial Steel "J.W."
Carbon before Test 0·13%
" after Test 0·13%.
Fig 3.
350
300
250
200
150
100
50
Seconds.
0
50
100
150
200
250
300
"Inverse Rate" Curve.

molybdenum is the electro-positive metal. The thermo-electric curves for various tungsten-molybdenum couples were found, in all cases, to follow very closely the graph of a simple mathematical expression of the type $y = cx^n$ where c is a constant and n is a power very nearly equal to 2. In the calculation of the equation of the curve, the origin was transferred for the sake of simplicity to the co-ordinates of the neutral temperature and simple units used for x and y. In the curve reproduced in Fig. 2 the equation which fitted in was $y = 0{\cdot}206x^{2}$ thus the curve is parabolic.

In columns 3 and 4 of Table 1 the thermo-electric property is calculated using the equation of the curve, also, by differentiating the equation, the power of the couple at various temperatures is readily calculated. At temperatures of 1,400°C., 1,500°C and 1,600°C the power of the couple comes out at 6.4, 7.4, 8.1 microvolts per degree respectively, offering quite a favourable comparison with a platinum platinum-10% rhodium couple, which has a power of approximately 10 microvolts per degree.

In taking heating and cooling curves of Armco iron and steel the thermo-junction was protected from the melt by a thin walled silica sheath closed at one end with a little alundum cement, also for steels the carbon content was found to remain constant when the specimen was enclosed in a crucible made from carborundum sand and lined with alundum, the open end of the crucible being closed with the moistened carborundum sand and allowed to dry.

The heating and cooling curve of a carbon steel is reproduced in Fig. 3. The carbon content of 0.13 per cent was unaltered by melting. The peritectic temperature which is said to occur at 1,486°C. to 1,490°C., is observed to occur at a temperature of 1,490°C. on both heating and cooling.