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TESTS OF SOME GIRDER HOOKS

BY

HERBERT L. WHITTEMORE, Mechanical Engineer

AMBROSE H. STANG, Associate Physicist

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By Herbert L. Whittemore and Ambrose H. Stang

ABSTRACT

Curved mild-steel hooks having rectangular cross sections, designed for 5, 10, and 15 tons, were loaded, using several increments, up to the proportional limit of the material.

The stresses on the inside and on the outside surfaces of the hooks were measured experimentally with strain gauges having 2-inch gauge length. Readings were taken along practically the entire length of the hooks.

The stresses were computed theoretically by adding algebraically the component normal to a right section of the hook and the stress due to bending at that section.

The stresses (at the critical section of the hook) were computed by the Winkler-Bach and the Andrews-Pearson formulas. The experimental and theoretical stresses were plotted and compared with the values obtained from the formulas. It was found that the experimental and theoretical stresses agreed very well.

The stresses obtained from the Winkler-Bach and the Andrews-Pearson formulas, which take into account the curvature of the hook, gave correct values for the stress at the critical section.

As these values were in no case more than 20 per cent greater than the experimental stresses, the use of the more exact formulas is not necessary in designing hooks, if a sufficiently large factor of safety is used.

Measurements of the opening of the hooks under load showed that when the proportional limit of the material was reached that the opening in no case exceeded one-sixteenth of an inch, proving that it is impossible to determine by visual inspection whether the hook has been stressed beyond the proportional limit.

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I. INTRODUCTION

1. PURPOSE

Mild-steel hooks having rectangular cross sections are often used for lifting steel girders. Generally, two hooks with their curved ends toward each other are placed on an oval link which, in turn, is carried by the crane hook. The nominal safe lifting capacity of these hooks is usually computed by adding the tensile and bending stresses. To determine the safety of hooks designed in this way, nine were tested. There were three for each of the following capacities: 5, 10, and 15 tons. It was also desired to determine if visual inspection was sufficient to decide when a hook had been stressed beyond the proportional limit of the material. Figure 1 shows one hook of each of the three sizes. Dimensioned drawings of the hooks are given in Figures 4, 7, and 10.

2. ACKNOWLEDGMENTS

The mechanical engineering department of the American Bridge Co., Ambridge, Pa., furnished the nine hooks for these tests and additional material for coupon specimens, as well as the fixtures for loading the hooks in the testing machine. Engineers from this company rendered considerable assistance in carrying out the experimental work, as well as in planning the investigation.

3. THEORY OF HOOK DESIGN

There are three current approximate theories of hook design: (a) The ordinary beam theory; (b) the Winkler-Bach curved beam theory, and (c) the Andrews-Pearson theory. All of these give identical results when applied to straight beams, but for hooks of considerable curvature, they differ more and more as the ratio of thickness to curvature is increased. Theoretically, the Andrews-Pearson theory represents the closest approximation, the Winkler-Bach the next, and the ordinary beam theory the roughest approximation for hooks.

(a) ORDINARY BEAM FORMULA.—The resultant stress at any point in a hook is made up of a stress, S_1 , due to the component of the tensile load on the hook and a stress, S_2 , due to the bending caused by the load. For a hook of rectangular cross section, the following formulas apply:

$$S_1 = \frac{L}{bd \sec \alpha} \text{ lb./in.}^2$$

where

L = load, pound.

FIGS. 1 AND 3.—Five, ten, and fifteen ton hooks, before and after test

FIG. 2.—A 15-ton hook in the testing machine

b = thickness of section, inches.

d = width of hook, inches.

α = supplement of the angle between the load line and the section of the hook perpendicular to the neutral axis.

and

$$S_2 = \frac{L y c}{\frac{1}{12} b d^3} \text{ lb./in.}^2$$

where

y = moment arm of the load, inches, or the distance from the load line to the neutral axis of the section.

c = distance of the point at which the stress is desired from the neutral axis of the section, inches.

S_2 is either tension on the inside of the hook or compression on the outside. For this computation, the neutral axis is taken through the center of area of the section; that is, half way between the inner and the outer surfaces of the hook. The total stress, then, on a section at right angles to the neutral surface of the hook is

$$S = S_1 \pm S_2 \text{ lb./in.}^2$$

In the derivation of this formula, it is assumed that the neutral axis passes through the centroid of the cross sectional area of the beam.

It follows from this assumption that the bending of a beam having a rectangular cross section causes equal tensile and compressive stresses in the extreme fibers.

(b) WINKLER-BACH FORMULA.—If the hook is considered as a curved beam, the neutral axis is shifted toward the center of curvature. The stress in the extreme fiber on the inside is increased, and on the outside of the beam is decreased compared with the stresses found by the aid of the ordinary beam formula. The radius of curvature at any section will affect the position of the neutral surface, increasing the tensile stresses due to bending and decreasing the compressive stresses. This theory of hooks is called the Winkler-Bach theory and the formulas may be found in textbooks on mechanics of materials.¹ According to Andrews, the formula for the total stress, S , due to the load is

¹ E. S. Andrews, "The stresses in hooks and other curved beams," James Selwyn & Co. (Ltd.), London, 1919, p. 8. E. S. Andrews and Karl Pearson, "Theory of the stresses in crane and coupling hooks," Drapers' Co. Research Memoirs, Technical Series, I, p. 7, Cambridge University Press; 1904. C. Bach, "Elasticität und Festigkeit," Berlin, 1890, p. 311 et seq. Church, "Mechanics of engineering, solids," 1916, p. 359. Merriman, "Mechanics of engineering," eleventh edition, p. 435, John Wiley & Son, New York.

$$S = \frac{L}{b d} \left[1 - \frac{\gamma}{r} \left(1 - \frac{c}{r-c} \times \frac{1}{A} \right) \right]$$

in which

$$A = \frac{r}{d} \left(\log_u \frac{2r+d}{2r-d} \right) - 1$$

where r = radius of curvature of the neutral surface, inches, and u = Napierian base.

(c) ANDREWS - PEARSON FORMULA.—These authors point out that if the effect of transverse deformation (Poisson's ratio) is considered, a formula is obtained which still more accurately represents the actual behavior of the beam. Unlike the previous formulas this formula applies only to sections of the beam free from shear. For bending of a simple beam, the Andrews-Pearson formula applies only to the section of maximum stress. Their investigation leads to the formula

$$S = \frac{L}{b d} \left[1 + \frac{\gamma}{r C} \left(\left(\frac{1}{1 \pm \frac{c}{r}} \right)^{1+n} - B \right) \right]$$

in which

$$B = \frac{r}{n d} \left[\left(\frac{r}{r - \frac{d}{2}} \right)^n - \left(\frac{r}{r + \frac{d}{2}} \right)^n \right]$$

$$D = \frac{r}{(1-n)d} \left[\left(\frac{r + \frac{d}{2}}{r} \right)^{1-n} - \left(\frac{r - \frac{d}{2}}{r} \right)^{1-n} \right]$$

and

$$C = B - D$$

where

$$n = \text{Poisson's ratio}$$

II. MATERIAL, SPECIMENS, AND METHOD OF TESTING

1. MATERIAL

The material in these hooks was mild steel. They were forged with the shanks 12 inches longer than required by the drawing and the extra material was used for determining the properties of the steel.

2. HOOKS

Although the hooks were forged (using a template) to the form shown in Figures 4, 7, and 10 there were slight variations in

the hooks of the same nominal size. In order to determine the exact outline, each hook was laid on edge on a piece of paper and a trace made of its shape. To check the thickness measured from the trace, the actual thickness, at five places across the width of the hook, was obtained with calipers. These readings were repeated for about a dozen cross sections of the hook. In most cases the thickness measured in these two ways agreed very closely, but where necessary the trace was changed to agree with the average of the calipered values. The designations for the hooks were as follows:

5-ton hooks, H-1, H-2, and H-3.

10-ton hooks, J-4, J-5, and J-6.

15-ton hooks, K-7, K-8, and K-9.

Two coupon specimens for each hook were cut longitudinally from the extra material. These had a 2-inch gauge length and were one-half inch in diameter.

3. ARRANGEMENT FOR LOADING

Figure 2, shows one of the 15-ton hooks in the 600,000-pound testing machine. The shank of the forged steel shackle passed through a spherical bearing on the upper head of the machine and was fastened with a nut. Thus the shackle was free to align itself with the load. The forged steel clevis block, shown in the lower part of the figure, was held by a bolt to the straining head of the machine and was connected to the hook by a heat-treated chrome nickel steel bolt passing through the hole in the hook.

4. DEFORMATION MEASUREMENTS

The strain, as the load was applied, was measured on 2-inch strain-gauge lines shown in Figures 4 to 12, inclusive. These drawings show the location of the gauge holes which were one-eighth inch from the curved surface.

The strain gauges are shown in Figure 2 on the movable head of the machine.

For each load increment, the distance from the tip to a reference mark on each side of the hook was measured with a steel scale, graduated in hundredths of an inch. This gauge line (marked "X") is shown only on Figures 5, 8, and 11, but the measurements were taken on all the hooks.

III. RESULTS AND DISCUSSION

1. PROPERTIES OF THE MATERIAL

The average results of the tensile tests of the coupon specimens from these hooks are given in Table 1.

TABLE 1.—Results of Tensile Tests of Coupon Specimens

Hook	Proportional limit	Yield point	Tensile strength	Modulus of elasticity	Elongation in 2 inches	Reduction of area
	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
H-1.....	37,800	38,500	62,970	30,000,000	38.2	62.2
H-2.....	38,700	38,700	62,400	28,500,000	39.5	61.5
H-3.....	33,500	33,700	61,370	28,850,000	40.0	63.4
J-4.....	26,500	28,500	57,700	30,100,000	40.5	67.5
J-5.....	22,500	27,500	58,170	29,900,000	36.5	62.6
J-6.....	29,100	31,500	58,620	30,000,000	30.5	63.5
K-7.....	25,750	31,000	61,300	29,500,000	39.0	63.5
K-8.....	26,200	28,000	56,700	30,220,000	37.2	64.7
K-9.....	26,400	31,000	58,650	29,800,000	36.7	63.0

Stress-strain diagrams for four specimens are shown in Figure 13. They are typical of the diagrams for all the material. The yield point was reached when the stress was increased a few thousand pounds per square inch above the proportional limit. The difference in these two values, for the first two specimens in Figure 13, was greater than for the specimens from any other hook. The difference in the curves for the two specimens from hook K-9 shows the variation which may occur in the material.

The mechanical properties of the material in compression are, presumably, nearly the same as those in tension, although no specimens were tested in compression.

2. EXPERIMENTAL STRESSES

(a) METHOD OF COMPUTATION.—Having the stress-strain diagram for the material, the stress for any deformation may be found directly from the diagram. It should be noted that this method of obtaining the stress from the strain-gauge readings gives the correct stress value above the proportional limit or even above the yield point provided the strain is continuously increased.

For those materials whose elastic properties closely follow Hooke's law, it becomes more convenient to compute the stresses from the straight line formula which is correct up to the proportional limit of the material.

Knowing the modulus of elasticity of the material from the coupon tests and the deformation of the hook from the strain-gauge readings, the stress is

$$S = e E$$

H-1.

FIG. 4.—Load-stress diagrams for the 5-ton hook H-1

where

e = strain, in. per in.

and

E = Young's modulus of elasticity, lb./in.²

These values were plotted and connected by dashed lines in the load-stress diagrams. They will, hereafter, be called experimental stresses.

(b) ERRORS.—In taking strain-gauge readings, the operator should apply the gauge to the gauge holes in the same manner each time and with the same pressure to obtain comparable results. While readings obtained in this way are not as accurate as those read from a strain gauge which is attached to the specimen on the gauge line, the adaptability of the hand strain gauge to a study of stress distribution, such as this and the reasonable accuracy obtained, makes its use very valuable. In taking such a large number of readings, accidental errors will occur. If the incorrect reading is not for the initial load, the effect is, merely, to give a wild point on the stress diagram. If, however, the initial reading is wrong, incorrect stress values are obtained for all loads. This is doubtless the reason for such apparent irregularities as those for gauge 1-D of hook H-1, 1-F of hook K-8, and 1-I of hook K-9.

In the stress-strain diagram for a tensile specimen, a smooth curve is generally drawn through the observed points and the modulus of elasticity, proportional limit, and the yield point values determined from the faired curve. This procedure would have been allowable in the present study and, further, it would have been permissible to have faired the stress values along the hook for any load. It was, however, considered better to give the actual values derived from the strain-gauge readings than to give the faired results.

In comparing the experimental stresses with values obtained in other ways, consideration should be given to the method of taking the strain-gauge readings by hand. Unavoidable errors of 2,000 lbs./in.² may have occurred in these values.

(c) RELATION OF STRESSES AT EXTREME FIBER AND AT THE GAUGE LINE.—Since the gauge lines were one-eighth inch from the edge of the hook where the extreme fiber stresses due to bending occur, the theoretical stresses were computed for the gauge lines. The comparison of the experimental and the theoretical values can, of course, be made as well for the gauge lines

H-2

FIG. 5.—Load-stress diagrams for the 5-ton hook H-2

as for the extreme fiber. The curved surfaces of the hooks were not machined, and it was found impossible to obtain accurate readings from the forged surfaces. The gauge lines were, therefore, placed on the machined edge of the hook as close as was practicable to the curved surfaces.

As soon as the extreme fiber had been stressed beyond the proportional limit, the proportionality of stress to distance from the neutral axis ceased and the deformation in fibers near the extreme edge increased more rapidly than the applied load. This caused the stress at the extreme fiber to differ from the stress at the gauge line by an unknown amount less than the difference calculated from pure elastic theory, the two becoming more nearly equal as the load increased. Since the stresses could not be evaluated beyond the proportional limit and only a rough estimate of their value could be made, it was thought sufficient to assume arbitrarily that for all higher loads the stress was equal to the proportional limit. This does not alter any of the conclusions, since they are based solely on values below the proportional limit.

3. THEORETICAL STRESSES

The load line was drawn on the trace of the hook through the center of curvature of the tip of the hook and of the rounded edge of the hole in the shank. After test, flattened portions of these curved surfaces were found to lie on this line. The other values needed for use in the formulas, which were not obtained by measurement of the hooks, were obtained graphically from the trace.

As the ordinary beam formula allows the stress to be computed for any point in the hook, the stress at every gauge line was obtained for each load. These were plotted as the full lines in the load-stress diagrams (figs. 4 to 12), and in the following discussion will be referred to as the theoretical stresses.

A study of the load-stress diagrams shows that when the material on the tensile side of the hook passes the proportional limit, the material on the compressive side, also, reaches the proportional limit, although the theoretical stresses in compression are lower than those in tension for a given load. At the critical section, the value of S_1 is only about one-sixteenth of the total stress, $S_1 + S_2$. After the material on the tensile side of the hook had reached the proportional limit, only a small increase in load would, therefore, be required to cause the material on the compressive side to reach the proportional limit.

H-3.

FIG. 6.—Load-stress diagrams for the 5-ton hook H-3

The actual distribution of stress in the metal near the hole in the shank is irregular. In nearly all the hooks, the experimental stresses for those gauge lines near the hole are higher than the theoretical stresses. The stress is evidently not distributed uniformly across the section, but is concentrated near the sides where the gauge readings were taken. The experimental stresses were calculated on the assumption of uniform distribution and from the size of the section at the center of the gauge length. The stress distribution along the hook is not linear in the vicinity of the hole, and the strain gauge obviously gives values of average stress over the finite gauge length. It should be noted that the holes in the 5-ton hooks were somewhat larger than those in the hooks used in actual service in order to permit of proper testing fixtures. This enlargement of the holes happened to be sufficient to make the stresses near the holes larger than at the critical section where the moment arm, from the load line to the center of the section, was a maximum.

The load-stress curves (figs. 4 to 12) show that, in general, there is good agreement between the theoretical and the experimental values. At the critical section the tensile experimental stresses tend toward higher values than the theoretical. The values of experimental stress, on the compressive side of the hook, were more irregular than on the tensile side and did not agree so well with the theoretical stress.

4. STRESS BY WINKLER-BACH AND ANDREWS-PEARSON FORMULAS

The tensile stress values at that section of each hook where the gauge line was nearest to parallelism with the load line have been computed by the curved beam theories; that is, Winkler-Bach and Andrews-Pearson formulas. These gauge lines, near or at the critical section of each hook, are the only ones where agreement with these formulas is to be expected, since both derivations are based on the assumption of the absence of shear deformations.

Table 2 gives these values as well as the theoretical and experimental values. The latter have been averaged from the strain-gauge readings which gave stresses below the proportional limit of the material. The difference in the stress values for hooks of the same nominal size is caused by small differences in the size of the hooks. Since there is a difference of not more than 2 per cent between the stresses computed by the Andrews-Pearson and the Winkler-Bach formulas, as shown in the last column of Table

2, the strain-gauge measurements were not sufficiently accurate to show which agreed more closely with the actual stress.

For the 5-ton and 10-ton hooks the average experimental stresses are higher than those obtained by even the Andrews-Pearson formula. The experimental values from the three hooks of each type indicate an agreement with the Winkler-Bach and the Andrews-Pearson theories and show that larger stresses were present than expected by the ordinary beam theory.

The agreement of the experimental stresses in the 15-ton hooks with the stresses given by the curved beam theories is, however, not very good. In fact, the hooks K-7 and K-9 gave experimental values almost in exact agreement with the ordinary beam theory. The preponderance of the experimental data, however, indicates that the stresses in such girder hooks are higher than one would expect from the ordinary beam theory. The greatest difference between the stresses calculated by the Andrews-Pearson and the ordinary beam formulas is less than 20 per cent, as shown in next to the last column of Table 2. On account of the labor and accuracy required for designing hooks by the curved beam formulas, it is believed that the ordinary theory is sufficiently accurate for practical purposes, especially since large factors of safety should always be used.

TABLE 2.—Comparison of Experimental and Computed Stresses at the Critical Section

Hook	Section	Stress due to load of 1,000 pounds				Ratios of stresses			
		Experimental	Ordinary	Winkler-Bach	Andrews-Pearson	Experimental to ordinary	Winkler-Bach to ordinary	Andrews-Pearson to ordinary	Andrews-Pearson to Winkler-Bach
		Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²				
H-1.....	2 E	1,195	1,126	1,300	1,326	1.06	1.15	1.18	1.02
H-2.....	2 E	1,437	1,187	1,362	1,391	1.21	1.15	1.17	1.02
H-3.....	2 E	1,651	1,209	1,386	1,414	1.37	1.15	1.15	1.02
Average for 5-ton hooks.....						1.21	1.15	1.17	1.02
J-4.....	2 J	1,105	1,030	1,058	1,071	1.07	1.03	1.04	1.01
J-5.....	2 J	950	925	954	960	1.03	1.03	1.04	1.01
J-6.....	2 J	1,008	923	945	948	1.09	1.02	1.03	1.01
Average for 10-ton hooks.....						1.06	1.03	1.04	1.01
K-7.....	2 D	422	417	483	494	1.01	1.16	1.19	1.02
K-8.....	2 D	450	397	462	472	1.13	1.16	1.19	1.02
K-9.....	2 E	420	423	491	501	1.00	1.16	1.18	1.02
Average for 15-ton hooks.....						1.05	1.16	1.19	1.02

FIG. 8.—Load-stress diagrams for the 10-ton hook J-5

5. OPENING OF HOOKS

For each load, the distance across the opening in the hooks was measured with a steel scale graduated in hundredths of an inch.

Table 3 shows the openings of the hooks for the loads which approximate the loads which brought the extreme fiber, at the critical section, to the proportional limit. These values are, in all cases, less than one-sixteenth of an inch, and prove that it is impossible to determine by visual inspection whether any part of the hook has been stressed beyond the proportional limit. Figure 3 shows one hook of each size, after loading so far beyond its rating that it was about to slip off the shackle.

TABLE 3.—Openings of Hooks

[The loads are approximately those which theoretically stress the extreme fibers at the critical section to the proportional limit]

Hook	Nominal capacity	Load	Original length	Opening
	Pounds	Pounds	Inches	Inch
H-1.....	10,000	29,000	6.60	0.02
H-2.....	10,000	25,000	6.60	.04
H-3.....	10,000	24,000	6.57	.03
Average.....				.03
J-4.....	20,000	29,000	11.14	.04
J-5.....	20,000	30,000	11.03	.04
J-6.....	20,000	30,000	10.93	.04
Average.....				.04
K-7.....	30,000	60,000	12.06	.01
K-8.....	30,000	59,000	12.24	.02
K-9.....	30,000	60,000	12.18	.02
Average.....				.02

IV. CONCLUSIONS

1. The stresses obtained from strain-gauge measurements on girder hooks of rectangular section agreed well with the stresses computed by the ordinary theory of combined tension and bending.

2. The experimental stresses at the critical section were higher than the values computed by the ordinary theory of combined tension and bending for all hooks except K-9. The results indicate that the Winkler-Bach and the Andrews-Pearson formulas, which take into account the curvature of the hook, give reasonable values for the stresses.

3. For hooks of these dimensions, the difference between the Winkler-Bach and the Andrews-Pearson values (2 per cent) is so small that the additional labor of computing the latter is not warranted.

J-6.

FIG. 9.—Load-stress diagrams for the 10-ton hook J-6

K-8.

FIG. 11.—Load-stress diagrams for the 15-ton hook K-8

FIG. 12.—Load-stress diagrams for the 15-ton hook K-9

4. The stress computed by the Winkler-Bach or the Andrews-Pearson formulas was in no case more than 20 per cent greater than the stress computed by the ordinary theory of combined tension and bending. If the factor of safety used in designing

FIG. 13.—Typical stress-strain curves of coupon specimens

hooks of this kind is sufficiently large, it is believed that the use of either of the more exact formulas is not necessary.

5. It is impossible to determine by visual inspection whether any part of the hook has been stressed beyond the proportional limit.

WASHINGTON, March 26, 1924.