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THE STATIC BENDING MACHINE AND ITS USE IN THE DETERMINATION OF THE EFFECT OF COMBINED STRESSES IN STEEL.

A Thesis Submitted to

The Faculty of

The Michigan Agricultural College.

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The extensive use of steel in the various lines of industry has made the study of its properties of great importance, and much has been done in the making of machines of various types for the purpose of testing it. There are on the market today several kinds of testing machines for determining the tensile strength, the hardness, the composition, and etc. of various kinds of this useful material and most up-to-date manufacturers have installed in their testing laboratories some of these.

One well known machine for this kind of work is the power-driven tension machine which is used in determining the tensile strength of steel or other materials. The specimen, which is usually a bar about eighteen inches long, is held vertically by clamps fastened rigidly in the machine and tension or "pull" is applied by the lowering of the bottom clamp through gears and a screw by a motor or other source of power. The amount of tension in pounds is given at any time by the balancing of a large scale beam on the machine. This make is known as the Riele Testing Machine.

Other examples are those makes known as The Olsen Hydraulic Machine, The Torsion Machine, The Amsler Hydraulic Machine and etc.

The American Society for Testing Materials appointed a committee to investigate the features of these machines and the following report was made on the speed of testing:

"On analyzing and comparing the details of 437 tests, we find some difference in results of the same material tested at the same or nearly the same speed. This is due, apparantly to the difference in testing machines, to the manner of measuring, or to the personal equation of the operator which plays such a large part in all testing, and finally to the differnce of the material itself, all of which are factors entering into commercial testing at one time or another, singly or collectively, and cannot be avoided under present conditions. The results of tensile strength and elongation show tolerable uniformity in twelve laboratories----Unless one is an expert in----using micrometers----there is a liability of errors, large and small, and the result is nothing but guess work-----There is a surprising uniformity in the results of elongation at all speeds and in all laboratories---Taking all these facts into consideration, your committee----recommends---a maximum speed of three inches per minute for steel of the forging grade, when a two inch section is used, and a maximum speed of six inches for steel of the boiler grade where an eight inch section is used."

The two-inch and eight-inch section means the length of the specimen between gage marks. It is a well known fact that the mechanical and heat-treatments of steel and probably other metals affect their physical properties. It is also well known that large members, such as large columns and I bars are not as strong as small specimens of the same kind of material. Therefore it has been advocated, and is now being carried out, that full sized members should be tested to study their behavior under stress. Machines of enormous capacity have been built, and are not at all uncommon, as large as 6,000,000 pounds. A 2,000,000 pound tension machine has been in existance for some time at the Phoenix Bridge Co. The United States government has recently installed a 10,000,000 pound machine.

The accuracy of the weighing scheme is important. Large machines are less sensitive than small ones, as regard the number of pounds required to make them act, but the proportion is about the same.

If inaccuracy is suspected, how can its amount be determined, or in other words, what is the best way to calibrate a machine? It is not usually possible to load a machine with pig iron. In making a system in loading levers the same inaccuracy is liable to accur as occured in the machine.

The American Society for Testing Materials' Committee on "Standard Methods of Testing", recommend the following in the proceedings of 1909:

"Calibration for Testing Machines:

(1) Test for accuracy by loading the weighing table with standard weights, and compare the actual weight at each addition with the reading on the beam. If the table is uniformly loaded in this manner with the full amount of weights that it will accomodate, the proportionality of the levers and the weighing beam can be successfully established. This relation, in a properly designed machine, will remain constant for all loads, but at a further test for sensitiveness under greater loads than can be accommodated in this manner, the following procedure is recommended:

(2) Place in the machine a tension bar of such a cross-section that the maximum capacity will not stress it past the elastic limit. Stress this bar to various extents through the full range of the machine, and at each load balance the beam and place upon the weighing table standard weights of 100 pounds. A weight 1/250 of the total load on the machine should produce a readable movement of the beam.

(3) Where evidence of the accuracy over the whole range of the

machine is desired, a known load may be applied by means of an extensometer and calibrated bar, whose modulus of elasticity has been determined with exactness.

(4) It is recommended that a devise be adopted conforming to the following requirements, in which the extensometer and bar are perminently attached to each other.

a. This bar shall be annealed or other-wise treated so as to determine the unequal or internal stress in the material, and to insure its elastic modulus being uniform for successive tests.

b. This bar shall be of high elastic limit material and of such cross section that the limit shall be well above the total capacity of the machine on which it is to be used.

c. The extensometer shall be preferably of the indicating or direct reading type, and shall indicate to 1/10,000 of an inch or less.

d. The extensometer shall be perminently attached to the bar, and shall measure the elongation on two opposite sides.

e. The method of securing the bar to the draw-head of the machine shall be positive and without slip, and shall insure axial location.

f. The length of the bar measured by the extensometer shall be sufficient, but the smallest extensometer division will correspond to a difference in loading of 100 pounds or less.

g. The extensometer shall be protected from injury by a perminently attached case with the cover movable for reading the scale.

h. The apparatus shall be plainly marked with the maximum load that can be safely applied without injury.

i. The apparatus shall itself be calibrated either by the

U.S. Bureau of Standards or in a manner that will insure equally trustworthy results."

All of the tests herein refered to are for the determination of the effect of simple stresses, that is, simple tension, compression , torsion or bending.

What happens when two or more of these are acting in a piece at the same time? Do their relative strengths remain the same? Are the various stresses added?

These are questions still unanswered and as the uses of steel increase their importance increases.

Lord Kelvin in the preparation of his article on Elasticity for the Encyclopedia Britanica, had a series of tests made upon piano wire. The wire having sufficient weight to keep it straight while suspended was subjected to a torque at the bottom; when additional weight was added it was found that the elastic limit of the wire in torsion was lowered.

Mr. J.J.Guest, in England, carried out a series of tests to obtain the effect of combined stresses on ductile materials, the materials used in the tests being wrought iron, mild steel, copper and brass. The results of these tests also lead to the same conclusion, that the elastic properties are lowered when the materials are subjected to combined stresses.

The slight knowledge of this subject and the entire absence of any information available for engineers inspired Mr. Edward L. Hancock to carry out a series of investigations to give information immediately available for practical work.

His tests included the following:

(a) Test of steel and iron solid rounds and hollow tubes in torsion while under tension.

(b) Test of steel and iron solid rounds and hollow tubes in tension while under torsion.

(c) Test of steel and iron solid rounds and hollow tubes with increasing tension and torsion.

(d) Test of steel and iron solid rounds and hollow tubes in compression while under torsion.

The apparatus used was an Olsen Machine with various contrivances of his own design for giving torsion. The cost was undoubtedly a great amount and the work required much time. His conclusions after four years work may be found in volume VIII of the proceedings of The American Society for Testing Materials.

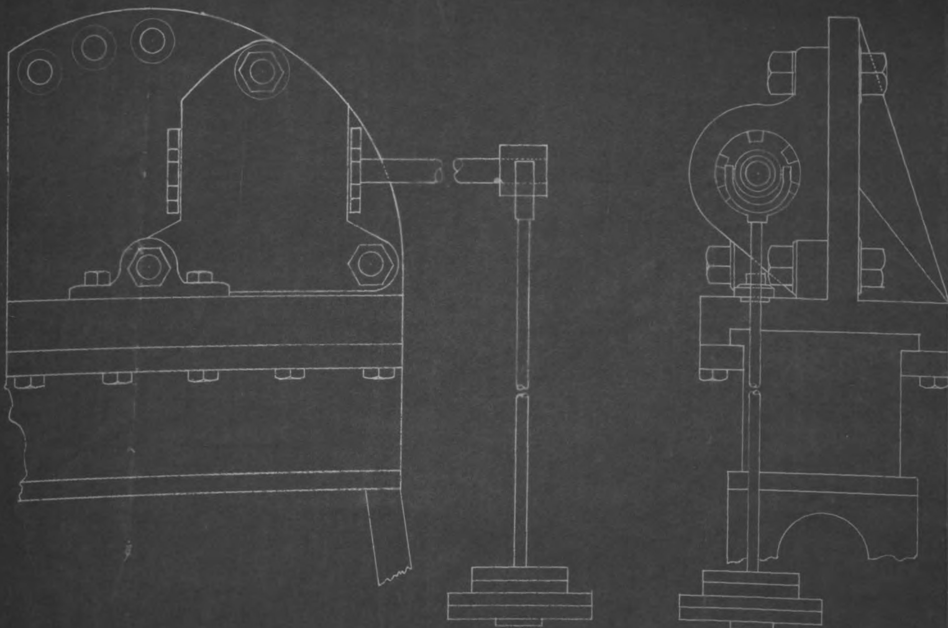
It was with the foregoing in mind that the Static Bending Machine was started and with these thoughts that the writers have labored for nearly a year with egarness to complete the machine and to test its value.

After several misfortunes,one being the loss of the shops by fire, the machine has been completed to such an extent that it can be used for combined compression and bending and it is the aim of the writers to determine the effect of these as much as possible in the few days remaining for the work.

This Static Bending Machine shown on a following page is easily understood from the picture. It is simply a machine for holding a rod as a cantilever loaded at the end with provisions made for setting the rod at horizontal,at 30 degrees with the horizontal, at 45 degrees with the horizontal or at 60 degrees with the horizontal, thereby adding compression as well as shear to the bending.

The rod is held in place by a split sleeve drawn up by a nut and the weight holder by another sleeve as shown. There are at present three sleeves; $\frac{3}{4}$ inch, 1 inch, and $1\frac{1}{4}$ inch diameters.

It is intended to make a torsion arm for the machine so that combined stresses of all kinds can be put in the specimen to be tested.



Static Bending Machine.

To Determine the Effect of Flexure and Compression:

When a specimen is stressed in flexure, the fibers on the convex side are in tension and those on the concave side are in compression. Flexure therefore puts both tension and compression in equal amounts in the stressed member and when the break occurs the ultimate strength in tension or compression, whichever is lower, has been exceeded. In steel the compressive and tensile strengths are usually about equal. If, therefore, a specimen of steel be broken in a tension machine and another be broken by bending, the unit-stress should be the same in both cases.

The same should hold also for stresses less than the breaking stress. The unit-stress at the elastic limit in tension should be equal to the unit-stress at the same point in bending, if the tensile and compressime strengths are equal. If there is a difference in this value, the strength in compression at the elastic limit must be less than the tensile strength by the amount equal to the difference between the unit-stress values obtained in the two cases. Now since the elastic limit is that point at which deformation ceases to be proportional to the load , it may be determined from a stress-strain diagram, or by noting the point at which the load drops as in the case of the machine used(the Static Bending Machine).

I. Therefore, test three bars (more if necessary) in the tension machine, recording the diameter of the bar in three or more places. The test should be carried on in the following manner:

Apparatus:

I log board

pair of 8 inch dividers

micrometer caliper

3 eighteen inch specimens

Mark on the specimen an eight inch space equidistant from the ends of the bar, and take the diameter readings with the micrometer between the markd. Insert the specimen to be tested in the jaws of the machine and apply the load at its lowest speed. Keep the beam balanced by moving the poise and note carefully the behavior of the scale beam. The elastic limit will be that point at which the scale beam drops. Record the reading on the beam. This should be donewith all three specimens and the average value of P/A taken as the unit stress at the elastic limit, P being the reading on the beam and A the average cross-sectional area of the specimens. If the values of P/A do not come practically the same, more than three tests should be run.

II. Now having determined the tensile strength per square inch at the elastic limit, test three or more bars in the Static Bending Machine in the following manner; Set the holder in the horizontal position and insert a bar (length to be determined for about a 400# load.) Place the weight holder on the end of the specimen and add weights carefully until there is a sudden drop. Record the length required also the weight used. Calculate the unit stress at the elastic limit by use of the formula S_b = MI/c which for a circular section is $32M/nd^3$ where M = bending moment in inch pounds and d - diameter of the specimen. Do this with three specimens if the values of S_b are nearly equal. If not use more. Take the average value as the unit stress in flexure and determine whether tension or compression by comparing results of test number one.

III. Test three or more bars with the machine set at 30 degrees and do as above.

IV. Do the same with the machine set at 45 degrees.

V. With the machine set at 60 degrees.

Compare the results obtained by the various tests with the formulae derived theoretically in Merriman's, American Cival Engineers Hand Book and Church' Mechanics of Engineering.

LIST OF RESULTS

3/4 INCH STOCK USED FOR THESE TESTS

Horizontal.

	No. 1.	No. 2.	No. 3.
Length of rod	14"	17"	$13\frac{1}{4}$"
Lever arm	14"	17"	$13\frac{1}{4}$"
Weight required	157#	140#	168#

30 degrees with horizontal.

	No. 1.	No.2.	No. 3.
Length of rod	16.375"	21"	24.25"
Lever arm	14.18"	18.19"	21"
Weight required	148#	111#	98#

45 degrees with horizontal.

	No. 1.	No. 2.	No.3.
Length of rod	30.375"	24.5"	32.75"
Lever arm	21.5"	17.32"	23.15"
Weight required	79#	115#	78.5#

60 degrees with horizontal.

	No. 1.	No. 2.	No.3.
Length of rod	39.75"	42.5"	31.5"
Lever arm	19.875"	21.25"	15.75"
Weight required	95#	79.5#	119#

LIST OF RESULTS.

1 inch stock used for these tests.

Horizontal

	#1	#2	#3
Length of rod	12"	12"	$11\frac{3}{4}$"
Lever arm	12"	12"	$11\frac{3}{4}$"
Weight required	449#	452#	440#

30 degrees with the horizontal

	#1	#2	#3
Length of rod	17.5"	14.75"	16.125"
Lever arm	15.15"	12.77"	13.96"
Weight required	368.#	452.#	440.#

45 degrees with the horizontal

	#1	#2	#3
Length of rod	20"	21"	24"
Lever arm	14.14"	14.85"	16.97"
Weight required	344#	331#	271#

60 degrees with the horizontal

	#1	#2	#3
Length of rod	47.75"	35.5"	
Lever arm	23.875"	17.75"	(No stock)
Weight required	164#	246#	

LIST OF RESULTS.

$1\frac{1}{4}$ inch stock used for these tests.

Horizontal

	#1	#2	#3
Length of rod	33.5"	29"	24.5
Lever arm	33.5"	29"	24.5
Weight required	278#	292#	406#

30 degrees with the horizontal

	#1	#2	#3
Length of rod	20"	22"	39"
Lever arm	17.32"	19.05"	33.77"
Weight required	570#	500#	252#

45 degrees with the horizontal

	#1	#2	#3
Length of rod	39"	29"	30"
Lever arm	27.57"	20.4"	21.21
Weight required	313#	427#	398#

60 degrees with the horizontal

The sleeve would not hold solid enough for this test.

$\frac{3}{4}$ inch stock.

		Horizontal
#1	M = 2198	S_b = 24.13M = 53,037
#2	M = 2338	S_b = " " = 56,419
#3	M = 2226	S_b = " " = 53,713
Average	2268	54,389
		At 30 degrees
#1	M = 2100	S_b = 24.13M = 50,677
#2	M = 2019	S_b = " " = 48,718
#3	M = 2058	S_b = " " = 49,659
Average	2059	49,683
		At 45 degrees
#1	M = 1698	S_b = 24.13M = 40,973
#2	M = 1992	S_b = " " = 48,718
#3	M = 1817	S_b = " " = 43,844
Average	1836	44,295
		At 60 degrees
#1	M = 1888	S_b = 24.13M = 45,557
#2	M = 1689	S_b = " " = 40,755
#3	M = 1874	S_b = " " = 45,219
Average	1817	43,443

1" stock

Horizontal

#1	M = 5424	S_b = 10.18M = 55216
#2	M = 5388	S_b = " " = 54850
#3	M = 5170	S_b = " " = 52630
	Av. 5327	Av. 54232

At 30 degrees

#1	M = 5575	S_b = 10.18M = 56753
#2	M = 5772	S_b = " " = 58759
#3	M = 5067	S_b = " " = 51222
	Av. 5471	Av. 55578

At 45 degrees

#1	M = 4865	S_b = 10.18M = 49515
#2	M = 4915	S_b = " " = 50035
#3	M = 4599	S_b = " " = 46818
	Av. 4793	Av. 48789

At 60 degrees

#1	M = 3915	S_b = 10.18M = 39854
#2	M = 4366	S_b = " " = 44140
	Av. 4140	Av. 41997

$1\frac{1}{4}$" stock

		Horizontal
#1	M = 9213	S_b = 48000
#2	M = 8468	S_b = 45118
#3	M = 9947	S_b = 51824
	Av. 9209	Av. 48314

		At 30 degrees
#1	M = 9872	S_b = 5.21M = 51433
#2	M = 9525	S_b = " " = 49625
#3	M = 9828	S_b = " " = 51204
	Av. 9742	Av. 50754

		At 45 degrees
#1	M = 8602	S_b = 5.21M = 44816
#2	M = 8710	S_b = " " = 45379
#3	M = 8542	S_b = " " = 44504
	Av.= 8618	Av. 44900

STRENGTH IN TENSION.

Determined by the tension machine.

$\frac{3}{4}$" bar — Average load = 21,280#

S = 48, 121 pounds / square inch

1" bar — Average load = 36,300#

S = 46,247 pounds / square inch

$1\frac{1}{4}$" bar — Average load = 56,680#

S = 46,181 pounds / square inch

Average S for all sizes = 46,850 pounds / square inch

COMPARISON of RESULTS.

Average unit strengths determined by the Static Bending Machine:

	0 degrees	30 degrees	45 degrees	60 degrees
¾" stock	54,[illegible]	49,883	44,295	43,413
1" "	54,232	5[illegible],575	48,739	41,[illegible]7
1¼" "	48,[illegible]14	50,[illegible]54	44,900	--------
Average	52,312	52,005	46,058	42,750

Average unit strength as determined by the tension machine is equal to 48,250 pounds per square inch.

Compression in pounds per square inch for the rod at 30 degrees.

$\frac{3}{4}$"	167#	125#	111#
1"	236#	466#	233#
$1\frac{1}{4}$"	232#	204#	103#
Av.	217#	265#	159#

Final average = 214#

For the rod at 45 degrees.

$\frac{3}{4}$"	111#	161#	110#
1"	307#	298#	244#
$1\frac{1}{4}$"	180#	246#	229#
Av.	199#	235#	194#

Final average = 209#

For the rod at 60 degrees.

$\frac{3}{4}$"	186#	156#	233#
1"	180#	271#	
$1\frac{1}{4}$"	----	----	----
Av.	183#	214#	233#

Final average = 210#

From the above data it is seen that the average compression was practically the same for all tests in which the rods where held at an angle. This being the case the average unit strengths for 30, 45 and 60 degrees should be equal. There is however, a big difference and apparantly the two stresses when added do not give the total stress. If we omitt the 0-degree -- $1\frac{1}{4}$" test and the 30-degree- 1" test, both of which appear to be incorrect, we have

as averages, adding 810" compression in case of the angles, 54,315 -- 50,218 -- 46,93[illegible] .-- 42,930. These values seem to diminish by about 4000# irrespective of the combining of the compression.

What is the cause of this?

This is a question which cannot be answered until many tests have been carried out and carefully studied.