THE DETERMINATION OF STRESSES IN MACHINE FRAMES

Thesis for degree of Mechanical Engineer submitted by
J.W. Baugher, Jr., and Arthur Roberts, Jr.

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-Introduction-

For a number of years strain gages of the Berry type, invented by Professor H.C.Berry of the University of Pennsylvania, have been used in determining the deformation, and the stresses bringing about this deformation, in structures of steel, reinforced concrete, and similar materials, such as bridges, and buildings of various types. Instruments of this kind read elongations to an accuracy in the neighborhood of 0.0002 of an inch for each division on the Ames gage head (recording dial), and the gage length, or length over which the elongation is found, is usually two inches or greater. Thus for an instrument measuring in the units mentioned above the deformation or strain recorded over a length of material of two inches would be 0.0001 of an inch per inch of the material under test. Consequently, if the deformation of the material per inch, and the modulus of elasticity of the material be substituted in the fundamental relation between unit stress, unit deformation, and modulus of elasticity, the determination of the stress in the material tested involves only a simple arithmetical calculation. Thus,

$$\frac{\text{unit stress}}{\text{unit deformation}} = \text{modulus of elasticity.}$$

That is, the unit stress in the material is the product of the unit deformation or unit strain observed with the strain gage and the modulus of elasticity of the material, or

unit stress = unit deformation X modulus of elasticity.

Therefore, in materials such as concrete, which have comparatively small moduli of elasticity, the stress may be found quite correctly for values as low as 400 or 500 pounds per square inch, and if fractions of divisions on the dial are estimated, smaller stresses may be determined with reasonable accuracy. In materials such as structural steel or cast iron, the moduli of elasticity of which are large as compared with that of concrete, stresses as low as several hundred pounds per square inch may be measured if fractional divisions of the dial are read.

Up to the present time, however, little or no application has been made of the strain gage to the finding of stresses in the various parts of machine frames, and it was with the object of determining the applicability of the gage in tests of this nature and of observing, at the same time, the magnitude of the stresses produced in the frame of a single-stage,double-acting, Ingersoll-Sergeant Company (now Ingersoll-Rand Company) air compressor that the following experiment was undertaken.

-BERRY STRAIN GAGE-

Operation of Instrument

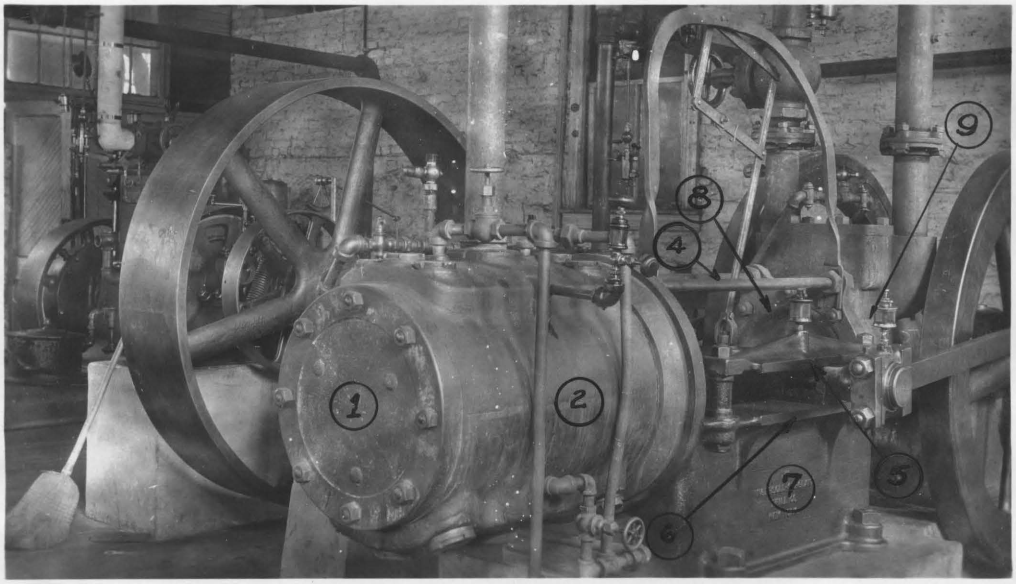
The Berry gage is illustrated in the figure. Any movement at A due to a change in length of the gage line is transmitted to the plunger EF of the Ames gage head through vertical movement of the arm BC, which is pivoted at B. The Ames gage head is sensitive to a movement at C of 0.001 of an inch. The ratio of the length of the arm BC to the leg AB is approximately five; therefore each division on the dial of the gage head will record a deformation of the gage line of 0.0002 of an inch ($\frac{.001}{5}$); that is, a movement of 0.0002 of an inch at A. In referring to an explanation similar to that presented above, Professor Arthur N. Talbot and Mr. Willis A. Slater of the University of Illinois state on page 26 of Bulletin Number 64 of the Engineering Experiment station entitled Tests of Reinforced Concrete Buildings: "However, this must not be taken to mean that the instrument or extensometer possesses this degree of accuracy in in measuring stresses, since some movement of the leg at A is certain to result from variation in the handling of the instrument". On page 35 of the same bulletin the following statement is made: "The ratio of multiplication in the Berry extensometer is not exactly equal to the ratio of the length of the arm to the length of the leg, the error being due to the fact that the plunger of the Ames gage head does not always travel in a line perpendicular to the multiplying lever. However, calculations show that the approximation results in an error in the measurement of steel stresses equal to only one-fourth of one per cent for an extreme case. It may be seen that this error can be neglected".

Calibration of the Berry Gage

The Berry strain gage used was calibrated against a Henning micrometer-screw extensometer on a round steel bar of known diameter which was subjected to tensile stress of from 1130 to 23,730 pounds per square inch in increment of 1130 pounds per square inch. The results of the calibration served only as a check on the values of the readings of the gage and indicated that the readings would be well within the limits of the error in the manipulation of the instrument.

Preparation of Machine

With the aid of a punch which comes with the Berry gage and which makes punch marks two inches apart marks were made in the frame of the compressor on the following parts as designated on the illustrations of the machine and on the sketches accompanying the pages of tabulated deformations and stresses.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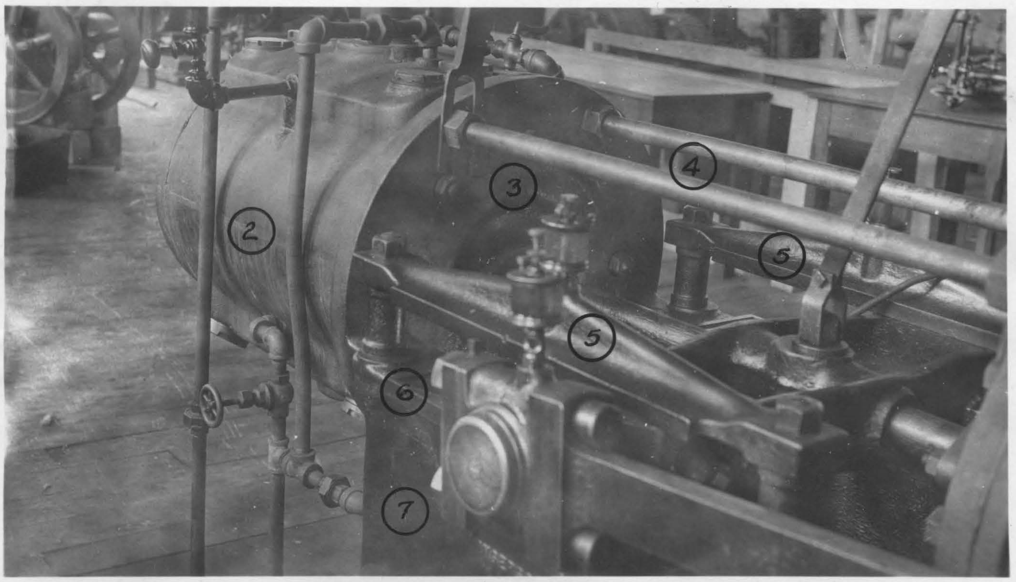
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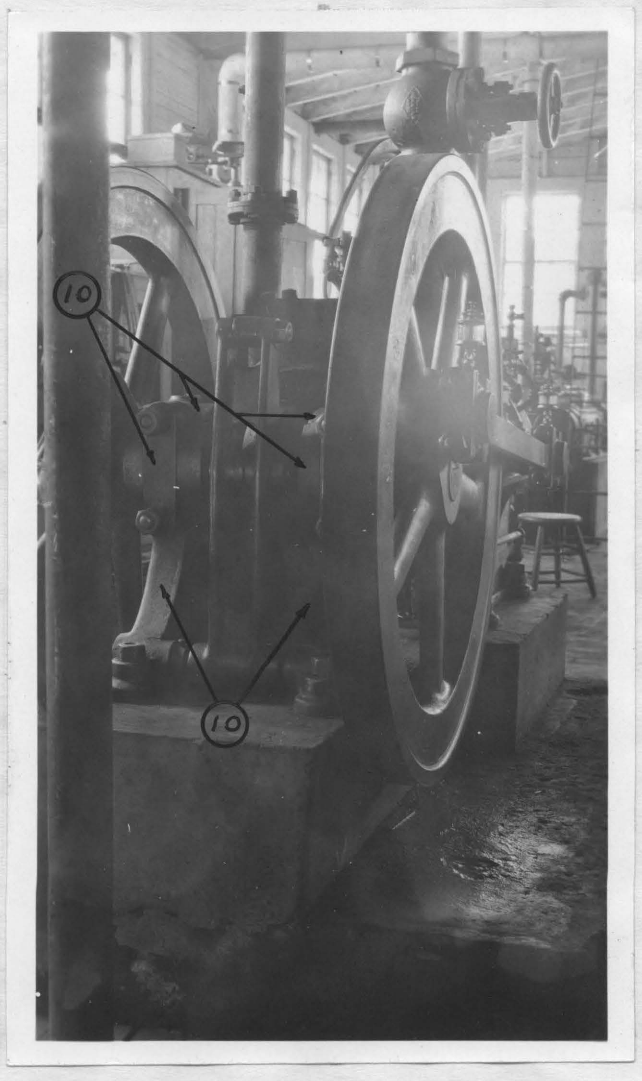
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(1) Compressor Cylinder Head (Head End)

Punch marks were made along a bolt diameter and along any other diameter, care being taken to have the center of the head in the center of the middle punch marks along each diameter.

(2) Compressor Cylinder Walls

Punch marks were made at approximately corresponding points at each end ~~end~~ on right and left sides (looking from the steam end) of the compressor ~~of the~~ cylinder walls. The marks were confined to the ends of the cylinder because it is at the end that the maximum stresses will necessarily occur on account of the higher compression near the ends of the strokes.

(3) Compressor Cylinder Head (Crank End)

On account of the shape of this member the punch marks had to be placed at irregular positions on its surface. Marks were placed at one point so that a reading could be taken as near the center of the head as possible.

(4) Tie Rods

On the tie rods on each side of the machine punch marks were made for three readings.

(5) Upper Crosshead Guides

The whole length of the upper crosshead guides were punch-marked at intervals of two inches.

(6) Lower Crosshead Guides

The lower crosshead guides were marked in a number of places on each side of the center, where it was believed the greatest stresses would occur.

(7) Bed Plate

Punch marks were made in a large number of positions over both sides of the bed plate and on the legs through which the machine was bolted to the foundation.

(8) Steam Cylinder Head (Crank End)

Various positions were chosen for the punch marks on the steam cylinder head. Marks were made, however, as near the center of the head as possible and along the "ears", which can be seen to deflect when the compressor is in operation.

Because of the motion of the valve rod it was virtually impossible to obtain readings of the deformation in the steam cylinder head on the head end.

(9) Steam Cylinder Walls

Both sides of the steam cylinder walls were punch-marked near the crank end. Readings could not be taken on other portions of the cylinder wall because of the rotation of the fly wheel.

(10) Bearing Pedestals and Covers

These members were marked at regular intervals of two inches for the entire distance along the tops of the bearing covers and along the ends of the pedestals. Marks were also made on the lugs where the pedestals were bolted to the foundation.

In all cases the marks were made, wherever possible, in several similar positions so that the reading at one position would serve as a check on the reading at a corresponding position, as well as the reading on one side of the machine would be a check on the corresponding reading on the opposite side, in the case of the cylinder walls, tie rods, and so forth.

Testing

Before the machine was run, a complete set of observations of all punch marks was made at room temperature about 65 degrees Fahrenheit.

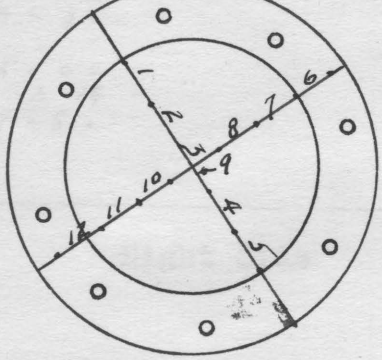
Whenever observations were made on the compressor in operation, it was allowed to run for about an hour to insure the uniform heating of parts and as constant condition as possible throughout the entire mechanism.

The compressor was run during the test at about 125 R.P.M. and with an air pressure in the receiver of about 70 pounds per square inch.

To obtain the stresses in the various parts the maximum reading of the Berry gage was noted while the machine was running, the machine was stopped, and the reading when the machine was not in operation was taken immediately. In this process the gage was held by hand in the punch marks in as constant a position as possible while the consecutive readings were recorded. Whenever any doubt as to the reading of the gage was experienced, several readings were taken and the average reading recorded. The number of corresponding readings which were obtained by the method employed in punch-marking the machine should, however, give the assurance of fairly accurate results.

Tabulated Results

(1) Compressor Cylinder Head (Head End)

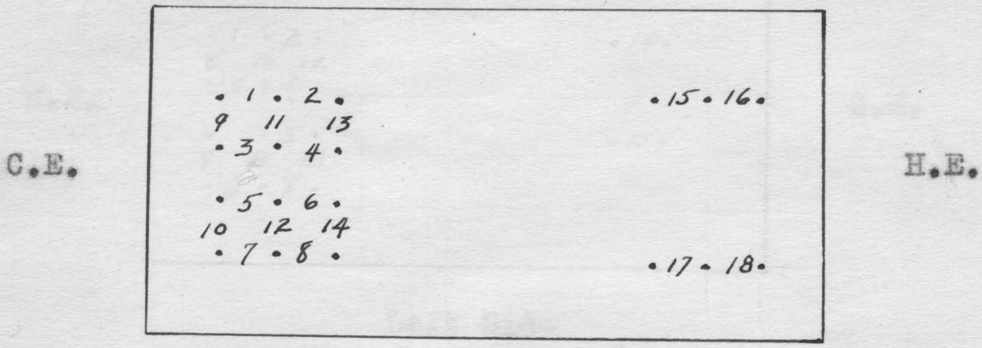


Note:
Diameter 1-5 should be shown as a bolt diameter.

No.	Gage Readings Room Temp	Running	Stopped	Stress lbs/sq. in.
1	49.5	63.9	63.9	000
2	30.0	43.0	43.0	000
3	55.0	70.6	70.1	750
4	46.5	57.0	56.75	375
5	34.3	44.9	44.8	150
6	46.5	57.6	57.6	000
7	41.2	54.5	54.5	000
8	49.5	64.8	64.7	150
9	48.5	60.2	59.7	750
10	48.7	59.1	59.0	150
11	55.3	61.5	61.5	000
12	53.4	61.2	61.1	150

Maximum stress in compressor cylinder head (head end) equals 750 lbs./sq. in.

(2) Compressor Cylinder Wall (Right Side)

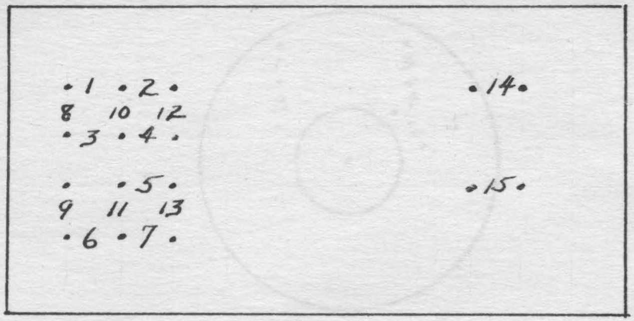


Right Side

No	Gage Room Temp.	Readings Running	Readings Stopped	Stress lbs./sq.in.
1	37.6	51.5	51.4	150
2	44.2	58.9	58.8	150
3	49.5	61.9	61.8	150
4	60.1	75.2	75.1	150
5	41.2	52.2	52.1	150
6	42.7	53.8	53.6	300
7	47.5	59.8	59.8	000
8	28.0	43.9	43.7	300
9	67.4	79.0	78.9	150
10	61.5	61.8	61.7	150
11	71.2	86.1	86.0	150
12	56.1	67.8	67.7	150
13	65.8	81.1	81.1	000
14	89.4	00.0	99.9	150
15	65.1	81.1	81.1	000
16	49.2	62.6	62.6	000
17	65.2	79.9	79.9	000
18	52.9	76.0	75.9	150

Maximum stress in compressor cylinder wall right side equals 300 lbs./ sq. in.

(2) Compressor Cylinder Wall (Left Side)

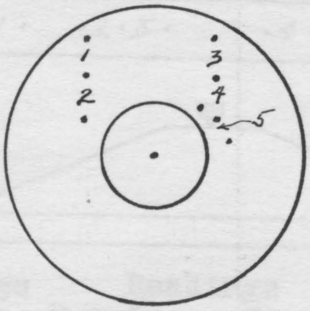


Left Side

No	Gage Room Temp	Readings Running	Stopped	Stress lbs/sq.in.
1	46.9	50.9	50.8	150
2	17.1	18.1	18.0	150
3	77.2	84.1	84.1	000
4	30.2	34.5	34.5	000
5	52.1	51.5	51.5	000
6	36.8	38.3	38.3	000
7	24.8	22.5	22.5	000
8	37.3	44.0	43.9	150
9	44.9	47.7	47.6	150
10	54.6	58.7	58.6	150
11	46.4	47.3	47.2	150
12	54.3	55.9	55.8	150
13	44.2	44.0	43.9	150
14	31.2	33.9	33.9	000
15	10.2	18.2	18.2	000

Maximum stress ------------------- 150 lbs/sq. in.

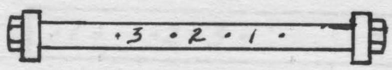
(3) Compressor Cylinder Head (Crank End) .



No	Gage Room Temp	Readings Running	Stopped	Stress lbs./sq.in.
1	65.5	71.9	71.9	000
2	73.0	80.1	79.9	300
3	95.1	109.6	109.6	000
4	78.0	67.8	67.7	150
5	36.7	56.7	56.5	300

Maximum stress---------------- 300 lbs/sq.in.

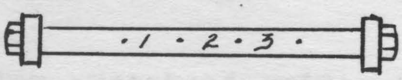
(4) Tie Rods (Right Side)

C.E.  H.E.

No	Gage Room Temp	Readings Running	Stopped	Stress lbs./sq.in.
1	79.0	81.9	81.8	300
2	76.8	77.8	77.7	300
3	79.1	79.1	79.0	300

Maximum stress--------------- 300 lbs./sq. in.

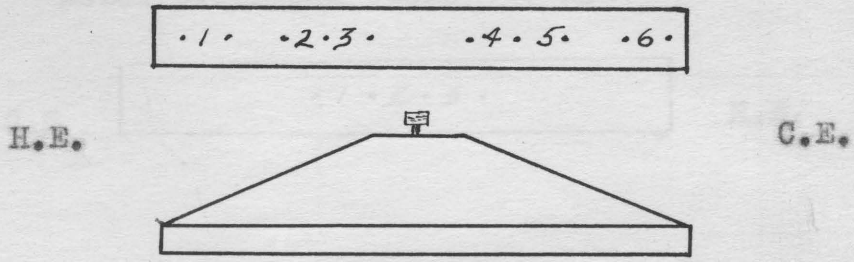
(4) Tie Rod (Left Side)

H.E.  C.E.

No	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in.
1	73.3	73.2	73.1	300
2	77.6	76.1	76.0	300
3	73.1	72.8	72.7	300

Maximum stress--------------- 300 lbs./sq.in.

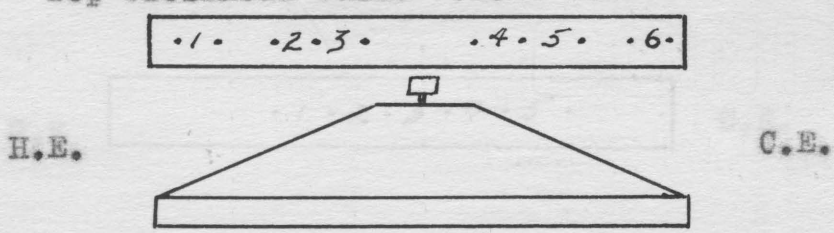
(5) Top Crosshead Guide (Right Side)



No	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in.
1	81.1	82.7	82.7	000
2	97.0	96.9	96.9	000
3	97.1	91.0	91.0	000
4	71.5	72.8	72.8	000
5	55.3	51.2	51.2	000
6	48.7	43.6	43.6	000

Zero stress in top crosshead guide (right side)

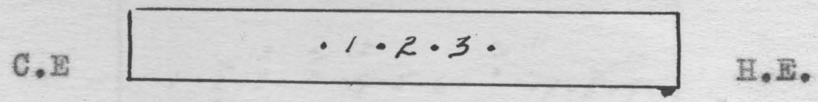
(5) Top Crosshead Guide (Left Side)



No.	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in.
1	84.0	81.5	81.5	000
2	59.3	55.6	55.6	000
3	77.0	73.1	73.1	000
4	80.8	79.7	79.7	000
5	73.0	68.1	68.1	000
6	71.9	67.1	67.1	000

Zero stress in top crosshead guide (left side)

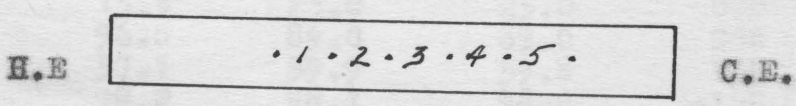
(6) Lower Crosshead Guide (Right Side)



No	Gage Room Temp.	Readings Running	Readings Stopped	Stress lbs./sq.in
1	63.0	65.1	64.9	300
2	94.5	43.4	43.3	150
3	45.8	91.1	91.05	075

Maximum stress-------------------300lbs./sq.in.

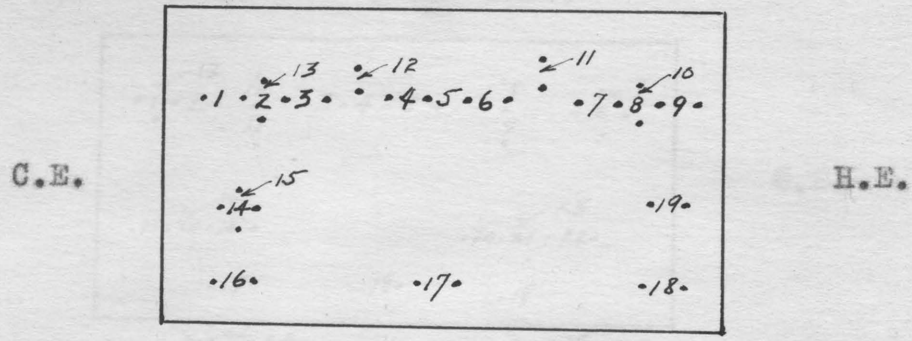
(6) Lower Crosshead Guide (Left Side)



No	Gage Room Temp.	Readings Running	Readings Stopped	Stress lbs./sq.in.
1	67.5	45.1	45.0	150
2	44.3	42.05	41.95	150
3	42.3	41.95	41.75	300
4	47.8	44.2	44.1	150
5	56.0	48.2	48.1	150

Maximum stress---------------------300lbs./sq.in.

(7) Bed Plate (Right Side)

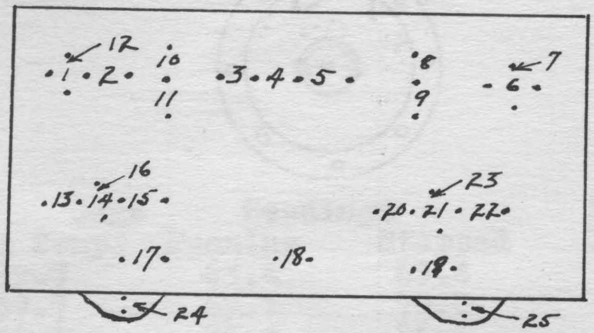


No.	Gage Readings Room Temp.	Running	Stopped	Stress lbs./sq.in	
1	61.5	61.5	61.4	150	
2	46.3	47.8	47.75	075	
3	71.1	67.4	67.5	-150	Compression
4	48.8	36.1	36.2	-150	"
5	84.0	82.1	82.0	150	
6	17.1	22.7	22.5	300	
7	73.8	78.1	78.05	075	
8	82.2	85.8	85.8	000	
9	73.0	71.2	71.05	225	
10	63.9	65.8	65.8	000	
11	67.2	74.5	74.5	000	
12	15.5	25.0	25.0	000	
13	96.0	89.0	89.0	000	
14	57.1	59.9	59.8	150	
15	99.0	98.1	98.2	-150	"
16	11.2	76.8	76.8	000	
17	81.2	79.8	79.8	000	
18	50.1	57.1	57.1	000	
19	73.6	76.0	76.0	000	

Maximum stress------------------------300 lbs./sq.in. tension
-150 " " " compression

(7) Bed Plate (Left Side)

H.E.

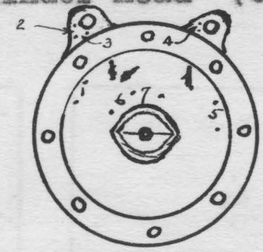


C.E.

No	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in.	
1	70.9	70.0	70.1	-150	Compression
2	79.7	78.95	78.9	075	
3	52.8	54.5	54.4	150	
4	65.4	66.8	66.7	150	
5	46.3	47.8	47.7	150	
6	73.8	72.0	72.1	-150	"
7	91.6	87.8	87.8	000	
8	51.1	29.9	29.9	000	
9	13.1	13.9	13.8	150	
10	52.1	41.2	41.2	000	
11	41.9	35.3	35.15	225	
12	68.6	70.5	70.45	075	
13	80.1	71.6	71.6	000	
14	73.7	74.9	74.9	000	
15	75.2	75.6	75.6	000	
16	89.1	81.1	81.0	150	
17	74.8	67.8	67.8	000	
18	57.2	58.05	58.0	075	
19	82.1	78.6	78.5	150	
20	59.0	56.7	56.7	000	
21	71.8	76.4	76.4	000	
22	56.1	58.05	57.95	150	
23	91.1	90.5	90.6	-150	"
24	67.0	65.9	65.9	000	
25	36.8	26.0	26.0	000	

Maximum stress----------------------225 lbs./sq.in. tension
-150 " " " compression

(8) Steam Cylinder Head (Crank End)

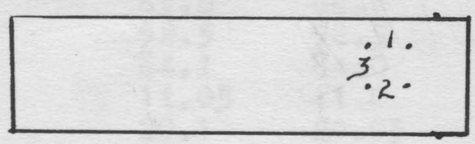


No.	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in.	
1	59.7	63.4	63.4	000	
2	57.7	69.1	70.0	-1350	Compression
3	68.5	86.4	86.6	-300	"
4	82.1	82.2	83.1	-1350	"
5	42.0	43.1	42.9	300	
6	75.2	69.7	69.7	000	
7	34.5	31.5	31.5	000	

Maximum stress--------- 300 tension, -1350 compression.

(9) Steam Cylinder Walls (Right Side)

H.E.



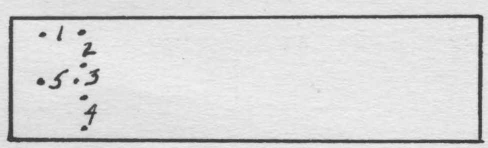
C.E.

No.	Gage Room Temp.	Readings Running	Stopped	Stress lbs/sq.in.	
1	69.1	75.1	74.9	300	
2	67.0	69.0	68.6	600	
3	29.2	45.0	45.05	-075	Compression

Maximum stress--------- 600 lbs./sq.in. tension
-075 " " " compression.

(9) Steam Cylinder Walls (Left Side)

C.E.

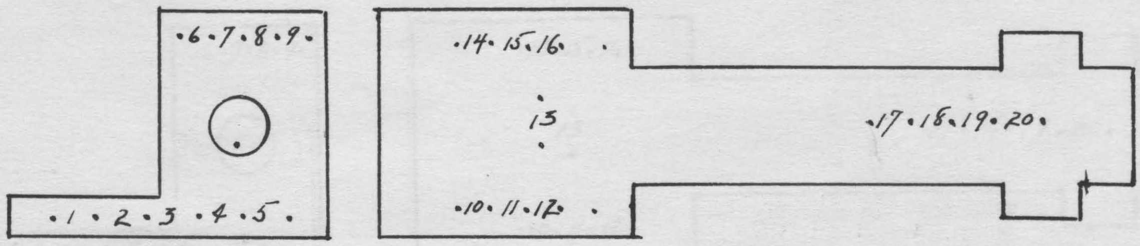


H.E.

No	Gage Room Temp.	Readings Running	Stopped	Stress lbs./sq.in
1	68.2	78.5	78.4	150
2	92.5	96.5	96.4	150
3	4.5	6.5	6.45	075
4	18.4	20.0	19.9	150
5	64.8	71.6	71.2	600

Maximum stress-----------600 lbs./sq.in tension.

(10) Bearing Pedestals and Covers (Right Side)

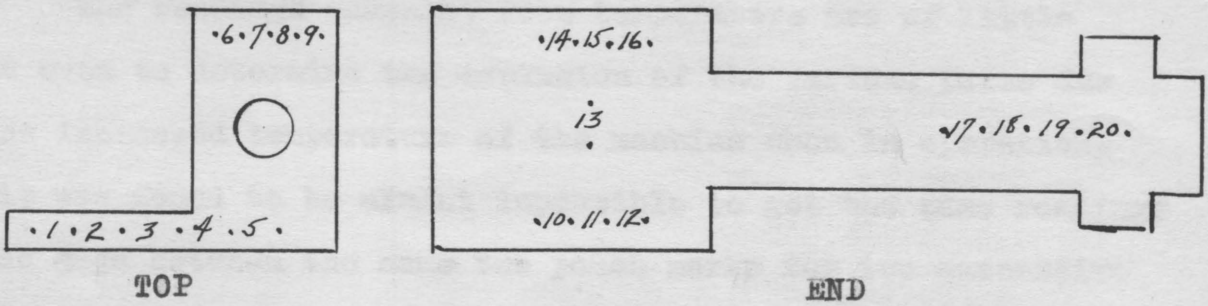


TOP END

No.	Gage Room Temp.	Readings Running	Readings Stopped	Stress lbs./sq.in.
1	31.6	21.2	21.0	300
2	70.4	68.0	67.8	300
3	16.5	25.7	25.0	1050
4	67.8	72.0	71.8	300
5	17.1	18.5	18.45	075
6	44.4	45.2	45.1	150
7	39.3	35.0	34.7	450
8	77.1	89.0	88.8	300
9	97.6	92.5	92.5	000
10	80.6	84.1	84.0	150
11	15.5	11.05	11.0	075
12	20.4	20.1	20.05	075
13	52.5	48.3	48.2	150
14	11.2	17.8	17.7	150
15	35.3	12.0	11.9	150
16	16.9	16.2	16.15	075
17	10.8	18.2	18.15	075
18	38.8	30.5	30.5	000
19	27.1	29.0	29.0	000
20	15.2	10.4	10.4	000

Maximum stress--------------- 1050 lbs/sq.in. tension.

(10) Bearing Pedestals and Covers (Left Side)



No.	Gage Room Temp.	Readings Running	Readings Stopped	Stress lbs./sq.in
1	63.1	73.0	72.5	750
2	42.2	53.0	52.5	750
3	33.9	34.5	34.0	750
4	22.0	22.5	22.4	150
5	75.1	83.05	83.0	075
6	89.8	80.5	80.4	150
7	42.9	35.6	35.5	150
8	11.1	1.0	1.0	000
9	22.2	24.0	24.0	000
10	25.1	24.0	24.0	000
11	97.4	80.0	79.8	300
12	89.9	25.1	24.85	375
13	45.5	47.5	47.3	300
14	31.4	10.0	9.95	075
15	89.9	3.3	3.0	450
16	32.1	97.0	96.8	300
17	65.5	78.0	77.95	075
18	86.7	94.05	94.0	075
19	62.4	93.2	93.1	150
20	100.9	96.2	96.2	000

Maximum stress-------------------- 750 lbs./sq.in tension.

CONCLUSION

The readings taken at room temperature are of little value even to determine the expansion of the various parts due to the increased temperature of the machine when in operation, for it was found to be almost impossible to get the same reading# of the gage between the same two punch marks for two successive trials if the gage was removed from the marks between readings.

It is apparent, as one might expect, that the maximum stress in the cylinder head of the head end of the compressor is in the center of the head, since the readings along both diameters gave the same results, a value which was greater than at any other point.

No deformation could be detected in the top crosshead guides and in the lower crosshead guides the deformation was quite small.

The largest stress found in the machine was that due to the bending of the "ears" thru which the tie rods are connected to the cylinder head. This stress was compression because the strain was observed on the inside fibers subjected to bending.

The next largest stress was found in the bearing cover on the right side of the machine. The stress in this gage line, however, did not agree with those found for similar positions on the same bearing cover or on the bearing cover on the left side. It is therefore quite likely that the value of the large stress observed was too great; but since it is well within the allowable value for cast iron, it is of little consequence.

It is quite improbable that the small compressive stresses observed at several positions on the bed plate and at one position on the steam cylinder wall were due to other causes other than the manipulation of the strain gage.

As stated before, all stresses were calculated from the fundamental relation

unit stress = unit deformation x modulus of elasticity.

The modulus of elasticity of the steel tie rods was taken as 30,000,000 pounds per square inch, while the modulus of elasticity of all cast iron members of the machine was taken as 15,000,000 pounds per square inch.

Since accepted values for the allowable stress in steel is 16000 pounds per square inch and in cast iron 3000 pounds per square inch, it may be aeen that all parts of the compressor which were tested are far within the limit of safety.