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TECHNICAL NOTE 3493

DEVELOPMENT OF EQUIPMENT AND OF EXPERIMENTAL TECHNIQUES FOR COLUMN CREEP TESTS

By Sharad A. Patel, Martin Bloom, Burton Erickson,
Alexander Chwick, and N. J. Hoff

Polytechnic Institute of Brooklyn

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SUMMARY

Equipment and procedures developed in order to test aluminum-alloy columns subjected to constant loads at elevated temperatures are described. The apparatus consists primarily of a lever type of loading mechanism and an electric oven. Particular emphasis was laid upon the determination of the influence of initial deviations from straightness upon the critical time of the column. Test results which were obtained with 15 2024-T4 aluminum-alloy columns having a slenderness ratio of 111 are presented. It was found that the critical time, that is, the time necessary for the column to buckle when subjected to a constant load, depends greatly upon the ratio of the applied load to the static critical load at the temperature of the test. The critical time is also a function of the initial deviation from straightness.

INTRODUCTION

The phenomenon of creep has been known for a long time. According to a recent paper by Orowan (ref. 1), it was first described by the physicist Weber in 1835. Modern research in creep began in 1911 when Andrade published his first paper on creep. Creep may be roughly defined as the property of a solid to continue to deform with time under a constant load. As creep in structural metals becomes noticeable only when the temperature of the metal is raised well above room temperature, engineers realized the importance of creep for the first time when objectionable changes in length were observed in components of high-temperature heat-power equipment.

In supersonic airplanes the temperature of structural elements is raised to sufficiently high values to make creep a danger to structural integrity. A similar situation exists in nuclear power plants. As airplanes and guided missiles fly at supersonic speeds only for limited intervals of time, the danger of failure of their structural elements in tensile creep fracture is somewhat remote. On the other hand, elements of the structure subjected to compression may well buckle during the lifetime of the structure even though the applied load is less than the critical load of the element at the elevated temperature.

As is well known, no column is absolutely straight, and the load applied to it is never perfectly centered. Because of these deviations from perfect straightness the applied axial compressive load has a lever arm with respect to the centroid of each section of the column. Under the simultaneous action of the bending moment, which is the product of the load with its lever arm, and the compressive load, the material of the column begins to creep noticeably if the temperature is high enough. Because of this creep the initial deviations from straightness increase with time. When the rate of creep is a linear function of the stress, the deviations increase first slowly and later more rapidly, becoming theoretically infinitely large only when time approaches infinity. This was shown by Hoff and Kempner in references 2 and 3. However, the creep law of metals is a nonlinear one and the deformations increase much more rapidly than the stress. For such nonlinear columns theory predicts indefinitely large deformations in a finite time. The time necessary for failure is called the critical time. In the tests described in the body of this report, the critical time varied from $1\frac{1}{4}$ minutes to $66\frac{1}{4}$ minutes.

It appears that the first theoretical investigation of creep buckling was carried out by Freudenthal (ref. 4). His results were reevaluated by Kempner and Pohle in 1953 (ref. 5). Recently, creep buckling was analyzed in some detail by Kempner, Patel, and Ness at the Polytechnic Institute of Brooklyn (refs. 6 to 9). These reports also contain charts from which the critical time of the column can be read if the initial deviation from straightness and the material properties of the column are known. Other contributors to the solution of the creep problem are Ross and Prentis (refs. 10 and 11), Marin (ref. 12), Jackson, Schwope, and Shober (ref. 13), Carlson and Schwope (ref. 14), Libove (refs. 15 and 16), and Shanley and his students (refs. 17 and 18).

The purpose of the investigation described in the present report was to establish methods of testing columns at elevated temperatures in creep buckling with the ultimate objective of obtaining an experimental verification of the creep behavior predicted by theory. The curves plotted on the basis of the 15 test results are similar to the theoretical curves published earlier. A complete verification of the theory must wait until the time when more data become available on the creep properties of the particular material used in manufacturing the columns.

This investigation was carried out at the Polytechnic Institute of Brooklyn under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. The authors are grateful

to Mr. Hans Menkes for his contribution to the design of the apparatus and to testing in the preliminary phases of the investigation and to Mr. S. Ledermann who took care of the electrical equipment.

TEST APPARATUS AND PROCEDURE

The main parts of the test apparatus are a lever type of loading mechanism designed to maintain constant axial compressive loads in the column and an oven capable of producing a constant elevated temperature. Details of the apparatus are given in the following discussion.

Loading Device

The axial compressive loads are applied to the column by means of a lever of I section with a mechanical advantage of 5. A loading extension projects from the lever into the oven where its hardened end surface applies a load to the column. The ends of the column specimens are fitted with adjustable knife-edge fixtures as shown in figure 1. Because these fixtures are stiffer than the column itself, the length of an equivalent uniform column is slightly smaller than the actual distance from knife edge to knife edge. Calculations have shown that with the columns of the present test program the difference is so small as to be negligible.

The knife-edged fulcrum of the lever presses upward against a V groove which is rigidly fastened to the frame of the apparatus. At the other end of the lever weights are suspended from a fixture which rests with a knife edge in a hardened V groove attached to the lever.

At this loading end of the lever a special apparatus is provided to allow close control over the variations in the column load during the heating process and over the rate of application of the load. The device is essentially an elastic cantilever rigidly attached to the loading frame and provided with an adjustable loading screw and a hardened steel ball. These details can be seen in the left side of figure 2. The strain gages cemented to this cantilever are calibrated in terms of the load acting upon the column; this load depends upon the weight applied to the lever and upon the position of the loading screw.

While the column is being heated, a small axial compressive load must be applied to it in order to maintain its position and adjustment. As the temperature of the column increases during the heating process, its length also increases and pushes the lever upward. This upward push of the column decreases the load on the cantilever unless the adjusting screw is readjusted. For this reason the load reading of the cantilever is followed carefully and the screw is so operated as to maintain constant the initial load in the column. An increase in the initial load during the heating process is objectionable because it may cause large creep deformations before the final temperature is reached uniformly over the length of the column.

When the final temperature is reached, the adjusting screw is moved down at a uniform rate until the entire applied load is transmitted to the column through the lever. During the actual column test, therefore, the cantilever does not carry any loads and the end of the lever is free to assume any position required by the geometry of the lever and the column.

Oven

The oven was designed to produce constant temperature in the range from 150° to $1,000^\circ$ F with a tolerance of $\pm 3^\circ$ F along the column.

The oven consists of a 7/8-inch Marinite box whose volume is approximately 3 cubic feet. It is divided by means of a screen and a system of baffles into two chambers. The electric-resistance heating units and a variable-speed circulating fan are located in the chamber on the left, while the right-hand chamber contains the specimen which is visible through the open door. (See fig. 2.) The angle of the baffles can be adjusted from the outside. To overcome the loss of heat through conduction in the steel structural elements a variable 100-watt immersion type of tube heater is installed in the loading extension of the lever and a variable 300-watt ring type of heater is installed in the steel support below the lower end of the specimen. These two heaters are individually controlled by means of powerstats.

The oven is not provided with windows so that there will be no losses of heat that may lead to a nonuniform temperature distribution. However, the chamber has a removable door in front, as shown in figure 2, which permits access to the specimen.

Heat losses are reduced to manageable proportions by means of a double layer of 2-inch-thick magnesia block insulation. The opening at the top of the oven necessary for the loading extension is provided with a heat trap. The construction of the door is similar to that of the box. The entire box is covered with 1/2-inch-thick plywood. This maintains the insulation in place and prevents the chipping of the insulating material.

In the heating chamber are installed 10 ring heaters. The bulk of the heat is provided by two single-step 750-watt heaters. In addition, there are two 300-watt heaters, each controlled by 350-watt powerstats manufactured by the Superior Electric Co. of Bristol, Conn. All these heating units are symmetrically located on the floor of the heating chamber. A three-step 750-watt heater and two single-step 300-watt heaters are located on each side wall.

All electrical connections provided for controlling the heat input and measuring the temperatures are brought to a central console in order to facilitate operation during the tests.

It is estimated that the steady-state power loss from the oven is approximately 850 watts when the temperature of the specimen is maintained at 600° F.

The loading device and the oven are mounted on six shock-absorbing shoes, as shown in figure 2, to eliminate the major portion of vibrations which might otherwise be transmitted to the specimen from the floor.

Temperature Measurement

Temperatures are measured by means of iron-constantan thermocouples and a Brown calibrating potentiometer No. 1117. The thermocouples are tied with copper wire directly to the specimen in a manner to insure that the thermocouple junctions remain in contact with the specimen surface.

In the preliminary tests five pairs of thermocouples were arranged along the column to obtain a detailed survey of the temperature distribution. The baffles were set in various positions in order to determine the best arrangement for uniform temperature distribution. The preliminary tests have shown that the fan was not necessary to maintain a uniform temperature.

When the technique was fully developed, it was found easy to maintain the temperature along the column within ±3° F. On the basis of this experience the final tests were run with only three pairs of thermocouples on each specimen. One of these pairs was placed at the middle of the column; a second pair, 3 inches above the middle; and the third pair, 3 inches below the middle.

Measurement of Deviations From Straightness

Simple theoretical considerations show that the change in curvature of a column or a beam is related to the change in the difference in the strain on two opposite sides of the column and to the depth of the column by the equation

$$\Delta\epsilon/h = 1/R \tag{1}$$

In this equation $\Delta\epsilon$ is the difference in strain measured on the convex and the concave sides of the column, $1/R$ is the change in the curvature of the column due to the load, and h is the depth of the column. Moreover, for small deformations

$$1/R = d^2w/dx^2 \tag{2}$$

where w is the additional deflection of the column. From equations (1) and (2)

$$\Delta\epsilon/h = d^2w/dx^2 \tag{3}$$

The initial deviation of the center line of the column from the line of action of the axial compressive load can be represented by the Fourier series

$$w_i = \sum_{n=1}^{\infty} a_n \sin (n\pi x/L) \tag{4}$$

where a_n is a constant, x is the axial coordinate, and L is the length of the column from knife edge to knife edge. Elastic theory shows that upon application of the axial compressive load P the initial deflections are increased by additional deflections w in accordance with the following equation:

$$w = \alpha \sum_{n=1}^{\infty} \left[1/\left(n^2 - \alpha\right)\right] a_n \sin (n\pi x/L) \tag{5}$$

This equation can be found, for instance, in reference 3. Of the symbols, α designates the ratio of the applied compressive load to the Euler load, the Euler load is $P_E = (\pi/L)^2EI$, E is Young's modulus, and I is the least moment of inertia of the cross section of the column. Equations (3) and (5) yield

$$\Delta\epsilon/h = -(\pi/L)^2\alpha \sum_{n=1}^{\infty} \left[n^2/\left(n^2 - \alpha\right)\right] a_n \sin (n\pi x/L) \tag{6}$$

In the final tests each column was provided with three pairs of SR-4 metalectric strain gages cemented to the column in the positions indicated in figure 3. When the initial shape of deviations from straightness is symmetric with respect to the middle of the column, gages 1 and 5 as well as gages 2 and 6 indicate the same strain at any applied load.

This symmetry of the deflection pattern can be approximated by a suitable manipulation of the positioning screws of the end fixtures. When this is accomplished, equation (6) reduces to

$$\Delta\epsilon/h = -(\pi/L)^2\alpha \sum_{n=1,3,5,\ldots}^{\infty} \left[n^2/(n^2 - \alpha)\right] a_n \sin (n\pi x/L) \qquad (7)$$

When the applied axial load P is not much smaller than the Euler load P_E, that is, if the value of α is near unity, the effect of the first harmonic is much greater than that of all the other harmonics.

If it is further assumed that the initial adjustment of the end-fixture positioning screws eliminated the second and the fourth harmonics of the initial deviations with a sufficient degree of accuracy, the deflected pattern obtained under the application of the load can be approximated by the equation

$$\Delta\epsilon/h = -(\pi/L)^2\alpha \left\{\left[1/(1 - \alpha)\right] a_1 \sin (\pi x/L) + \left[9/(9 - \alpha)\right] a_3 \sin (3\pi x/L)\right\} \qquad (8)$$

In this equation only the first and third components of the initial deviation pattern remain. Of course, they are unknown, but they can be determined if the changes in curvature are measured at two different points along the column under some known applied load. In the tests carried out in the investigation described herein, the length of the column was 12 inches and the changes in curvature were measured at $x_1 = L/4$ and at $x_2 = L/2$. The load ratio α was usually 0.9. Equation (8) was written twice, once for each one of the locations where the change-in-curvature readings were measured. The two linear algebraic equations obtained can be easily solved for a_1 and a_3. The solution is

$$\left.\begin{aligned} a_1 &= -2.162\left[1.414(\Delta\epsilon)_{L/4} + (\Delta\epsilon)_{L/2}\right] \\ a_3 &= -19.454\left[1.414(\Delta\epsilon)_{L/4} - (\Delta\epsilon)_{L/2}\right] \end{aligned}\right\} \qquad (9)$$

In the actual testing process the changes in curvature were measured at the top and the bottom of the column under some load less than the critical load at room temperature. It is to be noted that all the arguments brought forward and derivations given are valid only when the column behaves perfectly elastically. This is the case when a 2024-T4 aluminum column is tested at room temperature. The positioning screws of the end fixtures were adjusted until the changes in curvature were the same at the top and the bottom of the column. After completion of these adjustments the values of the curvature were measured at a load $P = 0.9P_E$ both at the middle of the column and at the quarter length. As far as the latter measurement is concerned, the accuracy was increased by taking the average of the readings at the top quarter and the bottom quarter. Finally, the values of the coefficients of the first and third harmonics of the initial deviation were calculated from equation (9).

This procedure permitted the experimenter to adjust the initial deviations of the column from straightness in such a manner as to obtain predetermined values for the first harmonic a_1 with a reasonable degree of accuracy. His work was facilitated by the observation that in many cases consideration of the first harmonic alone suffices for obtaining a reasonably accurate first approximation to the desired value of the first harmonic. When the third harmonic is neglected, equation (7) yields

$$a_1 = -(1/9h)(L/\pi)^2(\Delta\epsilon)_{L/2} \tag{10}$$

when $P = 0.9P_E$.

PRELIMINARY TESTS

Test Specimens

All the specimens tested were made of 2024-T4 aluminum alloy. The modulus of elasticity of the material was 10.5×10^6 psi. The nominal size of the column section was 0.375 by 0.50 inch. The ends of the column were rough cut with the saw and then finished to a length of 10.5 inches on the lathe. The specimens were tested in the as-received condition without any curing or temperature stabilizing before the experiment.

The minimum moment of inertia of the section was 0.0022 inch^4 and the minimum radius of gyration was 0.108 inch. The cross-sectional area of the column was 0.1875 square inch.

End fixtures were fitted to the two ends of the column with the knife edges arranged parallel to the wider faces. Each knife-edge fixture added 0.75 inch to the length of the column. Hence, the apparent length of the cold unloaded specimen, that is, the distance between the knife edges, was 12 inches. This length corresponded to a slenderness ratio of 111.

With this slenderness ratio the Euler load of the column at room temperature was 1,583 pounds and the corresponding critical stress, 8,443 psi.

The tests were carried out at a nominal temperature of 600° ± 3° F. This temperature is generally considered to be above the permissible range for aluminum alloys. The authors believe, however, that in short-range missiles flying for only a few seconds or minutes unusually high temperatures should be tolerated. Moreover, unusually high temperatures emphasize the creep effects and are, for this reason, attractive in a fundamental investigation.

Determination of Critical Load at Elevated Temperatures

In the procedure used for determining the critical load of the column at high temperature, the column was placed in the test rig while cold. A load was applied gradually to the column and the changes in curvature were measured. By adjustment of the positioning screws and simultaneous readings of the strain differences, the initial deviations of the column from straightness were brought to a minimum.

When satisfactorily small value was obtained for a_1, the load was slowly removed until only a small preload remained to hold the specimen in place and to prevent changes in its adjustment. This preload was usually 100 pounds. The door of the specimen chamber of the oven was closed and the heating current was switched on in the 3,000-watt heating units in the oven chamber and in the 300-watt heater under the lower end of the specimen. The power was left on for about 45 minutes, after which an approximate temperature of 600° F was reached. At that time the power in the oven chamber was cut down to approximately 950 watts and the 100-watt heater in the loading extension was switched on. The various powerstats were manipulated until the temperature along the column became uniform within 3° F. This process usually took about 20 more minutes.

Consequently, a total time of about 65 minutes elapsed before the specimen reached the desired uniform final temperature. During this heating process the initial load on the column was maintained constant by means of adjusting the loading screw of the cantilever as described earlier.

At this time the load was gradually increased by unscrewing the adjusting screw in the cantilever. In most tests the failing load of the column was reached in approximately 20 seconds. The corresponding rate of loading was considered slow enough to eliminate inertia effects and at the same time fast enough to minimize the effect of creep upon the behavior of the column.

In three tests carried out in such a manner, buckling loads of 1,131, 1,070, and 1,095 pounds were obtained. The average, namely, a load of 1,099 pounds, was therefore taken to represent the static buckling load of the column at 600° F.

FINAL TESTS

The final tests were carried out with 15 columns of 2024-T4 aluminum alloy in a manner almost identical to that described under the preliminary tests. The main difference was that the load was brought up reasonably rapidly to a maximum predetermined value smaller than the experimentally determined critical load of 1,099 pounds. At that value of the load the lever was free to move and the adjusting screw of the cantilever was about 1/2 inch below the point where it would have contacted the lever. This load was then maintained until the column buckled. The time necessary for failure was measured with a stopwatch.

The results of the tests are presented in figure 4 and in table I. In figure 4 the critical time is plotted in minutes against the amplitudes a_1 of the first harmonic of the initial deviations from straightness. Of the two curves shown, one is the approximate locus of the test points obtained with an axial compressive load of 980 pounds and the other, that of the test values derived from experiments with a 905-pound load. These load values correspond to 89 percent and to 82 percent of the critical load of the column at 600° F.

In column 2 of table I the letter represents the stock from which the specimen was cut, and the number refers to the location of the specimen within the bar stock. These locations are indicated in figure 5. The specimens whose numbers are provided with a bar were not tested. They were reserved for future tests in creep bending to provide a correlation between the bending tests and the buckling tests.

DISCUSSION AND CONCLUSIONS

A study of figure 4 reveals that 9 out of the 15 test points can be connected with simple smooth lines. The lines have the same appearance as the theoretical buckling-time curves presented in reference 8. Complete correlation of the test results with theory is not possible at the present time because some of the basic data on the creep behavior of columns in simple tension and compression for the particular material used in the tests are lacking. The remaining five points are not very far removed from the curves, but their critical times differ sufficiently from the general trend to deserve special attention.

Two of these five points, namely, those representing specimens 14 and 15, deviate from the upper curve intentionally. These tests were carried out in order to ascertain the effect of the length of the time for which the preload was applied. Table I shows that in test 14 the preload was 300 pounds rather than the usual 100 pounds. It is quite possible that this higher preload sufficed to cause enough creep during the heating period of about an hour to increase significantly the initial deviations of the column from straightness. A shift to the right of 0.002 inch would suffice to bring point 14 upon the upper curve. The development of a deformation of this magnitude during the hour of heating is not impossible. Specimen 15 may have shown higher loads than expected for a similar reason. Its initial load was 35 pounds instead of the usual 100 pounds. The smaller amount of deformation during the heating process may explain the deviation of this test point from the curve. The results obtained with specimens 14 and 15 indicate the necessity of employing strain gages capable of giving satisfactory readings at 600° F. With the present SR-4 gages measurements could be made only before the beginning of heating.

Analysis of the data presented in table I reveals that the deviations of the remaining irregular points from the curves may be at least partially caused by the higher harmonics. In every case the value of the third harmonic is unusually high either positively or negatively when the test point does not fall upon the curve. The highest value of a_3 in series 1 of table I is 0.00222 inch. As point 1 is the last point on the lower curve in figure 4, it is not possible to state whether this point should have been a little higher or a little lower.

Of the three tests which showed large third harmonics with a negative sign, the highest value of -0.00156 was recorded in test 2. Tests 7 and 6 follow in decreasing order of magnitude. All three specimens failed after an unusually long time when compared with the expected time values read from the experimental curve for the corresponding first harmonic amplitude; the longest time was recorded in test 7. In this test the first harmonic was unusually low. It appears that higher harmonics may become particularly important when the first harmonic is small.

In the second test series, namely, the one carried out with a load of 905 pounds, unusually high third-harmonic values can be observed with test specimens 10 and 11. These values were positive. Specimen 10 failed after a somewhat extended period of time, while specimen 11 buckled in an unusually short period of time when compared with the time values read from the experimental for the corresponding first harmonic amplitude.

In conclusion, it can be stated that the tests have shown the critical time to decrease with increasing initial deviations from straightness, with increasing compressive load during the test, and with increasing values of the preload, provided all other parameters are kept constant. It also appears that the higher harmonics have an influence upon the critical time. For this reason it would be advisable to investigate the effect of the higher harmonics both theoretically and experimentally. The latter can be made possible through the development of strain gages which can record strains satisfactorily at elevated temperatures. Such gages would also be useful in measuring the deviations from straightness after heating.

Polytechnic Institute of Brooklyn,
Brooklyn, N. Y., February 25, 1954.

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TABLE I

TEST RESULTS

Test	Specimen	Deviation amplitudes, in.		Temperature, °F	Preload, applied for 60 to 65 min, lb	Critical time, t_{cr}, min	Remarks
		a_1	a_3				
Series 1; test load, $P = 980$ lb							
1	A_1	0.0111	0.00222	600	100	1.25	
2	A_2	.00667	-.00156	600	100	3.33	Faulty time reading
3	A_5	.00500	.000522	600	100	2.80	
4	A_6	.00300	.000389	600	100	3.93	
5	B_6	.000543	-.000522	600	100	8.92	
6	A_3	.00111	-.000667	600	100	12.58	Buckled in opposite direction to a_1
7	A_4	.000445	-.00111	600	100	66.23	
Series 2; test load, $P = 905$ lb							
8	B_3	.00889	.00167	600	100	6.95	
9	A_7	.00732	-.0000222	602	100	9.25	
10	B_2	.00567	.00200	600	100	14.92	
11	A_8	.00345	.00300	600	100	16.75	Vibrations
12	B_4	.00228	.00110	600	100	31.5	
13	B_5	.000500	-.000233	600	100	59.83	
14	A_{10}	.000511	.000511	600	300	31.55	Loading time, 7 sec
15	B_1	.0122	-.00300	600	35	10.83	

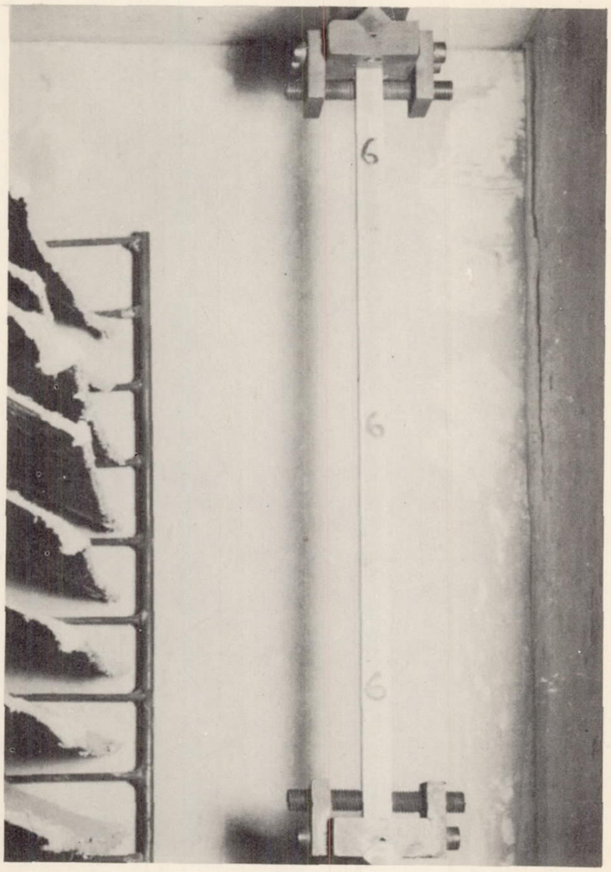

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Figure 1.- View of column in oven seen through oven door.

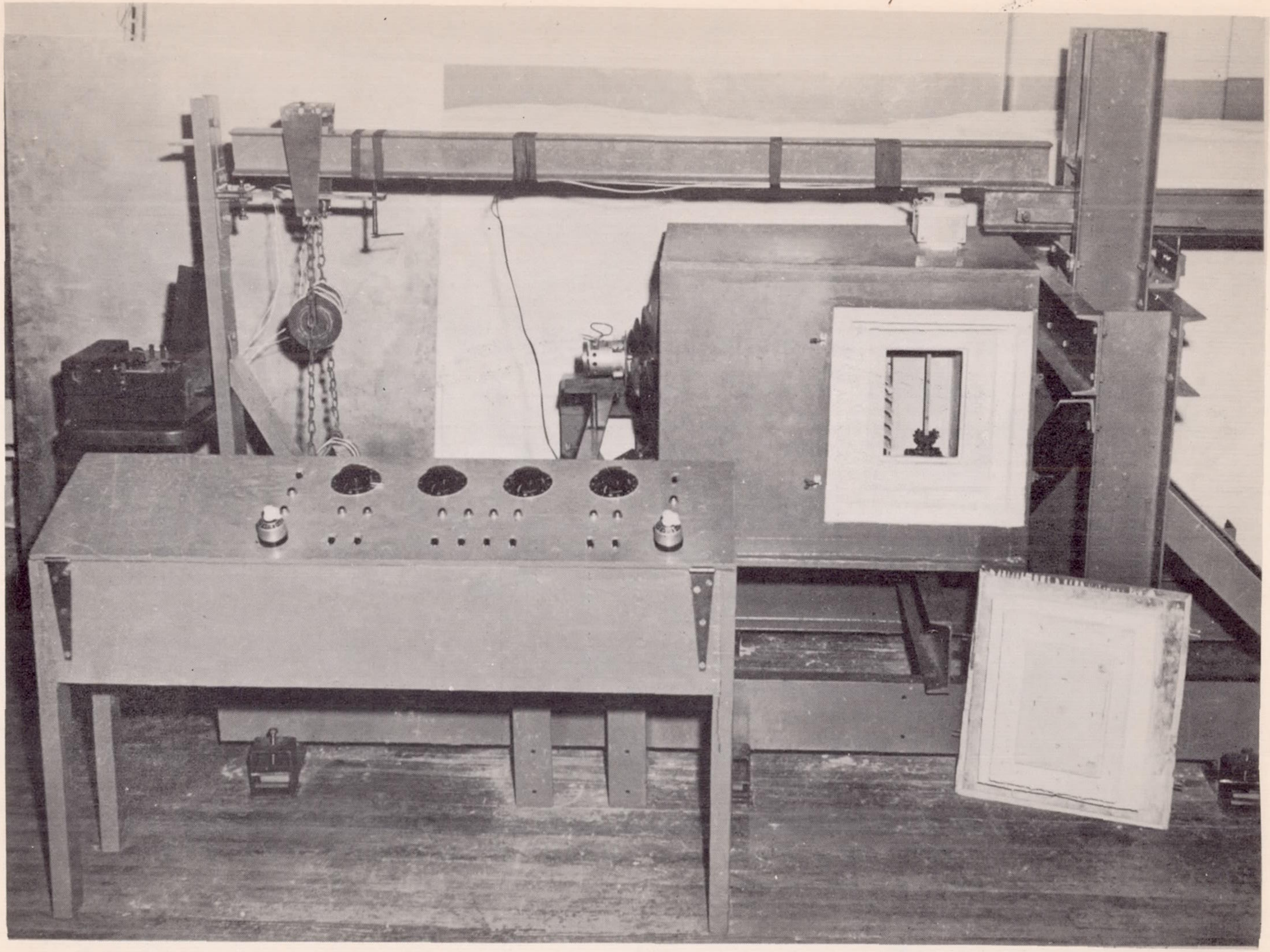

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Figure 2.- Test setup.

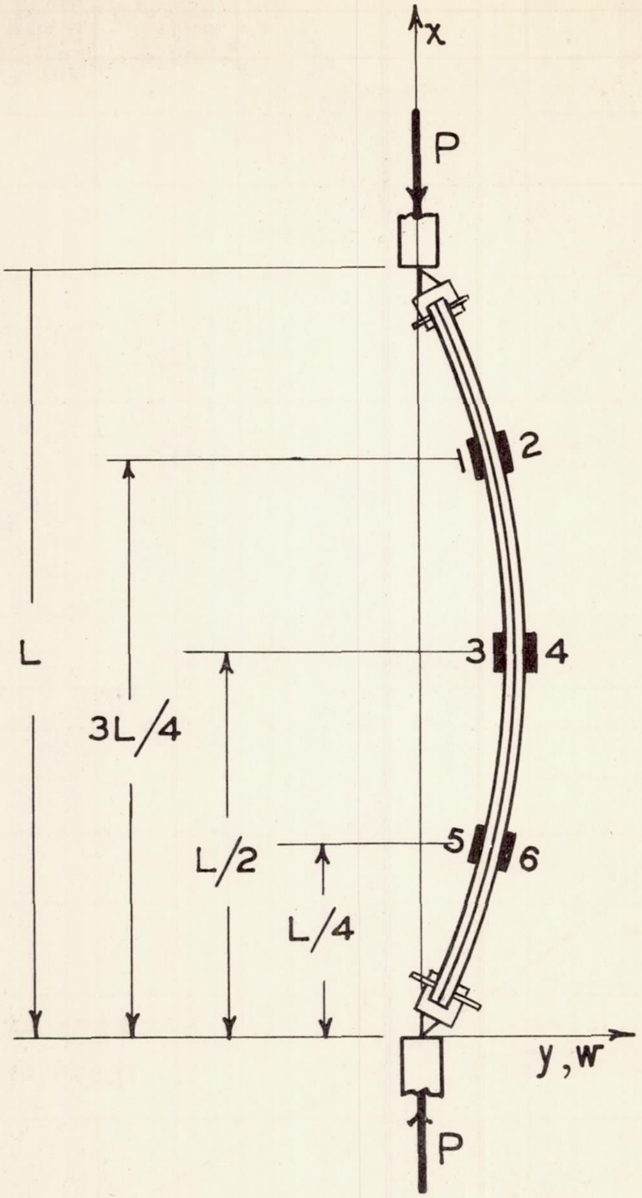

Figure 3.- Location of strain gages on column.

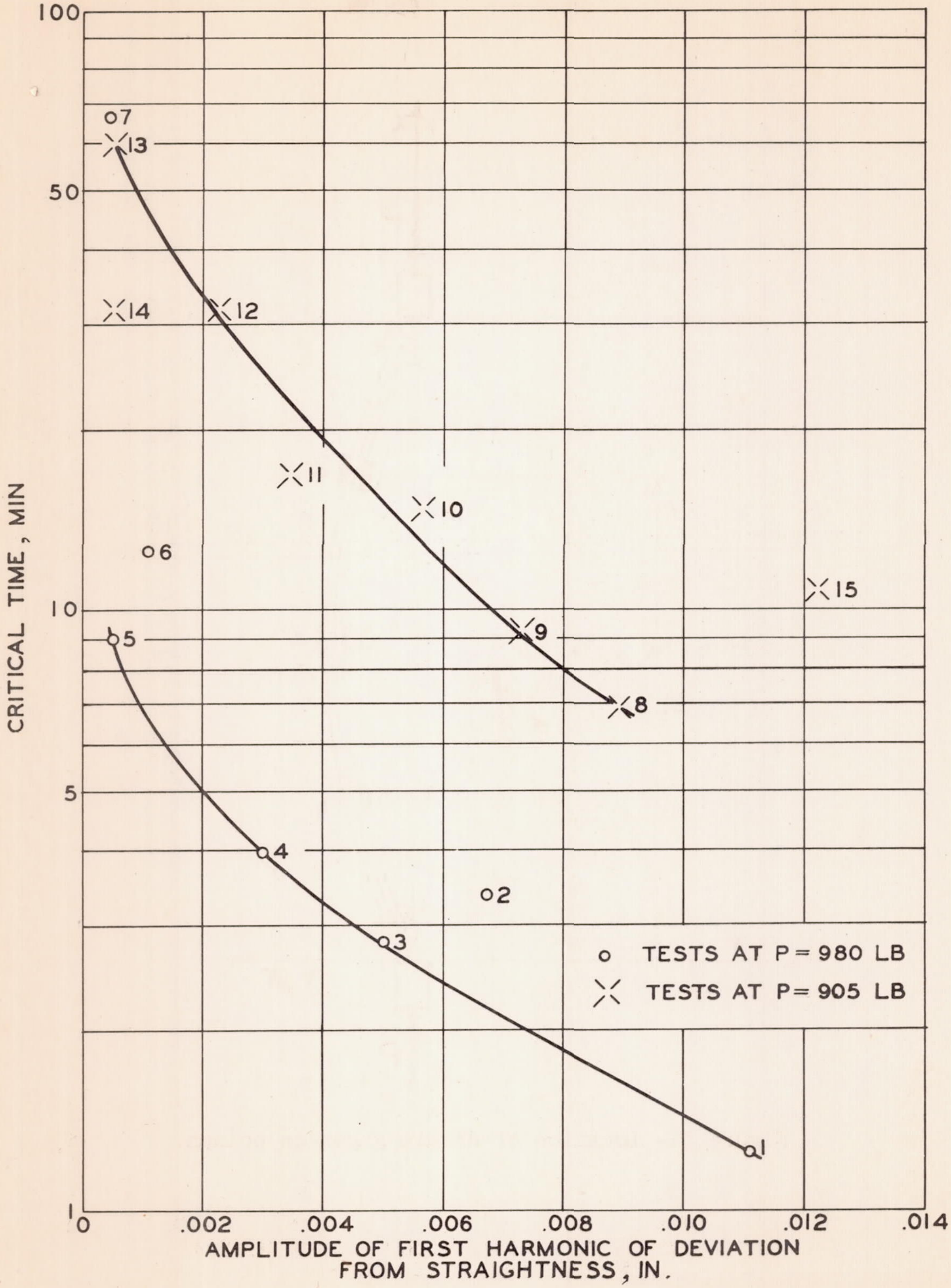

Figure 4.- Critical time of column. Critical axial compressive load P_{cr}, 1,099 pounds at 600° F and 1,581 pounds at room temperature.

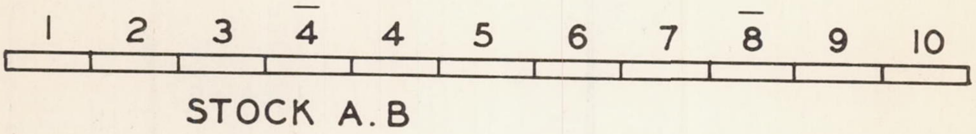

Figure 5.- Location of test specimens in aluminum-alloy bar.