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THE EFFECTS OF INELASTIC ACTION ON THE RESISTANCE TO VARIOUS TYPES OF LOADS OF DUCTILE MEMBERS MADE FROM VARIOUS CLASSES OF METALS

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FOREWORD

This report was prepared by the University of Illinois under USAF Contract No. AF 33(616)-5658. This contract was initiated under Project No. 7360, "Design Data for Metals"; Task No. 73607, "Radiation effects and Measurements". It was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center with Dr. A. J. Herzog acting as project engineer.

This report covers work conducted between April 1958 and November 1958.

The work was conducted in the Department of Theoretical and Applied Mechanics of the Engineering Experiment Station, University of Illinois. Professor James O. Smith was the Project Supervisor.

ABSTRACT

This report presents the results of an analytical and experimental investigation for the determination of the load necessary to produce a specified amount of inelastic deformation in members which are subjected to eccentric tensile loads at elevated temperatures for a specified time. Two different theories were used in analyzing the experimental data. The arc hyperbolic sine theory uses material properties obtained from an arc hyperbolic sine curve approximation of the stress-strain diagram of the material. The interaction-curve-moment-load-curve theory uses material properties obtained from two straight line approximation of the stress-strain diagram of the material.

In the experimental investigation, tests were made on eccentrically-loaded T-section members made of 17-7PH stainless steel at 1000° F. The test members were subjected to an initial eccentricity of either 25 or 51 per cent of the depth. It was found that the deflection of the central section of each member could be accurately predicted by either theory.

In addition to the present investigation, tension creep data was obtained from 6-in. gage length specimens of the 17-7PH stainless steel used in the rectangular-section investigation which was reported in Part VIII (Contract No. AF 33(616)-2753). A more reliable value of the modulus of elasticity of the material was determined. Theoretical moment-load curves, based on the new value for the modulus, were constructed and are compared with the experimental data. A discussion of these results is presented in this report.

Since publishing Part IX (Contract No. AF 33(616)-2753), an error has been found in the analysis of the test data for the eccentrically-loaded T-section members made of type 304 stainless steel. The corrected data are presented in this report.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER: Richard R. Kennedy

Richard R. Kennedy
Chief, Metals Branch
Materials Laboratory

THE EFFECTS OF INELASTIC ACTION ON THE RESISTANCE TO VARIOUS TYPES OF LOADS OF DUCTILE MEMBERS MADE FROM VARIOUS CLASSES OF METALS

Part X T-Section Eccentrically-Loaded Tension Members Made of 17-7PH Stainless Steel and Tested at 1000° F.

I INTRODUCTION

1. Preliminary Statement

In Parts I and IV of the reports submitted under Contract No. AF 33(616)-2753, investigations were undertaken to study the influence of inelastic deformation on the load carrying capacity of ductile members subjected to either eccentric tension or eccentric compression loads at room temperature. An interaction-curve-moment-load-curve method of solution was found to be satisfactory in determining the load and deflection necessary to produce a given depth of yielding in a given member and in predicting the collapse load of columns. The theoretical curves were based on the assumption that the stress-strain diagram of the material could be represented by two straight lines. Good agreement was found between theory and experiment.

In Parts VIII and IX of the investigations considered under Contract No. AF 33(616)-2753, rectangular-section members of type 304 and 17-7PH stainless steels and T-section members of type 304 stainless steel were subjected to eccentric tension loads at 1000° F. Two theoretical analyses were presented: (1) interaction-curve-moment-load-curve theory, and (2) arc hyperbolic sine curve theory based on the assumption that the isochronous stress-strain diagram of the material could be represented by an arc hyperbolic sine curve. The type 304 stainless steel did not creep during the 30 minute duration of the test, and the stress-strain diagram of the material at 1000° F was similar to that obtained at room temperature. The interaction-curve-moment-load-curve theory was found to be satisfactory in predicting the experimental results. Appreciable creep was observed in the case of the 17-7PH stainless steel members. The test data indicated that either theory would satisfactorily predict the load-deflection diagram for a given eccentrically-loaded member.

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2. Purpose and Scope

The purpose of the present investigation was to determine the suitability of the interaction-curve-moment-load-curve and arc hyperbolic sine curve theories for predicting the load-deflection relations for eccentrically-loaded tension members having only one plane of symmetry and made of 17-7PH stainless steel. A T-section member was chosen for this study.

Most of the theoretical analyses have been presented in previous reports. The derivations will not be repeated in this report; however, the final equations obtained from these derivations are presented for use in analyzing the test data.

A total of 12 creep tension specimens and 7 eccentrically-loaded T-section members were subjected to dead-weight creep loads at 1000° F. Good agreement was found between theory and experiment.

3. Additions and Corrections to Previous Reports

In Part VIII (Contract No. AF 33(616)-2753), the correlation between theory and experiment was not as good as expected for the eccentrically-loaded members made of heat treated 17-7PH stainless steel. The bad correlation was attributed to the fact that the modulus of elasticity was in error since it had been obtained from specimens having a 2-in. gage length. Since submitting Part VIII, specimens having a 6-in. gage length have been subjected to creep loads at 1000° F. The corrected modulus of elasticity was 14 per cent lower than that reported in Part VIII. The effect of this correction is to move the test points for the eccentrically-loaded members much closer to the theory. The corrected data are presented in this report.

An error was made in analyzing the test data for the eccentrically-loaded T-section members made of type 304 stainless steel which was presented in Part IX (Contract No. AF 33(616)-2753). The corrected data are presented in this report.

II THEORY

4. Arc Hyperbolic Sine Theory

The arc hyperbolic sine theory for predicting the load-deflection diagram for an eccentrically-loaded member was presented in Part VIII (Contract No. 33(616)-2753). Four assumptions were made in deriving the theory.

1. Plane sections remain plane.

2. The isochronous stress strain diagram of the material for a given time and at a given temperature can be represented by an equation of the form:

$$\sigma = \sigma_o \sinh^{-1} \frac{\epsilon}{\epsilon_o} \qquad (1)$$

in which σ_o and ϵ_o are experimental constants obtained from creep data (see Fig. 6).

3. The stress-strain relation for any fiber of the member is not influenced by the fact that the magnitude of the stress varies with time.

4. The deflected configuration of the eccentrically-loaded member is a segment of a circle.

The latter two assumptions are simplifying approximations and introduce errors into the theory. In an eccentrically-loaded tension member, the stress in the most strained fiber decreases with time so that the actual strain for a given stress is greater than that indicated by the theory, since the latter is based on constant load creep data. Thus, the theoretical deflection is nonconservative. The assumption that the member deforms into a segment of a circle also makes the deflection nonconservative since this assumption requires that every section of the member is subjected to the same moment as the central section for which the moment is a minimum. The experimental data indicate that the error introduced by these assumptions are not excessive. It should be noted that, in case of eccentrically-loaded columns, these assumptions make the theory conservative.

The derivation of the equations necessary to construct the load-deflection diagram for an eccentrically-loaded member will not be presented in this report; however, the equations will be presented. In Fig. 1, a T-section member is subjected to load P and moment M necessary to produce a strain ϵ_1 in the most strained fiber and to locate the neutral axis at a distance d from the centroidal axis. This determines the strain distribution since plane sections are assumed to remain plane. The stress distribution can now be determined by using Eq. 1. The magnitudes of P and M are given by the equations of equilibrium and are found to be

$$P = \frac{\sigma_{o1} qat^2}{K} \quad bB_K + (1-b)B_{\frac{qa-f}{qa}K} - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}}{\epsilon_{o1}} B_{\frac{q-1}{q}K \frac{\epsilon_{o1}}{\epsilon_{o2}}}$$
$$+ 1 - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}}{\epsilon_{o1}} \qquad (2)$$

$$M = \frac{\sigma_{o1} q^2 a^2 t^3}{K^2} \left[bC_K + (1-b) C_{\frac{qa-f}{qa}K} - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}^{\ 2}}{\epsilon_{o1}^{\ 2}} C_{\frac{q-1}{q}K \frac{\epsilon_{o1}}{\epsilon_{o2}}} \right] - (q-\beta)Pat \quad (3)$$

in which $K = \epsilon_1/\epsilon_{o1}$. The experimental constants σ_{o1} and ϵ_{o1} are for tension (see Eq. 1) and σ_{o2} and ϵ_{o2} are for compression. In these equations the functions B_N and C_N are defined as follows:

$$B_N = N \log_e (N + \sqrt{N^2 + 1}) - \sqrt{N^2 + 1} \quad (4)$$

$$C_N = \frac{1}{4} \left[(1 + 2N^2) \log_e (N + \sqrt{N^2 + 1}) - N\sqrt{N^2 + 1} \right] \quad (5)$$

Four place tables of B_N and C_N are given in Part VIII.

Since the member is assumed to deflect into a segment of a circle, the deflection δ of the central section of the eccentrically-loaded member of length L is given by the relation,

$$\delta = \frac{L^2 \epsilon_1}{8qa} \quad (6)$$

At this central section, the moment M can be written in terms of P, δ, and the initial eccentricity e as follows:

$$M = P (e - \delta) \quad (7)$$

Using eqs. 2, 3, 6, and 7, an expression for δ in terms of q and K can be obtained as follows:

$$\frac{e \pm \delta}{at} = \frac{e}{at} \pm \frac{L^2 \epsilon_1}{8qa^2 t^2}$$

$$= \frac{\frac{q}{K} \left[bC_K + (1-b) C_{\frac{qa-f}{qa}K} - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}^{\ 2}}{\epsilon_{o1}^{\ 2}} C_{\frac{q-1}{q}K \frac{\epsilon_{o1}}{\epsilon_{o2}}} \right]}{bB_K + (1-b) B_{\frac{qa-f}{qa}K} - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}}{\epsilon_{o1}} B_{\frac{q-1}{q}K \frac{\epsilon_{o1}}{\epsilon_{o2}}} + 1 - \frac{\sigma_{o2}}{\sigma_{o1}} \frac{\epsilon_{o2}}{\epsilon_{o1}}}$$

$$- q + \beta \quad (8)$$

In this investigation, it was assumed that $\sigma_{o1} = \sigma_{o2}$ and $\epsilon_{o1} = \epsilon_{o2}$ since only the tensile creep properties were determined; hence, Eqs. 2, 3, and 8 are independent of the properties of the material. The T-section considered in this investigation had the following relative dimensions: a = 6, B = 4, and f = 1.5. The load P for this cross-section can be obtained by Eq. 3 or Fig. 2 where the dimensionless load is plotted versus q for different values of K. The magnitude of q for a given value of K must be obtained from Eq. 8. To aid in this computation, the family of curves in Fig. 3 were constructed using Eq. 8, and Eq. 8 was rewritten to give the following relation:

$$q = \frac{\dfrac{L^2 \epsilon_1}{8a^2 t^2}}{\dfrac{e}{at} - \dfrac{e-\delta}{at}} \tag{9}$$

All quantities in this equation are known except q and δ. For a given value of K, assume a value for q and read off the value of $(e-\delta)/at$ from Fig. 3, and calculate q by Eq. 9. If the calculated value of q does not equal the assumed value, assume a new value of q and repeat the process. The trial and error solution does not require much time. Once q is known, the load P can be calculated by using Fig. 2.

<u>Load-Deflection Relation for Elastic Conditions</u>. The curves shown in Fig. 2 and 3 cannot be used for elastic conditions since Eq. 1 is not linear. Since the 17-7PH stainless steel is elastic at 1000° F for zero time, it is necessary that an equation be derived so that the load-deflection diagram of the eccentrically-loaded members can be constructed for elastic conditions. If the member is elastic, the radius of curvature can be written in terms of the moment,

$$\frac{1}{R} = \frac{M}{EI} \tag{10}$$

The radius of curvature can also be written in terms of the strain distribution shown in Fig. 1 to give

$$\frac{1}{R} = \frac{\epsilon_1}{qa} \tag{11}$$

Using Eqs. 6, 7, 10, and 11, the load P can be written in terms of the deflection δ as follows:

$$P(e-\delta) = \frac{8\delta EI}{L^2} \tag{12}$$

5. The Interaction-Curve-Moment-Load-Curve Theory

The interaction-curve-moment-load-curve theory for computing the load and deflection necessary to produce a given depth of yielding in an eccentrically-loaded T-section member has been presented in Part I (Contract No. 33(616)-2753). In this theory, the load and deflection were computed by determining the intersection of the moment-load curve with the interaction-curve associated with a given depth of yielding. The assumptions made in this theory are the same as for the arc hyperbolic sine theory except that the isochronous stress-strain diagram of the material is assumed to be represented by two straight lines (see Fig. 6).

Consider a T-section member whose cross-sectional dimensions are depth h, flange width b, flange thickness t_2, and web thickness t. If this member is subjected to an eccentric load of sufficient magnitude, yielding will penetrate to a depth a_1 on the flange side of the member which is in tension and to a depth a_2 on the compression side of the member. For the conditions that a_1 is less than or equal to the flange thickness t_2, the magnitudes of P and M are given by the following equations:

$$P = P_e - \frac{2A\sigma_e}{a}(c_1 - a_1) - (1-\alpha)\frac{\sigma_e}{a}(a_1^2 b - a_2^2 t) \qquad (13)$$

$$M = \frac{2\sigma_e I}{a} - (1-\alpha)\frac{\sigma_e}{a}\ a_1^2 b\left(c_1 - \frac{a_1}{3}\right) + a_2^2 t\left(c_2 - \frac{a_2}{3}\right) \qquad (14)$$

in which A is the cross-sectional area.

For conditions in which yielding has progressed through the tension flange into the web, while simultaneously yielding on the compression side (that is, a_1 is greater than or equal to t_2), the load and moment expressions are,

$$P = P_e - \frac{2A\sigma_e}{a}(c_1 - a_1) - (1-\alpha)\frac{\sigma_e}{a}\ ba_1^2 - (b-t)(a_1 - t_2)^2 - a_2^2 t \qquad (15)$$

$$M = \frac{2\sigma_e I}{a} - (1-\alpha)\frac{\sigma_e t}{a}\ \frac{2I}{c} - (a+a_2)^2\left(c_2 - \frac{a+a_2}{3}\right) + a_2^2\left(c_2 - \frac{a_2^2}{3}\right) \qquad (16)$$

Interaction curves for a given T-section member can be constructed by using Eqs. 13 through 16. It should be noted that Eqs. 13 and 14 are valid if either a_1 or a_2 is zero and Eqs. 15 and 16 are valid if a_2 is zero. The interaction curve for a given depth of yielding is constructed by assuming various values of a_1 and a_2 such that this sum is a constant. The plot of corresponding values of P and M result in the interaction curve. In general, the curve is made dimensionless by dividing the load P by $P_e = \sigma_e A$ and the moment M by $M_e = \sigma_e I/c_2$. Representative interaction curves for a given T-section member made of a given material are indicated in Fig. 9.

In order to construct the theoretical moment-load curves, shown in Fig. 9, it was necessary to assume that each eccentrically-loaded member deformed into a segment of a circle. Several points on each moment-load curve were obtained by locating the intersections of it with each of the family of interaction curves. These intersections were obtained by drawing a straight line through the origin and making an angle θ with the load axis (see Fig. 9). The slope of the straight line is given by the following relations:

$$\tan \theta = \frac{c_2 e}{\rho^2} - \frac{c_2}{\rho^2} \frac{L^2 \epsilon_e}{4kh} \tag{17}$$

$$\tan \theta = \frac{c_2 e}{\rho^2} - \frac{c_2}{\rho^2} \frac{L^2 \epsilon_e}{4kh} \frac{M_L}{M_U} \tag{18}$$

in which e is the initial eccentricity of the load, $\epsilon_e = \sigma_e/E$ and $k = (h-a_1-a_2)/h$. Eq. 17 is used if the line intersects the interaction curve in the curved portion, and Eq. 18 is used if the intersection occurs in the straight line portion of the interaction curve. If Eq. 18 is used, the solution is by trial and error since M_L is the moment at the unknown intersection and M_U is the moment for the upper end of the straight line portion of the interaction curve. After the moment-load curve has been determined, the deflection δ is given by the following relations:

$$\delta = \frac{L^2 \epsilon_e}{4kh} \tag{19}$$

or

$$\delta = \frac{L^2 \epsilon_e}{4kh} \frac{M_L}{M_U} \tag{20}$$

III MATERIALS AND METHOD OF TESTING

6. Materials Used, Test Members, and Testing Procedure

The T-section members and creep tension specimens were all machined from one 1/2-in. by 2-in. bar of 17-7PH stainless steel. These specimens were heat treated by heating to 1400° F for 90 minutes, cooling to 60° F in 60 minutes, and holding for 30 minutes, heating to 1050° F for 90 minutes, and air cooling.

In Fig. 4 are shown sketches of the creep tension specimens and of the eccentrically-loaded test members. The magnitudes of the cross-sectional dimensions for the T-section members and the initial eccentricity e are shown in Figs. 8 and 9 where the test data are plotted.

The test members were loaded in the furnaces described in Part VIII (Contract No. AF 33(616)-2753). The same procedure was followed in heating the creep furnace for each test member. Since 25 to 45 minutes were required to reach the test temperature and additional time was required to adjust to the proper temperature, all creep tests were started two hours after starting the furnace. The temperature was maintained at 1000 ± 2° F throughout the test.

Before applying the creep load to each test member, a hydraulic jack was employed to carry most of the load while the desired weights were placed on the load pan. This jack contained a bleed line with a solenoid valve. By energizing the solenoid, the load could be applied rapidly but gradually. The deformation readings were started as soon as the load was applied. Several readings were taken during the first 2 minutes; thereafter, readings were taken at 5 minutes and at every 5 minute interval until 30 minutes had elapsed.

7. Properties of Materials

A total of 12 tension specimens were subjected to constant load creep tests. Representative creep curves are shown in Fig 5. By plotting corresponding values of stress and strain at the beginning and end of the 30 minute creep test, the isochronous stress-strain diagrams shown in Fig. 6 were obtained. Each test point for zero time and for 30 minutes represents one test specimen. Four of these specimens had a gage length of 6-in. and the remaining 8 had a gage length of 2-in. The longer gage length specimens were used to determine the modulus of elasticity of the material, and the value ranged from 18,400,000 psi to 19,300,000 psi with an average value of 19,000,000 psi. These 4 specimens also indicated that the material was elastic for a few seconds at stress levels as high as 55,000 psi. Therefore, the data for the 2-in. specimens were corrected so that the point for zero time fell on the elastic line.

It will be noted that the isochronous stress-strain diagram for 30 minutes has been approximated by an arc hyperbolic sine curve (Eq. 1) and by two straight lines. The experimental constants for these two-stress-strain diagram representations are listed in Fig. 6. The test data indicates appreciable scatter, particularly at the higher stress levels.

8. Description of Load and Deformation-Measuring Apparatus

A schematic diagram of the fixtures used in loading the eccentrically-loaded members is shown in Fig. 7. The load was transmitted to the test member through the yoke, knife edges, and pin arrangement shown in Fig. 7. Each pin had a 90° groove machined to its center to receive 60° hardened knife edges.

The method of measuring the central deflection of the eccentrically-loaded member is also illustrated in Fig. 7. Three 1/8-in. diameter ceramic rods extended through the side of the furnace and contacted each of the yokes and the center of the member. A 1/1000-in. dial measured the relative movement of the center rod with respect to the other two. In all cases the test members were subjected to dead loads which were maintained for 30 minutes.

IV ANALYSIS OF RESULTS

9. 17-7PH Stainless Steel T-Section Members

Seven T-section members were subjected to eccentric tensile loads at a test temperature of 1000° F. All of the members had the same relative cross-sectional dimensions: depth 6t, width 4t, flange thickness 1.5t, and web thickness t. The magnitude of t was 0.121-in. for 4 members which were subjected to an initial eccentricity of 0.25 h. The remaining 3 members were subjected to an initial eccentricity of 0.51 h and had a web thickness of 0.122-in.

The load-deflection data for each of the seven eccentrically-loaded members are shown in Fig. 8. In each case the deflection is plotted for zero time and for 30 minutes. Theoretical load-deflection curves are shown by dashed lines for zero time and by solid lines for 30 minutes. The theoretical curves for zero time were constructed using Eq. 12 while those for 30 minutes were constructed using Eq. 9 along with the curves shown in Fig. 2 and 3.

The data presented in Fig. 8 indicate that the theory was conservative in all cases since the measured deflections were less than the theoretical deflections for either zero time or 30 minutes. The approximations made in the theory should have resulted in the theory being nonconservative. This seeming contradiction probably results from the fact that the theory assumed that the test member had a constant cross-section over the 6-in. test length while the test members (see Fig. 4) had only a 4-in. length of constant cross-section. If the remaining 1-in. on each end of the test length had been infinitely stiff, the theoretical deflection would have to be reduced 11 per cent. The sketch of the test members shown in Fig. 4 indicates that the ends are bulky compared to the T-section so that the theoretical deflections indicated by the curves in Fig. 8 are probably 5 to 10 per cent too large. A 10 per cent correction would bring the theoretical and experimental moment-load curves very close together and would make the theory nonconservative for most of the test points. Even without this correction, the comparison between theory and experiment is considered good; the experimental creep deflection, horizontal distance between test points at zero time and 30 minutes, was very closely approximated by theory.

In Fig. 8 the only questionable tests points are the data for the member subjected to a load of 5500 lb. The authors do not have an explanation for the peculiar behavior of this test member. However, the discrepancy between theory and experiment is attributed to either faulty testing technique or malfunction of the test apparatus.

The test data for the eccentrically-loaded T-section members were also compared with the interaction-curve-moment-load-curve theory. The isochronous stress-strain diagram for 30 minutes was represented by two straight lines as indicated in Fig. 6; the straight line of slope αE was drawn tangent to the curve for large inelastic strains since the creep strains in the most strained fibers of the test members were of this magnitude. The interaction curves shown in Fig. 9 were constructed using Eqs. 13 through 16. The theoretical moment-load curves were constructed using Eqs. 17 and 18. Each test point represents one test member as was the case in Fig. 8. A comparsion between Figs. 8 and 9 indicates that the two theories give similar results.

10. Type 304 Stainless Steel T-Section Members

In Part IX of the investigation considered under Contract No. AF 33(616)-2753, an error was made in analyzing the test data for the eccentrically-loaded T-section members made of type 304 stainless steel. This material did not creep at 1000° F, and the stress-strain diagram at 1000° F was similar in shape to that obtained at room temperature. Since the diagram could be represented very closely by two straight lines, the data was analyzed only by the interaction-curve-moment-load-curve theory. The corrected experimental points and theory are shown in Fig. 10. Experimental moment-load data are plotted for 5 different test members. The theoretical moment-load curves are represented by dashed lines. The radial solid lines are the moment-load curves for infinitely stiff members.

The plotted test points in Fig. 10 indicate that the theory was conservative in predicting the deflection; however, the agreement between theory and experiment is considered to be excellent up to 1/2-depth of yielding. At 3/4-depth of yielding, the deflection is conservative by an average of 25 per cent. (The deflection of the test member moves the test point vertically downward from the radial line toward the dashed line.) The fact that each end of the test member is stiffened would not account for all of this difference, since infinitely stiff ends would decrease the theoretical deflection by only 11 per cent. The only known variable, that would move the test points closer to the theory for the larger depths of yielding without affecting the correlation for smaller depths of yielding, is the yield strength. A 7 per cent increase in yield strength is sufficient to make the theoretical and experimental moment-load curves coincide. Some of the tension specimens had yield strength as much as 7 per cent greater than the average value which was used in analyzing the test data.

11. 17-7PH Stainless Steel Rectangular-Section Members

The test data for the 17-7PH stainless steel, rectangular-section, eccentrically-loaded members were presented in Part VIII (Contract No. AF 33(616)-2753). The correlation between theory and experiment was not as good as expected. Since the analysis was based on stress-strain properties obtained from specimens having a 2-in. gage length, it was suspected that the bad correlation was due to the fact that the modulus of elasticity was not correctly determined. The magnitude of the modulus which was obtained from the 2-in. gage length specimens was 23,000,000 psi.

At the time of machining the tension specimens of the material used in making the T-section members, two 6-in. gage length tension specimens were machined from the same bar from which the rectangular-section eccentrically-loaded members were machined. These specimens were heat treated and subjected to creep loading at 1000° F. The modulus of elasticity was found to be equal to 18,750,000 psi, and the data shown in Fig. 13 of Part VIII were recalculated and are shown in Fig. 11. Since the material was found to be elastic for a few seconds after applying the creep load, the stress-strain diagram for zero time is shown as a straight line and all the test points were corrected to fall on this straight line. The stress-strain diagram for 30 minutes is represented by an arc hyperbolic sine curve; the experimental constants for this curve are listed in Fig. 11.

The test data, for the 4 rectangular-section eccentrically-loaded tension members shown in Fig. 20 of Part VIII, are shown in Fig. 12 along with the theoretical load-deflection curves based on the material properties obtained from Fig. 11. The theoretical and experimental moment-load curves coincide for zero time; however, the theoretical moment-load curve is nonconservative by about 7 per cent at 30 minutes. As explained in Art. 9, the theory will be a few per cent more nonconservative because the ends of the member are stiffer than assumed in the theory. This correction will be less for the rectangular-section members than for the T-section members since the maximum load on the latter was only 20 per cent greater than the former and the thickness of the loading ends of the T-section members was twice the thickness for rectangular-section members. As the result of this correction, it is believed that the theory was nonconservative from 10 to 15 per cent for the rectangular-section members.

V SUMMARY AND CONCLUSIONS

12. Summary

Two methods have been proposed for computing the load and deflection necessary to produce, during a given time period at an elevated temperature, a specified amount of inelastic deformation in an eccentrically-loaded member. Both methods require the isochronous stress-strain diagram of the material for this temperature and time. This diagram is approximated by an arc hyperbolic sine curve for the arc hyperbolic sine curve theory and by two straight lines for the interaction-curve-moment-load-curve theory. The experimental phase of the investigation included 7 eccentrically-loaded T-section members made of 17-7PH stainless steel. These members were subjected to initial eccentricities of 25 and 51 per cent of the depth. The creep time for all tests was 30 minutes.

In addition to this investigation, additional data which was requested in Part VIII (Contract No. AF 33(616)-2753) is presented in this report. Since publishing Part IX, an error in the analysis of the data was discovered; the corrections are presented in this report.

13. Conclusions

1. At a temperature of 1000° F, the heat treated 17-7PH stainless steel remained elastic for a few seconds for stress levels at least as high as 55,000 psi. At this stress, however, the creep strain that occurred in the next 30 minutes was greater than the initial elastic strain. It was found that the isochronous stress-strain diagram for 30 minutes could be approximated by an arc hyperbolic sine curve as indicated by Eq. 1. In any inelastic analysis, it is necessary that the modulus of elasticity of the material be accurately determined; reproducible results were obtained in this investigation using creep specimens having a 6-in. gage length. The modulus of

elasticity was found to be 19,000,000 psi for the material in the bar used in making the T-section members and 18,750,000 psi for the material in the bar used in making the rectangular-section members.

2. Two methods were used in predicting the results of the eccentrically-loaded members. The interaction-curve-moment-load-curve theory was based on the assumption that the isochronous stress-strain diagram of the material could be approximated by two straight lines. The arc hyperbolic sine curve theory was based on the assumption that the isochronous stress-strain diagram of the material could be approximated by an arc hyperbolic sine curve. Of the two theories, the latter is more desirable for those materials which can be approximated by an arc hyperbolic sine curve, since the theory may be independent of the material constants and a function only of the shape of the cross-section of the test member. The former theory is dependent on both the shape of the cross-section of the test member and on the shape of the stress-strain diagram of the material.

3. Either of the theories should give nonconservative values of deflection for an eccentrically-loaded tension member subjected to a given load. The test data for the T-section members indicated that, on the average, the theory was less than 2 per cent nonconservative. The test data for the rectangular section members, based on the corrected value of the modulus of elasticity, indicated that the theory was nonconservative from 10 to 15 per cent.

4. The stress-strain data for the type 304 stainless steel could not be approximated by an arc hyperbolic sine curve; therefore, the interaction-curve-moment-load-curve theory was used in analyzing the eccentrically-loaded T-section members. The corrected data indicated similar results for test members subjected to initial eccentricities of 24 and 50 per cent of the depth. The comparison between theory and experiment was excellent up to one-half depth of yielding. At three-quarters depth of yielding the theoretical deflection was conservative from 20 to 25 per cent. An error of 7 per cent in determining the yield strength of the material would influence the deflection by about 25 per cent.

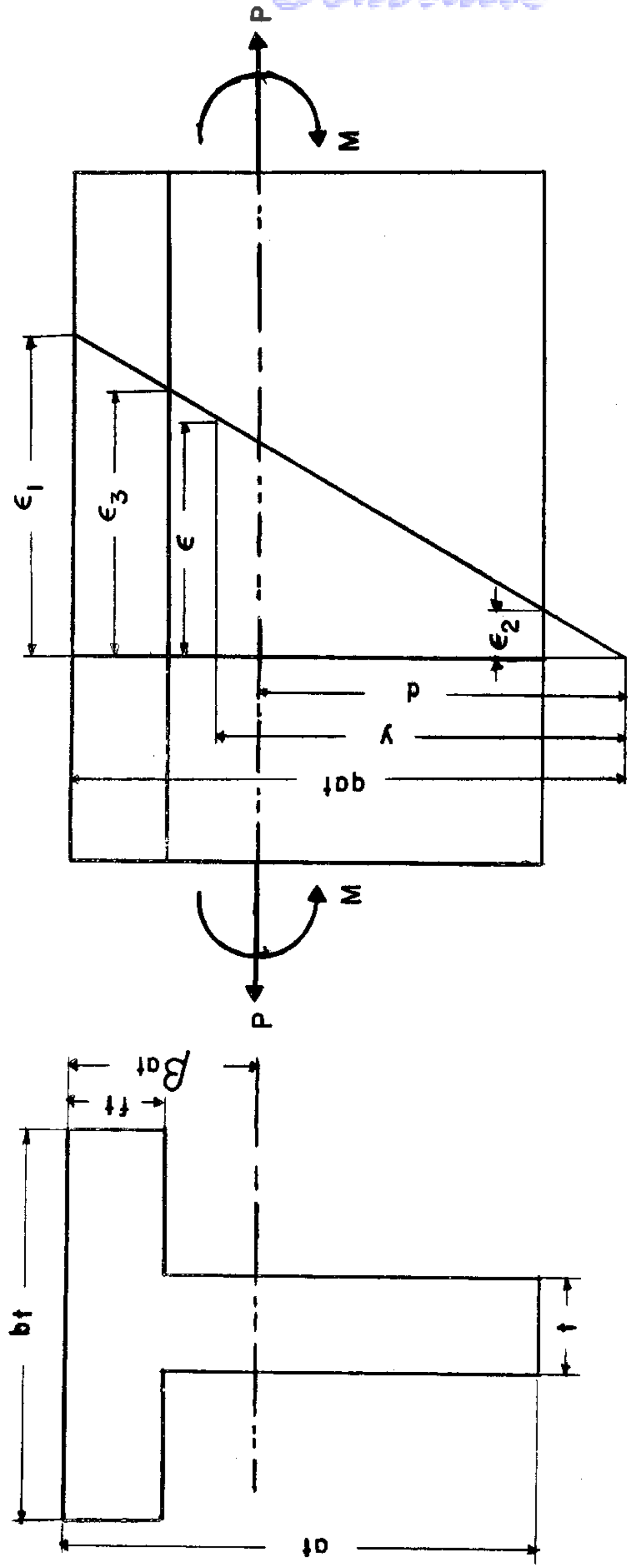

Fig. 1 T-Section Member Showing Dimensions of Cross-Section Loading Arrangement, and Strain Distribution

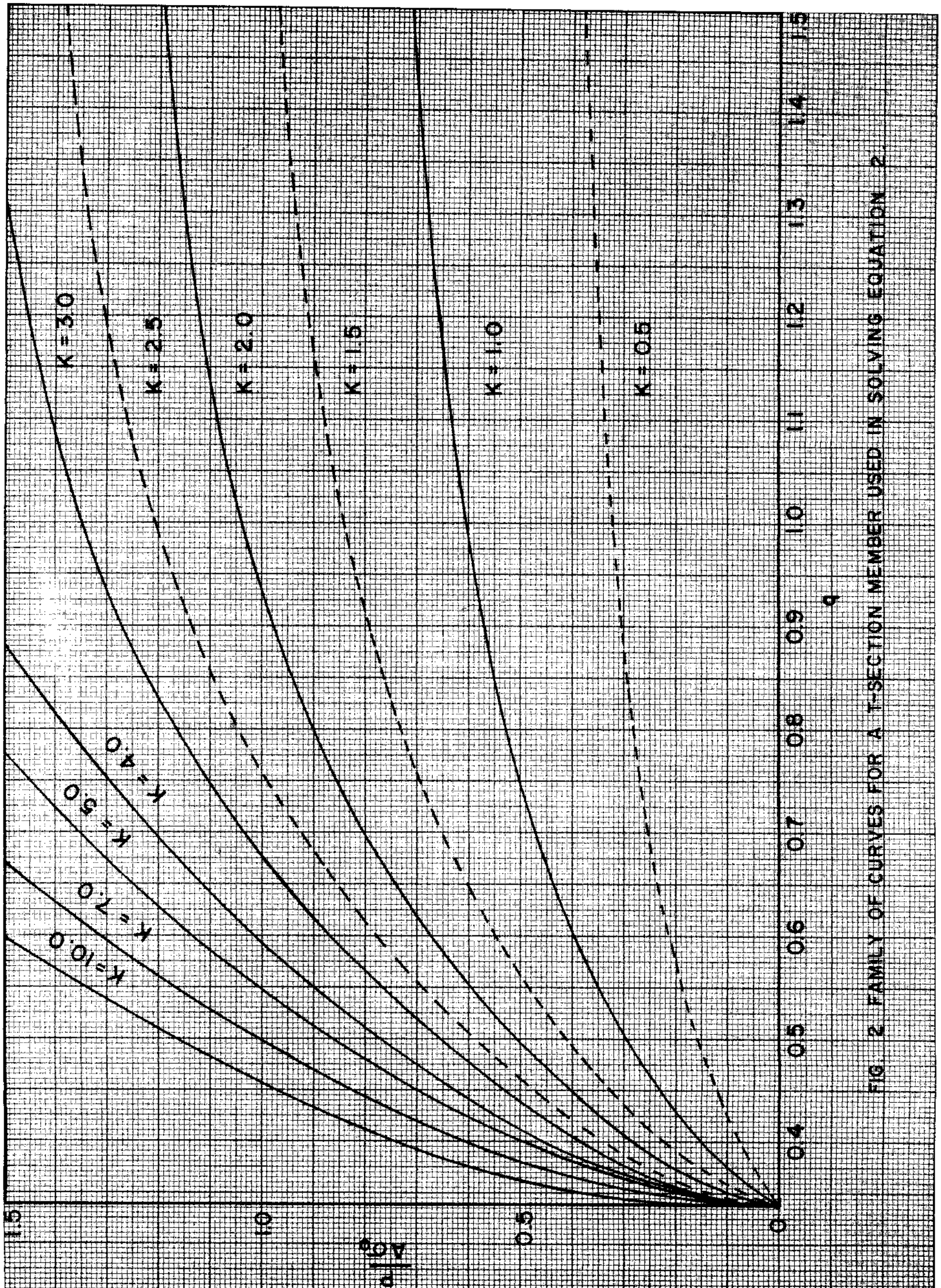

FIG. 2 FAMILY OF CURVES FOR A T-SECTION MEMBER USED IN SOLVING EQUATION 2

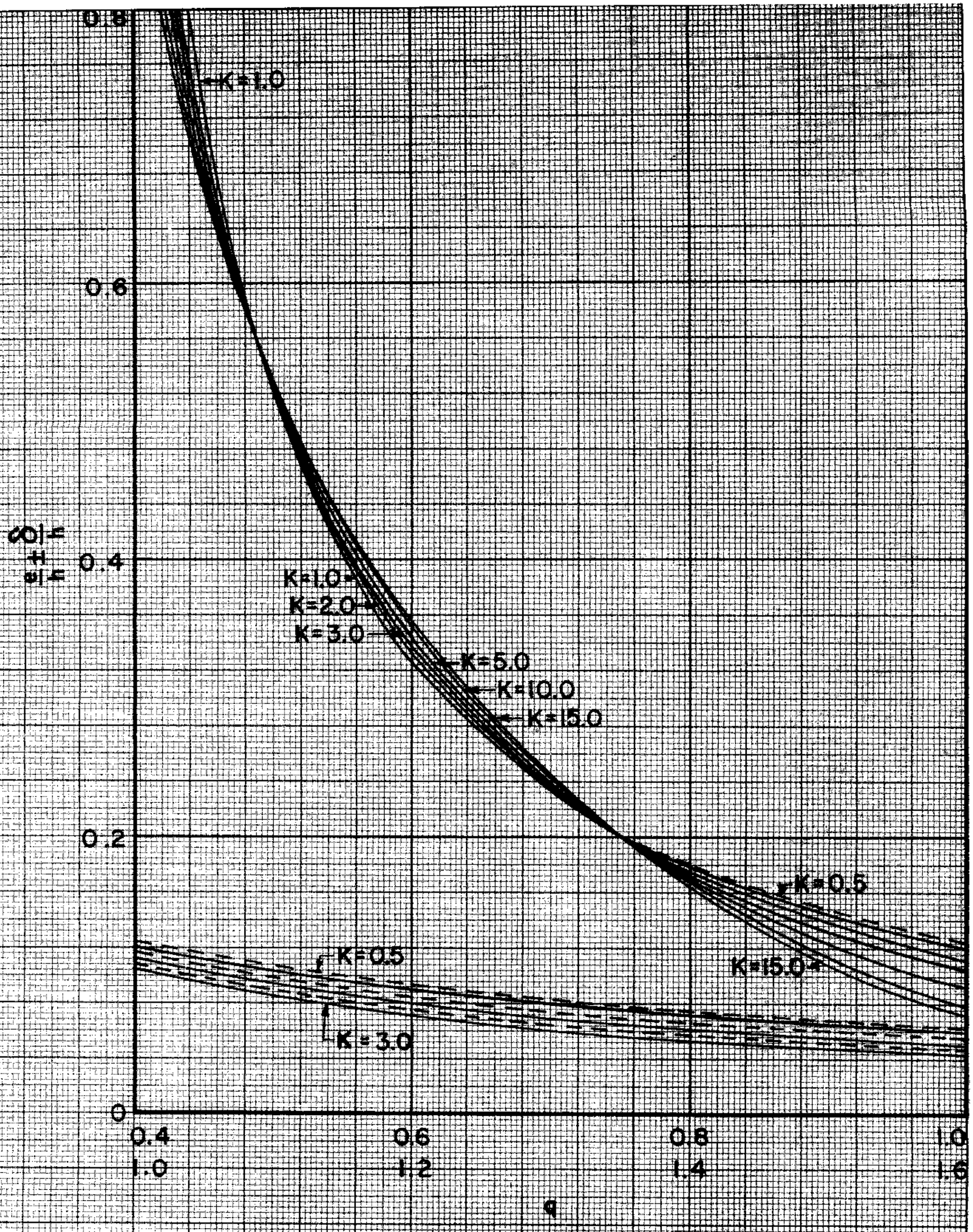

FIG. 3 FAMILY OF CURVES FOR A T-SECTION MEMBER USED IN DETERMINING THE VALUE OF q WHICH WILL SATISFY EQUATION 9

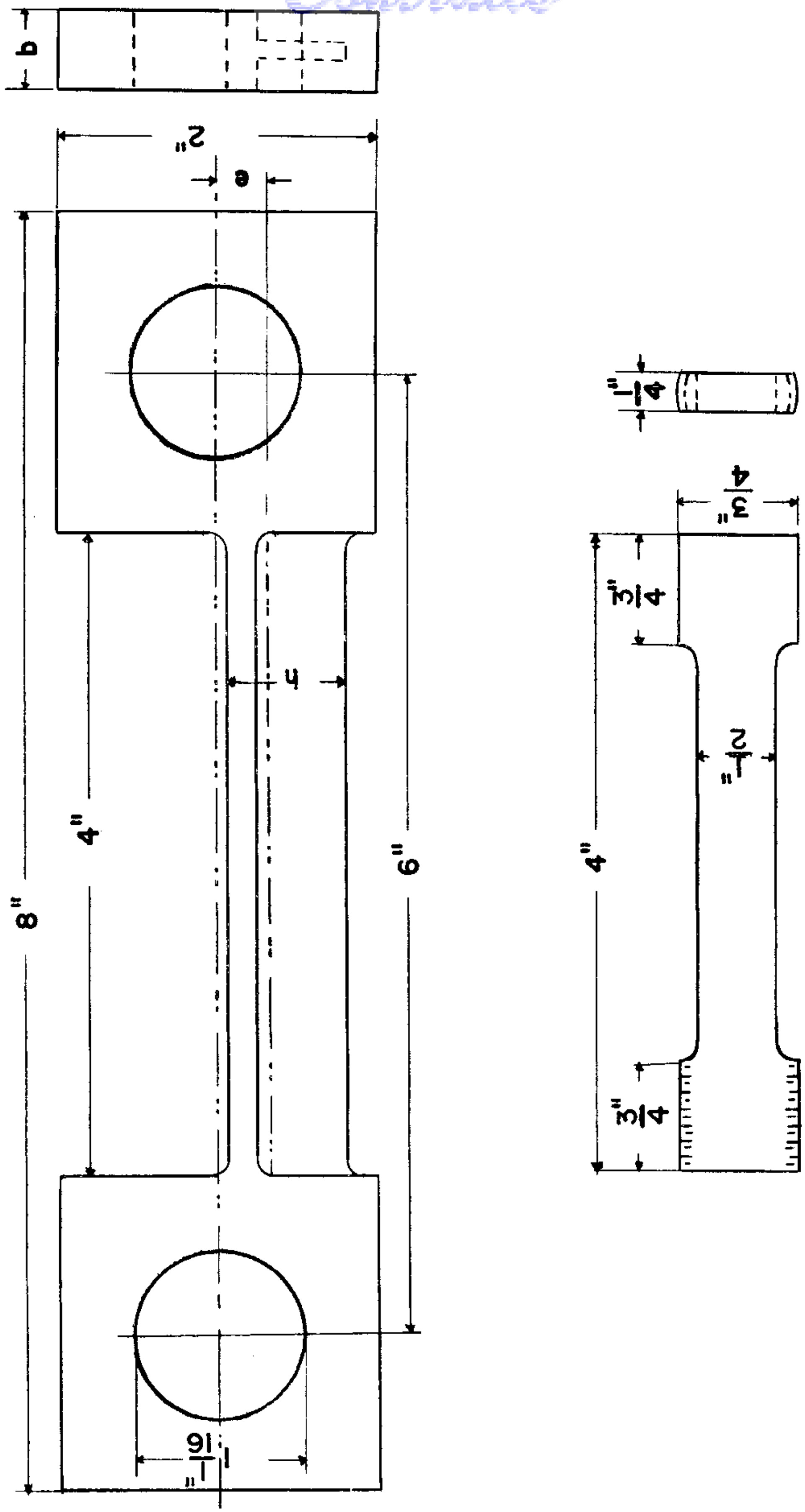

Fig. 4 Sketches of Test Members Showing Pertinent Dimensions

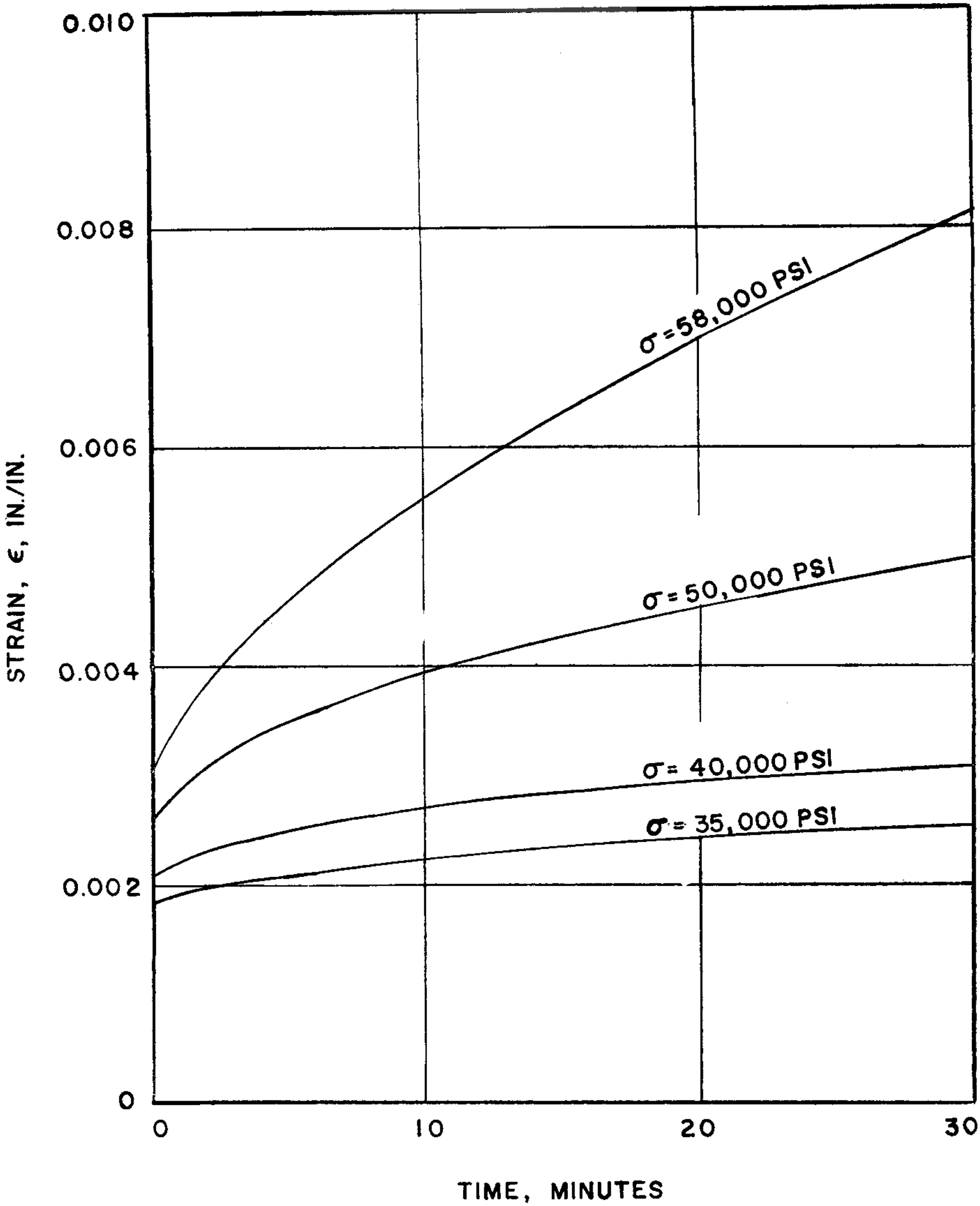

Fig. 5 Creep Curves for 17-7PH Stainless Steel at 1000 Degrees Fahrenheit

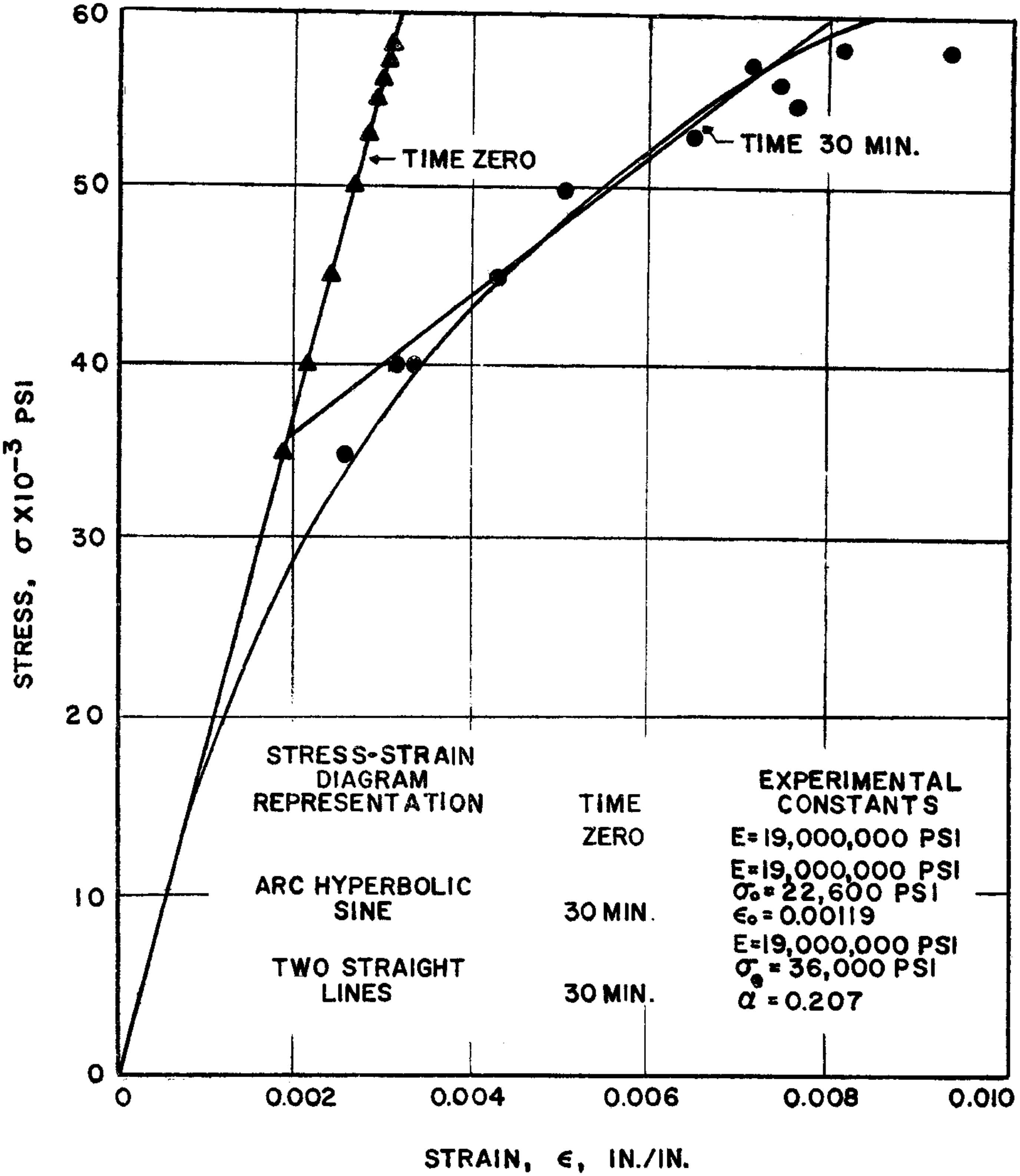

Fig. 6 Isochronous Stress-Strain Diagrams for 17-7PH Stainless Steel at 1000 Degrees Fahrenheit (T-Section Study)

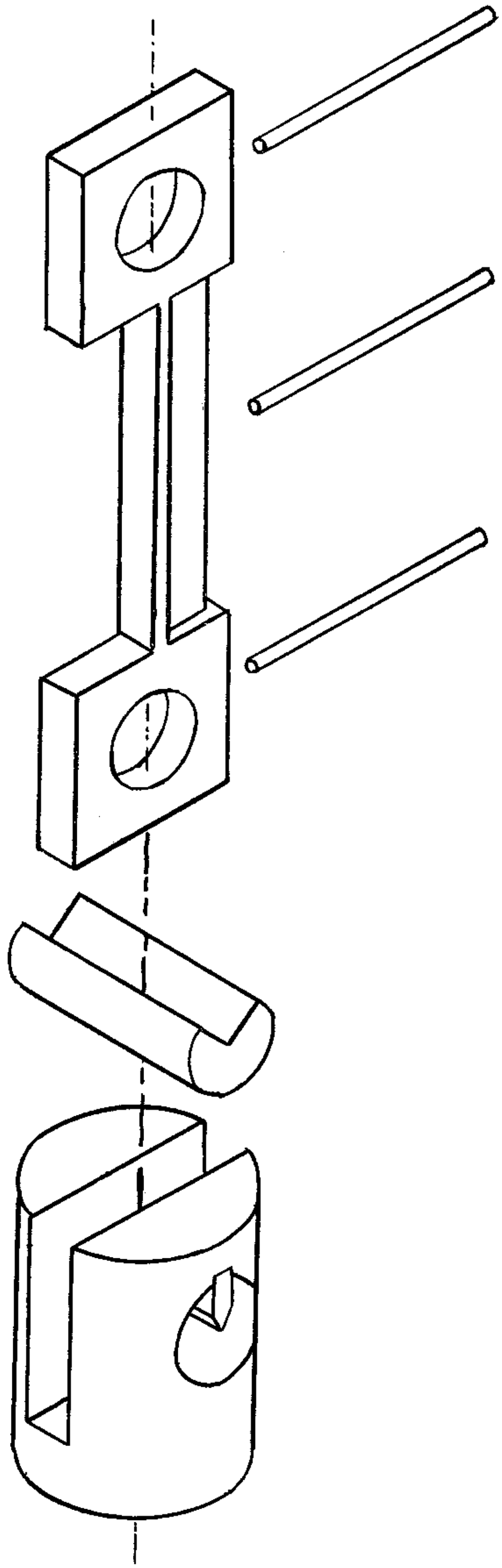

Fig. 7 Schematic Diagram of Fixtures Used in Testing T-Section Eccentrically-Loaded Members at Elevated Temperatures

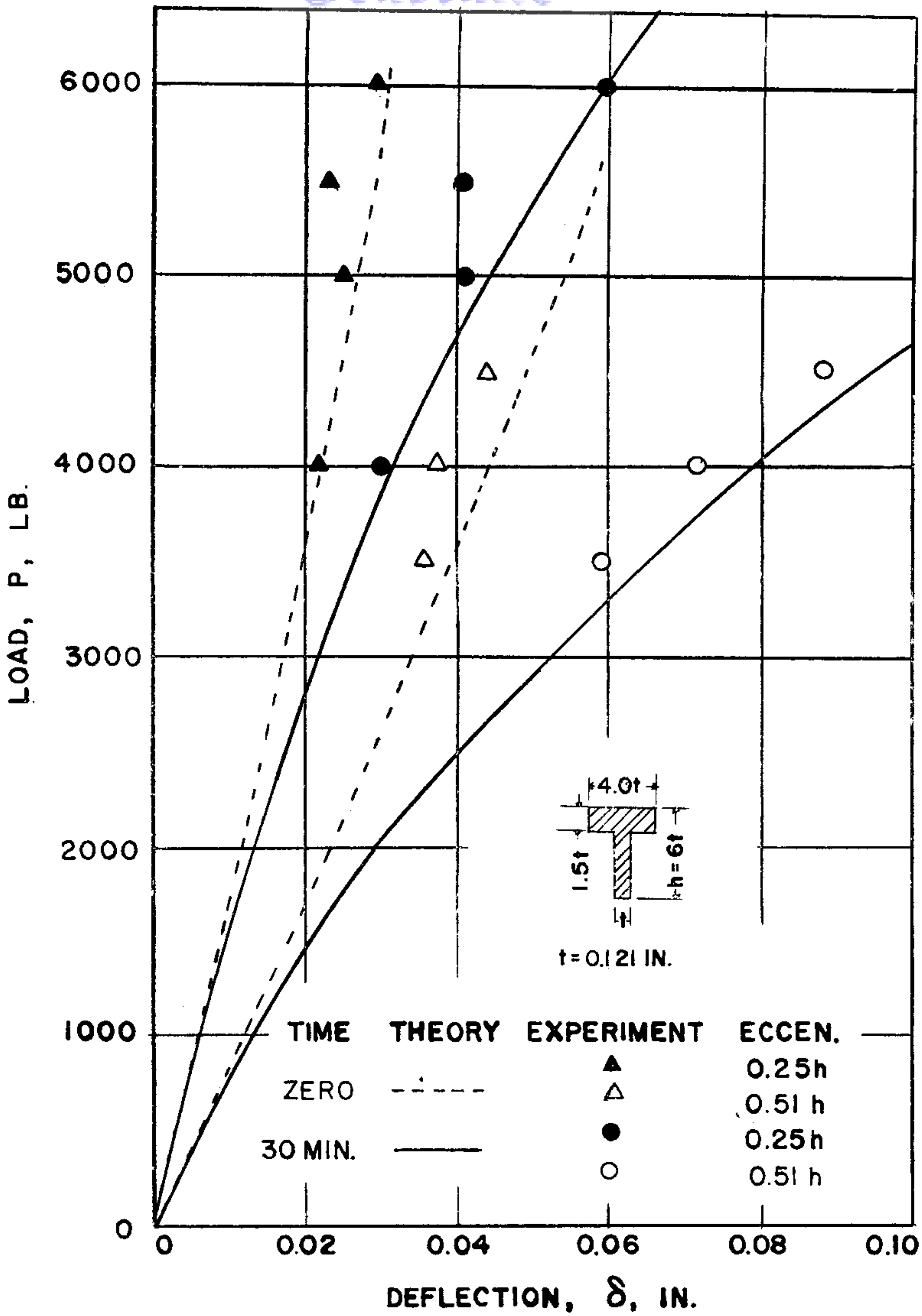

Fig. 8 Arc Hyperbolic Sine Curve Analysis of Eccentrically-Loaded T-Section Tension Members Made of 17-7PH Stainless Steel Tested at 1000 Degrees Fahrenheit

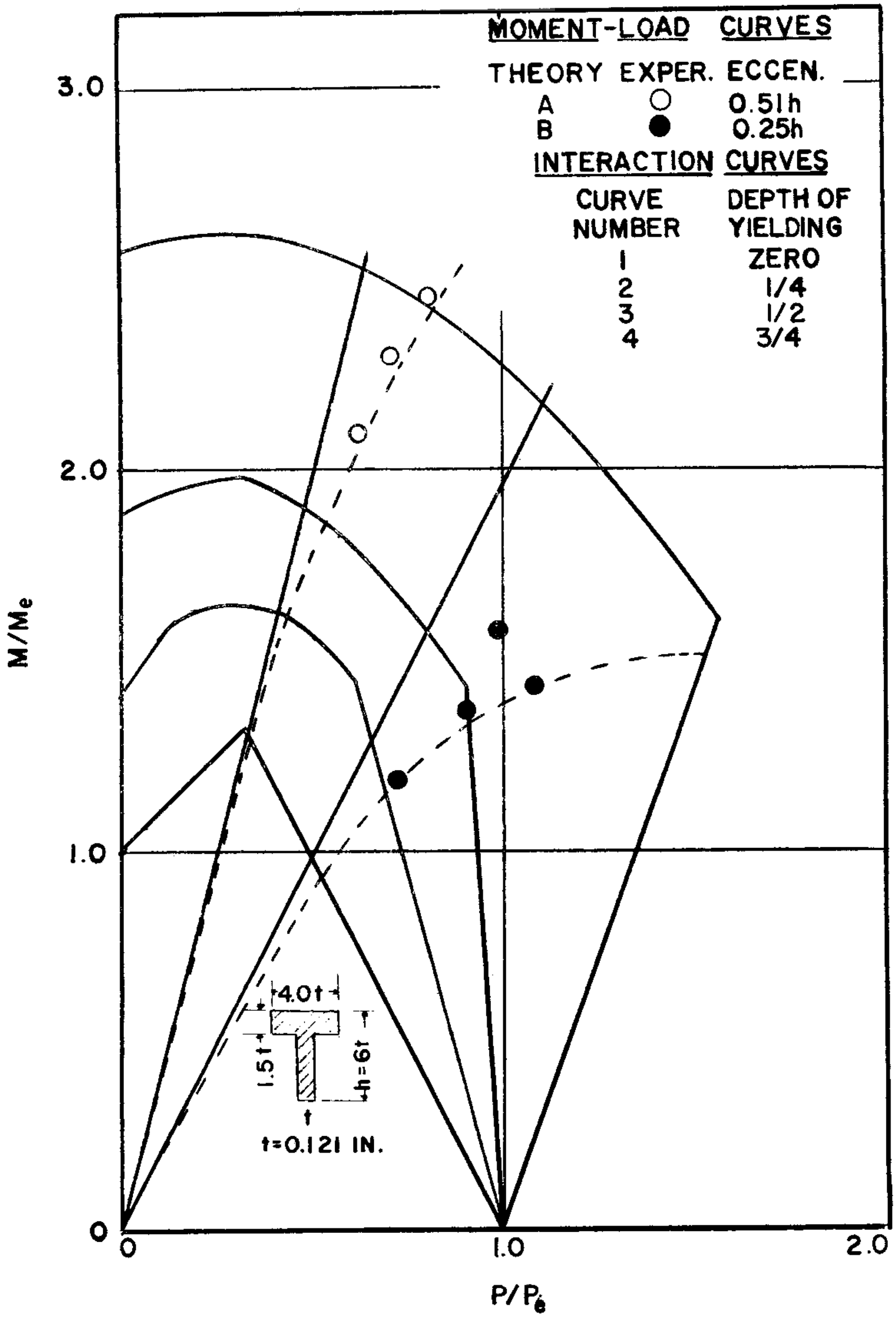

Fig. 9 Interaction-Curve-Moment-Load-Curve Analysis of Eccentrically-Loaded T-Section Members Made of 17-7PH Stainless Steel, Tested at 1000 Degrees Fahrenheit

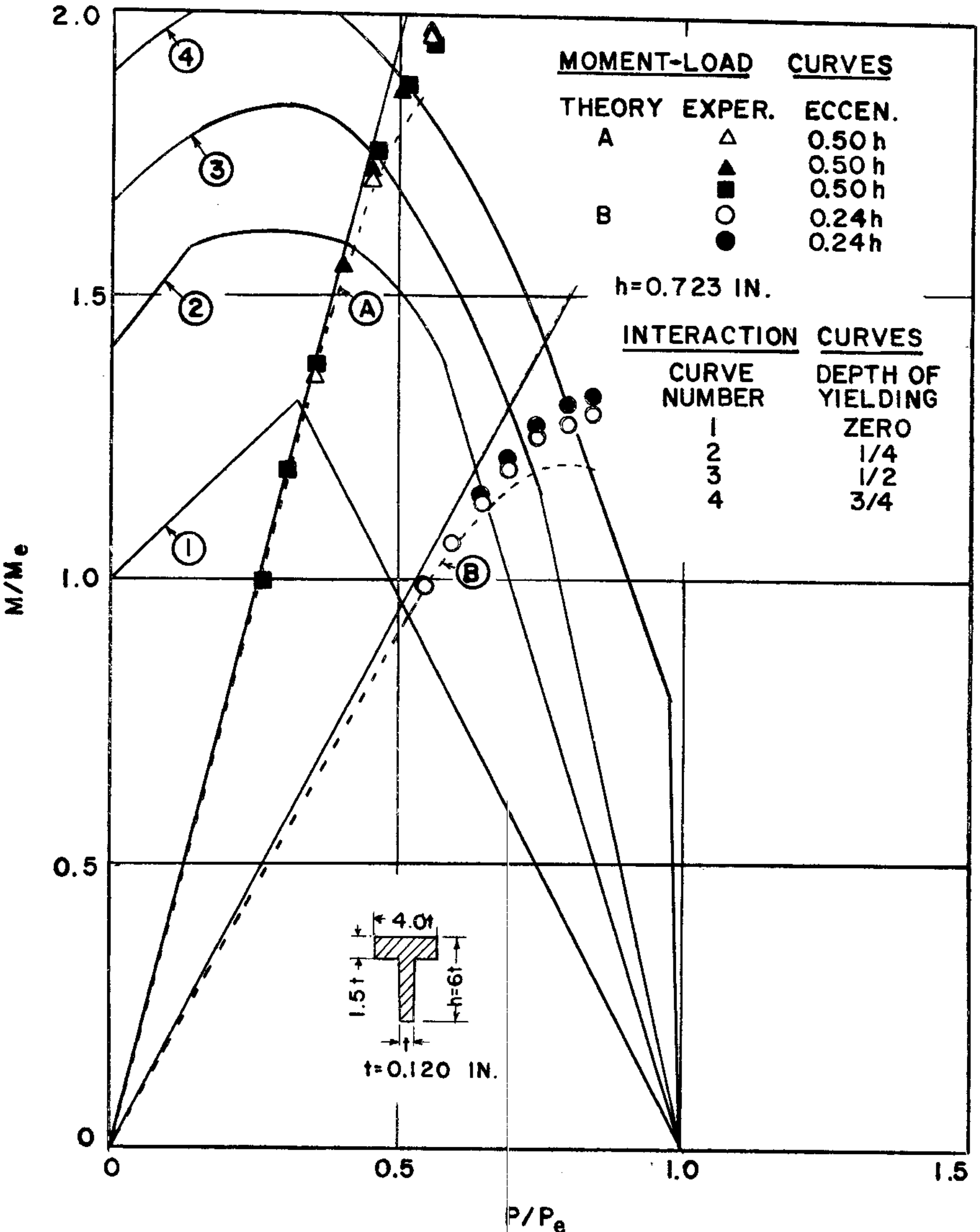

Fig. 10 Interaction-Curve-Moment-Load-Curve Analysis of Eccentrically-Loaded T-Section Members Made of Type 304 Stainless Steel, Tested at 1000 Degrees Fahrenheit

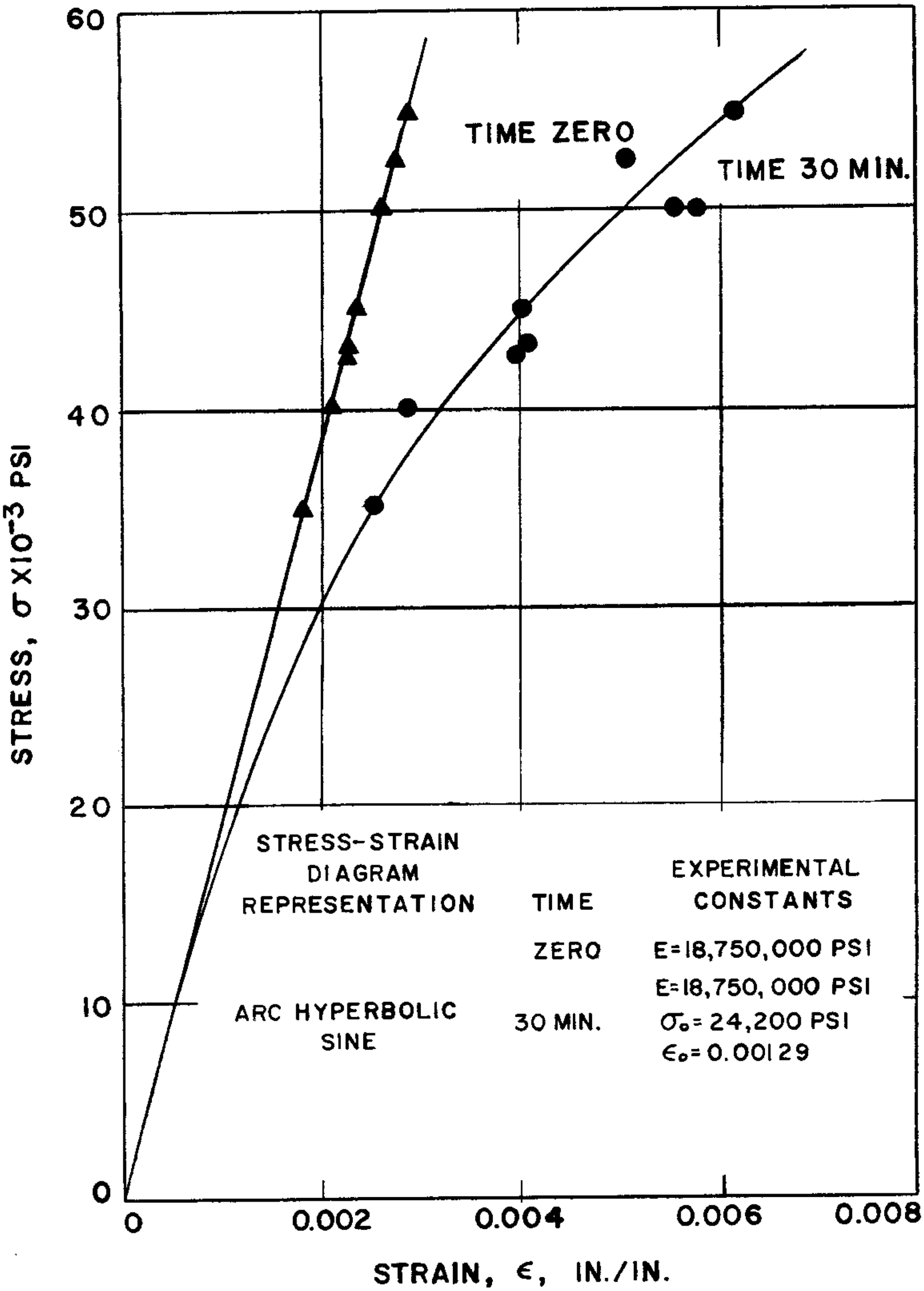

Fig. 11 Isochronous Stress-Strain Diagrams for 17-7Ph Stainless Steel at 1000 Degrees Fahrenheit (Rectangular Section Study)

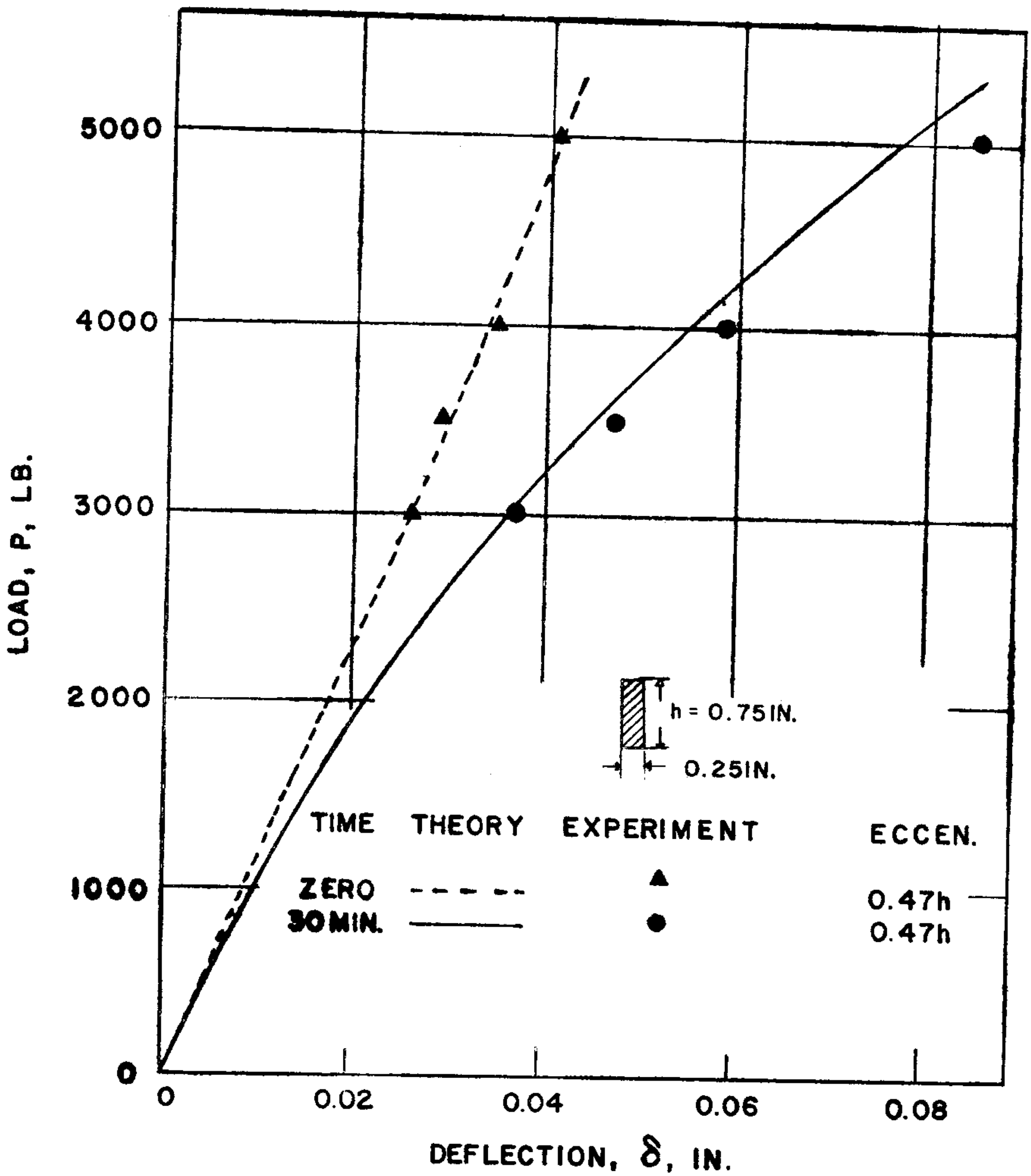

Fig. 12 Arc Hyperbolic Sine Curve Analysis of Eccentrically-Loaded Rectangular Section Tension Members Made of 17-7PH Stainless Steel, Tested at 1000 Degrees Fahrenheit