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ELEVATED-TEMPERATURE TESTS OF SIMPLY-SUPPORTED BEAMS AND CIRCULAR PLATES SUBJECTED TO TIME-VARYING LOADINGS

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ABSTRACT

This paper presents the measured elastic-plastic and elastic-plastic-creep responses of a number of simply-supported type 304 stainless steel beams and circular plates. Beams and plates exhibit the essential features of inelastic structural behavior; yet they are relatively simple. In beams, the stress fields are largely uniaxial, while multiaxial effects are introduced in plates. The specimens were laterally loaded at the center, and the tests were performed by subjecting the specimens to either a prescribed load or center-deflection history. The specimens were machined from a common, well-characterized heat of material, and all of the tests were performed at a temperature of 1100 F. The elastic-plastic tests consisted of short-time cycling of the center load, or deflection, between fixed limits. In the elastic-plastic-creep tests the center load, or deflection, was held constant for periods of time, but was periodically subjected to a step increase or decrease, including reversals. The test results are presented in terms of the load and center-deflection behaviors, which typify the overall structural behavior.

INTRODUCTION

Simply-supported beams and circular plates, loaded at their center, are two of the simplest possible types of structural tests for investigating inelastic structural behavior. It is, in fact, their simplicity that makes them particularly valuable for evaluating the basic aspects of inelastic constitutive theories and analysis procedures and for verifying features of inelastic analysis computer programs. Thus, tests of beams and plates play a key role in the Holifield National Laboratory (HNL) program to systematically develop and evaluate high-temperature design methods, and they can be a very useful and basic part of a benchmark problem verification and qualification effort.

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The test results presented in this paper come from a group of tests at 1100 F that were carefully planned and selected to complement one another. The original group of eight tests consisted of four beam tests and four plate tests with similar load histograms. Two of the beam tests and two of the plate tests were load controlled, while the remaining two of each were deflection controlled. Half of the tests began with short-time elastic-plastic cyclic loads, while the other half began with periods of time-dependent creep or relaxation. Thus, these tests, taken together, provide information on some of the essential

Note: Credit line in Acknowledgments.

aspects of elastic-plastic and creep behavior as well as information regarding the effects of prior elastic-plastic deformation on subsequent creep behavior and the effects of prior creep on subsequent elastic-plastic behavior. The results that are presented here were chosen to illustrate the essential behavioral features and to provide the analyst with a selection of simple benchmark problems which embody a variety of inelastic behavioral features.

The beams used in this investigation came from 1-in. plate product form of type 304 stainless steel heat 9T2796; the circular plates came from 3/4-in. plate of the same heat. This material, which is being used throughout the HNL High-Temperature Design Program, is well characterized, and the appropriate material properties required as input for inelastic analysis are given in the Appendix of this booklet. To assure that the material test data would be applicable, the finished beams and plates, as well as the material test specimens, were subjected to identical pretest heat treatments consisting of a full anneal at 2000 F (30 min) followed by rapid forced-air cooling to room temperature.

The remainder of this paper is divided into three major sections, which are designed to facilitate use of the results as benchmark problems. In the first section the problems are described. The specimen geometries and dimensions and the precise load histograms and boundary conditions are given. From this section the analyst should be able to model and set up an analysis of each of the problems. The second section describes the experimental approach. The test facility, instrumentation, and test procedures are briefly described so that the reader can more fully understand and judge the test results. The test results are presented graphically in the third major section, and the final section contains a brief discussion of the results.

PROBLEM DESCRIPTION

The beam and plate specimens are depicted in Fig. 1; the dimensions and the method of loading and supporting the specimens are shown. The beams were each 2 in. high, 1 in. wide, and 25 in. long, and they were simply supported so that the effective length was 24 in. The center load was applied through 0.75-in.-diam rollers and was down (+P) on the top surface or up (−P) on the bottom surface as shown. The simple end supports were through 0.75-in.-diam rollers which passed through the beam on its centerline.

The circular plate specimens were 0.50 in. thick and had an outside diameter of 20.75 in. The plates were simply supported by a line of 0.50-in.-diam ball bearings on a 20-in.-diam circle. Since the center load could be applied either down (+P) or up (−P), ball bearing supports were required on both the bottom and top surfaces, respectively. The center load was applied through a 2-in.-diam boss and loading bar as shown. A boss of the same dimensions was included on the bottom surface, and a nut and 2-in.-OD washer were used to clamp the plate to a 1-in.-diam threaded extension of the loading bar which passed through a hole in the plate. The objective of this arrangement was to provide a configuration which could be modeled as a 2-in.-diam solid bar, top and bottom, at the center of the plate.

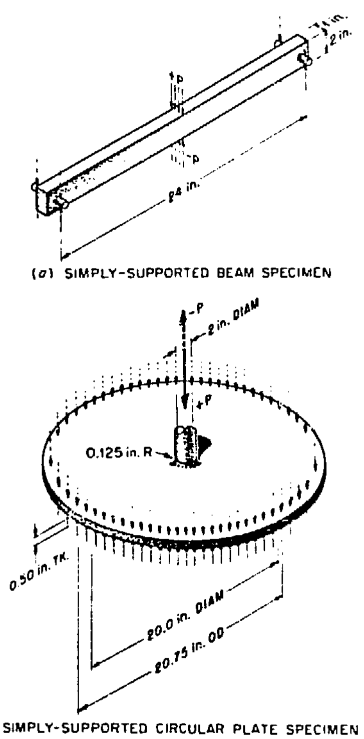

Fig. 1 Dimensions of simply-supported beam and circular plate test specimens

Figure 2 depicts the histograms used for the load-controlled tests and for the deflection-controlled tests, and Table 1 delineates the group of four beams and four plates from which the results presented in this paper were chosen. The figure numbers listed in Table 1 serve both to identify the results that are included in this paper and to show where in the paper the results are located. Footnotes to Table 1 give the magnitudes of the loads P_1 and P_2 and the deflection δ for each of the individual tests. More complete results for beam B8 and results for plates CP2 and CP3 may be found in Ref. (1).

The times t_1, t_2, and t_3 for the hold periods in Fig. 2a were each nominally 312 hr, and the times t_1 and t_2 in Fig. 2b were nominally 144 hr. The actual hold times sometimes differed slightly from the nominal, and the actual values are given with the results (Figs. 7, 10, 12, 15, and 17). All short-time load and deflection changes shown in Fig. 2 were ramp shaped, and the rate was based on 2 min per complete load or deflection cycle (30 sec per quarter cycle, such as points 2 to 3).[1]

The loading and deflection histories depicted in Fig. 2 and delineated in Table 1 for the separate tests were contrived to systematically study the effects of plastic and creep behaviors interspersed. Consider, for example, the pair of beam tests B9 and B10. Test B10 was subjected to the full histogram shown in Fig. 2a. Thus the first ten short-time load cycles may be analyzed as elastic-plastic behavior only. The creep portion of the test is considered to begin at point 2 and end at point 9. In the final ten short-time load cycles, creep effects can again be neglected. Test B9 was exactly the same as B10 except that the initial ten short-time cycles were eliminated; the B9 test started at point 2. Thus, the beam B9 and B10 test results, taken together, provide both elastic-plastic response data and creep response data for a virgin specimen.

[1] The 2 min/cycle rate corresponds approximately to a maximum strain rate (calculated on an elastic basis) of 0.005/min, the standard rate used in obtaining the uniaxial cyclic stress-strain curves included in the Appendix of this booklet.

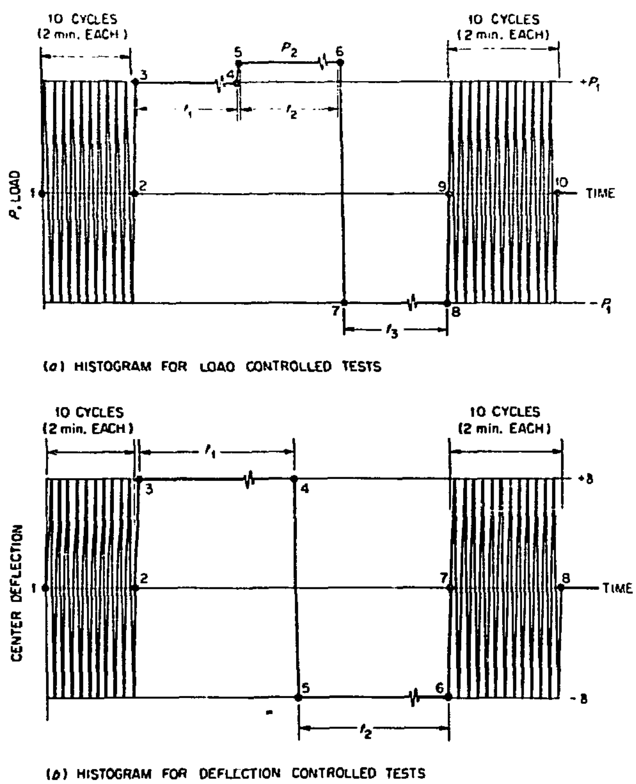

Fig. 2 General form of histograms for load- or deflection-controlled beam and circular plate tests

Table 1 Interrelated set of beam and plate tests at 1100 F

The figure number entries identify the center load vs deflection results presented in this paper.

	Test No.	Type of control	Test phase[a] (refer to Fig. 2)			
			Precreep cycles[a]	Short-time load or deflection changes	Creep or relaxation	Postcreep cycles[b]
Beams	B9[c]	Load	---	Fig. 6	Fig. 7	
	B10[c]	Load	Fig. 8	Fig. 9	Fig. 10	
	B7[d]	Deflection	---	Fig. 11	Fig. 12	
	B8[d]	Deflection	Fig. 13			
Plates	CP5[e]	Load	---	Fig. 14	Fig. 15	
	CP2[e]	Load				
	CP4[f]	Deflection	---	Fig. 16	Fig. 17	
	CP3[f]	Deflection				

[a]Each test consisted of all four phases except that beams B9 and B7 and plates CP5 and CP4 were not subjected to precreep cycling.

[b]No postcreep cyclic data are presented in this paper.

[c]P_1 = 2000 lb, P_2 = 2250 lb.

[d]δ = 0.10 in.

[e]P_1 = 3900 lb, P_2 = 4900 lb.

[f]δ = 0.11 in.

They also provide data regarding the effects of prior elastic-plastic behavior on subsequent creep (the creep response of beam B10 compared to that of B9) and the effects of prior creep on subsequent plasticity (the short-time response from points 4 to 5 in B9 compared to the response from 2 to 3). The responses in the creep hold periods also allow an assessment of creep hardening rules and procedures. The two tests in each of the remaining pairs of tests in Table 1 are related in the same manner as are beams B9 and B10.

EXPERIMENTAL APPROACH

A special elevated-temperature test facility was designed and built specifically for testing beams; and a second facility was built for testing circular plates. With the exception of the specimen loading and support details and the furnaces, the elevated-temperature plate test facility is essentially identical to the beam test facility. The beam facility is shown schematically in Fig. 3, and a photograph of the facility is shown in Fig. 4. The outline of the simply-supported, center-loaded beam specimen can be seen inside the furnace in Fig. 3, and in Fig. 4 the front portion of the furnace has been removed so that the beam can be seen. For long-term constant-load creep periods, a system of deadweights, acting through cables, pulleys, and a bell crank arrangement, is used to apply a vertical load, either up or down, through the creep loading arms shown on each side of the loading frame. To overcome the relatively small effects of friction, pneumatic load trimmers (one of which can be seen attached to the loading arm in Fig. 4) are used. These automatically-controlled trimmers have a maximum capability of 200 lb.

For short-time cycling and load changes and for all deflection-controlled testing, the loading arms are disconnected at the bell crank and a double-acting hydraulic ram, operating in the horizontal position is attached to the bell

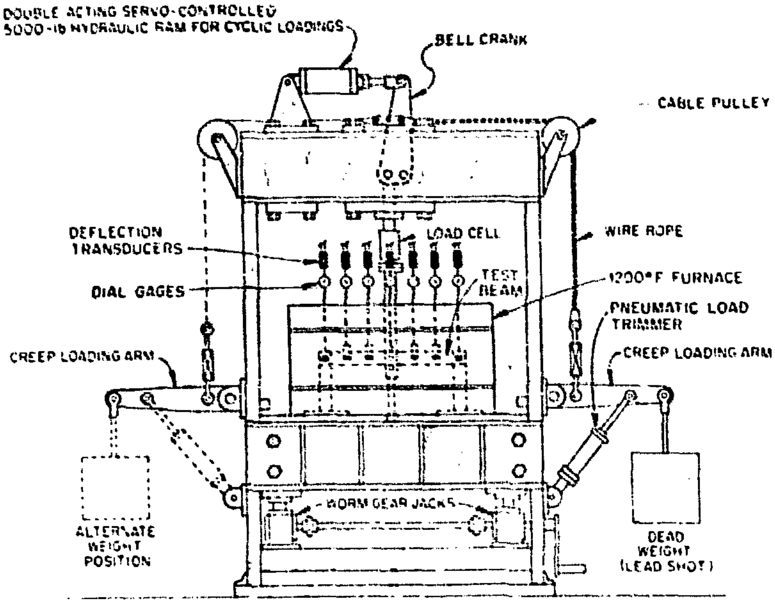

Fig. 3 Schematic drawing of elevated-temperature beam test facility

Fig. 4 Photograph of elevated-temperature beam test facility

bell crank. A servo-controlled hydraulic system with an MTS controller and a Data-trak programmer are used to activate the hydraulic ram.

Each beam and plate specimen was instrumented with ten thermocouples on the top and bottom surfaces, at least four symmetrically-located weldable resistance strain gages, and seven deflection measuring devices for determining lateral deflections. The thermocouples used were sheathed chromel-alumel, type K, 1/16 in. diam × 24 in. long, and were individually calibrated before and after each test. The strain gages were Ailtech SG425 gages. For the deflection measurements, quartz rods were attached to the beam midsurface as can be seen in Fig. 4. These rods passed through the insulated furnace box and were each attached to a dial gage and a direct current differential transformer (DCDT).[2] Two of the deflection measurement systems were located at the end supports, one was located at the beam center, and the remaining four systems were equally spaced along the beam, with two on each side of the center. Data were recorded periodically throughout each test using an automatic data scanning and logging system.

One of the plate specimens is shown in Fig. 5 mounted in the support structure and with the furnace partially assembled. The races of ball bearings on the top and bottom surfaces can be seen. A slight vertical gap was maintained in the race supports to prevent binding of the plate as it deflected during the test. In the case of the plates, the quartz rods for deflection measurements were capped with pointed metal tips that rested in small indentations in the upper surface of the plates. To assure continued contact with the plates, the rods were spring loaded.

The test procedure for both beam and plate tests consisted of heating the unloaded specimen to 1100 F and obtaining a uniform temperature over the specimen surface prior to starting the loading. This heatup and adjustment period was generally kept to less than 24 hr. During the tests an attempt was made to maintain the temperatures at 1100 F ± 5 F. Occasionally the temperature at some point on a specimen would exceed these tolerance limits by 3 or 4 F for relatively short periods. In general, however, the limits were met. The loads and deflections were controlled to within ±1% of the nominal values.

[2] Deflection readings from the DCDT's were recorded throughout the tests. The dial gages were read periodically and were used as a check and as backup for the DCDT's.

Fig. 5 Photograph of circular plate specimen in partially assembled oven

TEST RESULTS

The test results given in this section are in terms of the response of the center loads and center deflections, which typify the overall structural response. The results are arranged in the order that was shown in Table 1. Figure 2, which gave the load and deflection histograms, and Table 1 should be referred to along with the results given in this section.

The measured center deflection vs load for the initial loading of beam B9 to 2000 lb, as well as for the other load changes associated with the creep portions of the test, is shown in Fig. 6. The creep deflections that occurred

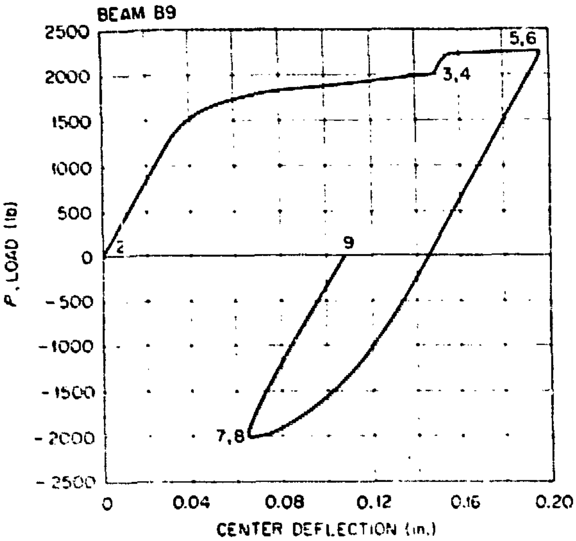

Fig. 6 Load vs center deflection for short-time load changes associated with creep portions of beam B9 test

at 2000, 2250, and -2000 lb have been subtracted so that the deflections shown are essentially elastic-plastic only. Referring back to Fig. 2a, the curves in Fig. 6 depict the measured response between points 2 and 3, 4 and 5, 6 and 7, and 8 and 9. These points are identified on Fig. 6, as they are on most of the figures in this section. Figure 7 is a companion plot to Fig. 6 and shows the creep deflection at the center of beam B9 as a function of time. Again, the numbers on the curves refer to points on the histogram of Fig. 2a.

Beam test B10 was identical to test B9 except for an initial ten short-time load cycles. The load-deflection behavior for these initial elastic-plastic cycles is depicted in Fig. 8. Figures 9 and 10 for beam B10 are analogous to Figs. 6 and 7 for beam B9. A comparison of the two sets of figures shows the hardening effect of the initial cyclic loading in B10.

Figure 11 shows the load vs center deflection for the deflection changes associated with the relaxation portions of beam test B7. The initial loading to a center deflection of 0.10 in. is shown by the curve from 2 to 3 (refer to Fig. 2b). The load decrease at a deflection of 0.10 in. (points 3 to 4) corresponds to the initial relaxation period. Figure 12 shows the load vs time response for the two relaxation hold periods.

The final beam result is shown in Fig. 13, which depicts the load vs center deflection behavior during the initial ten deflection cycles of beam B8. The response shown in this figure is essentially elastic-plastic.

Results for plate test CP5, which was load-controlled and had no precreep cyclic loading, are shown in Figs. 14 and 15. These two figures correspond to Figs. 6 and 7 for beam test B9. Finally, results for plate test CP4, which was

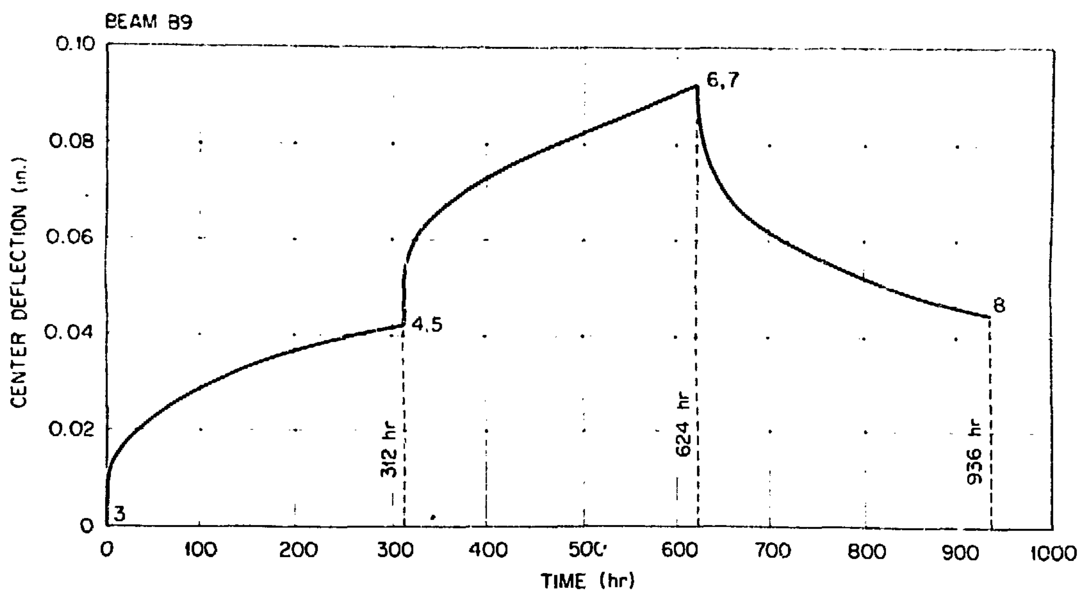

Fig. 7 Creep deflection vs time for center of beam B9

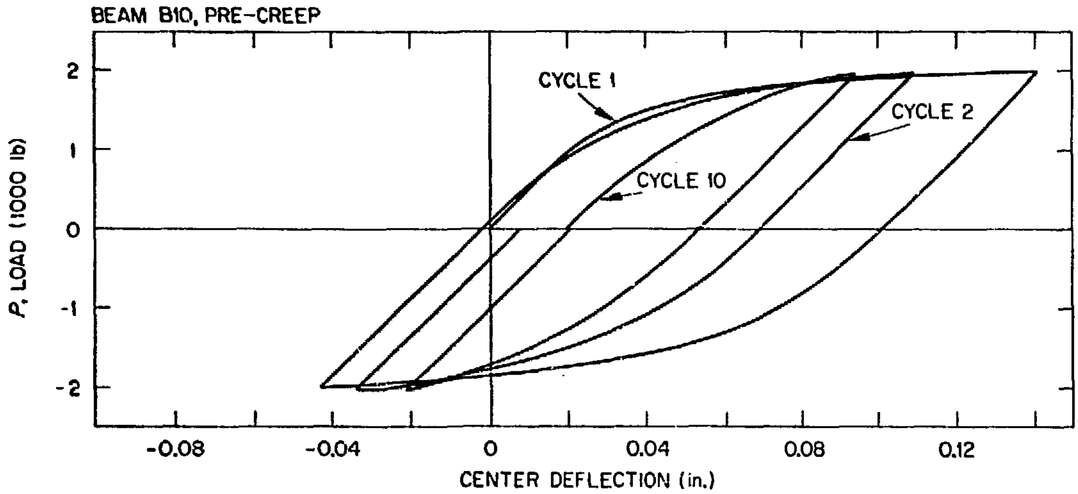

Fig. 8 Load vs center deflection during ten short-time, precreep load cycles of beam B10

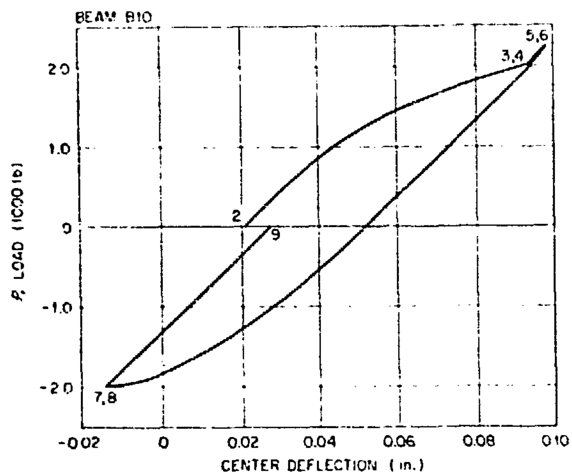

Fig. 9 Load vs center deflection for short-time load changes associated with creep portions of beam B10 test

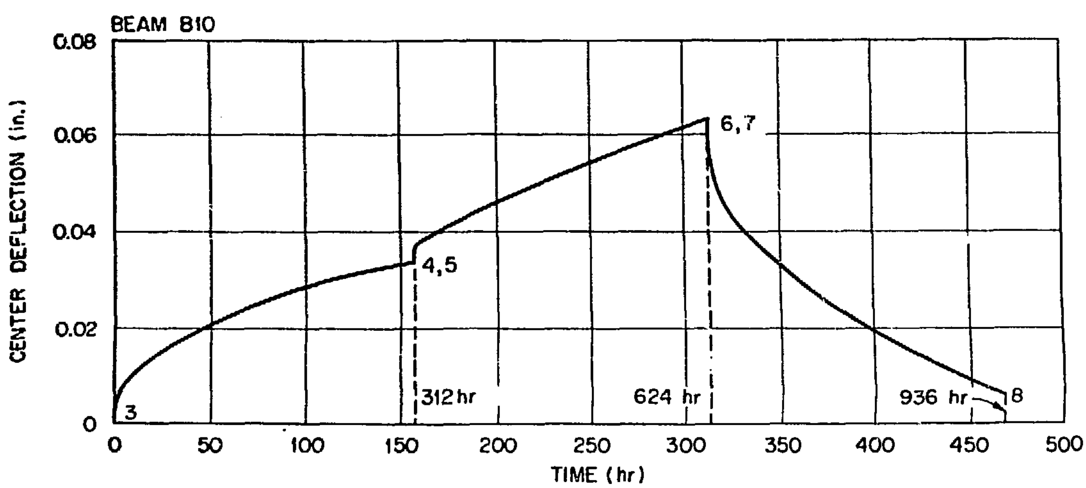

Fig. 10 Creep deflection vs time for center of beam B10

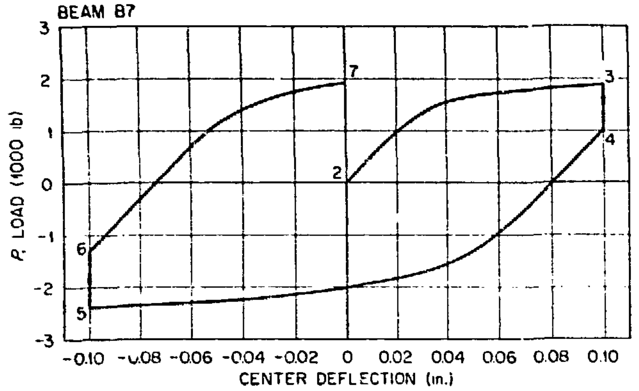

Fig. 11 Load vs center deflection changes associated with relaxation portions of beam B7 test

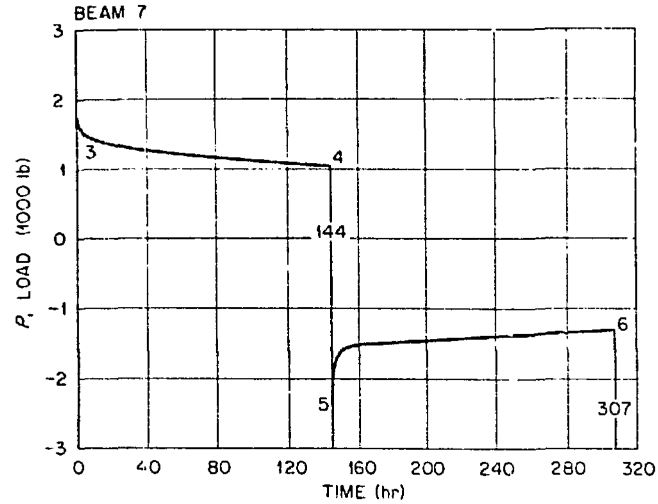

Fig. 12 Load relaxation vs time for beam B7

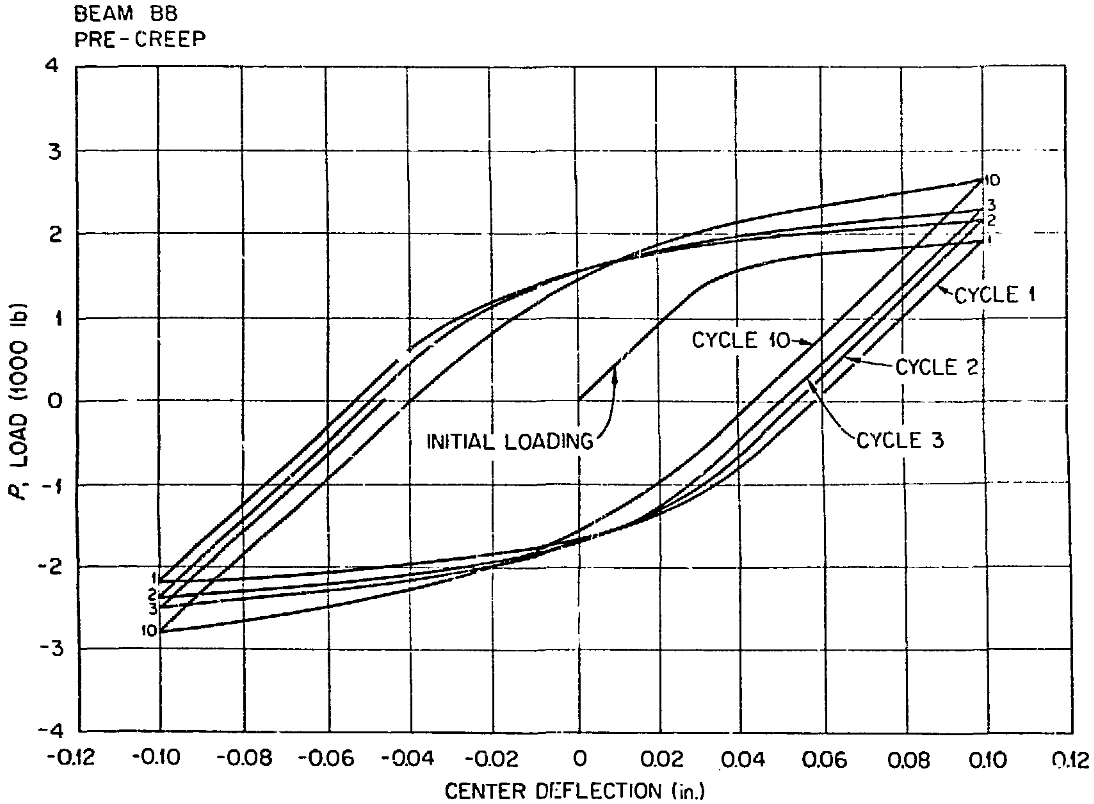

Fig. 13 Load vs center deflection during ten short-time, precreep deflection cycles of beam B8

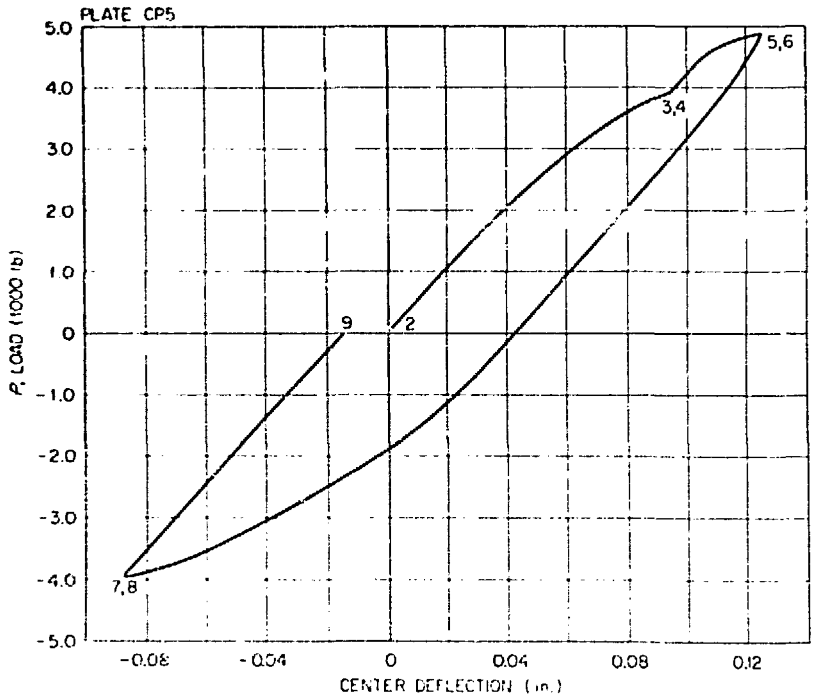

Fig. 14 Load vs center deflection for short-time load changes associated with creep portions of plate CP5 test

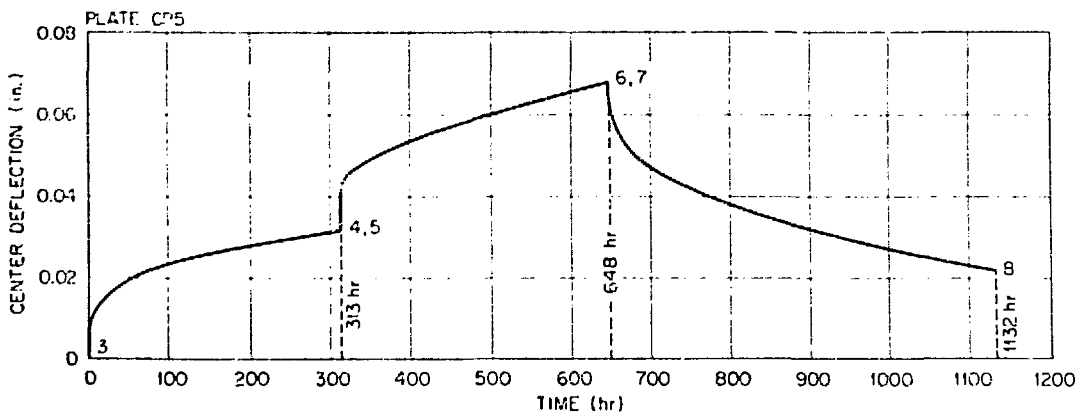

Fig. 15 Creep deflection vs time for center of plate CP5

deflection-controlled and had no precreep cyclic loading, are shown in Figs. 16 and 17. These two figures correspond to Figs. 11 and 12 for beam test B7.

DISCUSSION OF RESULTS

Although the test data that have been presented are intended to be used primarily as benchmark problem results for comparison with inelastic structural analysis predictions, an examination of the test data alone reveals several important characteristics of inelastic behavior. First, Figs. 6, 9, and 14, which depict the short-time responses of the load-controlled tests to the load changes associated with the creep periods, indicate the hardening effect that prior creep has on subsequent plasticity. Consider Fig. 6 specifically; the load change from 2000 to 2250 lb (points 4 to 5) after the initial creep period results initially in a near-elastic response even though considerable plastic deformation had occurred during the initial load application to 2000 lb. This apparent hardening may be due in small part to some stress redistribution that

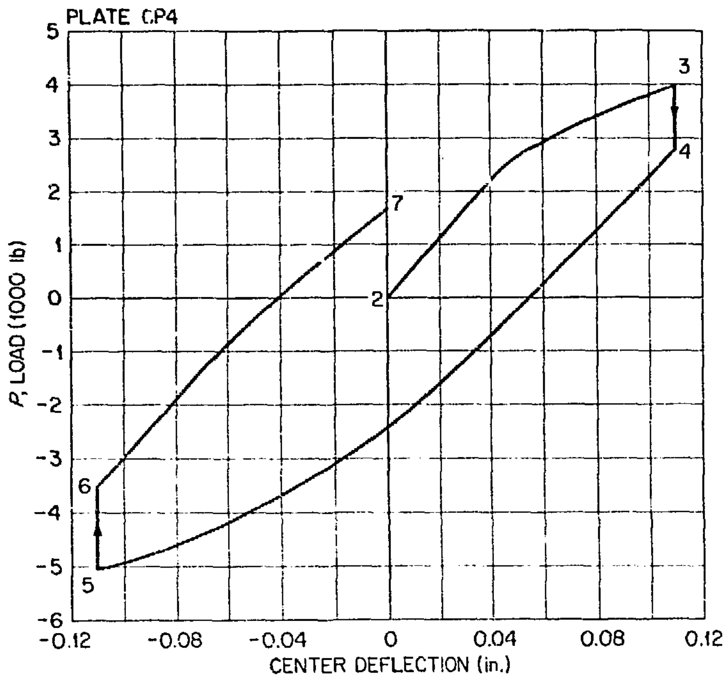

Fig. 16 Load vs center deflection changes associated with relaxation portions of plate CP4 test

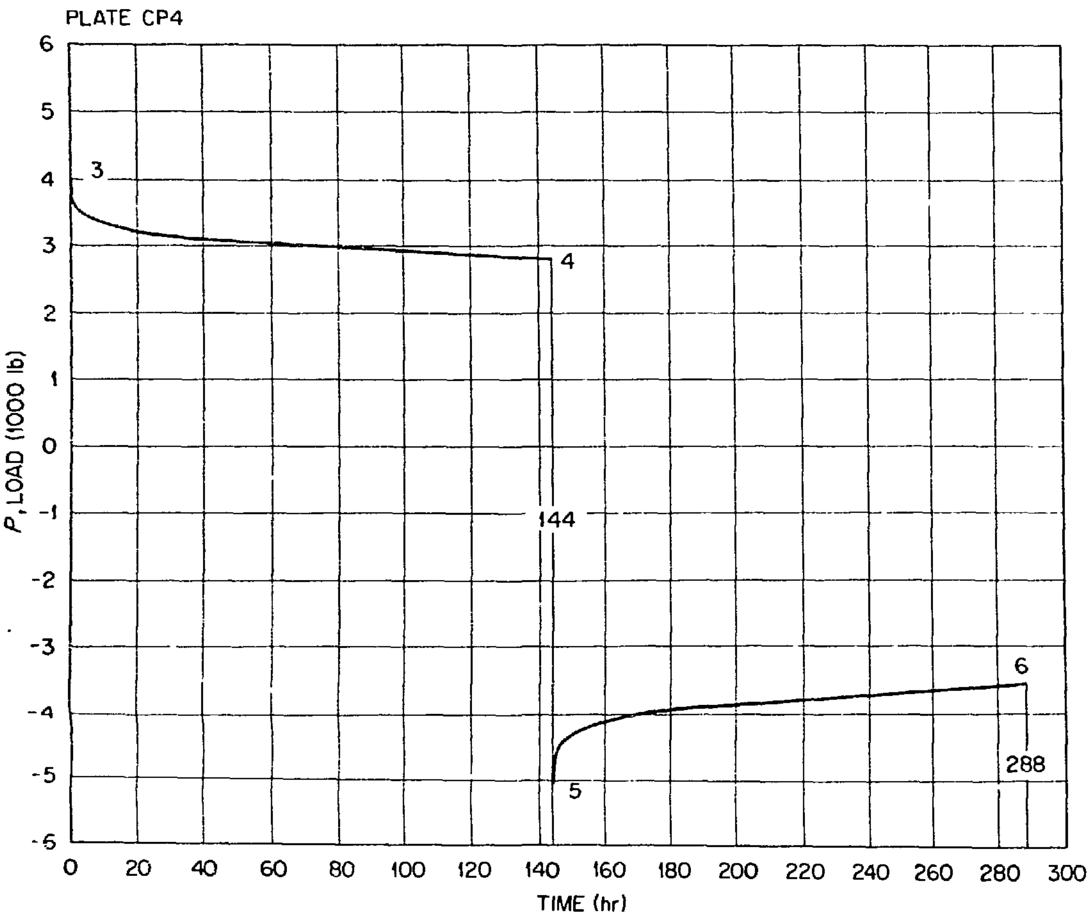

Fig. 17 Load relaxation vs time for plate CP4

takes place during the creep period, but it is more directly the result of hardening due to prior creep.[3]

Figure 8, which depicts the initial cyclic response of beam B10 to a cyclic load illustrates the pronounced effect that cyclic hardening can have on structural behavior. Cyclic hardening, which is discussed at some length in Ref. (2), is a prominent feature of the inelastic response of type 304 stainless steel. Cyclic hardening is also illustrated in Fig. 13, which shows the initial cyclic response of beam B8 to a cyclic deflection.

It is of interest to compare the initial cyclic response of beam B10 shown in Fig. 8 with the cyclic response of beam B9 to the ten postcreep load cycles [given in Ref. (3)]. In the latter case the loop width (at zero load) for the first cycle was about 0.026 in., and for the tenth cycle, about 0.012 in. These are considerably less than the loop widths in Fig. 8 and further illustrate the hardening effects of prior inelastic deformation.

A comparison of the creep responses of beams B9 and B10 in Figs. 7 and 10, respectively, would seem to indicate that the additional prior plastic deformation in beam B10 resulted in a slight decrease in subsequent creep response. The difference is probably due more to normal test-to-test variation than to the effects of prior plasticity. Uniaxial test results indicate little effect of prior small plastic strains on subsequent creep (2).

One final structural response feature can be identified by comparing Fig. 6, for beam B9, with Fig. 14, for plate CP5. Relative to the beam, the plate remains relatively stiff after initial yielding. In fact, the plastic deflection is relatively small in the plates even when the load is approximately twice the value at which initial yielding occurs. This response is typical of plate structures and is, of course, due to the basic biaxial stress field in the plates.

It is believed that the test results presented in this paper are representative and reasonably reproducible. For example, plate test CP5 was an exact duplicate of an earlier test, CP1. Comparisons of the results for the two identical tests show that the elastic-plastic deflection response of CP5 was about 10% less than that for plate CP1, and the creep response, about 25% less. These discrepancies are probably reasonably representative of the normal variations to be expected from test to test.

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[3] This basic feature of the inelastic behavior of type 304 stainless steel is described in Ref. (2) on the basis of uniaxial tests.

ACKNOWLEDGMENTS

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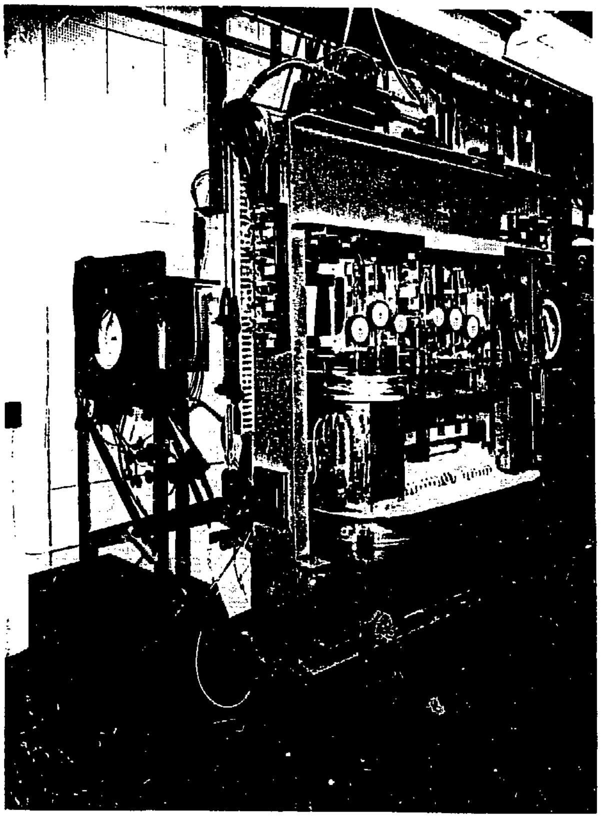

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Fig. 4

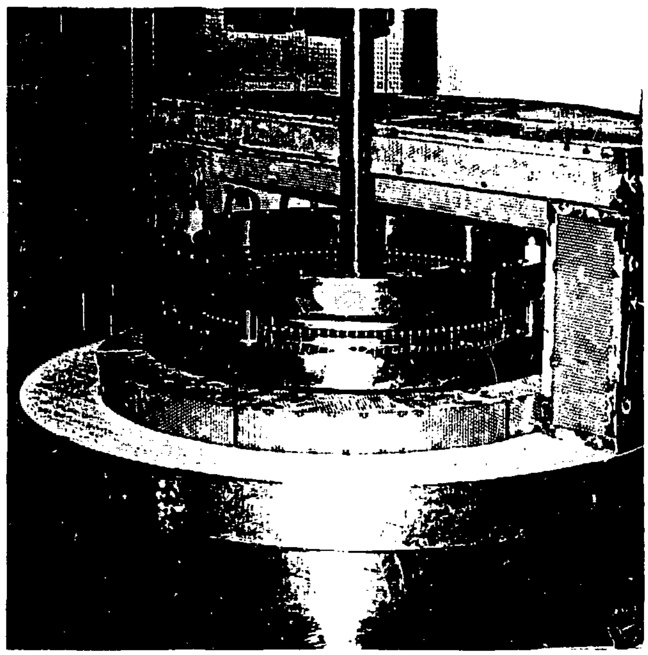

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Fig. 5