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**Elevated-Temperature Benchmark Tests of
Simply Supported Beams and Circular Plates
Subjected to Time-Varying Loadings**

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

J. M. Corum
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ABSTRACT

This report presents the measured elastic-plastic-creep responses of eight simply supported type 304 stainless steel beams and circular plates that were subjected to time-varying loadings at elevated temperature. The tests were performed to provide experimental benchmark problem data suitable for assessing inelastic analysis methods and for validating computer programs. Beams and plates exhibit the essential features of inelastic structural behavior; yet they are relatively simple and the experimental results are generally easy to interpret. The stress fields are largely uniaxial in beams, while multiaxial effects are introduced in plates. The specimens tested were laterally loaded at the center and subjected to either a prescribed load or a center deflection history. The specimens were machined from a common well-characterized heat of material, and all the tests were performed at a temperature of 593°C (1100°F). Test results are presented in terms of the load and center deflection behaviors, which typify the overall structural behavior. Additional deflection data, as well as strain gage results and mechanical properties data for the beam and plate material, are provided in the appendices.

1. INTRODUCTION

Detailed inelastic analyses may be required in the design of high-temperature reactor system components to demonstrate conformance with design codes and standards. Computer programs that employ complex constitutive theories and analysis procedures are used to perform these calculations, and questions of validation and acceptance of the analysis results are thus introduced. An assessment of analysis predictions can best be made by performing benchmark calculations, that is, by solving a number of carefully chosen structural problems for which experimentally determined response data exist.

The U.S. Atomic Energy Commission, predecessor of the Energy Research and Development Administration, recognized the need for experimental benchmark problem data, particularly at elevated temperatures, in 1969. To meet this need, the commission initiated plans for a series of inelastic structural tests on a variety of structural geometries ranging from simple to complex. Initial results from these efforts were presented in Ref. 1. Additional results from beams and plates are presented in this report. Although Ref. 1 discusses typical inelastic analysis predictions and shows some comparisons between theory and experiment, this report includes only experimental data.

Simply supported beams and circular plates loaded at their center are two of the simplest possible types of structural tests for investigating elastic structural behavior. In fact, it is 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 ORNL High-Temperature Structural Design 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 for computer programs.

The test results presented in this report are for a group of eight tests at 593°C (1100°F) that were carefully planned and selected to complement one another. The group consisted of four beam tests and four plate tests with similar load histograms. Two of each type of test were load controlled, while the remaining two 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. Taken together, these tests provide information on some of the essential 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 presented 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 characteristics.

The beams used in this investigation were from 25.4-mm (1-in.) plate product form of type 304 stainless steel, heat 9T2796; the circular plates were from 19-mm (0.75-in.) plate of the same heat. This material, which is being used throughout the ORNL High-Temperature Structural Design Program, is well characterized; the appropriate material properties required as input for inelastic analysis are given in Appendix A. To ensure that the material test data are 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 [1093°C (2000°F) for 30 min] followed by rapid forced-air cooling to room temperature.

The remainder of this report is divided into five major sections. Section 2 describes the beam and plate test specimens and presents the loading histograms and test parameters for the eight tests. The instrumentation used for the specimens is described in Section 3, while the test facilities and test procedures are discussed in Section 4. Finally, representative test results for each of the eight tests are presented in Section 5, and the results are discussed in Section 6.

To simplify the reader's task of assessing and comparing results from eight separate tests, each with several test phases, the results in the report are all in terms of the measured load-center deflection-time responses. For those interested in additional information, deflections at other locations, selected strains, and temperature variation data are given in Appendices B through I.

Appendix A contains a summary of the applicable material property data required as input to conventional elastic-plastic-creep analyses of the beam and plate specimens. The data provided include elastic constants, cyclic stress-strain data, and uniaxial constant-stress creep data for type 304 stainless steel, heat 9T2796, at 593°C (1100°F).

Appendix J presents measured time-dependent drift data for the high-temperature weldable resistance strain gages used in the tests. These data are provided to aid in interpreting and using the strain gage results presented in earlier appendices.

2. PROBLEM DESCRIPTION

The beam and plate specimens are depicted in Fig. 1 along with the dimensions and method of loading and supporting. The beams were each 50.8 mm high, 25.4 mm wide, and 0.66 m long ($2 \times 1 \times 26$ in.) and were simply supported so that the effective length was 0.61 m (24 in.). The center load was applied through 19-mm-diam (0.75-in.) rollers downward (+P) on the top surface or upward (-P) on the bottom surface shown. The simple end supports were through 19-mm-diam (0.75-in.) rollers which passed through the beam on its centerline.

The 12.7-mm-thick (0.50-in.) circular plate specimens had an outside diameter of 0.527 m (20.75 in.) and were simply supported by a line of 12.7-mm-diam (0.50-in.) ball bearings on a 0.508-m-diam (20-in.) 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. The center load was applied through a 50.8-mm-diam (2-in.) boss and loading bar as shown in the figure. A boss of the same dimensions was included on the bottom surface, and a nut and a 50.8-mm-OD (2-in.) washer were used to clamp the plate to a 25.4-mm-diam (1-in.) 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 50.8-mm-diam (2-in.) solid bar, top and bottom, at the center of the plate.

Figure 2 shows the histograms used for the load-controlled and the deflection-controlled tests, and Table 1 delineates the group of four beams and four plates from which the results presented in this report were chosen. The figure numbers and appendix designations in Table 1 show where results for each test are located in the report. Table 2 gives the values of the test parameters shown in Fig. 2. The numbered points shown on the histograms of Fig. 2, which are for reference purposes, are used throughout this report in the presentation of data.

The times (t_1 , t_2 , and t_3) for the hold periods were nominally 312 hr in Fig. 2a and 144 hr in Fig. 2b. As can be seen in Table 2, the actual hold times sometimes differed from these nominal values and the loads

(a) SIMPLY-SUPPORTED BEAM SPECIMEN

(b) SIMPLY-SUPPORTED CIRCULAR PLATE SPECIMEN

Fig. 1. Dimensions of simply supported beam and circular plate test specimens (in. $\times$ 25.4 = mm).

Table 1. Interrelated set of beam and plate tests at 593°C (1100°F)^a

	Test No.	Type of control	Test phase ^b (refer to Fig. 2)				Location of additional results
			Precreeep cycles ^b	Short-time load or deflection changes	Creep or relaxation	Postcreep cycles	
Beams	B9	Load	None	Fig. 11	Fig. 12	Fig. 13	Appendix B
	B10	Load	Fig. 14	Fig. 15	Fig. 16	Fig. 17	Appendix C
	B7	Deflection	None	Fig. 18	Fig. 19	Fig. 20	Appendix D
	B8	Deflection	Fig. 21	Fig. 22	Fig. 23	Fig. 24	Appendix E
Plates	CP5	Load	None	Fig. 25	Fig. 26	Fig. 27	Appendix F
	CP2	Load	Fig. 28	Fig. 29	Fig. 30	Fig. 31	Appendix G
	CP4	Deflection	None	Fig. 32	Fig. 33	Fig. 34	Appendix H
	CP3	Deflection	Fig. 35	Fig. 36	Fig. 37	Fig. 38	Appendix I

^aThe figure numbers identify the center load/center deflection results presented in the body of this report.

^bEach test consisted of four phases, except that beams B9 and B7 and plates CP5 and CP4 were not subjected to precreeep cycling.

Table 2. Parameter values in beam and plate test histograms
(refer to Fig. 2)

	Test No.	Number of precreep cycles	Load [N (lb)]		Deflection, δ [mm (in.)]	Time (hr)			Number of postcreep cycles
			P ₁	P ₂		t ₁	t ₂	t ₃	
Beams	B9	0	8,896 (2000)	10,008 (2250)		312	312	312	10
	B10	10	8,896 (2000)	10,008 (2250)		312	312	312	10
	B7	0			2.54 (0.10)	144	163		10 ^b
	B8	10			2.54 (0.10)	144	144		10 ^b
Plates	CP5	0	17,458 (3925) ^a	21,711 (4881)		313	335	484	10
	CP2	10	17,347 (3900)	21,795 (4900)		312	333	285	10
	CP4	0			2.79 (0.11)	144	144		10
	CP3	10			2.79 (0.11)	144	144		10

^aFor CP5, -P₁ = -17,347 N (-3900 lb).

^bThe ten postcreep deflection cycles in beam B8 were between center deflections of ± 2.79 mm (0.11 in.) rather than ± 2.54 mm (0.10 in.) as intended.

Fig. 2. General form of histograms for load- or deflection-controlled beam and circular plate tests. Refer to Table 2 for parameter values.

in plate test CP5 differed slightly from the intended values, which are those shown for plate test CP2.

All short-time load and deflection changes shown in Fig. 2 were ramp shaped, with the rate based on 2 min per complete load or deflection cycle (30 sec per quarter cycle, such as points 2 to 3). The 2-min/cycle rate corresponds approximately to a maximum strain rate (calculated on an elastic basis) of 0.005/min, which was the standard rate used in obtaining the uniaxial cyclic stress-strain data included in Appendix A.

The loading and deflection histories in Fig. 2 and Tables 1 and 2 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, taken together, the beam B9 and B10 test results provide both elastic-plastic response data and creep response data for a virgin specimen. 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.

3. SPECIMEN INSTRUMENTATION

The instrumentation for measuring displacement, strain, and temperature is shown in Figs. 3 and 4 for the beams and the circular plates, respectively. Each specimen had seven displacement-measuring devices for determining lateral strains, at least four symmetrically located resistance strain gages, and ten thermocouples located on the top and bottom surfaces. The instrumentation numbering system shown in Figs. 3 and 4 is used for all the results presented in this report.

Fig. 3. Schematic of instrumentation used on beam specimens. Only beam B8 had strain gages SG5-SG8 (in. $\times$ 25.4 = mm).

DT: DCDT
 DG: DIAL GAGE
 TC: THERMOCOUPLE
 SG: WELDABLE RESISTANCE
 STRAIN GAGE

NOTE:
 DIMENSIONS IN INCHES

Fig. 4. Schematic of instrumentation used on circular plate specimens. The instrumentation shown is located in the vicinity of a single diametral plane (in. $\times$ 25.4 = mm).

Figure 5 shows a beam specimen partially installed in the test facility. The displacement-measuring devices shown consisted of a quartz rod connected to a standard dial gage, which, in turn, was connected to a direct-current differential transformer (DCDT). Readings from the DCDTs, as well as from the strain gages, thermocouples, and load cell, were recorded on a data acquisition system. The dial gages were read periodically and served as backups for the DCDT data, particularly during periods when the data acquisition system was inoperable. The instrumentation

Fig. 5. Instrumented beam mounted in test facility.

and data acquisition system are described more fully in the following subsections.

3.1 Displacement-Measuring Devices

The DCDTs, Hewlett-Packard model 24, had ranges of 1.27 mm (0.05 in.) for positions 1 and 7 (Figs. 3 and 4); 6.35 mm (0.25 in.) for positions 2, 3, 5, and 6; and 25.4 mm (1.00 in.) for position 4. These devices are dc input-output differential transformers. The output is proportional to the linear displacement. The DCDTs consist of a core which moves axially inside a cylindrical coil assembly. The core is mounted on a small rod which, in this case, was attached to extensions of the dial gage operator shafts using special adapters. These, in turn, were connected to quartz rods which extended to the specimen inside the test furnace.

The four outboard dial gages (positions 1, 2, 6, and 7) were 0.0025-mm (0.0001-in.) gages, while the center three (positions 3, 4, and 5) were 0.025-mm (0.001-in.) gages.

For the beams, the quartz rods were seated in saddles (Fig. 5) which were attached to the midsurface of the beam.* For the plates, the quartz rods were capped with pointed metal tips that rested in small indentations in the top surface. The rods were spring loaded so as to ensure continued contact with the plates.

Prior to each test the DCDTs were calibrated by inserting gage blocks into the linkage described above. In addition to providing a check on the DCDT output, this procedure provided the factors used by the data acquisition system for converting the voltage output into engineering units.

3.2 Strain Gages

The strain gages used for these tests, Ailtech model SG 425, are 120- Ω half-bridge gages with one active gage leg and one zero gage factor temperature-compensating leg. The gage consists of a U-shaped active

*The quartz rods at the end supports bore directly on the top surface of the beam. The center rod (position 4) was attached to the beam on only one side as can be seen in Fig. 5.

leg with a helical dummy leg wrapped around it. Both legs are insulated with MgO powder and contained inside a stainless steel tube. The tube is welded to a flange which is then welded to the specimen surface.

The gages, as purchased, include integral sheathed lead wires. The active gage length is 17.78 mm (0.70 in.), and the maximum strain range is $\pm 0.6\%$. The gage factor, which is a function of temperature, is 4.0 ± 0.5 .

Each gage was conditioned prior to installation to improve high-temperature stability. They were thermally cycled at least three times through the temperature range 427 to 593°C (800 to 1100°F).

Since individual gage calibration could not easily be accomplished due to the nature of the attachment method, a representative gage from each batch was calibrated at room temperature against a foil gage.

In addition to the four or eight active gages used on each specimen, two gages of the same batch were attached to an unstrained block which was attached to the test specimens. These reference gages were monitored for drift throughout each test; representative results are presented in Appendix J.

3.3 Thermocouples

The thermocouples used were sheathed type K Chromel-Alumel, 1.59 mm (0.0625 in.) diam $\times$ 0.61 m (24 in.) long, made to ORNL Instrumentation and Controls Division specifications. All thermocouples were calibrated and certified at 593°C (1100°F) as a minimum, and only those thermocouples that were within the limits of $\pm 1.67^\circ\text{C}$ ($\pm 3^\circ\text{F}$) at 593°C were utilized. In service, all thermocouples were referenced to a temperature of 65.6°C (150°F) through a reference junction box.

3.4 Data Acquisition System

A Datum system with a PDP-8 computer was used for data acquisition. The system had the capability of scanning all the data points 200 times per second, averaging each point, and placing these averages on magnetic tape at a rate of one full data record per second. The actual rates used were varied as required.

4. EXPERIMENTAL FACILITIES AND TEST PROCEDURE

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 facilities are essentially identical.

4.1 Beam Facility

4.1.1 General

The beam facility is shown schematically in Fig. 6, and a photograph of the facility is shown in Fig. 7. The outline of the simply supported,

Fig. 6. Schematic drawing of elevated-temperature beam test facility ($1200^{\circ}\text{F} = 649^{\circ}\text{C}$).

Fig. 7. Elevated-temperature beam test facility.

center-loaded beam specimen can be seen inside the furnace in Fig. 6, and in Fig. 7 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 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. 7) 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 that operates in the horizontal position is attached to it. A servocontrolled hydraulic system with an MTS controller and a Data-Trak programmer are used to activate the hydraulic ram.

The motor-driven camera setup in Fig. 7 was used to record data, again as a backup, during short-time load or deflection changes. By positioning precision voltmeters for load and strain display and a timer on top of the furnace, load, deflections, strains, and time could all be recorded simultaneously by the camera, which is capable of photographing at a rate of up to four frames per second.

4.1.2 Beam support system

The beam support system is shown in Fig. 8. The Hastelloy B dowel pins through each end of the beam were supported in 31.75-mm-long (1.25-in.) slots in the 50.8-mm-diam (2-in.) support posts. To avoid problems of self-welding during the long-term, high-temperature tests, the end post slots were faced with thin Stellite inserts, top and bottom, which contacted the beam support dowels.

The center load P was applied through Hastelloy B dowels mounted within the center loading arm. Alignment of this loading arm was maintained by an extension guide rod which passed through a cylindrical bushing in the reaction surface of the loading frame below the beam.

PHOTO 4037 74

Fig. 8. Beam specimen in partially assembled oven.

4.1.3 Load cells

Appropriately sized dual-bridge load cells (BLH U3G2) were used for all the tests. The dual bridge permitted dedication of one bridge to the data acquisition system and the other to the MTS control system for control, chart recording, and digital readout. Each load cell was periodically calibrated at a standards laboratory and then rechecked prior to each test using a mV/V calibrator.

4.1.4 Deadweight loading system

During constant-load creep periods the servocontrolled ram was disconnected at the bell crank and the deadweight system was utilized. The bell crank (see Fig. 6) provided a 4:1 mechanical advantage and was connected by cables to the creep loading arms mounted at each side of the frame. The overall arrangement (bell crank and loading arms) provided a 20:1 mechanical advantage. The deadweight was provided by lead-filled containers attached to the creep loading arms. These containers were always preloaded to the appropriate load to provide a smooth transition from ram to deadweight loading.

As in all mechanical systems, small friction forces were present and potentially troublesome. Without the pneumatic load trimmer shown in Figs. 6 and 7, the load would tend to drop slightly during the creep periods with intermittent abrupt step recoveries. The trimmer was controlled by the load cell output through a current-to-air proportional converter. Deviations from the load were sensed by a Foxboro pneumatic controller which supplied sufficient force to the load arm to maintain the applied load within the preset limits of $\pm 1\%$ of the specified value.

4.1.5 Hydraulic loading system

Oil pressure to the hydraulic loading system was supplied from a 600 series Denison hydraulic pump with a variable-volume cylinder control. At one-fourth volume flow, the pump was capable of supplying 10.2 liter/min (2.7 gpm) at 6.895 MPa (1000 psi) to the servovalve. The output from the pump was constant, and flow to the hydraulic ram was controlled by the closed-loop servocontrol system from an MTS 442 controller.

The planned load or deflection program was inscribed on a Data-Trak chart. The Data-Trak applied a signal to the MTS controller, which controlled the oil flow through the servovalve. The controller employed several safety devices — overpressure protection, out-of-limits protection, etc. — that automatically closed high-pressure solenoid valves located in the entrance and exit lines to the servovalve, thus producing an instantaneous stop-action situation.

4.1.6 Furnace

The beam facility furnace, shown partially assembled in Figs. 7 and 8, was designed to permit simple assembly and disassembly over an extended period of time. It consisted of light stainless steel frame sections filled with 127 mm (5 in.) of high-temperature insulation and lined on the inside with perforated metal. Resistance heaters (270 V) attached to the four inside wall sections provided up to 8 kW of heat. Less than 2 kW was required to maintain a test specimen at 593°C (1100°F), thus greatly extending the life of the heaters.

The heaters were wired to permit three-zone control. The main heaters along the length of the beam made up one zone, while guard heaters at each end of the beam made up the other two. The main heaters were controlled by a Honeywell pneumatic temperature controller, with the total power limited by a hand-set Variac. Hand-set Variacs were used to control the two end zones.

4.2 Circular Plate Test Facility

As previously mentioned, the plate facility differs from the beam facility only in the details of the specimen support system and the furnace design. The plate facility is shown in Fig. 9; the load/deflection controller is on the left of the loading frame and the temperature controller is on the right.

Figure 10 shows a plate specimen mounted in the partially assembled furnace with the races of stainless steel ball bearings showing on the top and bottom surfaces. A slight vertical gap was maintained in the race supports to prevent binding of the plate as it deflected.

Fig. 9. Elevated-temperature circular plate test facility.

PHOTO 3295-77

Fig. 10. Circular plate specimen in partially assembled oven.

The resistance heaters for the plate were located in a serpentine manner around the periphery of the plate and in a plane configuration below it. These heaters were controlled as a single zone. No additional guard heaters were required.

4.3 Test Procedure

The test procedure for both beam and plate tests consisted in heating the unloaded specimen to 593°C (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 indicated temperatures at $593 \pm 2.78^{\circ}\text{C}$ ($1100 \pm 5^{\circ}\text{F}$). The actual measured temperature ranges during each of the tests are shown as functions of time in Appendices I through I. As shown there, the temperature variation sometimes exceeded the specified limits by a few degrees, usually for only short periods of time.

The loads and deflections were controlled to $\pm 1\%$ of the nominal values.

5. 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 shown in Tables 1 and 2. Figure 2, the load and deflection histograms, and Tables 1 and 2 should be referred to along with the results given in this section. As previously mentioned, the numbered points in Fig. 2 are referenced on each of the graphical presentations of the test data.

5.1 Load-Controlled Beam Tests

Beams B9 and B10 were companion load-controlled tests. The only difference between the two is that beam B10 was subjected to ten precreep load cycles and beam B9 was not.

The measured center deflection vs load for the initial loading of beam B9 to 8896 N (2000 lb), as well as for the other load changes associated with the creep portions of the test, is shown in Fig. 11. The creep

Fig. 11. Load vs center deflection for short-time load changes associated with creep portions of beam B9 test ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

deflections that occurred at 8896, 10,008, and -8896 N (2000, 2250, and -2000 lb) have been subtracted so that the deflections shown are essentially elastic-plastic. Referring to Fig. 2a, the curves in Fig. 11 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. 11, as they are on all of the figures in this section. Figure 12, a companion plot to Fig. 11, shows the creep deflection at the center of beam B9 as a function of time. Figure 13 depicts the load vs center deflection behavior during the final ten short-time load cycles (points 9 to 10 in Fig. 2a) of beam B9. For clarity, only the first, second, and tenth cycle responses are shown, and these are labeled by the circled numbers; the uncircled numbers always refer to points on the histogram.

The load-deflection behavior for the initial ten short-time load cycles of beam B10 is depicted in Fig. 14. Figures 15 and 16 for beam B10 are analogous to Figs. 11 and 12 for beam B9; they depict the short-time load-deflection response and the creep-deflection response, respectively, during the long-term portions of the test. Figure 17, which shows the postcreep load-cycling response of beam B10, is comparable to Fig. 13 for beam B9.

Additional results for beams B9 and B10 are given in Appendices B and C, respectively. All the measured deflections and strains for B9 are

Fig. 12. Creep deflection vs time for center of beam B9 (in. $\times$ 25.4 = mm).

BEAM B9

Fig. 13. Load vs center deflection during ten short-time, postcreep load cycles of beam B9. The measured deflection was zeroed at point 9 for this plot ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. 14. Load vs center deflection during ten short-time, precreep load cycles of beam B10 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 15. Load vs center deflection for short-time load changes associated with creep portions of beam B10. The measured deflection was zeroed at point 2 for this plot ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 16. Creep deflection vs time for center of beam B10 (in. $\times$ 25.4 = mm).

Fig. 17. Load vs center deflection during ten short-time, postcreep load cycles of beam B10 (lb $\times$ 4.448 = N, in. $\times$ 25.4 = mm).

presented for the entire test history. The measured strains are presented for beam B10.

5.2 Deflection-Controlled Beam Tests

Beams B7 and B8 were companion deflection-controlled tests, with B8 having the ten short-time precreep deflection cycles.

Figure 18 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 2.54 mm (0.10 in.) is shown by the curve from 2 to 3 (refer to Fig. 2b). The load decrease at a deflection of 2.54 mm (0.10 in.) (points 3 to 4) corresponds to the initial relaxation period. Figure 19 shows the load vs time response for the two relaxation hold periods, and Fig. 20 depicts the response during the ten short-time postcreep deflection cycles.

The precreep cyclic deflection response of beam B8 is shown in Fig. 21. Figures 22 to 24 for beam B8 correspond to Figs. 18 to 20 for beam B7. Comparisons of the corresponding figures show that the prior cycling in beam B8 resulted in higher loads at the beginning of each relaxation

Fig. 18 Load vs center deflection changes associated with relaxation portions of beam B7 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. 19. Load relaxation vs time for beam B7 ($1b \times 4.448 = N$).

Fig. 20. Load vs center deflection during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. 21. Load vs center deflection during ten short-time, precreep deflection cycles of beam B8 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 22. Load vs center deflection changes associated with relaxation portions of beam B8 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 23. Load relaxation vs time for beam B8 ($1b \times 4.448 = N$).

Fig. 24. Load vs center deflection during ten short-time, postcreep deflection cycles of beam B8 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

period and, consequently, in more relaxation. Note that the deflection range for the postcreep cycles was ± 2.79 mm (0.11 in.) for beam B8 but ± 2.54 mm (0.10 in.) for beam B7.

Additional results for beams B7 and B8 are given in Appendices D and E, respectively. All the measured deflections and strains for beam B7 are presented for the entire test history. Deflection and strain responses during the ten precreep cycles are given for beam B8, as is the strain response during the ten postcreep deflection cycles.

5.3 Load-Controlled Plate Tests

Circular plates CP5 and CP2 were companion load-controlled tests akin to load-controlled beam tests B9 and B10. Like the beam tests, the only difference between the two plate tests was that plate CP2 was subjected to ten precreep load cycles while plate CP5 was not.

The measured load vs center deflection response of plate CP5 is shown in Fig. 25 for the load changes associated with the creep portions of the test. Figure 26 shows the creep deflection at the center of plate CP5 as a function of time, and Fig. 27 depicts the load vs center deflection behavior during the final ten short-time load cycles.

The load-deflection behavior for the initial ten short-time load cycles of plate CP2 is depicted in Fig. 28. Again, comparison of this figure with the previous figure for the postcreep cyclic response of plate CP5 illustrates the hardening effect of the previous inelastic history in the case of CP5.

Figures 29 and 30 for plate CP2 are analogous to Figs. 25 and 26 for plate CP5; they depict the short-time load-deflection response and the creep-deflection response, respectively, during the long-term portions of the test. Finally, Fig. 31 shows the postcreep load cycling response of plate CP2.

Additional results for plates CP5 and CP2 can be found in Appendices F and G, respectively. All the measured deflections and strains for plate CP5 are presented for the entire test history. The measured strains during the precreep and postcreep load cycles are presented for plate CP2.

Fig. 25. Load vs center deflection for short-time load changes associated with creep portions of plate CP5 (1b $\times$ 4.448 = N, in. $\times$ 25.4 = mm).

Fig. 26. Creep deflection vs time for center of plate CP5 (in. $\times$ 25.4 = mm).

Fig. 27. Load vs center deflection during ten short-time, postcreep load cycles of plate CP5. The measured deflection was zeroed at point 9 for this plot ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. 28. Load vs center deflection during ten short-time, precreep load cycles of plate CP2 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. 29. Load vs center deflection for short-time load changes associated with creep portions of plate CP2. The measured deflection was zeroed at point 2 for this plot ($1b \times 4.448 = N$, $in. \times 2.54 = mm$).

Fig. 30. Creep deflection vs time for center of plate CP2 ($in. \times 25.4 = mm$).

Fig. 31. Load vs center deflection during ten short-time, postcreep load cycles of plate CP2. The measured deflection was zeroed at point 9 for this plot ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

5.4 Deflection-Controlled Plate Tests

Plates CP4 and CP3 were companion deflection-controlled tests, with CP3 having the ten short-time precreep deflection cycles. These tests were akin to the beam B7 and B8 tests, which were also deflection controlled.

The load vs center deflection response of plate CP4 during the deflection changes associated with the relaxation portions of the test are shown in Fig. 32. Figure 33 shows the load vs time response for the two relaxation hold periods, while Fig. 34 depicts the response during the ten short-time postcreep deflection cycles.

The precreep cyclic deflection response of plate CP3 is shown in Fig. 35. Figures 36 to 38 correspond to Figs. 32 to 34 for plate CP4.

Fig. 32. Load vs center deflection changes associated with relaxation portions of plate CP4 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. 33. Load relaxation vs time for plate CP4 ($1b \times 4.448 = N$).

Fig. 34. Load vs center deflection during ten short-time, postcreep deflection cycles of plate CP4 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 35. Load vs center deflection during ten short-time, precreep deflection cycles of plate CP3 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. 36. Load vs center deflection changes associated with relaxation portions of plate CP3 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. 37. Load relaxation vs time for plate CP3 ($1b \times 4.448 = N$).

Fig. 38. Load vs center deflection during ten short-time, postcreep deflection cycles of plate CP3 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Additional results for plate CP4 are given in Appendix H, along with additional load deflection data and strain gage data for the entire load history. Appendix I, for plate CP3, contains only the measured specimen temperature data for the test.

6. DISCUSSION OF RESULTS

High-temperature test results have been presented for eight beam and plate tests that were carefully planned and selected to complement one another. The results exemplify the basic features of elastic-plastic and creep behaviors for relatively complex load histories. Because of this, and because beams and plates are relatively simple, the results should be ideally suited for benchmark problem calculations.

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. 11, 15, 25, and 29, 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. 11 specifically; the load change from 8896 to 10,008 N (2000 to 2250 lb) (points 4 to 5) after the first creep period initially results in a near-elastic response even though considerable plastic deformation had occurred during the initial load application to 8896 N. This apparent hardening may be due in small part to some stress redistribution that takes place during the creep period, but it is more directly the result of hardening due to prior creep.*

Figure 14, 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. 21, which shows the initial cyclic response of beam B8 to a cyclic deflection, and in Figs. 28 and 35 for plates CP2 and CP3, respectively.

It is of interest to compare the initial cyclic response of beam B10 (Fig. 14) with the cyclic response of beam B9 to the ten postcreep load cycles shown in Fig. 14. In the latter case the loop width (at zero load)

*This basic feature of the inelastic behavior of type 304 stainless steel is described in Ref. 2 on the basis of uniaxial tests. It also is illustrated in Appendix A of this report.

for the first cycle was about 0.660 mm (0.026 in.) and about 0.305 mm (0.012 in.) for the tenth cycle. These are considerably less than the loop widths in Fig. 14 and further illustrate the hardening effects of prior inelastic deformation.

A comparison of the creep responses of beams B9 and B10 in Figs. 12 and 16, respectively, seems 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.

One final structural response feature can be identified by comparing Figs. 11 and 25, which are for beam B9 and plate CP5, respectively. Relative to the beam, the plate remains stiff after initial yielding. In fact, the plastic deflection is 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 load-carrying mechanism in the plates.

It is believed that the test results presented in this report 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; the creep response was about 25% less. These discrepancies are reasonably representative of the normal variations to be expected from test to test.

One final and important point should be made relative to the interpretation of inelastic benchmark calculation results. The correlation of analytical predictions with experimental results for inelastic problems is by no means a straightforward procedure. Unlike the elastic case, where exact agreement can theoretically be expected and strived for, there will always be differences between predicted and measured inelastic structural behavior. This is because carefully controlled high-temperature tests are difficult to perform, accurate measurements are difficult to make, and inelastic material behavior is a highly complex phenomenon consisting of processes and interactions that defy complete understanding and exact description. There can be considerable variation in behavior

from specimen to specimen, and the constitutive equations that are likely to be used represent only first approximations to the descriptions of inelastic behavior. Thus, rather than exact quantitative predictions, inelastic analyses qualitatively predict the basic characteristics or the essential features of inelastic response.

ACKNOWLEDGMENTS

The authors wish to acknowledge with appreciation the contributions of several individuals at Oak Ridge National Laboratory to the effort described herein. T. G. Hill and S. J. Claiborne instrumented the specimens and helped to perform the tests; T. M. Cate assisted with the instrumentation and controls; and D. T. Godwin was responsible for converting the recorded test data to usable figures.

REFERENCES

1. *Pressure Vessels and Piping: Verification and Qualification of Inelastic Analysis Computer Programs*, American Society of Mechanical Engineers, G00088, 1975.
2. J. M. Corum et al., *Interim Guidelines for Detailed Inelastic Analysis of High-Temperature Reactor System Components*, ORNL-5014 (December 1974).

APPENDICES

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APPENDIX A. MECHANICAL PROPERTIES DATA
FOR ELASTIC-PLASTIC-CREEP ANALYSES

This appendix contains a summary of the applicable material property data required as input to conventional elastic-plastic-creep analyses of the experimental benchmark problems described in this report. The data provided include elastic constants, cyclic stress-strain information, and uniaxial constant-stress creep data, all for a temperature of 593°C (1100°F).

Introduction

All the beam and plate specimens described in this report were machined from plate product forms of a single heat of type 304 stainless steel. This heat, which is designated as 9T2796, was purchased in several product forms for use in the ORNL program to develop high-temperature structural design methods and in various mechanical property testing programs as well. Table A.1 gives the vendor chemistry obtained on the two plate thicknesses from which the structural models were obtained along with the applicable RDT or ASTM standard. To assure a uniformity and consistency of material response in the various test efforts, all material and structural test specimens were fully annealed prior to testing.*

Characterization tests have shown that the mechanical properties of the product forms in the fully annealed condition are very similar.¹ Thus, although some of the data presented in this appendix were obtained from tests using 19.1-mm (0.75-in.) plate product form and others from tests using 25.4-mm (1-in.) plate product form, they are applicable to either.

*Each product form of heat 9T2796 was annealed at the mill. However, straightening operations after annealing often induce additional work hardening and necessitate a reanneal, or laboratory anneal, for consistency. The reannealing consisted in heating to 1093°C (2000°F) for 30 min, followed by rapid cooling to room temperature.

Table A.1. Vendor chemistry^a obtained on plate product forms
of type 304 stainless steel heat 9T2796 from which
beam and plate specimens were obtained

Structural specimens	Specification	Thickness [mm (in.)]	C	Mn	P	S	Si	Ni	Cr	Mo	N
Plates	RDT M5-1T (A240)	19.1 (3/4)	0.051	1.23	0.027	0.017	0.48	9.68	18.52	0.33	NA ^b
Beams	RDT M5-1T (A240)	25.4 (1)	0.048	1.28	0.030	0.016	0.48	9.72	18.44	0.32	NA ^b

^aWeight percent.

^bNA = not available.

Stress-Strain Data

The elastic constants for type 304 stainless steel at the temperature of interest [593°C (1100°F)] are Young's modulus² (E), 149.6×10^3 MPa (21.7×10^6 psi), and Poisson's ratio,³ 0.31.

To analyze the beam and plate specimens, cyclic stress-strain data are required. Figure A.1 shows a representative cyclic curve at 593°C for a total strain range of 0.4% and a strain rate of 0.005/min. The maximum strain of 0.2% is reasonably representative of the elastic-plastic strains reached in the beam and plate tests.

Bilinear representations of cyclic curves are usually used in cyclic inelastic analyses; thus, bilinear representations of the cyclic curve in Fig. A.1 were determined according to the recommendations of Ref. 4. These bilinear representations are illustrated on the original nonlinear curve. Note that the slope E_p of the elastic-plastic portions of the bilinear representations is 4619.7 MPa (0.67×10^6 psi) for each cycle.

Reference 4 suggests two procedures for approximately accounting for cyclic hardening in an analysis. In each, kinematic hardening relations are used, but the size of the yield surface, or loading surface, is increased during the course of plastic flow to account for the hardening. The procedures are:

1. For the initial plastic loading of each element of the structure, the bilinear representation of the initial monotonic curve is used, and for the first reversed loading and all subsequent loadings, the bilinear representation of the tenth cycle is used. The appropriate strain range curve is chosen on the basis of the plastic strains expected in the component being analyzed.

2. As an alternative to the single jump from the monotonic initial loading stress-strain curve to the tenth-cycle curve, a gradual change may be used. The analyst may have sufficient data to adequately approximate the bilinear yield stress as a function of accumulated plastic strain. The yield stress at each load step in a given element of the structure may then be based on the actual accumulated plastic strain at that point. This procedure retains the kinematic hardening relations and the bilinear stress-strain representations but avoids the abrupt change

in hardening that is associated with the switch from the initial curve to the tenth-cycle curve.

The information necessary to employ either of the above alternatives is presented in Fig. A.2, which shows the bilinear yield stresses determined from Fig. A.1 (and similar results at other temperatures) as a function of accumulated plastic strain (summed without regard to sign). The inset in Fig. A.2 illustrates how the yields were determined, and the numbered tick marks on the curves identify the yield point for each reversal.

Recent studies at ORNL have shown that bilinear yield stress correlates well with prior inelastic work. This represents another option, or procedure, for gradually changing the yield stress during the course of an inelastic analysis. Figure A.3 shows the correlation at 595°C (1100°F). In this figure, the yield parameter κ is used, where κ is related to the yield stress σ by $\sigma = \sqrt{3}\kappa$. Data points are shown for cyclic stress-strain tests at total strain ranges of 0.4, 0.6, and 1.0%. Data from precrept specimens are also shown, suggesting that total prior inelastic work (accumulated during creep and plastic deformations) can be used to establish the current yield stress. This procedure thus takes some account of the effects of prior creep on subsequent elastic-plastic hardening.

Hopefully, the data given in Figs. A.1 through A.3 will be sufficient not only for the analyst to apply any one of the procedures outlined above, but also for the application and evaluation of other constitutive relations and procedures.

Creep Data

To perform a time-dependent elevated-temperature structural analysis, the analyst must have a description of the uniaxial constant-stress creep response of the material at the temperature(s) of interest. This description is derived from the usual uniaxial creep curves and may take the form of a mathematical relation (creep law) or simply tabular data describing the curves. Since the relatively simple creep laws developed to represent the uniaxial constant-stress creep test data never exactly fit the data over the entire stress and time range of interest, an error is introduced into the resulting creep analysis predictions. Although this error is usually small and of little consequence in design-type analyses, it

does introduce an undesirable uncertainty into comparisons of predictions and structural test results, and more basic sources of error may thereby be masked.

To eliminate the uncertainty associated with using a specific creep law, a tabular creep data matrix was developed and is given in Table A.2. This matrix is based on approximately 30 creep tests at 593°C (1100°F), with stress values ranging from 51.7 to 275.8 MPa (7.5 to 40 ksi). The tabular values, which were obtained by a repeated process of smoothing and cross-plotting the test results, appear to be a good representation of the creep behavior of type 304 stainless steel heat 9T2796 at 593°C. The uniaxial creep curves described by the data matrix in Table A.2 are shown in Figs. A.4a and b. The dashed lines in Fig. A.4a represent straight-line extrapolations beyond the last entries in Table A.2.

The analyst may either use the tabulated creep values directly or a creep law based on the tabulated data may be developed and used.

Acknowledgment

The cyclic stress-strain representations given in this appendix are based on test data obtained by R. W. Swindeman of ORNL and C. E. Jaske of Battelle-Columbus Laboratories. The tabular creep data are based on test data obtained by Swindeman. The authors gratefully acknowledge the contribution of these individuals.

References

1. R. W. Swindeman et al., *Product Form Characterization of Type 304 Stainless Steel (Ht 9T2796)*, ORNL-5222 (February 1977).
2. Code Case 1592, *Interpretations of ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, New York, 1974.
3. *Nuclear Systems Materials Handbook*, Vol. 1, Section 2, "304 SS Annealed," Property Code 2110 (3-15-71), published by HEDL, TID-26666.
4. J. M. Corum et al., *Interim Guidelines for Detailed Inelastic Analysis of High-Temperature Reactor System Components*, ORNL-5014 (December 1974).

Table A.2. Uniaxial creep strain (%) matrix for type 304 stainless steel (heat 9T2796) at 593°C (1100°F)

Stress ² (1000 psi)	Time (hr)										
	1	2	5	10	20	50	100	200	500	1000	2000
1	0.00006	0.00010	0.00022	0.00040	0.00060	0.00067	0.00078	0.00098	0.00150	0.00200	0.00250
2	0.00018	0.00032	0.00065	0.00100	0.00140	0.00170	0.00210	0.00270	0.00400	0.00470	0.00550
3	0.00036	0.00070	0.00120	0.00182	0.00250	0.00300	0.00355	0.00450	0.00700	0.00830	0.01000
4	0.00060	0.00115	0.00187	0.00280	0.00400	0.00475	0.00575	0.00750	0.01000	0.01250	0.01500
5	0.00095	0.00173	0.00275	0.00410	0.00570	0.00700	0.00830	0.01010	0.01500	0.01870	0.02250
6	0.00110	0.00250	0.00400	0.00575	0.00775	0.00980	0.01200	0.01600	0.02220	0.02750	0.03200
7	0.00210	0.00355	0.00550	0.00800	0.01070	0.01375	0.01700	0.02250	0.03100	0.03800	0.04700
8	0.00290	0.00485	0.00765	0.01070	0.01450	0.01950	0.02400	0.03100	0.04300	0.05300	0.06800
9	0.00400	0.00650	0.01000	0.01400	0.01900	0.02650	0.03300	0.04350	0.06000	0.07500	0.10100
10	0.00515	0.00830	0.01300	0.01815	0.02400	0.03600	0.04700	0.06000	0.08300	0.10700	0.14000
11	0.00650	0.01035	0.01650	0.02300	0.03150	0.04900	0.06500	0.08500	0.12000	0.15300	0.19500
12	0.00750	0.01240	0.02000	0.02900	0.04200	0.06500	0.08900	0.11500	0.16500	0.21000	0.27000
13	0.00910	0.01475	0.02450	0.03600	0.05400	0.08500	0.11700	0.15500	0.22000	0.28500	0.37200
14	0.01150	0.01720	0.02800	0.04200	0.06750	0.10750	0.15200	0.20250	0.29500	0.38000	0.49400
15	0.01355	0.01965	0.03350	0.05300	0.08500	0.13350	0.19100	0.25950	0.38000	0.49300	0.62500
16	0.01515	0.02220	0.03800	0.06100	0.10300	0.16500	0.24700	0.32250	0.48000	0.62750	0.80000
17	0.01700	0.02450	0.04500	0.07200	0.11600	0.20250	0.29800	0.39400	0.60000	0.80000	1.04500
18	0.02500	0.03500	0.05600	0.08600	0.14000	0.24000	0.35500	0.51000	0.77500	1.05000	1.40000
19	0.02800	0.04200	0.08000	0.12500	0.19000	0.30000	0.45000	0.65000	0.99000	1.40000	2.00000
20	0.03300	0.05000	0.09500	0.16000	0.24000	0.38500	0.57500	0.82000	1.27500	1.95000	2.70000
21	0.03600	0.06000	0.12200	0.20000	0.31000	0.49000	0.71000	1.02500	1.67500	2.70000	
22	0.04000	0.07700	0.15500	0.25000	0.39000	0.62000	0.88500	1.31000	2.25000		
23	0.05000	0.09500	0.19500	0.31000	0.48000	0.77500	1.11000	1.68500	3.00000		
24	0.06500	0.12000	0.23500	0.38000	0.60000	0.95500	1.40000	2.17500			
25	0.08000	0.15000	0.29000	0.47000	0.72500	1.20000	1.77500	2.80000			
26	0.09500	0.17700	0.35000	0.57500	0.90000	1.51000	2.25000	3.50000			
27	0.11500	0.22000	0.42300	0.70000	1.10000	1.90000	2.80000				
28	0.14500	0.26000	0.50000	0.85000	1.35500	2.34000					
29	0.18000	0.32500	0.61500	1.03500	1.68000	2.87500					
30	0.22500	0.40000	0.77000	1.25500	2.07500	3.42500					
31	0.28000	0.50500	0.98000	1.54500	2.55000						
32	0.35000	0.63200	1.25000	1.90000	3.06500						
33	0.43500	0.80000	1.57500	2.31000							
34	0.53500	0.98000	1.92500	2.80000							
35	0.65500	1.21500	2.31000	3.32500							

2,1000 psi = 6.895 MPa.

HEAT 9T2796, TYPE 304
STAINLESS STEEL, C.005/min

Fig. A.1. Cyclic stress-strain curve for annealed type 304 stainless steel, heat 9T2796, at 593°C (1100°F) — 0.4% total strain range (1000 psi $\times$ 6.895 = MPa).

Fig. A.2. Bilinear yield stress vs accumulated plastic strain for annealed type 304 stainless steel, heat 9T2796, at various temperatures [1000 psi $\times$ 6.895 = MPa, ($^{\circ}\text{F} - 32$) $\times$ 0.5556 = $^{\circ}\text{C}$].

Fig. A.3. Yield parameter ratio κ/κ_0 vs accumulated inelastic work for annealed type 304 stainless steel, heat 9T2796, at 593°C (1100°F). Data are from cyclic stress-strain tests of virgin specimens and stress-strain tests of precrept specimens (in.-lb/in.³ $\times$ 6895 = J/m³).

Fig. A.4. Predicted uniaxial constant-stress creep response of type 304 stainless steel, heat 9T2796, at 593°C (1100°F) based on tabulated creep data matrix (Table A.1) (ksi $\times$ 6.895 = MPa).

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APPENDIX B. ADDITIONAL TEST RESULTS FOR BEAM B9

Beam B9 was a load-controlled test without precreep cycles. Figure B.1 depicts the range of temperatures during the test as indicated at discrete times by the ten thermocouples whose locations are depicted in Fig. 3. These thermocouples were located over the middle 406 mm (16 in.) of the beam. As can be seen, the goal of maintaining the indicated temperature at $593 \pm 2.78^{\circ}\text{C}$ ($1100 \pm 5^{\circ}\text{F}$) was closely approached for most of the test.

Figures B.2 through B.4 show additional load vs deflection and load vs strain data* for the load changes associated with the creep portions of the test. The creep deflections and strains have been subtracted out in these figures.

Figures B.5 through B.7 show the corresponding deflection vs time and strain vs time data, and Figs. B.8 through B.15 depict the load vs deflection and load vs strain results for the postcreep cycles.**

*Refer to Fig. 3 for locations of the deflections and strains. The gage numbers are shown circled on the figures.

**In the figures for the postcreep cycles, the circled numbers refer to the cycle. Results are shown for the first, second, and tenth cycles.

Fig. B.1. Measured temperature range over middle 406 mm (16 in.) of beam B9 during 593°C (1100°F) test [$\text{lb} \times 4.448 = \text{N}$, $(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}$].

Fig. B.2. Load vs deflection (DT3 and DT5) for short-time load changes associated with creep portions of beam B9 test ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. B.3. Load vs deflection (DT2 and DT6) for short-time load changes associated with creep portions of beam B9 test ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. B.4. Load vs strain (SG1-SG4) for short-time load changes associated with creep portions of beam B9 test. Note that the signs of SG1 and SG3 have been changed ($1b \times 4.448 = N$).

Fig. B.5. Creep deflections (DT3 and DT5) vs time for beam B9 (in. $\times$ 25.4 = mm).

Fig. B.6. Creep deflections (DT2 and DT6) vs time for beam B9 (in. $\times$ 25.4 = mm).

Fig. B.7. Creep strains (SG1-SG4) vs time for beam B9. Note that the signs of SG1 and SG3 have been changed.

Fig. B.8. Load vs deflection (DT2) during ten short-time, postcreep load cycles of beam B9. The measured deflection was zeroed at point 9 for this plot ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. B.9. Load vs deflection (DT3) during ten short-time, postcreep load cycles of beam B9. The measured deflection was zeroed at point 9 for this plot ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. B.10. Load vs deflection (DTS) during ten short-time, post-creep load cycles of beam B9. The measured deflection was zeroed at point 9 for this plot ($1\text{b} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

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Fig. B.11. Load vs deflection (DT6) during ten short-time, post-creep load cycles of beam B9. The measured deflection was zeroed at point 9 for this plot ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. B.12. Load vs strain (SG1) during ten short-time, postcreep load cycles of beam B9. The measured strain was zeroed at point 9 for this plot. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. B.13. Load vs strain (SG2) during ten short-time, postcreep load cycles of beam B9. The measured strain was zeroed at point 9 for this plot ($1b \times 4.448 = N$).

Fig. B.14. Load vs strain (SG3) during ten short-time, postcreep load cycles of beam B9. The measured strain was zeroed at point 9 for this plot. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. B.15. Load vs strain (SG4) during ten short-time, postcreep load cycles of beam B9. The measured strain was zeroed at point 9 for this plot ($1b \times 4.448 = N$).

APPENDIX C. ADDITIONAL TEST RESULTS FOR BEAM B10

Beam B10 was a load-controlled test with precreep cycles. Figure C.1 depicts the temperatures measured during the test. As can be seen, the specimen ran at a slightly lower temperature [about 1.1°C (2°F)] than intended. The gaps in the data plots are a result of outages of the high-speed data acquisition system. During these periods, deflection and strain data were recorded by hand and/or on strip-chart recorders.

Figures C.2 through C.10 show the strain gage data obtained during the test. The response of the four gages during the ten precreep cycles is shown in Figs. C.2 through C.5.* Data for the load changes associated with the creep portions of the test are shown in Figs. C.6 and C.7, and the time-dependent data are shown in Fig. C.8.** Finally, postcreep cyclic data are shown in Figs. C.9 and C.10.* Note that the absence of data for a particular gage indicates that the gage failed or began to exhibit obviously erratic behavior.

*The circled numbers in the figures for the precreep and postcreep cycles denote the cycle number.

**The circled numbers in Figs. C.6 through C.8 refer to the strain gage number.

Fig. C.1. Measured temperature range over middle 406 mm (16 in.) of beam B10 during 593°C (1100°F) test [$\text{lb} \times 4.448 = \text{N}$, $(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}$].

Fig. C.2. Load vs strain (SGI) during ten short-time precreep load cycles of beam B10. Note that the sign of the strain has been changed ($1\text{ lb} \times 4.448 = \text{N}$).

Fig. C.3. Load vs strain (SG2) during ten short-time precreep load cycles of beam B10 ($1b \times 4.448 = N$).

Fig. C.4. Load vs strain (SG3) during ten short-time precreep load cycles of beam B10. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. C.5. Load vs strain (SG4) during ten short-time precreep load cycles of beam B10 ($1b \times 4.448 = N$).

Fig. C.6. Load vs strain (SG1 and SG3) for short-time load changes associated with creep portions of beam B10 test. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. C.7. Load vs strain (SG2 and SG4) for short-time load changes associated with creep portions of beam B10 test ($1b \times 4.448 = N$).

Fig. C.8. Creep strains (SG1, SG3, SG4) vs time for beam B10. Note that the signs of SG1 and SG3 have been changed.

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Fig. C.9. Load vs strain (SG3) during ten short-time, postcreep load cycles of beam B10. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. C.10. Load vs strain (SG4) during ten short-time, postcreep load cycles of beam B10 ($1b \times 4.448 = N$).

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APPENDIX D. ADDITIONAL TEST RESULTS FOR BEAM B7

Beam B7 was a deflection-controlled test without precreep cycles. Figure D.1 shows the measured temperature ranges during the test. Generally, the temperatures in this test were within the intended range.

Figures D.2 and D.3 show the load vs deflection response data for the relaxation portions of the test.* Although the center deflection was held constant from points 3 to 4 and 5 to 6, deflections at other locations along the beam were not so restrained. During the load-relaxation periods these latter deflections exhibited small but erratic variations. Rather than trying to interpret and smooth out these variations, we have simply indicated that the true data path cannot be resolved. We are confident, however, that the end points are reasonable.

Figures D.4 and D.5 show the corresponding load vs strain data.* Again, the actual paths during the load-relaxation phases of the test could not be resolved.

Figures D.6 and D.7 depict the deflection vs time and strain vs time responses, respectively, during the load-relaxation period.* Figures D.8 through D.15 depict the load vs deflection and load vs strain response for the postcreep cycles.**

*The circled numbers in Figs. D.2 through D.7 refer to gage numbers.

**The circled numbers in Figs. D.8 through D.15 denote cycle number.

Fig. D.1. Measured temperature range over middle 406 mm (16 in.) of beam B7 during 593°C (1100°F) test $[(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}]$.

Fig. D.2. Load vs deflection (DT3 and DT5) changes associated with relaxation portions of beam B7 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. D.3. Load vs deflection (DT2 and DT6) changes associated with relaxation portions of beam B7 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. D.4. Load vs strain (SG1 and SG3) changes associated with relaxation portions of beam B7. Note that the signs of the strains have been changed ($1b \times 4.448 = N$).

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Fig. D.5. Load vs strain (SG2 and SG4) changes associated with relaxation portions of beam B7. Note that the signs of the strains have been changed ($1b \times 4.448 = N$).

Fig. D.6. Deflection (DT2, DT3, DT5, DT6) vs time for beam B7
(in. $\times$ 25.4 = mm).

Fig. D.7. Strain (SG1-SG3) vs time for beam B7. Note that the signs of the strains have been changed.

Fig. D.8. Load vs deflection (DT2) during ten short-time, postcreep deflection cycles of beam B7 ($1 \text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. D.9. Load vs deflection (DT5) during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. D.10. Load vs deflection (DT5) during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. D.11. Load vs deflection (DT6) during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. D.12. Load vs strain (SG1) during ten short-time, postcreep deflection cycles of beam B7. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. D.13. Load vs strain (SG2) during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$).

Fig. D.14. Load vs strain (SG3) during ten short-time, postcreep deflection cycles of beam B7. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. D.15. Load vs strain (SG4) during ten short-time, postcreep deflection cycles of beam B7 ($1b \times 4.448 = N$).

APPENDIX E. ADDITIONAL TEST RESULTS FOR BEAM B8

Beam B8 was a deflection-controlled test with precreep cycles. The temperature plot for the test is shown in Fig. E.1, where it can be seen that the specimen operated about 2.8°C (5°F) above the intended level during the latter three-fourths of the test.

Load vs deflection data are shown in Figs. E.2 through E.5 for the ten precreep cycles.* Load vs strain data for the precreep cycles are shown in Figs. E.6 through E.13.* Results for all eight gages used on this specimen are shown (see Fig. 3).

Load vs strain data for the ten postcreep cycles are presented in Figs. E.14 through E.19.* Note that gages SG4 and SG8 were inoperative during this end-of-test cycling.

*Circled numbers in Figs. E.2 through E.19 refer to cycle number.

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Fig. E.1. Measured temperature range over middle 406 mm (16 in.) of beam B8 during 593°C (1100°F) test $[(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}]$.

Fig. E.2. Load vs deflection (DT2) during ten short-time, precreep deflection cycles of beam B8 ($1b \times 4.44b = N$, in. $\times 25.4 = \text{mm}$).

Fig. E.3. Load vs deflection (DT3) during ten short-time, precreep deflection cycles of beam B8 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. E.4. Load vs deflection (DTS) during ten short-time, precreep deflection cycles of beam B8 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. E.5. Load vs deflection (DT6) during two short-time, precreep deflection cycles of beam B8 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. E.6. Load vs strain (SGI) during ten short-time, precreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.7. Load vs strain (SG2) during ten short-time, precreep deflection cycles of beam B8 ($1b \times 4.448 = N$).

Fig. E.8. Load vs strain (SG3) during ten short-time, precreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($lb \times 4.448 = N$).

Fig. E.9. Load vs strain (SG4) during ten short-time, precreep deflection cycles of beam B8 ($1b \times 4.448 = N$).

Fig. E.10. Load vs strain (SG5) during ten short-time, precreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.11. Load vs strain (SG6) during ten short-time, precreep deflection cycles of beam B8 ($1b \times 4.448 = N$).

Fig. E.12. Load vs strain (SG7) during ten short-time, precreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1\text{b} \times 4.448 = \text{N}$).

Fig. E.13. Load vs strain (SC8) during ten short-time precreep deflection cycles of beam B8 ($1b \times 4.448 = N$).

Fig. E.14. Load vs strain (SGI) during ten short-time, postcreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.15. Load vs strain (SG2) during ten short-time, postcreep deflection cycles of beam B8 ($\text{lb} \times 4.448 = \text{N}$).

Fig. E.16. Load vs strain (SG3) during ten short-time, postcreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.17. Load vs strain (SGS) during ten short-time, postcreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.18. Load vs strain (SG6) during ten short-time, postcreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. E.19. Load vs strain (SG7) during ten short-time, postcreep deflection cycles of beam B8. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

APPENDIX F. ADDITIONAL TEST RESULTS FOR PLATE CPS

Plate CPS was a load-controlled test without precreep cycles. The measured temperature ranges over the middle 342.9 mm (13.5 in.) of a single diameter of the plate are depicted in Fig. F.1. These temperature ranges were those indicated by ten thermocouples, as shown in Fig. 4. Although the temperature range was adequately small, the mean temperature was about 1.4°C (2.5°F) higher than desired.

Load vs deflection and load vs strain data are shown in Figs. F.2 through F.4 for the short-time load changes associated with the creep portions of the test.* The locations of the deflection and strain measurements were shown in Fig. 4.

The deflection vs time and strain vs time data for the creep portions of the test are shown in Figs. F.5 through F.7.* Finally, the load vs deflection and load vs strain data for the ten postcreep cycles are shown in Figs. F.8 through F.14.** Note that strain gage SG4 was inoperative throughout the test.

*Refer to Fig. 4 for locations of the deflections and strains. Circled numbers in Figs. F.2 through F.7 refer to the gage numbers.

**Circled numbers in Figs. F.8 through F.14 refer to the cycle number.

Fig. F.1. Measured temperature range over middle 338.6 mm (13.33 in.) of instrumented diameter of plate CP5 during 593°C (1100°F) test [$\text{lb} \times 4.448 = \text{N}$, $(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}$].

Fig. F.2. Load vs deflection (DT3 and DT5) for short-time load changes associated with creep portions of plate CP5 test (lb $\times$ 4.448 = N, in. $\times$ 25.4 = mm).

Fig. F.3. Load vs deflection (DT2 and DT6) for short-time load changes associated with creep portions of plate CP5 test (1b $\times$ 4.448 = N, in. $\times$ 25.4 = mm).

Fig. F.4. Load vs strain (SG1-SG3) for short-time load changes associated with creep portions of plate CP5 test. Note that the signs of SG1 and SG3 have been changed ($1b \times 4.448 = N$).

Fig. F.5. Creep deflections (DT3 and DT5) vs time for plate CP5
(in. $\times$ 25.4 = mm).

Fig. F.6. Creep deflections (DT2 and DT6) vs time for plate CP5
(in. $\times$ 25.4 = mm).

Fig. F.7. Creep strains (SG1-SG3) vs time for plate CP5. Note that the signs of SG1 and SG3 have been changed.

Fig. F.8. Load vs deflection (DT2) during ten short-time, postcreep load cycles of plate CP5 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. F.9. Load vs deflection (DT3) during ten short-time, postcreep load cycles of plate CP5 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. F.10. Load vs deflection (DT5) during ten short-time, postcreep load cycles of plate CP5 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. F.11. Load vs deflection (DT6) during ten short-time, postcreep load cycles of plate CP5 ($\text{lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. F.12. Load vs strain (SGI) during ten short-time, postcreep load cycles of plate CP5. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. F.13. Load vs strain (SG2) during ten short-time, postcreep load cycles of plate CP5 ($\text{lb} \times 4.448 = \text{N}$).

Fig. F.14. Load vs strain (SG3) during ten short-time, postcreep load cycles of plate CP5. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

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APPENDIX G. ADDITIONAL TEST RESULTS FOR PLATE CP2

Plate CP2 was a load-controlled test with precreep cycling. The measured temperature ranges for the test are depicted in Fig. G.1, where it can be seen that the desired temperature level and range were closely matched.

Figures G.2 through G.5 depict the measured load vs strain response for the ten precreep load cycles.* Companion plots for the postcreep load cycles are shown in Figs. G.6 through G.8 (gage SG1 was inoperative during the end-of-test cycling).*

*Circled numbers in these figures refer to the cycle number.

Fig. G.1. Measured temperature range over middle 338.6 mm (13.33 in.) of instrumented diameter of plate CP2 during 595°C (1100°F) test [$\text{lb} \times 4.448 = \text{N}$, $(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}$].

Fig. G.3. Load vs strain (SG2) during ten short-time precreep load cycles of plate CP2 ($1\text{b} \times 4.448 = \text{N}$).

Fig. G.4. Load vs strain (SG3) during ten short-time precreep load cycles of plate CP2. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. G.5. Load vs strain (SG4) during ten short-time precreep load cycles of plate CP2 ($1b \times 4.448 = N$).

Fig. G.7. Load vs strain (SG3) during ten short-time, postcreep load cycles of plate CP2. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. G.8. Load vs strain (SC4) during ten short-time, postcreep load cycles of plate CP2 ($1b \times 4.448 = N$).

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APPENDIX H. ADDITIONAL TEST RESULTS FOR PLATE CP4

Plate CP4 was a deflection-controlled test without precreep cycles. The measured temperature ranges for the test are shown in Fig. H.1, where it can be seen that the plate ran about 1.4°C (2.5°F) higher than desired during the first two-thirds of the test.

Load vs deflection and load vs strain data are shown in Figs. H.2 through H.4 for the deflection changes associated with the relaxation portions of the test.* Strain vs time data for the relaxation periods are shown in Fig. H.5.* Load vs deflection and load vs strain data are shown in Figs. H.6 through H.12 for the ten postcreep deflection cycles.**

*Circled numbers in Figs. H.2 through H.5 refer to the gage number.

**Circled numbers in Figs. H.6 through H.12 refer to the cycle number.

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Fig. H.1. Measured temperature range over middle 338.6 mm (13.33 in.) of instrumented diameter of plate CP4 during 593°C (1100°F) test $[(^{\circ}\text{F} - 32) \times 0.5556 = ^{\circ}\text{C}]$.

Fig. II.2. Load vs deflection (DT3 and DT5) changes associated with relaxation portions of plate CP4 ($1\text{b} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. H.3. Load vs deflection (DT2 and DT6) changes associated with relaxation portions of plate CP4 ($1b \times 4.448 = N$, in. $\times 25.4 = \text{mm}$).

Fig. H.4. Load vs strain (SG2-SG4) changes associated with relaxation portions of plate CP4. Note that the sign of the SG3 strain has been changed ($\text{lb} \times 4.448 = \text{N}$).

Fig. H 5. Strain (SG2-SG4) vs time for plate CP4. Note that the sign of the SG3 strain has been changed.

Fig. H.6. Load vs deflection (DT2) during ten short-time, postcreep deflection cycles of plate CP4 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. H.7. Load vs deflection (DT3) during ten short-time, postcreep deflection cycles of plate CP4 ($1b \times 4.44P = N$, in. $\times 25.4 = \text{mm}$).

Fig. H.8. Load vs deflection (DT5) during ten short-time, postcreep deflection cycles of plate CP4 ($1\text{ lb} \times 4.448 = \text{N}$, $\text{in.} \times 25.4 = \text{mm}$).

Fig. H.9. Load vs deflection (DT6) during ten short-time, postcreep deflection cycles of plate CP4 ($1b \times 4.448 = N$, $in. \times 25.4 = mm$).

Fig. H.10. Load vs strain (SG2) during ten short-time, postcreep deflection cycles of plate CP4 ($\text{lb} \times 4.448 = \text{N}$).

Fig. H.11. Load vs strain (SG3) during ten short-time, postcreep deflection cycles of plate CP4. Note that the sign of the strain has been changed ($1b \times 4.448 = N$).

Fig. H.12. Load vs strain (SG4) during ten short-time, postcreep deflection cycles of plate CP4 ($1b \times 4.448 = N$).

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APPENDIX I. ADDITIONAL TEST RESULTS FOR PLATE CP3

Plate CP3 was a deflection-controlled test with precreep deflection cycles. The measured temperature ranges for the test are depicted in Fig. I.1. In this case the temperatures were very closely controlled, well within the goal of $593 \pm 2.78^\circ\text{C}$ ($1100 \pm 5^\circ\text{F}$).

No additional deflection and strain data were processed for this plate test.

Fig. I.1. Measured temperature range over middle 338.6 mm (13.33 in.) of instrumented diameter of plate CP3 during 593°C (1100°F) test $[(^\circ\text{F} - 32) \times 0.5556 = ^\circ\text{C}]$.

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APPENDIX J. TIME-DEPENDENT BEHAVIOR OF AILTECH SG425 STRAIN GAGES AT 593°C (1100°F)

The Ailtech model SG425 weldable resistance strain gages used in the beam and plate tests are rated by the manufacturer as being suitable for short-term static strain measurements at temperatures to 649°C (1200°F). The gages do drift with time at high temperatures, but this drift was minimized in these tests by pretest conditioning of the gages as described in Section 3.2.

In addition to the active gages used on each specimen, two identical gages were mounted in each case on an unstrained block of type 304 stainless steel, and one of these blocks was attached to each of the test specimens. These reference gages were monitored for drift throughout each test; representative results are shown in Fig. J.1 for five of the structural specimens.

Although the observed drift rates are probably less than those reported by the gage manufacturer, they are nevertheless significant relative to the time-dependent strains measured in the beam and plate tests, and they are not consistent from gage to gage. Consequently, we do not believe that the measured time-dependent strains can be reliably adjusted, using these drift data, to obtain quantitative strain information. Qualitatively, however, the measured time-dependent strains are believed to be indicative of the behavioral trends and should serve a useful purpose in that respect.

We believe that the short-time strain data (associated with pre- and postcreep cycling and with load and deflection changes) are essentially unaffected by the slow drift. This belief is supported by the accuracy and consistency of the measured elastic responses throughout each test.

In summary, we believe that the short-time strain gage data are accurate and reliable but that the time-dependent data can be used only in a qualitative sense.

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Fig. J.1. Typical apparent strains from reference gages on unstressed blocks attached to beam and plate specimens.