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DESIGN AND ANALYSIS OF MULTIAXIAL
CREEP TESTS*

by

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Abstract

MASTER

Often in the presentation of material data, not all significant measurements are tabulated, nor are all normal and abnormal fluctuations reported. In this paper a procedure is described for presenting the complete data as obtained from tests of thin-walled tubular creep test specimens. Thereafter, a procedure for processing the data is presented. The processed data is based in part upon results of detailed inelastic finite element analyses performed to determine uniform and constant stress quantities and effective gage lengths.

Because little prior experience exists in the use of fully instrumented internally pressurized cylinder tests to generate multiaxial thermal creep curves, the automated data acquisition and data reduction scheme developed in this test program will be of value to others currently involved in setting up similar testing programs. The data handling system significantly reduces the repetitive work involved in the generation of the material creep data at elevated temperatures. Also, this effort provides a baseline for standardization of the methods of data acquisition and data interpretation and for simplification of data transmittal among organizations.

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INTRODUCTION

This paper describes the procedures, calculations and computer programs developed for handling data in a thermal creep testing project. Tubular specimens, nominally 1.6 in. inside diameter and 1.8 in. outside diameter, fabricated from austenitic stainless steel were tested at constant elevated temperature (1100°F) under constant (and stepped) combined axial and pressure loadings. For these and similar tests the resulting semi-automatic system is useful for data handling.

The organization of the data handling system is illustrated in Figure 1. It begins with a set of laboratory data sheets which are designed to provide a complete and definitive record of the test. The creation and display of these records are described.

Emphasis is placed upon the detailed inelastic finite element analyses of the test specimen which were performed. The actual stress distribution is nonuniform and nonconstant and the actual strain distribution is nonuniform as well as nonconstant under constant loading. Techniques for calculation of the equivalent uniform and constant stress quantities and the equivalent uniform strain quantities are developed and compared with results obtained from detailed inelastic analyses of the tubular specimen. Based upon these quantities, the creep behavior plots of (Block 6 of Figure 1) are obtained. This detailed characterization is essential to the use of the tests to develop an analytical model for multi-axial thermal creep deformation.

The development of an analytical model for creep behavior under constant stress (Block 7 of Figure 1) is discussed. Repeated calculations at this step and at previous processing steps are essential

to obtaining a thorough understanding of the test data and maximum refinement of the creep deformation model. Such repeated processing is greatly facilitated by the data handling system. It is concluded that the analytical procedures for interpretation of the data and the automated system for processing the data are significant end-products of the test program. Further details on the experimental data and data handling system are given in References 1 to 3.

DATA HANDLING SYSTEM

The data handling system was developed as part of the overall program to obtain multiaxial thermal creep data and to create thermal creep deformation models for comparison with corresponding models based upon uniaxial data. Tubular specimens were fabricated from austenitic stainless steel as shown in Figure 2 and were tested at constant elevated temperature under constant combined axial and pressure loadings. Measurements of pressure, axial load, temperature and deformation were recorded during the tests.

The scope of the data handling system developed for this test program extends from acquisition of the data (laboratory data sheets) through storage, retrieval, tabulation, display, reductions and transmittal of the data, as illustrated in Figure 1. The principal reasons for introducing automation into the data handling are to: (1) eliminate errors from manual transfers of data, (2) provide a convenient and permanent record of data, (3) make the data readily accessible to computer programs for data display and reduction, and (4) transmit complete data records among organizations.

Laboratory Data Sheets: - The laboratory data sheets provide for preparation of a complete record of information generated for a tubular specimen creep test. The preparation of the data sheets forms an important link in the chain of events which comprise a successful test. These data sheets are designed for automatic processing for reasons of accuracy and efficiency. The engineering aspects of the laboratory data sheets are discussed in Appendix B.

Two points concerning the data sheets merit emphasis. Firstly, completeness is to be understood to include definitive identification of the test specimen, test machines and instrumentation as well as all measurements and relevant comments on events occurring during the test. For example, in the case of the test specimen, the information identifies such things as the source material, basic material properties, design drawing, fabrication procedure and quality assurance records. This is essential to knowledgeable evaluation of the measured data.

The second point to be emphasized is related to the first point. The data sheets yield records which are easily accessible and useable. This is accomplished by using printed data sheets which are keypunched onto computer cards for further automatic processing. The alternative of manual transcription of complete test records is considered to be unworkable. The alternative of hardware for acquisition and storage of measurements leaves a residual need for recording the auxiliary information required in complete test records.

Experimental Data Presentation: - Working from the completed laboratory data sheets, the complete record of the test information is key-punched onto computer cards. A computer program, DATARED, reads these cards and performs any or all of the options shown in Figure 1 (Block 4, Figure 1) of the program. Records of data obtained from a number of separate tubular specimen tests are accumulated on the same permanent file using the CDC-UPDATE system. Individual records of data are identified using the test identification number. This file of information is the heart of the data handling procedure.

The experimental data can be printed and plotted using options 2 and 3 (Blocks 5 and 6 of Figure 1) of the computer program. Any specified test, or all experimental results, stored in the data file can be printed in a readable format similar to that of the laboratory data sheets discussed previously. In the plotting option (option 3), an effective stress is determined and the strain measurements are converted to components of creep strain from which effective creep strain is calculated. Illustrative plots of pressure error, hoop creep strain and effective creep strain are shown in Figures 3 to 5 for a typical tubular specimen test. The calculation of the effective stress and effective creep strain is discussed in the next section.

A computer program (CREEP FIT) which was developed by ORNL (Reference ⁴), is used to fit the experimental data by a single exponential creep equation (Reference ⁵). The creation and display of the single exponential creep model is accomplished using option 4 (Block 7 of Figure 1). The experimental data points and the derived curve for a typical tubular specimen test are shown in Figure 6.

INTERPRETATION OF EXPERIMENTAL DATA

Loadings: - Development of a creep model requires data obtained under constant applied load and stress conditions. Actual conditions fluctuate during a test. Equivalent constant loadings F_e are readily obtained by averaging the $(N + 1)$ measurements F_i taken at times t_i during the test, i.e.,

$$F_e = \frac{\sum_{i=1}^N (t_{i+1} - t_i) F_i}{\sum_{i=1}^N (t_{i+1} - t_i)} \quad (1)$$

Equivalent constant temperature and pressure values are obtained in this way. Axial load is imposed by deadweight in this test program and does not require averaging. Where more than one measurement of the same quantity is taken at time t_i , the average value is used as F_i in Equation (1).

Effective Stress:- When a tubular specimen test includes pressure loading, the spatial distributions of the stress components and strain components are not uniform. Even for very thin cylinders, the radial stress varies from a value equal to the pressure at the inside surface to a zero value at the outside surface. The circumferential stress also varies significantly through the thickness for the tubular specimens used in this program. Specifically, assuming elastic behavior and pressure loadings, the ratio of circumferential stress at the inside surface to circumferential stress at the outside surface is 1.13. The

effective stress is also higher at the inside surface than at the outside surface for the tubular specimens.

The conceptual significance of the nonuniformity of stress and strain is far reaching. The type of data needed for the derivation of creep behavior models is an effective creep strain history obtained under a constant effective stress. Because a single constant effective stress value does not exist for a tubular specimen test, it is necessary to define a single effective stress value which is 'equivalent' to the actual stress distribution.

A detailed inelastic analysis of a typical tubular specimen test was performed to evaluate the effects of nonuniformity in the stress and strain behavior and to establish equivalent uniform values. Useful equivalent uniform values were established thereby permitting use of the tubular specimen tests for the creation of analytical models of creep behavior. Failure to establish meaningful equivalent uniform values would have limited use of the test data to confirmation of, rather than creation of, creep strain deformation models.

The tubular specimen was idealized as a short length of tube under conditions of generalized plane strain. Typical constant test conditions were applied in the manner of the experimental procedure.

Predictions of inelastic stress and strain history were obtained. The initial load induced plastic strains in the three finite elements nearest the inside surface of the tubular specimen ($r = 0.805$ in., $\bar{\epsilon}_p = 0.0023\%$). The plastic strains increased slightly due to redistribution of stress during the first creep time increment (10 hours) and thereafter remained constant ($r = 0.805$ in., $\bar{\epsilon}_p = 0.0026\%$). No plastic strains were induced during unloading at the end of the test (2000 hours).

Figures 7 through 10 provide a semi-quantitative presentation of the behavior of the tubular specimen during the creep period. Both spatial and temporal variations are indicated. Figure 7 shows the spatial variation of the radial stress from a large compressive value near the inside surface (where the pressure is applied) to a small value near the outside surface. After a short transient period of increasing compressive stress, the radial stress distribution is nonuniform but constant.

Figure 8 shows that the circumferential stress is positive and an order of magnitude larger than the radial stress. The circumferential stress is largest at the inside surface but the spatial range of stress is small compared to the stress level. It is clear that the initial stress range is quickly reduced by decreasing the higher inside values and increasing the lower outside values. The spatial distribution of circumferential stress remains somewhat nonuniform but nearly constant after this initial transient period. Moreover, the average circumferential stress is nearly constant from the outset.

The predicted axial stress behavior shown in Figure 9 is very similar to that of the circumferential stress. However, the axial stress is highest at the outside surface and smallest at the inside surface. The range of the axial stress decreases slowly throughout the 2000 hour test period.

Figure 10 presents the predicted spatial and temporal variations of effective stress. The effective stress is higher on the inside than the outside. The range decreases rapidly in the short initial transient and then increases slowly throughout the test period. This behavior

closely parallels that of the circumferential stress. The average effective stress is nearly constant from the outset.

The principal stress ratio (σ_z/σ_θ) at the inside surface is 1.0 at $t = 0$ and $t = 2000$ hrs. thus showing no temporal variation. However, at the outside surface this ratio has a value 1.09 which characterizes its spatial variation.

Based upon the foregoing examination it is clear that the stress distribution is noticeably nonuniform and nonconstant. However, the spatial variations are smooth and are rapidly reduced in a small fraction of the test duration. It is concluded that the calculation and use of an equivalent uniform and constant effective stress is meaningful. This calculation is outlined below.

The circumferential and axial stress resultants are given without approximation (using the notation of Figure 11) by;

$$N_\theta = ap \quad (2a)$$

$$N_z = \frac{a^2 p}{(a+b)} + \frac{P}{\pi(a+b)} \quad (2b)$$

Nominal stress values may be determined from these known stress resultants by dividing by the wall thickness;

$$\sigma_r = -\frac{P}{2} \quad (3a)$$

$$\sigma_\theta = \frac{ap}{(b-a)} \quad (3b)$$

$$\sigma_z = \frac{a^2 p}{(b^2 - a^2)} + \frac{P}{\pi(b^2 - a^2)} \quad (3c)$$

The justification for the stress quantities σ_θ and σ_z rests solely on the fact that multiplication by the thickness yields the correct stress

resultants. The stress quantity σ_r is taken as the average of the surface values. The σ_r , σ_θ and σ_z constitute a uniform stress distribution which is equivalent in an average sense to the actual nonuniform stress distribution.

Consider the numerical example used in the detailed inelastic analysis where; $a = 0.8$ in., $b = 0.9$ in., $p = 1,049.4$ psi., and $P = 2,670$ pounds. The uniform stresses obtained using Equation (3) are $\sigma_r = -524.7$ psi, $\sigma_\theta = 3,351.2$ psi, and $\sigma_z = 8,950$ psi. Based upon these values, the uniform and constant effective stress for this test is $\bar{\sigma} = 9,210$ psi. It is instructive to note that the effective stress based upon: 1) thin cylinder equations is $\bar{\sigma} = 9,725$ psi, 2) thick shell equations at the mean radius is $\bar{\sigma} = 9,157$ psi, 3) thick shell equations averaged over space is $\bar{\sigma} = 9,210$ psi, and 4) detailed inelastic predictions averaged over space and time is $\bar{\sigma} = 9,187$ psi.

These comparisons support the use of Equation (3) in determination of the effective stress level, $\bar{\sigma}$, because the value is close to that obtained from the detailed inelastic analysis.

$$\bar{\sigma} = \frac{1}{\sqrt{2}} [(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2]^{1/2} \quad (4)$$

Effective Strain: - An equivalent uniform, but nonconstant, effective creep strain is required for development of a thermal creep deformation model. Results from the detailed inelastic analysis described above in the context of establishing an effective stress measure were also examined with regard to establishing an effective creep strain measure. Spatial variations in strains were found to be somewhat greater but very similar to those in stresses. Based upon this examination it was

concluded that the behavior of the tubular specimens would admit meaningful characterization by an equivalent uniform effective creep strain.

Based upon deformation considerations, axisymmetric strains in the tubular specimen are given by:

$$\epsilon_r = \frac{\partial u}{\partial r} \quad (5a)$$

$$\epsilon_\theta = \frac{u}{r} \quad (5b)$$

$$\epsilon_z = \frac{\partial w}{\partial z} \quad (5c)$$

Generalized plane strain behavior is assumed, and the axial strain is determined by the change in gage length. Attention is restricted to creep strain behavior which is incompressible behavior. Based upon the assumption of relatively small radial stresses, the radial displacements induced during creep deformation are taken to be uniform through the thickness and are determined by the change in diameter. It follows from these considerations that the average creep strain components and effective creep strains which are used together with the uniform stress distribution are given by:

$$\epsilon_{cr} = -\epsilon_{c\theta} - \epsilon_{cz} \quad (6a)$$

$$\epsilon_{c\theta} = \frac{\Delta D}{(a+b)} \quad (6b)$$

$$\epsilon_{cz} = \frac{\Delta L}{L_{eff}} \quad (6c)$$

$$\bar{\epsilon}_c = \sqrt{\frac{2}{3}} \left[(\epsilon_{cr} - \epsilon_{c\theta})^2 + (\epsilon_{c\theta} - \epsilon_{cz})^2 + (\epsilon_{cz} - \epsilon_{cr})^2 \right]^{1/2} \quad (7)$$

The quantities ΔD and ΔL in Equations (6b) and (6c) are the diametral and axial extensometer measurements which are recorded on the laboratory data sheets. The determination of the effective axial gage length L_{eff} is problematical and is addressed in the following subsection.

Axial Gage Length: - The axial displacement is measured by an extensometer, attached to the shoulder of the specimen as shown in Figure 2. The gage length of the extensometer is about 9.4 inches. This includes a geometrically uniform portion and a geometrically nonuniform portion of the tube. For the development of creep equations under biaxial loading conditions, it is necessary to obtain the axial creep strain in the uniform portion of the tube where a true generalized plane strain situation exists and the stresses, strains, and stress ratios do not vary axially. This poses the problem at hand. What should the value of the effective gage length L_{eff} be such that deformations ΔL measured over the axial extensometer gage length are converted (in Equation 6c) to correct axial strain values at the midlength of the specimen? i.e.,

$$\epsilon_z = \frac{\Delta L_{9.4}}{L_{eff}} \quad (8)$$

where: ϵ_z = Axial strain at the midlength of the tube.

$L_{9.4}$ = Deformation in 9.4-inch extensometer gage length.

L_{eff} = Effective gage length of the tube.

Detailed analytical simulation of the inelastic deformation of the test specimen and attachments is required to determine the appropriate effective gage length. A highly refined axisymmetric finite element idealization was developed and used to examine deformations at three effective stress levels (10, 15 & 20 ksi) for each of three biaxial stress ratios ($\sigma_{\theta}/\sigma_z = 0, 1 \text{ \& } 2$).

The axial strain at the mid-thickness of the tube for a typical elastic analysis case is plotted against the distance z measured from the center of the tube in Figure 12. This strain is nearly constant up to about 3-1/2 inches from the mid-section of the tube. There is a steep strain gradient as the cross-section changes to the thick portion of the tube. Thereafter, the strain levels out. If the material nonlinearity is introduced due to the plastic yielding or creep, then the strain distribution shown in Figure 12 should be expected to change. Moreover, it is reasonable to expect a change due to biaxiality ratio.

(NO GAP)

The detailed inelastic analysis results from each case were examined to obtain an effective gage length at several points in time. The values obtained for L_{eff} are plotted together in Figure ¹³~~14~~ and represent the end-product of extensive computation and evaluation.

It is clear from Figure ¹³~~14~~ that the anticipated dependence of effective gage length upon stress level is insignificant within the range of stress levels considered. It is also clear that the dependence of effective gage length upon biaxial stress ratio is substantial. The time dependence of the gage length is also significant; but less so. Direct consideration of a time dependent effective length is considered to be unmanageable. However, indirect consideration of this time dependence can be accommodated by choosing a time averaged value and this was done. Additionally, the effective gage length values for each stress level at a specific biaxial stress ratio were averaged.

The end result of the detailed inelastic analyses and the foregoing interpretive comments is given as Figure ¹⁴~~15~~. The effective axial gage length used in processing the experimental data varies by 17% between biaxiality ratios of 0 and 2 and is obtained from Figure ¹⁴~~15~~ as a function of the biaxial stress ratio for any specific test. This result, together with the information presented above, completes the presentation of the equations and the rationale which underlie the processing of the tubular creep test specimen data.

The basic result of the experimental data processing calculations is an effective stress and strain history presentation such as Figure ⁵~~8~~. For a specific assumed form of creep deformation model, an analytical-experimental correlation of the type shown in Figure ⁶~~9~~ is produced. The choice of a "best" form of creep deformation model is a heuristic process which is simplified by the data records and computational features of the data handling system. Extension of this system to accommodate stress and temperature dependence in the creep deformation model would further increase its value.

CLOSURE

Special care was taken in this program in preparing the test specimens, machines and instrumentation because of the high degree of accuracy required to obtain meaningful thermal creep data. The initial tests performed made apparent the need for corresponding refinement in the test records and in the data interpretation. Improved records were needed to support refinement of the test operation and data interpretation. Also, a refined technical basis was needed to purge all significant analytical error from the data interpretation.

The data handling system described herein provides data records with the required completeness. This is done without the expense of data acquisition hardware with storage capability and the result is available for use by others doing similar testing. The graphical displays of measurements generated by the data handling system provide timely readable feedback which is useful for guidance of test operations. Special value is also attached to the convenience with which data can be transmitted to persons involved in the compilation and analysis of thermal creep data.

The analytical procedures presented herein provide effective creep stress and strain results with a minimum of analytical error. This is accomplished in spite of the significantly nonuniform behavior which is the Achilles heel of tests to create thermal creep deformation models. These analytical procedures, developed by extensive detailed inelastic to evaluate effects of nonuniformities, provide valuable guidance such that costly analyses of this type may be ^{minimized} ~~avoided~~ in similar testing programs.

Finally, the system for handling data and the procedures for interpretation of data extend to features which greatly facilitate the curve fitting calculations required to obtain an analytical model for creep deformation. The data storage features make the data readily accessible for such calculations. The built-in computational features include routines for curve fitting with an exponential form of creep deformation model. Other test data and other functional forms may be added by persons pursuing developmental programs to refine analytical models for creep deformation.

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APPENDIX A. NOTATION

P	=	Axial load
p	=	Internal pressure
r	=	Radial coordinate to point in tubular test specimen
z	=	Axial coordinate of test specimen measured from midlength
a	=	Inside radius
b	=	Outside radius
u	=	Radial displacement
w	=	Axial displacement
σ_r	=	Radial stress
σ_θ	=	Hoop stress
σ_z	=	Axial stress
$\bar{\sigma}$	=	Effective stress
N_θ	=	Hoop stress resultant
N_z	=	Axial stress resultant
ϵ_r	=	Radial strain
ϵ_θ	=	Hoop strain
ϵ_z	=	Axial strain
ϵ_{cr}	=	Radial creep strain
ϵ_{ce}	=	Hoop creep strain
ϵ_{cz}	=	Axial creep strain
$\bar{\epsilon}_p$	=	Effective plastic strain
$\bar{\epsilon}_c$	=	Effective creep strain
t_i	=	Elapsed time at which measurements F_i are recorded
$(N+1)$	=	Number of time points at which test data are recorded
F_i	=	Value of function $F(t)$ recorded at time t_i
F_e	=	Time averaged value of function $F(t)$
ΔD	=	Change in diameter of test specimen
ΔL	=	Change in length of test specimen between extensometer tabs
L_{eff}	=	Effective length of test specimen

APPENDIX B LABORATORY DATA SHEETS

The items of information ^{which are} ~~to be~~ written directly on the data sheets by the person performing the creep test^s are designed to be sufficient to enable knowledgeable use of the test data. Six types of printed sheets are provided. Five of the six sheets are filled out only once for each test. The sixth data sheet, shown in Figure ¹⁵ 3, contains the measurements made during the test and the number of data sheets of this type depends upon the number of measurements and the number of explanatory comments entered with the creep measurements. ^{The five types of} The five types of data sheets which are not shown (see Reference 1) are described below.

The first data sheet, entitled Processing Control Cards, is related exclusively to the computer control cards. The purpose of this data sheet is to make a set of experimental data sufficiently complete to allow submission for processing without the addition of any information.

The second data sheet, entitled Description of Test, provides key items of identification and a summary description of the test. The scope includes test specimen identification, testing conditions and test results. The names of principal participants in the performance of the test are also included on this data sheet, in the event that the intended self-standing character of the test record is not achieved and subsequent contact with the participants is necessary.

The third data sheet, entitled Description of Equipment, identifies all items of equipment and instrumentation used in the test. The specified company inventory identification numbers allow access to company files containing detailed information on capabilities, accuracy, calibration data, etc. This information is vital in the validation of the test results. For example, readings taken using a specific instrument may be undercut by malfunctions discovered subsequent to test.

^{the}

The fourth data sheet, entitled Test Specimen, provides a complete description of the test specimen. The lines of description specify, explicitly and by reference, information on the material such as heat number, heat treatment, product form, composition, etc. The source of definitive information regarding the preparation of a particular test specimen and any supplementary information regarding the fabrication is also provided on this data sheet.

The fifth data sheet provides information on the applied loadings and the predicted behavior. The nominal values of the duration and intensity of loadings for each of the segments in the load histogram are specified on this data sheet. However, the reduction of the test data is based upon the actual values recorded during the test. The relevant references to be included in this data sheet include pre-test analyses and ultimately post-test analyses with analytical-experimental correlations.

Finally, the sixth data sheet, shown in Figure ¹⁵ 3, entitled Data Record, is used to record all creep test measurements. ~~The data is recorded in a log and right portions.~~ If a letter 'F' is entered in the first column, the information in the remainder of the line is interpreted as a comment related to the last previous line of the measurements recorded. Inclusion of a sufficient number of footnotes enables knowledgeable use of the experimental data.

FIG. 1 ORGANIZATION OF DATA HANDLING SYSTEM.

①

Figure 7-18 High Temperature Tubular Test Specimen

NOM P=1050. (30 PSI ERR= 2.9 PERCENT) (IF ERR=30 SEE RAW DATA)

CYLINDRICAL SPECIMEN CREEP TEST. CIRCUM CREEP STRAIN VERSUS TIME

TEST 10 - 9 ALOAD= 2670.0 PRESS=1050.7 TEMP=1100

SIGR= -525.3 SIGC= 8405.5 SIGZ= 8954.9 SIGET= 9.2

T=TOP M=MIDDLE B=BOTTOM A=AVERAGE

Figure. Hoop Creep Strain Versus Time

COMPARISON OF CYL. SPEC. EFF. CREEP STRAIN WITH UNIAXIAL CREEP MODELS
 TEST 10 - 9 ALOAD= 2670.0 PRESS=1050.7 TEMP=1100
 SIGR= -523.3 SIGC= 8405.5 SIGZ= 8954.9 SIGEFF= 9.2
 1=TUBE SPEC 2=ALL DATA 3=1000 HR 4=HANDBOOK 5=BLACKBURN 1973

10/30/74

COMPARISON OF SINGLE EXPONENTIAL CREEP EQUATION AND EXPERIMENTAL DATA

TEST 10-9

LOAD= 2679.0 PRESS (PSI)=1050.7 TEMP (F)=1100.0

X = EXPERIMENTAL STRAIN SOLID LINE = GENERATED STRAIN

11/ 5/74

Figure 7-4. Radial Stress History

Figure 7-5. Circumferential Stress History

6259-21,22

Figure 7-6. Axial Stress History

Figure 7-7. Equivalent Stress History

6259-23.24

Figure 4-13. Tubular Specimen Section

6259-43

Figure 7-21: Variation of the Axial Strain Along the Length of the Tube.

6391-37

Figure 7-39 Variation of Effective Gage Length with Elapsed Creep Time

Figure 7-40 Average Effective Gage Length Variation with Stress Ratio