

Draft ASME Section III Division 5 Code Cases to extend EPP strain limits and creep-fatigue design methods to Grade 91

Applied Materials Division

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Draft ASME Section III Division 5 Code Cases to extend EPP strain limits and creep-fatigue design methods to Grade 91

prepared by
M. C. Messner and T.-L. Sham
Applied Materials Division, Argonne National Laboratory

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Abstract

This report describes the drafting of Code Cases extending the ASME Boiler and Pressure Vessel Code Section III, Division 5, Subsection HB, Subpart B design by elastic perfect-plastic (EPP) analysis methods to Grade 91 steel. The primary technical challenge is that Grade 91 steel is a cyclic softening material and so modifications to the current ASME design approach for austenitic stainless steel were required to produce conservative designs. Previous work established the technical basis required to support these modifications. This report provides the full package for balloting by ASME – both revised Code Case language and associated background documentation for two nuclear code cases: N-861 covering ratcheting strain limits and N-862 covering creep-fatigue damage. The completion of this work and successful balloting at ASME, currently underway, allows designers to apply the efficient EPP methods to Grade 91 high temperature structural components.

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1. Introduction

This report describes the extension of the ASME elastic perfectly plastic (EPP) design methods to components designed and fabricated from Grade 91 steel (9Cr-1Mo-V). This report consists of the balloting packages provided to ASME to support the formal modification of the existing EPP Nuclear Codes Cases N-861 and N-862, currently only applicable to 304 and 316 stainless steel. Chapter 2 and Chapter 3 contain these balloting packages. Chapter 2 applies to Code Case N-861, which applies the EPP design method to the ASME Section III, Division 5, Subsection HB, Subpart B ratcheting strain limits. Chapter 3 applies to Code Case N-862 on creep-fatigue criteria. Both chapters follow the same outline: the first section of the chapter provides the actual Code Case language and the second subsection provides the background document provided to the relevant ASME Code Committees along with the Code Case. Chapter 4 summarizes the current status of the revised, Grade 91 Code Cases in the ASME Code Committee structure at the time this report was finalized.

The current ASME EPP approach for stainless steel represents a better balance of analysis complexity, rule complexity, and accuracy in life prediction when compared to the baseline Section III, Division 5, Subsection HB, Subpart B design by elastic analysis and design by inelastic analysis methods. The goal for the EPP methods is to provide designers a way to rapidly evaluate prospective designs with sufficient accuracy to make informed design decisions. The implementation and adoption of this new design method therefore has the potential to reduce design costs and increase the spectrum of designs that can be economically evaluated, leading to high temperature reactor components with reduced overall cost and improved safety performance.

The technical background for extending the existing EPP design methods to Grade 91 was developed in past years with support from the Advanced Reactor Technologies (ART) Program and is summarized in two Argonne National Laboratory (ANL) technical reports:

- Messner, M. C. and Sham, T.-L. “Initial development and extension of EPP methods to Grade 91.” Argonne National Laboratory technical report ANL-ART-133, 2018.
- Messner, M. C. and Sham, T.-L. “FY17 Status Report on the Initial EPP Finite Element Analysis of Grade 91 Steel.” Argonne National Laboratory technical report ANL-ART-94, 2017.

The ASME background documents summarize this technical basis for Code Committee use. The figures used in the background documents reproduced here are mostly drawn from these two previous reports.

The exception is new work on the softening factors used in the EPP ratcheting strain limits procedure for Grade 91 at temperatures greater than 600° C. A new process for setting these factors was developed this fiscal year after feedback from some of the ASME Code Committee members. This new softening factors, the new process, and the tests run at Oak Ridge National Laboratory supporting the new factors, are described in Chapter 2.

The current ASME EPP methods for stainless steel tacitly assume a cyclic hardening material response. This allows the methods to bound the accumulated deformation (for N-861) and accumulated creep-fatigue damage (for N-862) in a component using a simplified EPP analysis

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with a pseudo-yield stress, which may not equal the actual material yield stress. The EPP analysis is a tool for generating a bounding analysis result, rather than an accurate representation of the material's constitutive response. Because the austenitic steels are hardening materials the previous version of the method bases these pseudo-yield stresses on material test data collected from virgin material that has not been pre-cycled. For N-861 this material test data is the yield stress and the values of the isochronous stress-strain curve, which summarize time-dependent deformation in the material. For N-862 this test data are creep rupture stress values. As the stainless steels work and cycle harden, cyclic deformation would only increase these material properties, meaning using the values collected from uncycled material is conservative.

Grade 91 is however a cyclic softening material which means cyclic deformation will degrade the material properties required in the EPP design calculations. Calculations and experiments summarized in Chapter 3 demonstrate that the ASME method of handling creep-fatigue interaction, the creep-fatigue damage or D-diagram, already accounts for the effect of cyclic softening in Code Case N-862 and so minimal modifications are required to extend this Code Case. However, in Code Case N-861 softening factors on the material yield stress and isochronous stress-strain curves are required to account for the effect of cyclic softening. This report summarizes the past work on establishing the conservative softening factors now included in the modified draft Code Case. Additional work this fiscal year developed an alternative method for establishing softening factors at very high temperatures, which was used to determine the final factors sent to ASME for ballot.

The Code Case language and background documents presented here form the basis of the package currently being balloted at ASME. The final chapter of this report summarizes the balloting progress and discusses the path towards final AMSE approval for the revised Code Cases.

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2. N-861: Ratcheting

2.1. Draft Code Case Language

Case N-861-1

Satisfaction of Strain limits for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis.

Section III, Division 5

Inquiry: What alternative rules may be used for the evaluation of strain limits for Type 304 SS, Type 316 SS, and 9Cr-1Mo-V steel in compliance with Section III, Division 5, Subsection HB, Subpart B, HBB-3252 and Nonmandatory Appendix HBB-T?

Response: Strain limits for 304 SS, 316 SS, and 9Cr-1Mo-V steel per Section III, Division 5, Table HBB-I-14.1(a) may be evaluated using elastic-perfectly plastic material models instead of the procedures of Section III, Division 5, HBB-T-1320, HBB-T-1330, and HBB-T-1713 when performed in accordance with the requirements of this Code Case.

1 General Requirements.

Except as identified herein, all requirements of Section III, Division 5, Subsection HB, Subpart B apply to components designed in accordance with this Code Case.

The design methodology employed for evaluation of strain limits is based on rapid cycle ratcheting analyses using a small strain theory elastic-perfectly plastic material model where the yield stress is adjusted based on a pseudo yield stress selected to bound accumulated inelastic strain. Guidance on ratcheting analysis is provided in Appendix I. In this code case the term “pseudo yield stress” refers to a temperature dependent isochronous stress based on the total time duration of high temperature service and a target inelastic strain multiplied by a softening factor, not to exceed the yield strength of the material at temperature multiplied by a softening factor. The pseudo yield stress is explicitly defined in Section 4, Step 2 of this Code Case.

- (a) This design methodology is not applicable to skeletal structures, e.g. a bar with uniform axial load throughout, nor structures where geometrical nonlinearities exist, e.g. canopy or omega seals.
- (b) The stamping and data reports shall indicate this Case number and applicable revision.

2 Load Definition.

Define all applicable loads and load cases per Section III, Division 5, HBB-3113.2, Service Loadings.

2.1 Composite cycle definition

For the purpose of performing an elastic-perfectly plastic ratcheting analysis an overall cycle must be defined which includes all relevant features from the individual Level A, B and C Service Loadings identified in the Design Specification. Relevant features include, as a minimum, the time dependent sequence of thermal, mechanical and pressure loading including

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starting and ending conditions. Such an overall cycle is defined herein as a composite cycle subject to the following requirements.

- (a) An individual cycle as defined in the Design Specifications cannot be further subdivided into individual cycles to satisfy these requirements.
- (b) Except as described in (c), a single cycle from each Level A, B and C Service Loading cycle type shall be included in the composite cycle for evaluation of strain limits.
- (c) Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define an additional composite cycle(s) to be evaluated separately from the composite cycle defined in
- (d) Multiple composite cycles that include Level C Service Loadings may be defined for separate evaluation. The total number of Level C Service Loading cycles shall not exceed 25.

3 Numerical Model.

Develop a numerical model of the component including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The model must also be accurate for small details, such as small holes, fillets, corner radii, and other stress risers. The local temperature history shall be determined from a thermal transient analysis based on the thermal boundary conditions determined from the loading conditions defined in Section 2.

4 Requirements for Satisfaction of Strain Limits.

Perform a ratcheting analysis for each of the composite cyclic histories defined in Subsection 2.1. Each of these cyclic histories must be shown to be free from ratcheting based on the pseudo yield stress S_{xT} as defined in Step 2. In the following steps, inelastic strain for a particular stress, time and temperature is obtained by subtracting the elastic strain from the total strain as given by the isochronous stress strain curve at the same stress, time and temperature. Additional requirements for weldments are shown in Section 5.

Step 1: Define t_{design} as the total time duration of high temperature service for all Level A, B, and C Service Loadings when the temperature is above the range covered by Tables 2A, 2B, and 4 of Section II, Part D.

Step 2: Select a target inelastic strain, x , where $0 < x < \varepsilon_{avg}$ and ε_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Define a pseudo yield stress S_{xT} at each location, using the temperature determined from the transient thermal analysis. This pseudo yield stress is equal to the lesser of the quantities defined below in 4.2.1. and 4.2.2.

- (a) The yield strength S_y given in Section III, Division 5, Table HBB-I-14.5 multiplied by the softening factor F_y given in Table 2.1. Values in Table 2.1 may be linearly interpolated between the listed temperatures.
- (b) The stress to cause x inelastic strain in time t_{design} , as determined from the isochronous stress strain curves in Section III, Division 5, Figure HBB-T-1800 multiplied by the temperature-

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dependent softening factor F_{ISSC} in Table 2. Values in Table 2.2 may be linearly interpolated between the listed temperatures.

Table 2.1 Softening Factor F_y

Temperature, °F (°C)	304 SS	316 SS	9Cr-1Mo-V
700 (371)	1.0	1.0	0.88
800 (427)	1.0	1.0	0.85
900 (482)	1.0	1.0	0.84
1000 (538)	1.0	1.0	0.81
1100 (593)	1.0	1.0	0.76
1200 (649)	1.0	1.0	0.63
1300 (704)	1.0	1.0	n/a
1400 (760)	1.0	1.0	n/a
1500 (816)	1.0	1.0	n/a

Table 2.2 Softening Factor F_{ISSC}

Temperature, °F (°C)	304 SS	316 SS	9Cr-1Mo-V
700 (371)	1.0	1.0	0.87
800 (427)	1.0	1.0	0.83
900 (482)	1.0	1.0	0.81
1000 (538)	1.0	1.0	0.76
1100 (593)	1.0	1.0	0.72
1200 (649)	1.0	1.0	0.30
1300 (704)	1.0	1.0	n/a
1400 (760)	1.0	1.0	n/a
1500 (816)	1.0	1.0	n/a

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Step 3: Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in paragraph 2.1(b) above with temperature-dependent pseudo yield stress S_{xT} . If ratcheting does not occur, obtain the plastic strain distribution throughout the component. The plastic strain, ε_p , is evaluated according to

$$\varepsilon_p = \sqrt{\frac{2}{3} \left[(\varepsilon_x^p)^2 + (\varepsilon_y^p)^2 + (\varepsilon_z^p)^2 + 2(\varepsilon_{xy}^p)^2 + 2(\varepsilon_{yz}^p)^2 + 2(\varepsilon_{zx}^p)^2 \right]}$$

where the plastic strain components, ε_x^p , ε_y^p , ε_z^p , ε_{xy}^p , ε_{yz}^p and ε_{zx}^p , are those accumulated at the end of the composite cycle.

Step 4. Assess acceptability in accordance with (a) and (b) below by using the plastic strains, ε_p , from Step 3. If the requirements of both (a) and (b) are satisfied, then the strain limits of Section III, Division 5, HBB-T-1310 for base metal and HBB-T-1713 for weldments are also considered satisfied. This condition is illustrated in Figure 2.1(a).

(a) The requirement, $x + \varepsilon_p \leq \varepsilon_{avg}$, must be satisfied at least at one point for all through-thickness locations. As defined in Step 2, ε_{avg} is equal to 0.01 for base metal or 0.005 for weldments. Failure of this requirement is illustrated in Figure 2.1(b).

(b) The requirement, $x + \varepsilon_p \leq \varepsilon_{local}$, must be satisfied at all points. The local strain limit, ε_{local} , is equal to 0.05 for base metal and 0.025 for weldments. Failure of this requirement is illustrated in Figure 2.1(c).

(c) In order to proceed if either of the requirements of (b) or (c) are not satisfied, return to Step 2 and select a smaller value of the target inelastic strain, x . If it is not possible to find a value of x that does not ratchet and also satisfies the requirements of Step 4, then the loading conditions of Section 2 applied to the component configuration defined in Section 3 do not meet the requirements of this code case.

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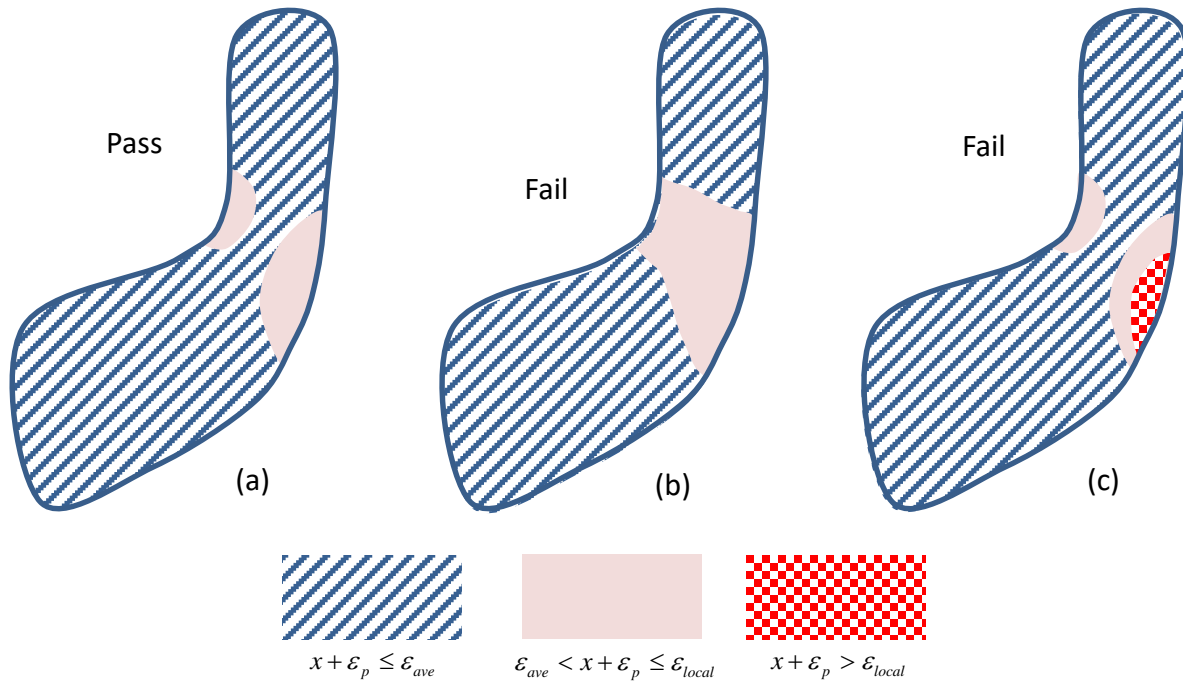


Figure 2.1. Strain limits Pass/Fail criteria illustrated

5 Weldments.

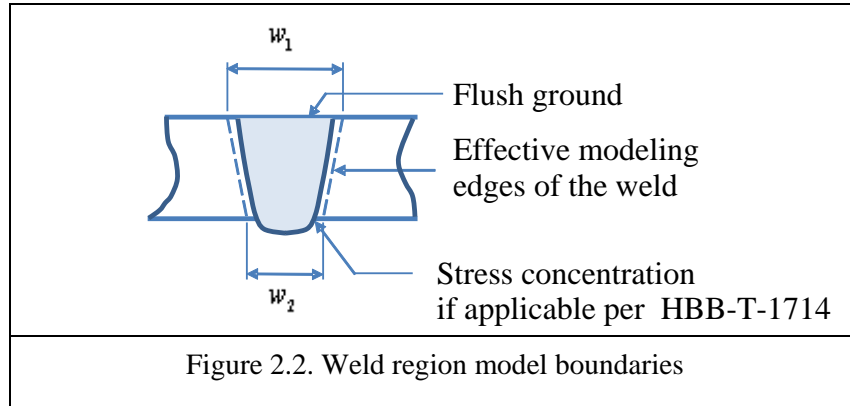
Implementation of the strain limits for weldments defined above in Section 4 requires additional consideration.

5.1 Weld region model boundaries.

The weld shown in Figure 2.2 represents a general full-penetration butt weld in a shell. Other weld configurations are needed for construction of an elevated temperature component in accordance Section III, Division 5, Subsection HB, Subpart B. Section III, Division 5, HBB-4200 refers to various Section III, Division 1 Article NB-4000 paragraphs for weld configurations and requirements. These Subsection NB weld configurations are represented by the shaded region.

Figure 2 shows a full-penetration butt weld as an example. As shown, w_1 and w_2 , as needed to define the weld region for use of this Case, are approximations consistent with the specified weld configuration and parameters. The specified weld region must include applicable stress concentrations in accordance with the requirements for analysis of geometry of Section III, Division 5, HBB-T-1714.

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5.2 Requirements

The requirements for analysis of geometry of Section III, Division 5, HBB-T-1714 are applicable for satisfaction of the requirements of this Code Case.

5.3 Properties

The thermal/physical properties of weldments may be assumed to be the same as the corresponding base metal for the base metal - weld combinations listed in Section III, Division 5, Table HBB-I-14.10

5.4. Dissimilar metal welds.

This Code Case may not be used to evaluate strain limits in dissimilar metal welds.

Appendix I

Shakedown Analysis

Perform a ratcheting analysis to demonstrate compliance with strain limits as follows:

- (i) Define Composite Cycle Load Time-Histories and Step(s)
 - (a) Composite cycle load may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.
 - (b) Time-independent parts of the cycle may be truncated because elastic-perfectly plastic analysis is not time dependent.
 - (c) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one state to the next.
 - (d) Subject to the requirements in (b), the composite cycle time does not affect the result of the shakedown analysis.
 - (e) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.

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- (f) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.

(ii) Define Analysis Types.

- (a) A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First a thermal analysis is performed to generate temperature histories. Next the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal analysis are the same or do not conflict, depending on the requirements of the analysis software.
- (b) Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic, that is the beginning and end temperature distributions should be the same.

(iii) Define Material Properties.

- (a) For thermal analyses, density, temperature- dependent specific heat and conductivity will generally be required.
- (b) For the mechanical analyses the temperature-dependent properties required are modulus, Poisson's ratio and mean expansion coefficient. Density may also be required.

(iv) Perform Analyses.

- (a) Perform an elastic-plastic cyclic mechanical and thermal stress analysis using the temperature-dependent yield property defined above. Enough cycles are required to demonstrate shakedown or otherwise.
- (b) Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, or division of the cycle into more than one step as in (a)(6) of this Appendix.
- (c) Numerical shakedown analysis using finite element analysis are extremely sensitive to the numerical parameters controlling the solution accuracy. Shakedown analysis should require the analysis method to report as accurate solutions as possible by decreasing solver tolerances and otherwise altering the solver parameters.

(v) Ratcheting.

- (a) Ratcheting is defined as non-cyclic strain accumulation. That is, the total strain components differ from cycle to cycle.
- (b) Shakedown is defined as the opposite of ratcheting – a model shakes down if the strains at all points become periodic with increasing numbers of load cycles.
- (c) Failure to shakedown may be identified by plotting histories of strain at critical locations in the model.

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- (d) Because of accumulated numerical error finite element analysis results will never shakedown exactly. Plastic shakedown, defined as shakedown behavior where the steady cycle contains some plastic deformation, is acceptable for this Code Case. Models that shake down plastically will have appreciable integration errors, manifested as slight non-periodicity in the cycle strains. The analyst must distinguish this “false ratcheting” from actual ratcheting in making the shakedown/ratcheting determination.

2.2. Background document

Overview

The goal of this Code Case revision is to extend a previously developed method for using simplified, elastic-perfectly plastic analysis (EPP) for evaluating structures against the Section III, Division 5, Subsection HB, Subpart B (HBB) strain limits design criteria to 9Cr-1Mo-V steel. The method has been previously established and codified for 304 and 316 stainless steels through Code Case N-861. This background document does not reiterate the detailed derivation of the method nor the validation experiments and numerical studies used to demonstrate its conservatism. For this basic background method refer to the following bibliography:

- Background documents for Code Case N-861 (RC14-1445).
- Carter, P. “Analysis of cyclic creep and rupture. Part 1: bounding theorems and cyclic reference stresses.” *International Journal of Pressure Vessels and Piping*, 82(1): pp. 15-26, 2005.
- Carter, P. “Analysis of cyclic creep and rupture. Part 2: Calculation of cyclic reference stresses and ratcheting interaction diagrams.” *International Journal of Pressure Vessels and Piping*, 82(1): pp. 27-33, 2005.
- Carter, P., Jetter, R. I., and Sham, T.-L. “Application of elastic-perfectly plastic analysis to assessment of creep strain” In the *Proceedings of the ASME 2012 Pressure Vessels & Piping Conference*, Toronto, Canada, PVP 2012-78082, 2012.

This proposed Revision 1 of N-861 extends the method to cover 9Cr-1Mo-V (Grade 91) steel.

The EPP method for strain limits evaluation described in these references is general – it should apply to any material. However, Grade 91 steel differs from the austenitic stainless steels for which the EPP methods were validated in that Grade 91 shows cyclic softening behavior at moderately elevated temperatures and even work softening behavior at high temperatures, greater than 600° C. Cyclic softening means that the material flow stress decreases with the number of prior cycles in strain controlled cyclic loading (fatigue loading). This means, for example, the maximum stress observed in a cycle tends to decrease as a function of cycle count for Grade 91, whereas it tends to increase as a function of cycle count in cyclic-hardening materials like 316 and 304 stainless steels.

Cyclic softening could negatively impact the EPP methods because they use isochronous stress-strain curve values and the material yield strength to lower-bound the residual stress pattern that will develop during cyclic creep-plasticity. The Code values for both the isochronous stress-strain curves and the yield strength are based on experiments starting from material in the unsoftened condition. Therefore, for softening materials, the Code values may fail to adequately bound the true flow stress after a substantial number of prior fatigue cycles.

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This background document describes a methodology used to determine if cyclic softening negatively affects the previously-established EPP method. The approach uses a consistent comparison to an inelastic model to demonstrate that the baseline EPP method, already established for 304 and 316 stainless steels, is not conservative for cyclic softening materials. However, a simple modification of the method allows it to address cyclic softening effects.

This document provides a brief overview of the base EPP method, an abbreviated description of the technique used to evaluate potential problems introduced by cyclic softening, a discussion of what changes to the method are required to address cyclic softening, and a discussion of the modifications to the proposed revision when compared to Code Case N-861. Two publically available DOE reports provide full details on the analysis used to justify the extension of the method to Grade 91:

- Messner, M. C. and Sham, T.-L. “Initial development and extension of EPP methods to Grade 91.” Argonne National Laboratory technical report ANL-ART-133, 2018.
- Messner, M. C. and Sham, T.-L. “FY17 Status Report on the Initial EPP Finite Element Analysis of Grade 91 Steel.” Argonne National Laboratory technical report ANL-ART-94, 2017.

Overview of the EPP method

The objective for the EPP methods is to simplify the complicated Section III, Division 5, HBB Appendix T rules based on an elastic stress analysis. Furthermore, the EPP methods can make use of modern finite element analysis. For example, they do not require stress classification or linearization.

The EPP strain limits method attempts to bound the amount of strain accumulated in the actual component using a cyclic plasticity solution. The key idea is that arbitrary cyclic plasticity shakedown solutions bound the true residual stress distribution in the structure. So if you can find a shakedown solution with a residual stress distribution that implies a creep strain accumulation that meets the Code strain limits then you have conservatively bounded the true strain accumulation in the structure and your design will conservatively meet the Code criteria. The Code Case defines an iterative procedure for finding such a cyclic plasticity solution. This procedure assesses the amount of creep strain resulting from a given residual stress distribution by referencing the material isochronous stress-strain curves. There is an additional check to ensure that the residual stress pattern nowhere exceeds the actual material yield strength.

Of course, as mentioned above, Code Case N-861 uses unsoftened yield strength values and unsoftened material isochronous stress-strain curves.

The previous work cited above establishes the conservatism of this method for austenitic stainless steels and the nickel-based Alloy 617 (RC16-999). The only question this Code Case addresses is if modifications to the base method are required to account for cyclic softening in Grade 91.

Assessing the method for cyclic softening conditions

To answer this question consider a consistent comparison to a full inelastic analysis. First, we develop an inelastic constitutive model with continuum damage that describes the deformation of

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a cyclic softening material. A full description of the model used here is given in the DOE reports mentioned above. The key features of this constitutive model are that it:

1. describes a realistic constitutive response, something that is reasonably representative of a Class A material;
2. it describes a cyclic softening response, so that we can use it to assess the effects of cyclic softening.

It will not be important that the constitutive model perfectly describes the response of any real material. However, the model used here represents the response of Grade 91 steel as described by the Section III, Division 5 isochronous stress-strain curves, fatigue curves, and rupture life correlations.

Given this realistic material model we then generate synthetic design data sufficient to execute an EPP strain limits analysis. This means we develop relations for the Young's modulus, Poisson's ratio, coefficient of thermal expansion, yield stress as a function of temperature and isochronous stress-strain curves for different times and temperatures. For each type of data we simulate a series of tests, for example creep tests for the isochronous stress-strain curves, and correlate the data to develop design data in *exactly the same way prescribed in the Code for adding a new Class A material*.

This process produces a set of design data that is *consistent* with the base inelastic model. We can compare the results of a full inelastic simulation of a component with an EPP strain limits evaluation of the component using the consistent design data. This comparison is perfectly fair. It assesses the design method itself independent of any experimental or material variability present in actual experimental data. If the consistent EPP calculation produces a non-conservative design life when compared to the full inelastic simulation then there is a problem in the design method itself that must be corrected.

Figure 2.3 shows an example problem used to assess the impact of cyclic softening on the EPP strain limits method. The geometry is a thin walled vessel away from any stress discontinuities under a combination of a constant pressure and a varying linear through-wall thermal gradient. Because we are interested in the effect of cyclic softening the vessel load was concocted to allow us to vary the amount of pre-fatigue cycles the vessel sees before creep-fatigue loading. The vessel first undergoes n_{pre} thermal fatigue cycles, where the outer wall temperature changes from T_a to T_b without any hold period. After these pre-fatigue cycles the thermal loading switches to creep-fatigue – the outer wall temperature increases to T_b , holds at the hot temperature for 100 hours, and decreases back to T_a .

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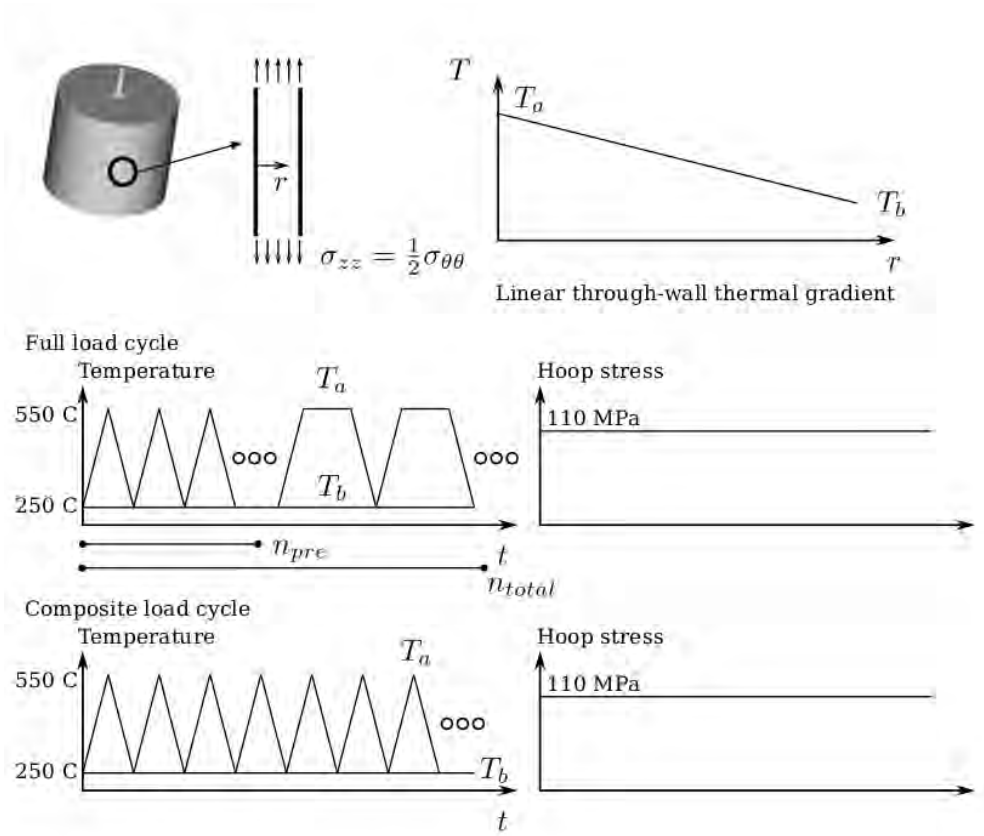


Figure 2.3. Test geometry and load cycle history used to assess the EPP strain limits method (Messner, 2018).

We analyzed the vessel for several different values of n_{pre} with two methods: the full inelastic, simulations and a consistent companion EPP calculation. The design life for the full inelastic simulations was calculated simply by repeating the load cycle with holds until the simulations exceed the Code strain limits (1% average, 2% linearized, 5% maximum). If cyclic softening negatively impacts the conservatism of the EPP strain limits method then the EPP design life should become less and less conservative as the number of cycles increases.

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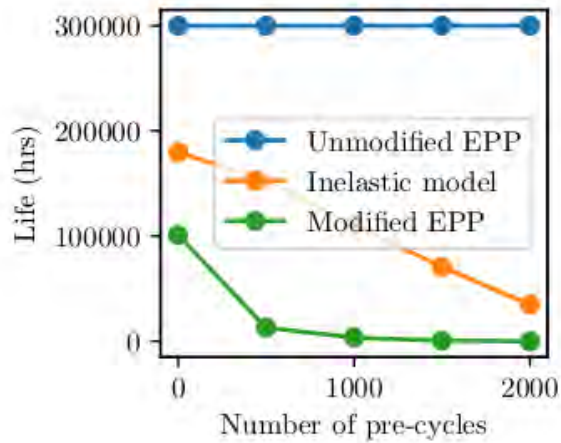


Figure 2.4 The strain limits design life for the inelastic simulations, the unmodified EPP method, and the modified EPP method using softened isochronous stress-strain curves and yield strengths (Messner, 2018).

Figure 2.4 plots the results. This figure compares the strain limits design life for the full inelastic simulations against the design life implied by the unmodified EPP strain limits procedure. The plot shows that the unmodified EPP method is non-conservative – it predicts a longer design life than the design life from the inelastic simulations. Furthermore, the difference between the unmodified EPP and the inelastic design life becomes more acute as the number of pre-fatigue cycles increases. This suggests the problem is that the EPP method does not adequately account for the effects of cyclic softening.

The reason for this is simple: the base EPP method, applied to cyclic hardening stainless steels, relies on the design isochronous stress-strain curves and yield stresses bounding the actual material flow stress during cyclic deformation. For cyclic hardening materials this supposition is reasonable: cycling will only increase the flow stress. For cyclic softening materials it is not reasonable, as the flow stress will decrease with cycling, potentially falling below the Code values of yield strength and the values implied by the Code isochronous stress-strain curves.

Conceptually, fixing the EPP method to account for cyclic softening is easy: simply use the actual, softened isochronous stress-strain curves and yield stress values. The yield stress data would be, in theory, be generated by first pre-cycling a sample a number of times in strain controlled loading with a strain range that matches the actual strain range in the structure and then unloading the sample and running a tension test to establish the softened material yield stress. The softened isochronous stress-strain curves could, again in theory, be established in a similar way from a series of creep tests conducted with pre-cycled, softened material. Following this test protocol and tabulating the resulting values in the Code Case is, as discussed in the next section, practically impossible. However, it is easy to do with simulations with the reference inelastic model. Figure 3 shows an example of the softened model isochronous stress-strain curves at 550° C after 1,000 pre-fatigue cycles with a strain range of 0.4%. A similar process can be used to establish softened yield stress values.

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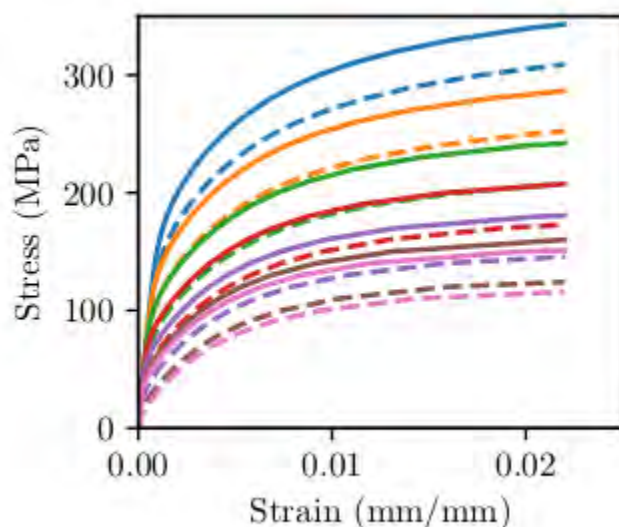


Figure 2.5 Simulated softened isochronous stress-strain curves at 550° C after 1,000 pre-fatigue cycles with a strain range of 0.4%. The solid curves are simulated isochronous stress-strain curves with no pre-cycling, i.e. simulated versions of the standard Section III, Division 5 HBB isochronous stress-strain curves. The dashed lines are corresponding softened isochronous stress-strain curves. From top to bottom the colors represent the hot tensile curve and then isochronous curves for 10, 100, 1,000, 10,000, 100,000, and 500,000 hours life (Messner, 2018).

Figure 2.5 then shows that using the softened isochronous stress-strain curves and softened yield stress values produces conservative EPP design lives when compared to the full inelastic simulations. So conceptually we have a fix for the EPP strain limits method for Grade 91: use softened values of the yield stress and the isochronous stress-strain curves accounting for prior cyclic softening.

Softening factors

While using softened isochronous stress-strain curves and softened yield stress values would be an ideal solution in practice it would be difficult or impossible to establish these curves experimentally or tabulate a complete set of values in a Code document. Softening yield stress values could be established from pre-cycled tension tests. The sample would first be cycled a given number of times in strain control through a certain magnitude of fully reversed loading. The sample would be unloaded, and then reloaded under strain rate control, as in a standard uniaxial tension tests. The yield strength could be determined with the usual ASTM method. Similarly, softened creep tests could be used to establish isochronous stress-strain curves.

The amount of softening depends on the number of previous cycles, the cycle magnitude, the type of loading (stress or strain controlled), the loading tension/compression ratio, and the temperature. In addition there are the usual variables affecting the yield stress; temperature, and the variables affecting the isochronous stress-strain curves; temperature, time, and stress. Testing and correlating data covering the complete set of all these variables would be practically impossible. Additionally, a softened pseudo-yield stress that depended on the number of prior

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load cycles would be difficult to implement in the current EPP methods. The current EPP methods use a composite load cycle representing the complete service load spectrum, rather than an individual calculation for each type of cycle. This means that the base EPP methods have no intrinsic method for tracking the number of times a single cycle will occur nor a way to apply different softened pseudo-yield stresses to different types of cycles.

To reduce the required amount of data and to better fit the idea of a softened pseudo-yield stress into the existing EPP methods we rely on the idea of a saturated softened material flow stress.

Figure 2.6 plots the maximum flow stress versus cycle count for a strain-controlled cyclic test on Grade 91 at 600° C for fully-reversed loading with $\Delta\varepsilon = 1\%$. An extrapolation out to a hypothetical saturated softened state overlays the experimental data.

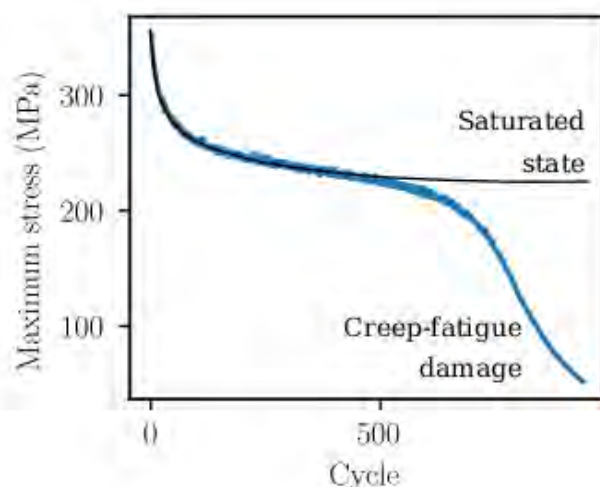


Figure 2.6. Results of a strain-controlled cycle (fatigue) test on a sample of Grade 91, conducted at Argonne National Laboratory. (Messner, 2018).

Clearly the cyclic flow stress continues to decrease in the actual experiment, not actually achieving any saturated softened condition. However, based on the shape of the curve we can deduce two regions of softening. The initial softening appears to decay towards a saturated flow stress. However, at around 500 cycles a new mechanism takes over which more or less linearly decreases the flow stress, tending towards complete failure. Micromechanically we can attribute the first type of softening to rearrangements in the dislocation structure of Grade 91. Grade 91 has a very high initial dislocation density arranged in a well-formed dislocation network substructure. Under load at elevated temperature this dislocation structure tends to recover, reducing the static dislocation density and reducing the flow stress. Micromechanically we would expect this process to eventually saturate to some steady-state dislocation arrangement, given enough time and loading. However, in this test, before that can occur creep-fatigue damage begins to substantially affect the material flow stress. This mechanism, which results from the cavitation and coalescence of voids on grain boundaries, does not saturate and will tend towards causing material failure.

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The method developed here for calculating softening isochronous stress-strain curve values and softened yield stresses for the EPP method is based on assuming we can “turn off” damage in the material and extrapolate test results out to the (theoretical) saturated, softened condition. We then calculate the softened material properties from this saturated state. If the material actually achieved the saturated condition it would be conservative to use softened properties in this condition for design because they lower-bound the material flow stress during the previous cycles and, once the material reaches this condition, they do not change with additional cycling. This concept of a saturated, softened condition allows us to eliminate cycle counting from the EPP procedure and vastly reduces the amount of new data we need to collect and tabulate in the Code Case.

It is reasonable to extrapolate out to a theoretical softened condition for the EPP strain limits Code Case because *we expect that the Code creep-fatigue design checks (e.g. the EPP creep-fatigue Code Case) will prevent a structure from reaching the damage-dominated regime of softening*. Even though this may not be a conservative assumption when examining the Code strain limits criteria in isolation it is a reasonable and conservative method when taken in conjunction with the Code creep-fatigue failure criteria.

Given these assumptions, saturated, softened yield stress values are easy to obtain from standard creep-fatigue or fatigue strain controlled tests. Figure 2.7 demonstrates how we can extrapolate the results of such tests out to a hypothetical saturated condition. This figure plots the flow stress on the tension side of each cycle as a function of the number of cycles for a number of different experiments (Kim and Weertman, 1988; Koo and Kwon, 2011; Zhang and Aktaa, 2016). All the data can be reasonably extrapolated to such a condition with an exponential decay model. The saturated, softened yield stress is then the asymptote of the decay model.

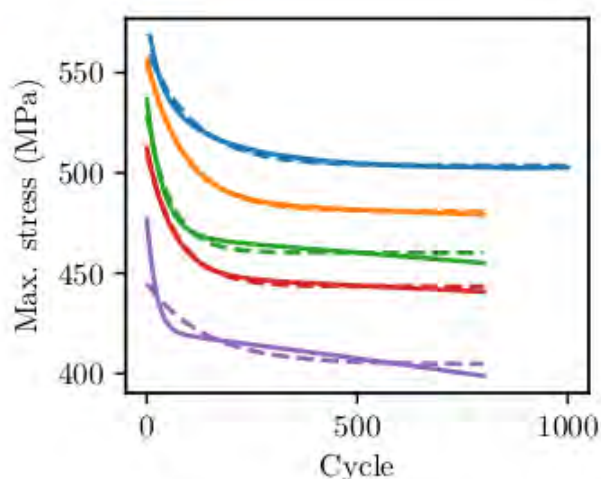


Figure 2.7. Cyclic data used to establish experimental yield stress softening factors (Messner, 2018). Experimental data in solid lines, extrapolations in dashed lines.

To normalize the data to the Code values of yield strength we calculate, for each test, a softening factor equal to:

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$$F_y = \frac{\sigma_{sat}}{\sigma_{init}}$$

where σ_{init} is the initial experimental maximum stress on the first half cycle and σ_{sat} is the extrapolated saturated maximum cycle stress. We repeated this process for a variety of experiments and averaged the results to determine the temperature dependent softening factors listed in Table 2.3. The proposed Code Case applies these softening factors to the Code yield strength in determining the pseudo yield stress. That is, rather than using S_y directly the designer instead uses $F_y S_y$.

Temperature (°C)	F_y
25	0.88
500	0.84
600	0.72
650	0.62

Table 2.3. Experimental yield strength softening factors.

A similar approach is used to determine softened isochronous stress-strain values. However, collecting the requisite experimental data is much more difficult. In principal, isochronous stress-strain curves could be constructed from a large dataset of pre-cycled creep tests. These types of tests are not commonly conducted and so there is no available literature data to draw from. Additionally, extrapolating such a testing database to a saturated state would not be straightforward as it would require some model for how cyclic softening affects creep deformation and rupture.

Instead, we derived softening factors based on the inelastic model for Grade 91 described above. With the model there is no need to extrapolate to a saturated state as the damage model can simply be turned off in the simulations. Without damage the constitutive model tends towards a saturated flow stress with increasing cyclic deformation. The simulations required to establish softened isochronous curves first cycle the material model until the flow stress saturates and then simulates a creep test. This data can be collated into softened isochronous stress-strain curves as a function of temperature.

As with the yield stress, we normalize this data into a set of factors which can then be applied to the Section III, Division 5 design data – in this case the design isochronous stress-strain curves. For each combination of time, temperature, and strain a softening factor can be defined as

$$F_{ISSC} = \frac{\sigma_{soft}}{\sigma_{base}}$$

where σ_{base} is the relevant stress value for the model's unsoftened isochronous stress-strain curves and σ_{soft} is the corresponding softened value. The values of these softening factors do not vary much over the first 1% inelastic strain and so the values in Table 2 are all for a strain of 1%. The values do change as a function of time – prior softening generally affects short term creep less than long term creep. Table 2.4 gives two values of softening factors – the lowest factor for all times up to 300,000 hours and the lowest factor for all times up to 500,000 hours. The proposed Code Case uses the 300,000 hour values as that is currently the maximum

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allowable design life for Grade 91. The 500,000 hour values are provided to aid any future work extending the Code allowable life for Grade 91.

At 650° C the model softening factor is zero. The model predicts very rapid and very severe cyclic softening, nearly indistinguishable from damage. *This does not imply the material cannot be used in service conditions that will cause creep-fatigue damage at this temperature.* Instead it implies that microstructural softening and damage are indistinguishable (or, alternatively, damage begins on the first cycle) and so the extrapolation method outlined above cannot be used to develop softening factors applicable to any number of design cycles. An alternative method was used to establish the recommended softening factor for 650° C, discussed below.

Temperature (°C)	F_{ISSC} (300,000 hr)	F_{ISSC} (500,000 hr)
375	0.87	0.87
400	0.85	0.85
500	0.79	0.79
600	0.72	0.71
650	0.0	0.0

Table 2.4 Model isochronous stress-strain curve softening factors.

As with the yield stress factors, we propose applying these softening factors to the Code isochronous stress-strain curves when determining that part of the ratcheting pseudo yield stress.

We were able to validate these model softening factors for a single temperature (600° C) using a specialized experiment conducted at Oak Ridge National Laboratory specifically for this Code case. In the test a sample of Grade 91 was alternatively crept at a constant stress for several days and then cycled under strain controlled fatigue conditions (Figure 2.8). The average creep rate was recorded for each period of creep and the results plotted as a function of cycles. This data was then extrapolated out to a hypothetical saturated, softened creep rate. The ratio between the initial experimental creep rate and the extrapolated saturated rate was determined. This ratio was then used to derive softened isochronous stress-strain curves by assuming the creep rate remains constant over a creep test. This is a relatively poor assumption as it neglects primary and tertiary creep but it did allow us to calculate softened curves based on a single, specialized test. The experimental value determined for 300,000 hours life and 600° C with this method is 0.68, which agrees well with the model value of 0.72.

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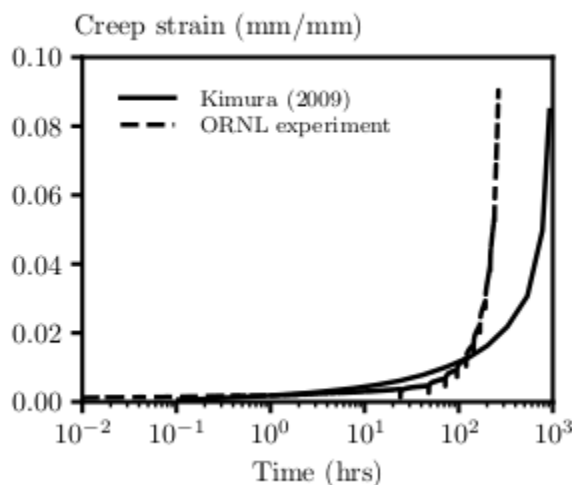


Figure 2.8. ORNL experimental data for the combined fatigue-creep test, compared to a reference creep curve for Grade 91 from Kimura, 2009 (Messner 2017).

High temperature softening factors

As described above, the model cannot distinguish damage from softening at very high temperatures above 600°C. To establish the softening factor at this temperature two specialized cyclic tests of the type described above were performed at Oak Ridge National Laboratory at 625°C and 650°C. In each test the sample was cycled under strain-controlled, fully reversed loading for 100 cycles through a strain range of 1%. Then the sample was held fixed at a constant stress, 130.6 MPa for 625°C and 99.7 MPa for 650°C, for approximately 24 hours to establish a steady creep rate. This process was repeated until the sample failed.

Using the procedure outlined above these tests can be converted into isochronous stress-strain curve softening factors for each 100 cycle increment. Figure 2.9 plots the calculated softening factors for 625°C and Figure 2.10 plots the factors for 650°C. In both cases the experimental results match the model predictions – the softening factors plotted as a function of cycle count show no trend that could be extrapolated out to a theoretical saturated, softened state. Damage and softening are indistinguishable.

To establish softening factors above 600°C we instead rely on a different argument. The loading conditions in these tests – both the strain range and the hold time – will bound the conditions experienced by a component in service. For example, the time corresponding to a stress of 99.7 MPa at 650°C from the Code minimum stress-to-rupture Table HBB-I-14.6F is only 178 hours. Similarly, at strain range of 1% will bound the strain range experience in service by actual components. Figures 7 and 8 provide direct experimental evidence that for these bounding loading conditions softening factors of 0.5 for 625°C and 0.3 for 650°C are reasonable for 700 to 800 load cycles. 700 cycles should reasonably bound the number of service loading cycles experienced by an actual component. Therefore, we set the softening factor at 650°C to the experimentally-determined value of 0.3. An additional entry of 0.5 at 625°C is not necessary because linearly extrapolating between the model factor of 0.72 at 600°C and a factor of 0.3 at 650°C produces a factor of 0.51 at 625°C, sufficiently close to the experimental value of 0.5.

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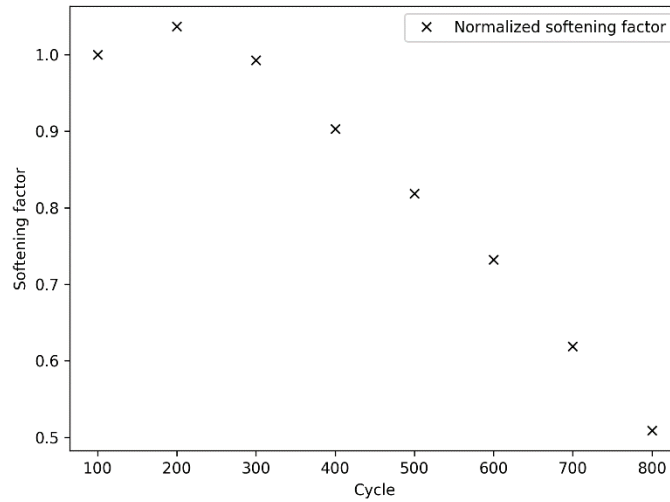


Figure 2.9. Softening factors as a function of cycle count for 625°C as calculated from the ORNL experimental data.

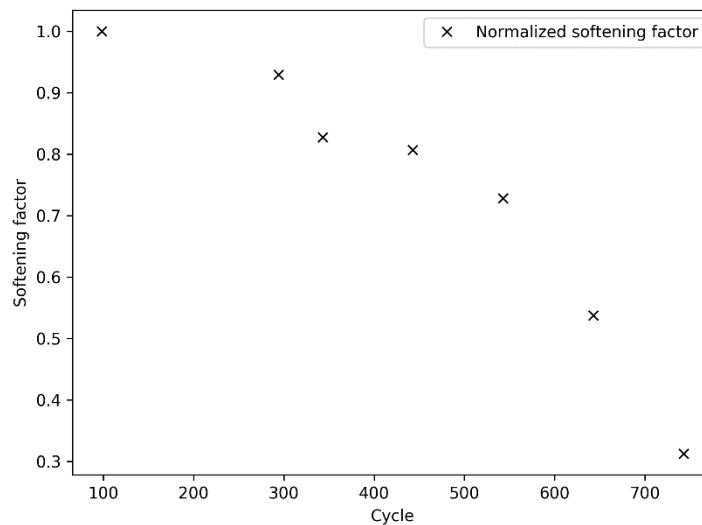


Figure 2.10. Softening factors as a function of cycle count for 650°C as calculated from the ORNL experimental data.

Modifications to the base Code Case N-861

The only substantial modification to the existing Code Case N-861 Revision 0 for 304 and 316 SS is to add a requirement applying the softening factors when calculating the pseudo-yield stress. For the stainless steels the softening factors are 1.0, which is exactly equivalent to the Revision 0 method. The softening factors for Grade 91 proposed in the Code Case are based on the work described in the previous section. The softening factors have been interpolated to evenly spaced temperatures in Fahrenheit.

In addition to this substantive modification the proposed Code Case includes minor revisions to N-861. The inquiry and response was altered to allow the use of the method for 9Cr-1Mo-V,

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some minor textual errors were corrected, and the Appendix updated with some new advice to designers on shakedown analysis based on prior experience working with N-861 and N-862.

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3. N-862: Creep-fatigue

3.1. Draft Code Case Language

Code Case N-862-1

Calculation of Creep-Fatigue for Division 5 Class A Components at Elevated Temperature Service Using Elastic-Perfectly Plastic Analysis

Section III, Division 5

Inquiry: What alternative rules may be used for the calculation of creep-fatigue damage in compliance with Section III, Division 5, Subsection HB, Subpart B, HBB-3252 and Nonmandatory Appendix HBB-T for Type 304 SS, Type 316 SS, and 9Cr-1Mo-V steel?

Response: Fatigue and cyclic creep damage may be evaluated for 304 SS, 316 SS, 9Cr-1Mo-V steel per Section III, Division 5, Table HBB-I-14.1(a) using elastic-perfectly plastic material models instead of the procedures of Section III, Division 5, HBB-T-1420, HBB-T-1430, and HBB-T-1715 when performed in accordance with the requirements of this Code Case.

1 General Requirements.

Except as identified herein, all requirements of Section III, Division 5, Subsection HB, Subpart B apply to components designed in accordance with this Code Case.

The design methodology employed for evaluation of cyclic creep damage is based on rapid cycle elastic shakedown analyses using an elastic-perfectly plastic material model, small strain theory and a “pseudo” yield strength selected to bound creep damage. In this Code Case, “shakedown” refers to the achievement of cyclic elastic behavior throughout the part, based on real or pseudo yield properties. In this code case the term “pseudo yield stress” refers to a temperature dependent minimum stress-to-rupture value based on a selected trial time duration, not to exceed the yield strength of the material at temperature and is explicitly defined in Section 4, Step 2 of this Code Case. Guidance on shakedown analysis is provided in Appendix I of this Code Case.

The combination of Levels A, B, and C Service loadings shall be evaluated for accumulated creep and fatigue damage, including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage at each point in the component shall satisfy the following relation:

$$D_c + D_f \leq D \quad (1)$$

where

D = total creep-fatigue damage as limited by Section III, Division 5, Figure HBB-T-1420-2

D_c = cyclic creep damage as determined in Section 4, below, of this Code Case

D_f = fatigue damage as determined in Section 5, below, of this Code Case

(a) This design methodology is not applicable to structures where geometrical nonlinearities exist, e.g. canopy and omega seals.

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(b) The stamping and data reports shall indicate the Case number and applicable revisions.

2 Load Definition.

Define all applicable loads and load cases per Section III, Division 5, HBB-3113.2, Service Loadings.

2.1. Composite cycle definition.

For the purpose of performing an elastic-perfectly plastic shakedown analysis, an overall cycle must be defined which includes all relevant features from the individual Level A, B and C Service Loadings identified in the Design Specification. Relevant features include as a minimum the time dependent sequence of thermal, mechanical and pressure loading including starting and ending conditions. Such an overall cycle is defined herein as a composite cycle subject to the following requirements.

(a) An individual cycle as defined in the Design Specifications cannot be split into individual cycles to satisfy these requirements.

(b) Except as described in (c), below, a single cycle from each Level A, B and C Service Loading cycle type shall be included in the composite cycle for evaluation of creep-fatigue.

(c) Level C Service Loadings may be combined with the applicable Level A and B Service Loadings to define a composite cycle(s) to be evaluated separately from the cycle defined in (b). Multiple composite cycles that include Level C Service Loadings may be defined for separate evaluation. The total number of Level C Service Loading cycles shall not exceed 25.

3 Numerical Model.

Develop a numerical model of the component including all relevant geometric characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The model must also be accurate for small details, such as small holes, fillets, corner radii, and other stress risers. The local temperature history shall be determined from a thermal transient analysis based on the thermal boundary conditions determined from the loading conditions defined in Section 2.

4 Calculation of Cyclic Creep Damage.

Perform a shakedown analysis for each of the composite cyclic histories defined in 2.1. Each of these cyclic histories must be shown to shakedown based on the pseudo yield stress defined in Step 2. Additional requirements for welds are found in Section 6.

Step 1: Define t_{design} as the total time duration for all Level A, B, and C Service Loadings when the temperature is above the range covered by Section II, Part D, Subpart 1, Tables 2A, 2B, and 4.

Step 2: Select a trial time duration, T'_d in order to define a pseudo yield stress, $S_{T'_d}$, at each location, using the temperature determined from the transient thermal analysis. This pseudo yield stress is equal to the lesser of the quantities defined in (a) and (b) below.

(a) The yield strength S_y given in Section III, Division 5, Table I-14.5;

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(b) S_r , where S_r is the minimum stress to rupture in time T'_d from Section III, Division 5, Figures HBB-I-14.6 multiplied by the factor, K' , from Table HBB-1411-1 using the tabulated values for elastic analysis.

Step 3: Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in Section 2 above with temperature-dependent pseudo yield stress $S_{T'_d}$. The assessment temperature shall be taken as the local instantaneous temperature at every location in the numerical model of the component. If shakedown occurs, that is, cycles with eventual elastic behavior everywhere, proceed to Step 4. If shakedown does not occur the applied loading does not meet the requirements of this Code Case.

Step 4: The maximum creep damage over the structure for the composite cycle under consideration is:

$$D_c = \frac{t_{design}}{T'_d} \quad (2)$$

The above value of D_c is used to evaluate total damage in Section 1, Eq. (1). If the pseudo yield strength in Section 4, Step 2 is governed by the yield strength as defined in Section 4, Step 2, (a), then the trial time duration for use in Eq. (2) is given by the time at which the minimum stress to rupture is equal to the yield strength; $S_r = S_y$. Linear extrapolation of S_r values corresponding to the two longest tabulated times can be used to obtain the trial time duration when necessary.

4.4.1. Steps 2, 3 and 4 may be repeated to revise the value of D_c by selecting alternative values of the trial time duration, T'_d . Longer values of T'_d will reduce the calculated creep damage. However, these longer values will lead to lower values of the pseudo yield stress, $S_{T'_d}$, which will make shakedown more difficult.

5 Calculation of Fatigue Damage.

The fatigue damage summation, D_f , in Section 1, Eq. (1) is determined in accordance with Steps 1 through 3 below. Additional requirements for welds are found in Section 6.

Step 1: Determine all the total, elastic plus plastic, strain components for the composite cycle at each point of interest from the shakedown analysis performed in Step 3 of Section 4 above.

Step 2: Calculating the equivalent strain range in accordance with Section III, Division 5, HBB-T-1413 or HBB-T-141, when applicable, with Poisson's ratio $\nu^* = 0.3$.

5.3. Step 3: Determine the fatigue damage for each composite cycle from the expression:

$$D_f = \sum_j \frac{n_j}{(N_d)_j} \quad (3)$$

where

n_j = number of applied repetitions of cycle type, j

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$(N_d)_j$ = number of design allowable cycles for cycle type, j , determined from one of the design fatigue curves from Section III, Division 5, Figures HBB-T-1420-1 corresponding to the maximum metal temperature occurring during the cycle.

The value of D_f used to evaluate total damage in Section 1 Eq. (1) is the maximum value at any location in the numerical model.

6. Weldments.

Implementation of the evaluation of creep-fatigue damage in Sections 4 and 5 above for weldments requires additional consideration.

6.1 Weld Region

In the weld region, the pseudo yield stress value defined by T'_d in Section 4, Step 2(b) is reduced further by multiplying the value of S_r for the base metal by the applicable weldment stress rupture factor from Section III, Division 5, Table HBB-I-14.10.

6.2 Allowable Cycles

The number of allowable cycles, $(N_d)_j$, in the weld region is one half the number of allowable cycles from Section III, Division 5, Figures HBB-T-1420-1 for base material.

6.3 Requirements

The requirements for analysis of geometry of Section III, Division 5, HBB-T-1714 are applicable for satisfaction of the requirements of this Code Case.

6.4 Properties

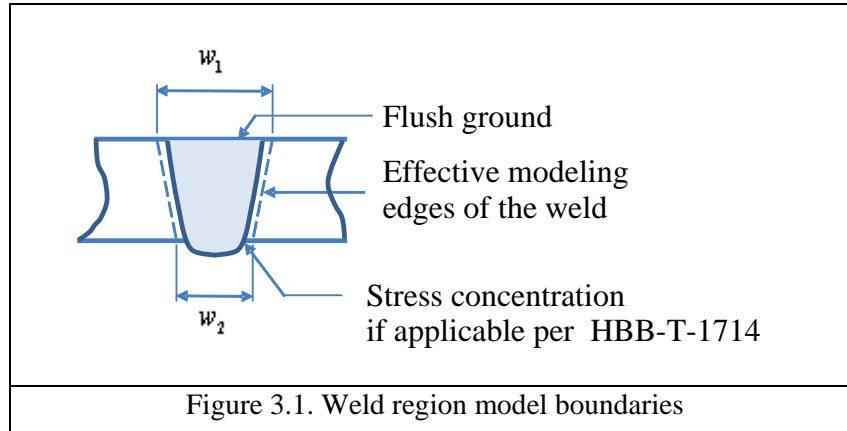
The thermal/physical properties of weldments may be assumed to be the same as the corresponding base metal for the base metal - weld combinations listed in Section III, Division 5, Table HBB-I-14.10.

6.5 Weld region model boundaries.

The weld shown in Figure 1 represents a general full-penetration butt weld in a shell. Other weld configurations are needed for construction of an elevated temperature component in accordance with Section III, Division 5, Subsection HB, Subpart B. Section III, Division 5, HBB-4200 refers to various Section III, Division 1, Article NB-4000 paragraphs for weld configurations and requirements. These Subsection NB weld configurations are represented by the shaded region.

Figure 3.1 shows a full-penetration butt weld as an example. As shown, w_1 and w_2 , as needed to define the weld region for use of this Case, are approximations consistent with the specified weld configuration and parameters. The specified weld region must include applicable stress concentrations in accordance with the requirements for analysis of geometry of Section III, Division 5, HBB-T-1714.

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6.6. Dissimilar metal welds.

This Code Case does not permit the evaluation of creep-fatigue in dissimilar metal welds.

Appendix I

Shakedown Analysis

Perform a ratcheting analysis to demonstrate compliance with strain limits as follows:

- (i) Define Composite Cycle Load Time-Histories and Step(s)
 - (a) Composite cycle load may consist of histories of mechanical loads, pressure loads, displacements, temperatures and thermal boundary conditions.
 - (b) Time-independent parts of the cycle may be truncated because elastic-perfectly plastic analysis is not time dependent.
 - (c) The cycle should not have discontinuities. Discontinuities arising from the selection of the specified cycles to form a composite cycle should be eliminated by a simple and reasonable transition from one state to the next.
 - (d) Subject to the requirements in (b), the composite cycle time does not affect the result of the shakedown analysis.
 - (e) Temperatures, thermal boundary conditions, boundary displacements and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.
 - (f) A single analysis step may represent one cycle. Dividing a single cycle into more than one step to facilitate definition of the load cycle, and to ensure that maximum loads are analyzed, is often helpful.
- (ii) Define Analysis Types.
 - (a) A sequentially coupled thermal-mechanical analysis of the composite cycle may be performed. First a thermal analysis is performed to generate temperature histories. Next the mechanical analyses are performed using these temperature histories as inputs. Care must be taken that times in the mechanical analysis step and in the previous thermal

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analysis are the same or do not conflict, depending on the requirements of the analysis software.

- (b) Alternatively, a coupled thermal-mechanical analysis may be performed. The composite temperature history to be used in the mechanical analysis should be cyclic, that is the beginning and end temperature distributions should be the same.

(iii) Define Material Properties.

- (a) For thermal analyses, density, temperature- dependent specific heat and conductivity will generally be required.
- (b) For the mechanical analyses the temperature-dependent properties required are modulus, Poisson's ratio and mean expansion coefficient. Density may also be required.

(iv) Perform Analyses.

- (a) Perform an elastic-plastic cyclic mechanical and thermal stress analysis using the temperature-dependent yield property defined above. Enough cycles are required to demonstrate shakedown or otherwise.
- (b) Care must be taken to ensure that the analysis deals with all the changes within a cycle. Elastic-plastic routines increase increment size where possible, and may miss a detail in the loading. A conservative limit to maximum increment size can address this problem, or division of the cycle into more than one step as in (a)(6) of this Appendix.
- (c) Numerical shakedown analysis using finite element analysis are extremely sensitive to the numerical parameters controlling the solution accuracy. Shakedown analysis should require the analysis method to report as accurate solutions as possible by decreasing solver tolerances and otherwise altering the solver parameters.

(v) Shakedown.

- (a) Shakedown is defined in this Code Case as eventual elastic behavior everywhere in the model.
- (b) Failure to shakedown may be identified by plotting histories of equivalent plastic strain. Alternatively, the dissipated plastic work can be plotted to quickly judge if an entire model has achieved elastic shakedown. The dissipated work should eventually stop increasing if the model elastically shakes down.
- (c) Because of accumulated numerical error finite element analysis results will never shakedown exactly. However, because this Code Case requires elastic shakedown the accumulated cycle-to-cycle strains or dissipated work in an analysis of an elastic shakedown configuration should be extremely small, on the order of the unit roundoff error.

3.2. Background document

Overview

The goal of this Code Case is to extend a previously developed method for using simplified, elastic-perfectly plastic analysis (EPP) for evaluating structures against the Section III, Division

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5 creep-fatigue design criteria to 9Cr-1Mo-V steel. The method has been previously established and codified for 304 and 316 stainless steel through Code Case N-862. This background document does not reiterate the detailed derivation of the method nor the validation experiments and numerical studies used to demonstrate its conservatism. For this basic background method refer to the following bibliography:

- Background documents for Code Case N-862.
- Carter, P. “Analysis of cyclic creep and rupture. Part 1: bounding theorems and cyclic reference stresses.” *International Journal of Pressure Vessels and Piping*, 82(1): pp. 15-26, 2005.
- Carter, P. “Analysis of cyclic creep and rupture. Part 2: Calculation of cyclic reference stresses and ratcheting interaction diagrams.” *International Journal of Pressure Vessels and Piping*, 82(1): pp. 27-33, 2005.
- Carter, P., Jetter, R. I., and Sham, T.-L. “Application of shakedown analysis to evaluation of creep-fatigue limits.” In the *Proceedings of the ASME 2012 Pressure Vessels & Piping Conference*, Toronto, Canada, 2012.

The proposal is a Revision 1 of the original Code Case N-862 adding Grade 91 as an acceptable material for use with the method.

The EPP method for creep-fatigue evaluation described in these references is general – it should apply to any material. However, 9Cr-1Mo-V (Grade 91) steel differs from the austenitic stainless steels for which the EPP methods were validated in that Grade 91 shows cyclic softening behavior at moderately elevated temperatures and even work softening behavior at high temperatures, greater than 600° C. Cyclic softening means that the material flow stress decreases with the number of prior cycles in strain controlled cyclic loading (fatigue loading). This means, for example, the maximum stress observed in a cycle tends to decrease as a function of cycle count for Grade 91, whereas it tends to increase as a function of cycle count in cyclic-hardening materials like 316 and 304.

The EPP creep-fatigue method relies on bounding the rupture stress of the material using the Code values of the rupture stress, S_r . These values are correlated from creep test data representative of the material in the reference, unsoftened condition. If prior cycling lowers the rupture stress, which it tends to for cyclic softening materials, then this could impact the conservatism of the bound on the rupture life used by the EPP method to compute conservative values of creep damage. If the EPP method does not conservatively bound creep damage then it may fail to conservatively bound the overall creep-fatigue damage.

This background document describes a methodology used to determine if cyclic softening negatively affects the previously-established EPP method for creep-fatigue evaluation. The approach uses a consistent comparison to an inelastic model to demonstrate that the baseline EPP method, already established for 304 and 316 stainless steel, will be adequately conservative when applied to Grade 91, despite cyclic softening. The reason is that the Code creep-fatigue interaction diagram, used in the EPP method to compute creep-fatigue damage, already accounts for the interaction of cyclic softening on rupture life. In fact, the creep fatigue interaction diagram was basically developed to account for the effect of prior fatigue on creep rupture and vice-versa, so it is unsurprising that no modifications are required to account for cyclic softening.

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This document provides a brief overview of the base EPP method, an abbreviated description of the technique used to evaluate potential problems introduced by cyclic softening, and a discussion of the modifications in the proposed Code Case when compared to Code Case N-862 (which are minimal). A publically available DOE report provides full details on the analysis used to justify the extension of the method to Grade 91:

- Messner, M. C. and Sham, T.-L. “Initial development and extension of EPP methods to Grade 91.” Argonne National Laboratory technical report ANL-ART-133, 2018.

Overview of the EPP method

The objective for the EPP methods in general is to simplify the complicated Section III, Division 5, HBB Appendix T rules based on an elastic stress analysis. Furthermore, the EPP methods can make use of modern finite element analysis. For example, they do not require stress classification or linearization and the creep-fatigue method can be evaluated point-by-point over the entire structures, as opposed to the Appendix T methods that deal with through-thickness sections.

The EPP creep-fatigue method relies on bounding the rupture life of a structure by finding an elastic shakedown solution with a residual stress field that bounds the actual creep damage in a structure. The EPP procedure is iterative so that a designer can search for the rapid cycle solution, which is the best possible (least over-conservative) bound. The Code Case computes creep damage using this rapid cycle solution. The procedure then directs the designer to evaluate fatigue damage using the standard Appendix T rules using the strain range given by the rapid cycle solution. This strain range already accounts for inelasticity and so the complicated modifications required in Appendix T for strain ranges based on elastic analysis are not required. Finally, given the fatigue and creep damage the designer uses the Appendix T creep-fatigue interaction diagram as an acceptance criteria for creep-fatigue damage. This processes explicitly accounts for the interaction of prior fatigue on creep.

The previous work cited above establishes the conservatism of this method for austenitic stainless steel and the nickel-based Alloy 617. The only question this Code Case addresses is if modifications to the base method are required to account for cyclic softening.

Assessing the method for cyclic softening conditions

To answer this question consider a consistent comparison to a full inelastic analysis. First, we develop an inelastic constitutive model that describes creep-fatigue deformation and damage in a cyclic softening material. A full description of the model used here is given in the DOE report mentioned above. The key features of this constitutive model are that it:

1. describes a realistic constitutive response, something that is reasonably representative of a Class A material;
2. it realistically describes failure under creep-fatigue loading, using a continuum damage model;
3. it describes a cyclic softening response, so that we can use it to assess the effects of cyclic softening.

It will not be important that the constitutive model perfectly describes the response of any real material. However, the model used here represents the response of Grade 91 steel as described

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by the Section III, Division 5 isochronous stress-strain curves, fatigue curves, and rupture life correlations.

Given this realistic material model we then generate synthetic design data sufficient to execute an EPP creep-fatigue analysis. This means we develop relations for the Young's modulus, Poisson's ratio, coefficient of thermal expansion, yield stress, rupture stress, fatigue life, and creep-fatigue interaction diagram based on simulated experiments. For each type of data we simulate a series of tests, for example for the fatigue curves a series of strain-controlled fatigue tests, and correlate the data to develop design allowables in *exactly the same way prescribed in the Code for adding an new Class A material*.

This process produces a set of design data that is consistent with the base inelastic model. We can compare the results of a full inelastic simulation of a component with an EPP creep-fatigue design life evaluation of the component using the consistent design data. This comparison is fair. It assesses the design method itself independent of any experimental or material variability present in actual experimental data. If the consistent EPP calculation produces a non-conservative design life when compared to the full inelastic simulation then there is a problem in the design method itself that must be corrected.

Figure 3.2 shows an example problem used to assess the impact of cyclic softening on the EPP creep-fatigue method. The geometry is a thin walled vessel away from any stress discontinuities under a combination of a constant pressure and a varying linear through-wall thermal gradient. Because we are interested in the effect of cyclic softening the vessel load was defined to allow us to vary the amount of pre-fatigue the vessel sees before creep-fatigue loading. The vessel first undergoes n_{pre} thermal fatigue cycles, where the outer wall temperature changes from T_a to T_b without any hold period. After these pre-fatigue cycle the thermal loading switches to creep fatigue – the outer wall temperature increases to T_b , holds at the hot temperature for 100 hours, and decreases back to T_a .

We analyzed the vessel for several different values of n_{pre} with two methods: the full inelastic, creep-fatigue damage simulations and a consistent companion EPP calculation. If cyclic softening negatively impacts the conservatism of the EPP creep-fatigue method then the EPP design life should become less and less conservative as the number of cycles increases. Figure 3.3 compares the full inelastic and EPP results. The EPP method is always conservative compared to the full inelastic calculation, no matter how many pre-fatigue cycles are applied to the vessel. This suggests that the current EPP method will be conservative without modifications, even for cyclic softening materials.

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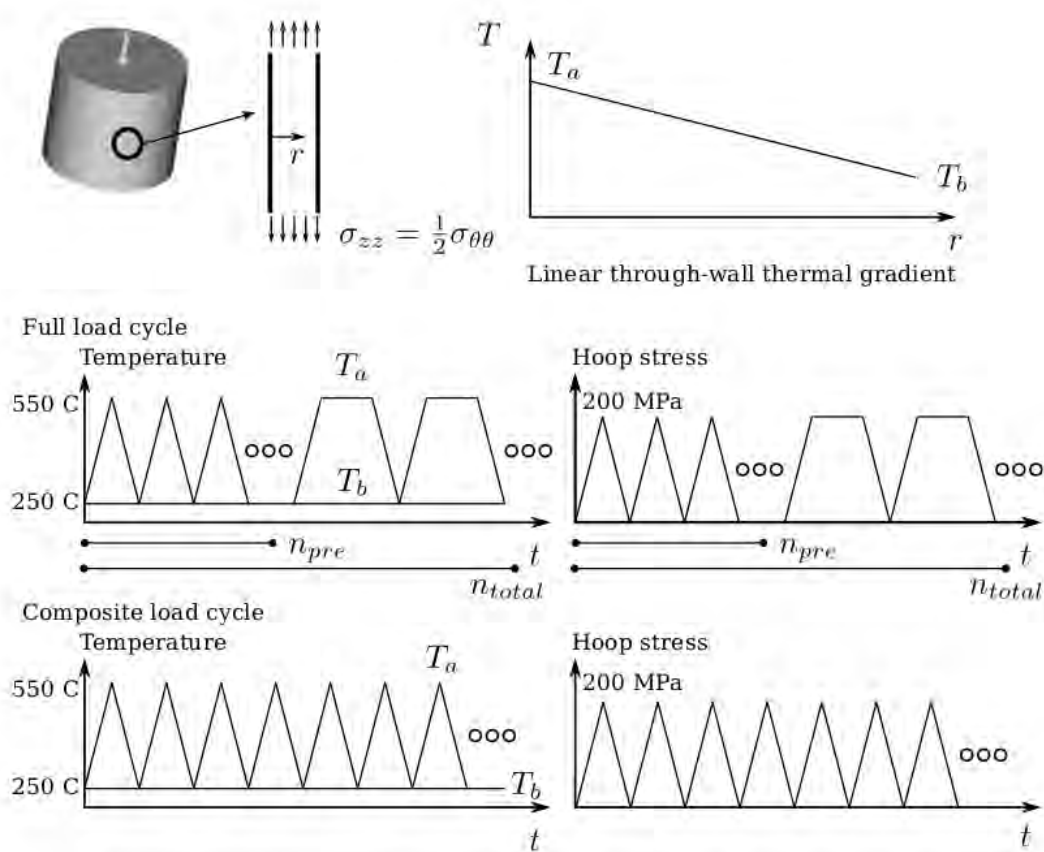


Figure 3.2. Example problem used to assess the effect of cyclic softening on the EPP creep-fatigue method (Messner, 2018).

No modifications are required because the basic method already accounts for cyclic softening through the creep-fatigue interaction diagram. The purpose of the diagram is to account for the interaction of creep and fatigue loading – exactly the concern for cyclic softening materials. The diagram is generated by plotting the results of a number of creep-fatigue experiments which, for Grade 91, clearly include any effect cyclic softening has on creep damage directly in the test data. As such, the EPP creep-fatigue method, which references the diagrams in computing creep-fatigue damage, already accounts for cyclic softening. No modifications are required to the method already approved for the austenitic stainless steels.

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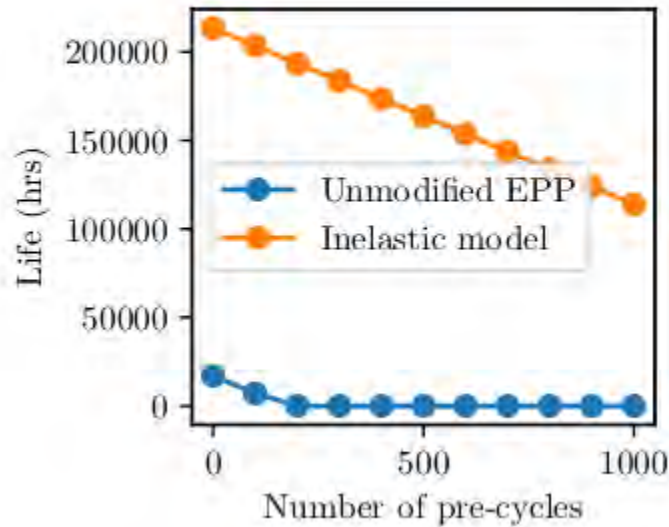


Figure 3.3. Results of the comparison: the unmodified EPP method is always conservative, even with a substantial number of pre-fatigue cycles (Messner, 2018).

Modifications to the base Code Case N-862

There are minimal modifications in the proposed revised Code Case when compared to the approved Code Case N-862 Revision 0 for 304 and 316 stainless steel. The inquiry and response have been modified to apply the Code Case to 9Cr-1Mo-V. Some minor textual errors have been corrected. Finally, Appendix I was altered to include new advice to the analyst on running shakedown calculations that has been gained from extensive use of Code Case N-862. These modification include advice on setting the solver parameters in finite element analysis software and suggestions on what quantities to plot to easily establish whether a particular simulation has shaken down to elastic action.

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4. Conclusions

This report represents the substantial completion of work extending the EPP Code Cases to cover Grade 91 steel. The balloting package contained here has been reviewed by ASME up to the Working Group level. At the time of writing the revised Code Cases were being balloted to at the Subgroup level. Unless substantial technical concerns are raised at the subgroups, the final ballot before the BPV III book committee will occur after a presentation at the August 2019 Code Week. ASME policy is to make revised Code Cases available for use immediately, and so designers could begin to apply the EPP methods to Grade 91 components soon after BPV III approval.

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Applied Materials Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439

www.anl.gov



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