Approval Date: February 11, 2016

Editor: update date

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-862-1

Editor: add -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?

Editor: replace text with highlighted

Reply: Fatigue and creep damage may be evaluated for ~~Type 304 SS and 316 SS~~ Type 304 SS, Type 316 SS, and 9Cr-1Mo-V 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 creep damage is based on 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 4, Step 2 of this Code Case. Guidance on shakedown analysis is provided in ~~Mandatory~~ Appendix I of this Code Case.

Editor: make changes to text

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:

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

where

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

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

D_f = fatigue damage, as determined in 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.

(b) The stamping and data reports shall indicate the 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 shakedown analysis, an overall cycle must be defined that 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 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 2.

4 CALCULATION OF 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 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.

(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 Section III, Division 5, Table HBB-T-1411-1 using the tabulated values for elastic analysis.

Step 3. Perform a cyclic elastic-perfectly plastic analysis for each composite cycle defined in 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

$$D_c = \frac{t_{\text{design}}}{T'_d} \tag{2}$$

The above value of D_c is used to evaluate total damage in 1, eq. (1). If the pseudo-yield strength in Step 2 is governed by the yield strength as defined in 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.

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 1, eq. (1) is determined in accordance with Steps 1 through 3 below. Additional requirements for welds are found in 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 4, Step 3 of 4 above.

Step 2. Calculate the equivalent strain range in accordance with Section III, Division 5, HBB-T-1413, or HBB-T-1414 when applicable, with Poisson's ratio, $\nu^* = 0.3$.

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

$$D_f = \sum_j \frac{n_j}{\left(N_d\right)_j} \tag{3}$$

where

n = number of applied repetitions of cycle type, j

$(N_d)_j$ = 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 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 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 4, Step 2(b) is reduced further by multiplying the value of S_r for the base metal by the applicable weld strength reduction 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 materials.

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

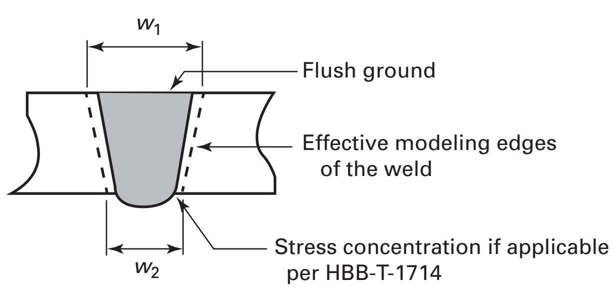
The weld shown in Figure 1 represents a general full-penetration butt weld in a shell. Other weld configurations are needed for construction of an elevated temperature component in accordance with Section III, Division 5, Subsection HB, Subpart B. Section III, Division 5, HBB-4200 refers to various Section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

Figure 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.

6.6 DISSIMILAR METAL WELDS

The requirements for dissimilar metal welds are in the course of preparation.

Figure 1
Weld Region Model Boundaries



R18-1764

Editor: remove word

~~MANDATORY~~ APPENDIX I
SHAKEDOWN ANALYSIS

I-1 GENERAL

Perform a shakedown analysis to calculate bounding cyclic creep damage as follows:

(a) Define Composite Cycle Load Time-Histories and Step (s)

(1) Composite cycle load may consist of histories of mechanical loads, pressure loads, displacements, temperatures, and thermal boundary conditions.

(2) Time-independent parts of the cycle may be truncated because the elastic-perfectly plastic analysis is not time dependent.

(3) 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 operating state to the next.

(4) Subject to the requirements in (b), the composite cycle time does not affect the result of the shakedown analysis.

(5) Temperatures, thermal boundary conditions, boundary displacements, and mechanical loads over a cycle should be cyclic; that is, begin and end at the same value.

(6) 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.

(b) Define Analysis Types.

(1) 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.

Editor: Add number as indented list

Editor: Add number as indented list

(2) 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.

(c) Define Material Properties

(1) For thermal analyses, density, temperature-dependent specific heat, and conductivity will generally be required.

(2) For the mechanical analyses, the temperature-dependent properties required are elastic modulus, Poisson's ratio, and mean expansion coefficient. Density may also be required.

~~*(d) Perform Analyses.* Perform an elastic plastic cyclic mechanical and thermal stress analysis using the temperature dependent yield stress defined above. Enough cycles are required to demonstrate shakedown or otherwise.~~

~~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.~~

~~*(e) Shakedown.* Shakedown is defined in this Code Case as eventual elastic behavior everywhere in the model. Failure to shakedown may be identified by plotting histories of equivalent plastic strain.~~

Editor: Replace strike through text with the section on the following page

R18-1764

(d) Perform Analyses.

(1) Perform an elastic-perfectly plastic cyclic mechanical and thermal stress analysis using the temperature-dependent yield stress defined above. Enough cycles are required to demonstrate shakedown or otherwise.

(2) 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 discussed in (a)(6) of this Appendix may also be used.

(3) Numerical shakedown analysis using finite element analysis is 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.

(e) Shakedown.

(1) Shakedown is defined in this Code Case as eventual elastic behavior everywhere in the model.

(2) 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.

(3) 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 (10^{-15} for double precision arithmetic and 10^{-7} for single precision arithmetic).

(4) Because of differences in finite element solver implementations, this appendix only represents best practices and may not be applicable to all finite element software. The designer ultimately must determine whether the analysis achieves elastic shakedown when executing this Code Case.