ASME Cyclic Creep Evaluation of Critical Piping Component using CREEP Subroutine and ORNL Test Data

Brent M. Saba

Saba Metallurgical and Plant Engineering Services, LLC

Abstract: *A critical piping component, constructed of Alloy 800-HT, is evaluated for cyclic creep concerns. The inelastic strain analysis portion of the analysis is conducted assuming the material as perfectly plastic. This method of perfect plasticity was preferred due to the lack of kinematic hardening data for Alloy 800-HT, especially at temperatures above the 800°F limitation of the ASME Section VIII Div. 2 Code. A CREEP subroutine was created using Oak Ridge National Laboratory test data and curve fitting equations. The CREEP subroutine was then allowed to realistically model primary creep, secondary creep, creep initiation, and creep relaxation. Cyclic creep conditions (equivalent strain range and equivalent creep stress) were evaluated using ASME Section III-NH. The individual creep contribution to the combined fatigue life was nil; however, the creep relaxation on plastic cycling was quite significant. Without the CREEP subroutine with the ORNL data, obtaining this creep-plastic relationship would have been difficult to duplicate, requiring a much more conservative approach.*

Keywords: *ASME Codes, Creep, Creep-Fatigue, Creep Initiation, Creep Relaxation, CREEP Subroutine, Cycle-by-Cycle Analysis, Cyclic-Creep, Elastic-Inelastic Analysis, Equivalent Creep Stress, Equivalent Strain Range, Fatigue, Fatigue Life, Low-Cycle Fatigue, Fortran, Finite Element Analysis, Perfect Plasticity, Pipe Components, Primary Creep, Secondary Creep, Thermal Stress*

1. Introduction

Abaqus is used to evaluate a critical piping component in a major refinery process that is subject to cyclic creep conditions. The piping component, a wye, is constructed of Alloy 800-HT (UNS N08811), a Nickel-Chromium-Iron alloy with aluminum and titanium additions. The wye is under significant load fluctuations from attached piping, primarily due to thermal expansion under cyclic temperatures. The hot end of the cycle occurs within the creep regime for Alloy 800-HT. For this study, modeling of both primary and secondary creep effects are crucial to an accurate solution. To meet this objective, a CREEP subroutine has been created. Creep data and curve fitting data for 800-H material, performed by Oak Ridge National Laboratory (ORNL) was used as the basis for the Abaqus CREEP subroutine. Cyclic creep is outside the realm of the typically used ASME Section VIII Division 2. Instead, nuclear Code ASME Section III – NH is required for evaluation.

2. ORNL 800-H Creep Data

The 800-H creep test data from the Oak Ridge National Laboratory (ORNL) [1] was used to develop a FORTRAN creep subroutine, which is then used to define the creep properties within Abaqus. The ORNL data consists of nearly 130 pages of raw material data for creep of 800-H material under varying thickness, temperatures, and loading. The document also contains an additional 70 pages of equation curve fitting and verification. It is these curves that are used as the basis for the creep subroutine in this cyclic-creep analysis.

Typically, under steady-state creep conditions, primary creep is not a concern; however, under this cyclic condition, primary creep is believed to be of significant importance. One of the main objectives of this full cycle analysis is to include the effects of primary creep in the material creep properties, as well as consideration to time to creep initiation. The equation of the curve fit data provided by ORNL includes both primary and secondary creep characteristics.

Figure 1 shows one of the 100+ raw data plots of strain percent versus time (at defined temperatures and stress). This plot is selected as it is typical to the vast majority of data plots provided in the report, except that this plot has test data for only a short duration (most others are 1000s of hours).

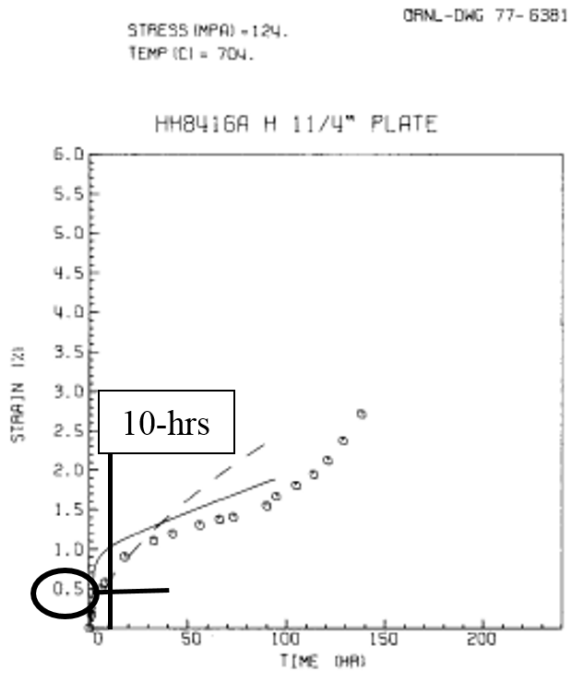

Figure 1: Test Data for 800-H at 124-MPa at 704°C

Selection of this chart allows close study of how quickly creep strain is initiated, relative to the overall cycle time (several hours). In this figure, each minor increment is 10-hrs. It can be seen

that within 10-hrs, 0.5% of creep strain has already occurred. All of the strain at this point is primary creep. From observation from this figure, initiation of creep appears to occur within minutes. For sake of this analysis, creep initiation is considered to occur instantaneously.

3. ORNL Curve Fit and Creep Variables

The total primary creep strain can be combined with the total secondary creep strain and divided by time to tertiary creep to formulate an overall creep rate ($\acute{\varepsilon}_2$). The methods ORNL uses to capture $\acute{\varepsilon}_2$ are not exactly as the last sentence states, but instead they use several other variables (i.e. time to rupture, minimum creep rate, etc.) to calculate $\acute{\varepsilon}_2$. The methods they use provide a much greater degree of accuracy of curve fitting over the simple methods initially stated. The curve fit of their $\acute{\varepsilon}_2$ has a coefficient of determination (R^2) equal to approximately 75%.

ORNL uses two methods to calculate $\acute{\varepsilon}_2$. There exists only minor differences in the results of the two curve fits. For the CREEP subroutine, the curve fit equation of particular use is the following:

$$\log(\dot{e}_2) = 24.31 - \frac{40270}{T} + \frac{7040}{T} \cdot \log(\sigma) \qquad (1)$$

$\acute{\varepsilon}_2$ = strain rate (primary and secondary combined)
T = temperature (°C)
σ = stress (MPa)

One of the steady-state evaluation criteria for creep is time to tertiary creep (80% of this time being a design restriction). An equation for $\acute{\varepsilon}_2$ now exists that provides the rate between zero and tertiary creep. The next step is to determine how long it takes to get to tertiary creep based on a given stress and temperature. The following equation is the best curve fit data to determine this time, defined as e_{ss} by ORNL:

$$\log(e_{ss}) = 4.865 - \frac{8360}{T} + \frac{1440}{T} \cdot \log(\sigma) \qquad (2)$$

e_{ss} = time to tertiary stress (hrs)

Equation (2) is not valid for lower creep temperatures and stress levels, but for the current design of high temperatures and relatively high stresses, this equation is adequate.

4. CREEP Subroutine

The CREEP subroutine was written within Visual Studio 2010 Professional, using Intel Visual Fortran Composer XE 2013. Notes from installation process and setup of these programs to run the Abaqus subroutine are shown in Appendix 1. A printout of the source Fortran coding for the CREEP subroutine is shown in Appendix 2.

Only Equation No. 1 is necessary to develop the variables and constants in the Fortran Code. The first set of defined constants are taken directly from Equation No. 1:

A = 24.31
B = 40.270
C = 7040

Several of the variables are also defined in Equation 1:

T = Temperature (originally in °C, but converted to °F using "T1"
QTILD = σ (equivalent deviatoric Mises stress)
F = log ($\dot{e}_2$)

This leads to the development of the critical variables that define creep within the CREEP subroutine [2]:

DECRA(1) = equivalent (uniaxial) deviatoric creep strain increment = EXP (F) * DTIME
DECRA(5) = $\frac{\partial(\dot{e}_2)}{\partial(QTILD)}$ = (DTIME*EXP(F)*C/(T1*QTILD1))*FACTOR1
DTIME = time increment (hrs)

The most difficult task, mathematically speaking is taking the partial derivative of $\dot{e}_2$ with respect to QTILD in order to determine DECRA(5). This partial derivative is solved by substitution. For consistency sake, the partial derivative sign will be retained for the plain differential.

$$\log(\dot{e}_2) = 24.31 - \frac{40270}{T} + \frac{7040}{T} \cdot \log(\sigma) \quad (1)$$

Log($\dot{e}_2$) will be replaced by R, F=$\dot{e}_2$, C = 7040, and σ = QTILD. Also, when taking the partial derivative the 1st and 2nd terms on the right-hand side of Equation No. 1 will become zero. The equation can now be written as:

$$R = \frac{C}{T} \cdot \log(QTILD) \quad (2)$$

The partial derivative of $\frac{\partial(F)}{\partial(QTILD)}$ is then equal to:

$$\frac{\partial(F)}{\partial(QTILD)} = \frac{\partial(R)}{\partial(QTILD)} * \frac{\partial(F)}{\partial(R)} \quad (3)$$

The first term in Equation No. 3 is the desired variable DECRA(5). The second and third terms are calculated as follows:

$$\frac{\partial(R)}{\partial(QTILD)} = \frac{C}{T} * \frac{1}{QTILD} \quad (4)$$

$$\frac{\partial(R)}{\partial(F)} = \frac{1}{F} \quad (5)$$

Now, Equation No. 3 can be solved:

$$\frac{\partial(F)}{\partial(QTILD)} = \frac{\partial(R)}{\partial(QTILD)} * \frac{\partial(F)}{\partial(R)} = \frac{C}{T*QTILD} * F * DTIME = \frac{DECRA(1)*C}{T1*QTILD1} * FACTOR1 \quad (6)$$

DTIME is added due to the use of implicit integration [2]. F*DTIME is equal to DECRA(1). Both T1 and QTILD1 are English unit variable equivalents. FACTOR1 is a metric to English unit correction factor necessary to balance this partial derivative. Equation No. 6 is the exact form used in the subroutine for DECRA(5).

Some additional notes for this subroutine are the following:

- LEXIMP.EQ.1 flags the creep integration as implicit [2].
- A minimum creep is set for temperatures below 1000°F.
- Stress cannot be zero or negative; these stress values become 0.01-psi.
- The time increment in Abaqus must be in hours.

5. Elastic/Plastic/Creep (Subroutine) Cycle-by-Cycle Analysis

The wye component is CAD modeled, meshed, loaded/constrained and run through six complete cycles. Temperatures for the hot end cycle are derived from a heat transfer model using calculated convection coefficients.

5.1 Meshed FEA Model

A 3D CAD model was cut down to a quarter symmetry model, where it was further partitioned to create structured and swept meshes using solid hexahedral elements. The quarter symmetry model was meshed, and then the mesh mirrored and merged together to create a symmetrically meshed model (Figure 2). All thicknesses have a minimum of three elements across the cross-section. A mesh sensitivity study was performed on a similar previously analyzed model showing three elements across the cross-section provided stable results.

A reference point is assigned at each flange face center. Kinematic couplings are created using the reference points as the master node and the flange face as the slave surface. A local cylindrical coordinate system is created at the center of each flange face. The kinematic coupling is applied such that all degrees of freedom are fixed, except for the radial direction. This allows the flange face to expand without stress due to thermal expansion. Piping displacements/ rotations, obtained from an external pipe program, are applied to the reference points, which help keep the entire wye properly fixed in space. These piping displacements/rotations vary with each step.

Figure 2: Solid CAD Model of Wye

5.2 Heat Transfer Analysis

The process convection coefficients are applied, producing the temperature contour map shown in Figure 3. These results are for one of the two hot cycle extremes. One cycle goes from ambient to hot on one side of wye leg, to an intermediate (sustained) temperature, to hot on the other side of the wye leg, and then back down to ambient.

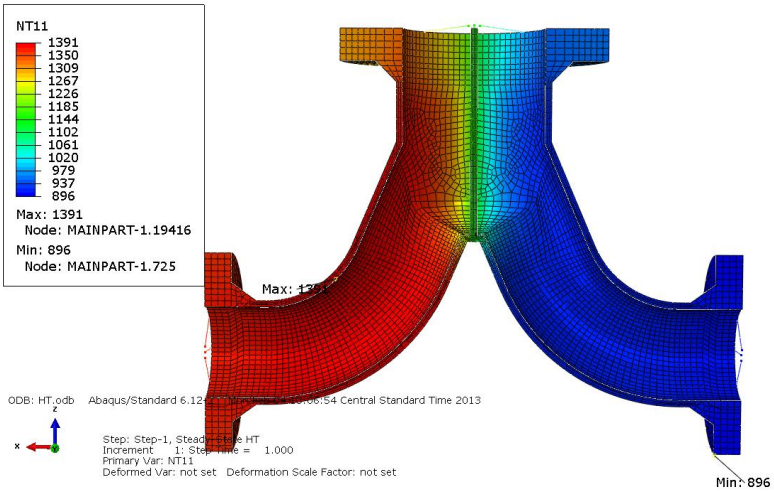

Figure 3: Thermal Results of Wye at Hot Cycle

5.3 Cycle-by-Cycle Step Setup

The aforementioned cycle is actually expanded slightly when setting up the steps within Abaqus. During each increase in temperature to the hot end (two occasions per cycle), only the piping and pressure loads are applied (General Static). A subsequent VISCO step then applies the creep, with temperature and piping/pressure loads held constant. The hold time for the creep allows for creep relaxation.

5.4 Additional Material Properties

Total strain will be a requirement for low cycle stress component evaluation for this wye. Normally, this would require a combined isotropic/kinematic hardening model. Due to the lack of reliable kinematic data for 800-HT, especially at the higher temperatures, the decision was made to take a more conservative route, which is the treatment of the material as perfectly plastic. After this analysis was performed, 2013 ASME Section VIII Div. 2 Code [3] became public and in it was the inclusion of the acceptable use of perfectly plastic treatment for low cycle fatigue analyses. All data is temperature dependent, and the remaining material property assignments are elastic and expansion.

6. FEA Results

Piping internal pressure produces minimal stresses for this application. The predominant cyclic loading factor is the piping loads. Since these are applied in a displacement controlled fashion, the plastic shakedown occurs, and not ratcheting. The creep actually acts to facilitate plastic shakedown instead of elastic shakedown (when switching between one hot leg to the other), resulting in nearly complete creep relaxation. That is, plasticity forms as the external piping loads

are applied, the creep relaxes these stresses to near zero, and then upon reduction of the piping loads, plasticity continues to accumulate.

Evaluation of yielding is better examined looking at changes in accumulated plastic strain. Table 1 is a record of the maximum accumulated plastic strain at the end of each cycle stage. Creep steps are omitted as they do not generate plasticity.

Table 1: Accumulated Plastic Strain for Each Cycle Stage – Worst Location

	Cycle #1	Cycle #2	Cycle #3	Cycle #4	Cycle #5	Cycle #6
Ambient	0	0.0062	0.0115	0.0164	0.0211	0.0254
Sustained	0.0021	0.0062	0.0115	0.0164	0.0211	0.0254
Hot Leg 1	0.0024	0.0073	0.0126	0.0175	0.0211	0.0265
Sustained	0.0040	0.0080	0.0132	0.0175	0.0225	0.0268
Hot Leg 2	0.0042	0.0096	0.0147	0.0195	0.0240	0.0283
Sustained	0.0062	0.0115	0.0164	0.0211	0.0254	0.0296
Ambient	0.0062	0.0115	0.0164	0.0211	0.0254	0.0296

From the results in Table 1, it is seen that plastic strain accumulation is extended between each cycle transition. The magnitude of the plastic strain change per cycle is shown in Table 2.

Table 2: Accumulated Plastic Strain for Each Cycle Stage – Worst Location

	1st Cycle	**2nd Cycle**	**3rd Cycle**	**4th Cycle**	**5th Cycle**	**6th Cycle**
Change in Plastic Strain	0.0062	0.0053	0.0049	0.0047	0.0043	0.0042

What is important in Table 2 is that although plastic accumulation is decreasing each cycle, the complete cycle is still operating in plastic shakedown (continual plastic accumulation each cycle). The degree of creep relaxation is shown in Figures 4 and 5. Figure 4 occurs in Cycle #3 at the Hot Leg 1 condition of pipe loading and thermal stresses. Figure 5 shows how after several hours of creep, the stresses relax to near zero.

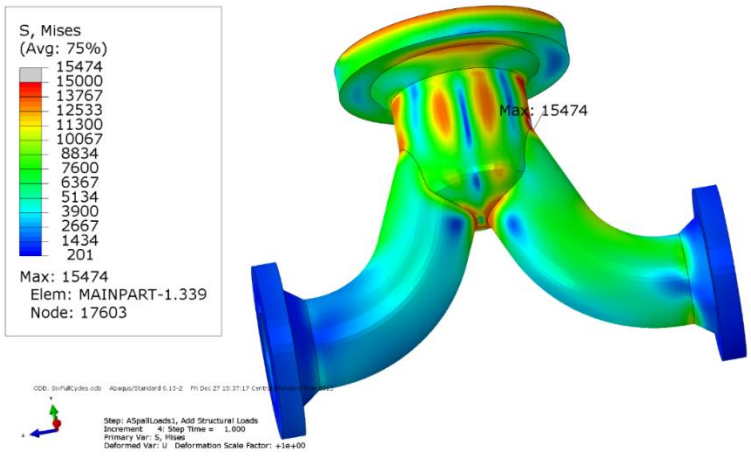

Figure 4: Cycle #3 – Hot Leg 1 - Stress prior to Creep Step

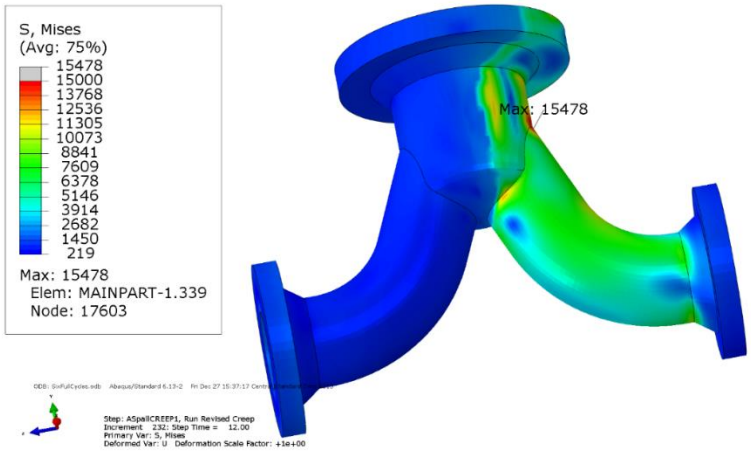

Figure 5: Cycle #3 – Hot Leg 1 - Stress after Creep Step

7. Equivalent Strain Range

From ASME III-NH Section NH-T-1413 [4], an equation for equivalent strain range is provided (Eq. 11 from Code). An equivalent strain range is used to evaluate the fatigue damage sum for both elastic and inelastic analyses. The first step for the inelastic analysis is to capture all strain components of all cycle points. The minimum extreme will be the ambient stage. The maximum extreme has to be determined by evaluation of each stage to produce an equivalent strain range. The highest value for the equivalent strain range will then indicate which stage contains the

maximum extreme. Even though there are two hot legs per cycle, the principal strain increases in a parabolic shape during each complete cycle. Therefore, there is only one minimum and one maximum. This simply means that the strain between hot leg heat-up switching does not provide any additional fatigue cycles to consider.

Figure NH-T-1420-1C (Design Fatigue Strain Range, e_t, for Ni-Fe-Cr Alloy 800H) from ASME III-NH allows for the use of the now calculated equivalent strain range. The additional variable in this chart (Figure 6) is local temperature.

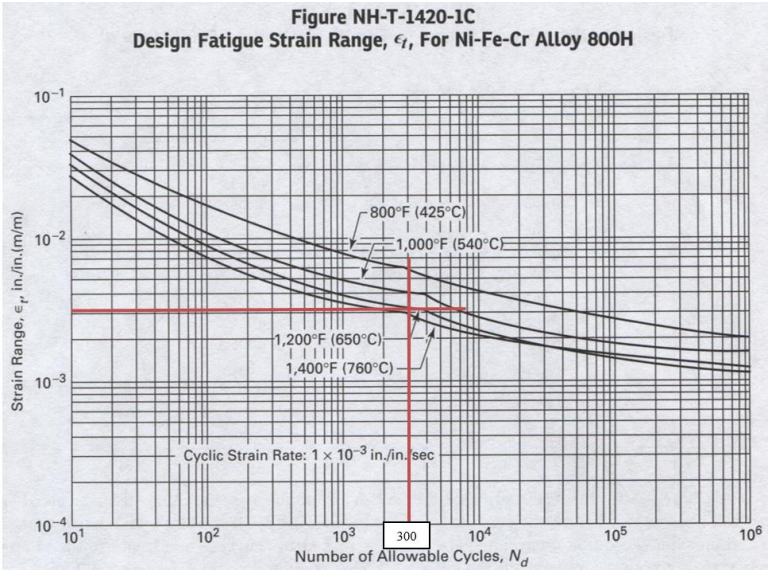

Figure 6: Design Fatigue Strain Range Curve for Alloy 800-H (ASME III-NH)

8. Equivalent Creep Stress

The stress data collected is the maximum principal stress, which is the tensile stress affected by creep. Tensile stresses have approximately $1/10^{th}$ the creep life that of compressive stresses under identical loads and temperatures [5]. The average maximum principal stress during the 6^{th} cycle of Hot Leg 2 at Node #11753 is 1888-psi. Of particular note was that the stress dropped to nearly 2300-psi within 1-hr of maximum hot leg temperature. The von Mises stress intensity is quite less than 1888-psi; therefore, the maximum principal stress value was used for evaluation purposes. Per Code this value must be divided by 0.67 (from III-NH Table NH-T-1411-1), resulting in an equivalent stress value of 2820-psi.

ASME III-NH provides Figure NH-I-14.6C (Minimum Stress-to-Rupture – Ni-Fe-Cr (Alloy 800H)) for evaluation of creep. Figure 7 shows this relevant minimum stress-to-rupture set of curves. Notice in this figure that the average stress of 2820-psi is well below the 1250°F curve.

Therefore, creep is not considered a concern at this location of the wye, even with consideration to stress rupture factors for Alloy 800 welded with SFA-5.14 ERNiCr-3 (Inco-82), as provided by ASME III-NH Table NH-I-14.10C-2. The equivalent stress value in a weld is 2820-psi/0.8 = 3525-psi.

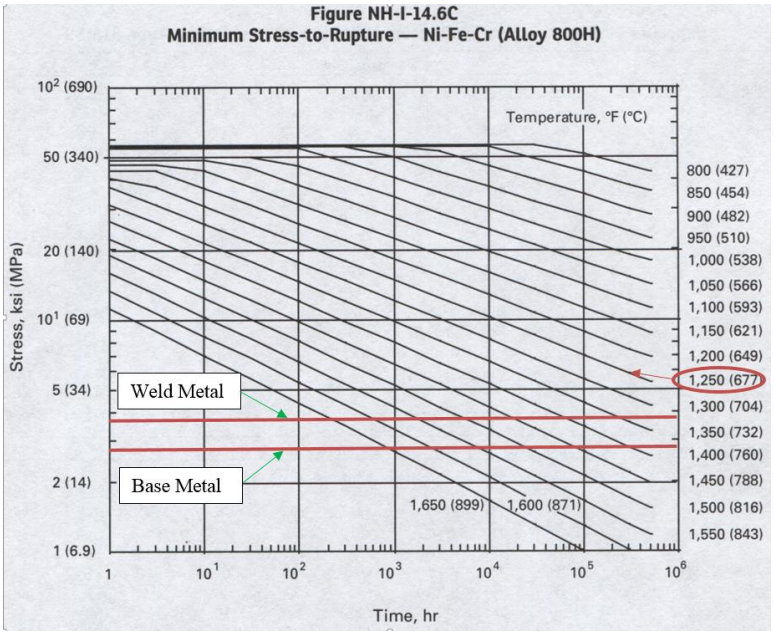

Figure 7: Design Fatigue Strain Range Curve for Alloy 800-H (ASME III-NH)

9. Creep-Fatigue Analysis per ASME Section III-NH

One method for evaluation of creep fatigue (ASME III-NH) is according to the following equation:

$$\left[\sum\left(\frac{n_c}{N_d}\right)_j + \sum\left(\frac{\Delta T}{T_d}\right)_k\right] < D_{cf} \quad (7)$$

D_{cf} = total creep-fatigue factor obtained from Figure 8
$(N_d)_j$ = number of design allowable cycles for cycle type, j, obtained from a design fatigue data using the maximum strain value during the cycle
$(n_c)_j$ = number of applied repetitions of cycle type, j
$(T_d)_k$ = allowable time duration determined from stress-to-rupture data for a given stress (S_r'/K') for base metal and $[(S_r'/K'R)]$ for weldments, and the maximum temperature at the point of interest and occurring during the time interval, k
$(\Delta T)_k$ = duration of the time interval, k

As indicated in the previous section, creep stress rupture is not predicted at the operating stress condition and temperature. Therefore, the second side of the equation goes to zero.

$$\left[\sum\frac{n_c}{300/2} + 0\right] < D_{cf}$$

$$\left[\frac{n_c}{150}\right] < 1.0$$

Since the creep contribution is zero, D_{cf} is 1.0 per Figure 8. Per NH-T-1715 (Creep-Fatigue Reduction Factors), the N_d value was divided by two to account for the weld. Resultantly, the number of allowable cycles is 150.

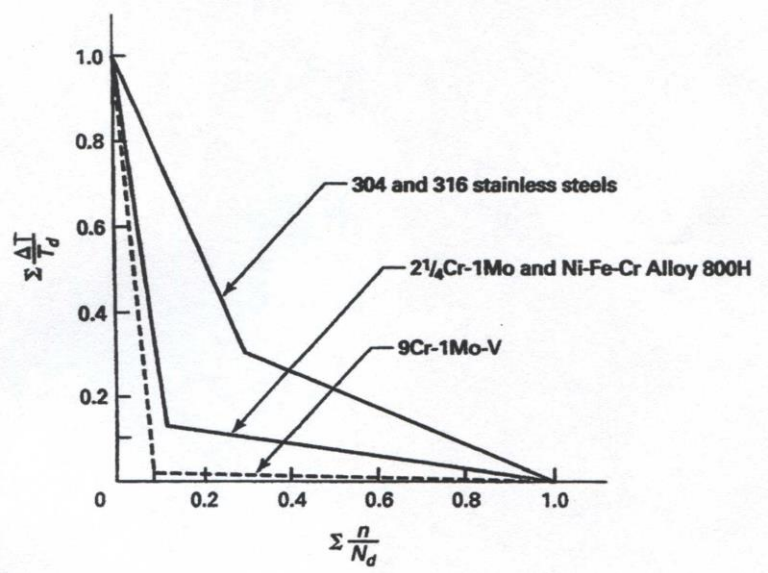

Figure 8: Creep-Fatigue Damage Envelope (ASME III-NH) for 800-H

10. Summary

Although the creep contribution to the number of allowable cycles was nil, the effects of creep, particularly creep relaxation, on the plastic strain range were quite significant. Realistic modeling of the primary and secondary creep behaviors were critical in obtaining reliable creep behavior. The ORNL test data for 800-H allowed for the creation of a CREEP subroutine, which allowed for accomplishment of this goal. Equivalent plastic strain and equivalent creep stress were then captured, allowing for evaluation of cyclic-creep conditions using ASME Section III-NH Rules.

11. References

1. Booker, M.K., Baylor, V. B., and Booker, B.L.P., "Survey of Available Creep and Tensile Data for Alloy 800H", Oak Ridge National Laboratory, Oak Ridge, TN, 1978.
2. Abaqus 6.10 User Subroutines Reference Manual, Dassault Systemes Simulia Corp., Providence, RI, 2010.
3. ASME, "Section VIII Rules for Construction of Pressure Vessels – Division 2 Alternate Rules", ASME B&P Vessel Committee on Pressure Vessels, New York, NY, 2013.
4. ASME, "Section III-NH Rules for Construction of Pressure Vessels", ASME Boiler and Pressure Vessel Committee on Pressure Vessels, New York, NY, 2013.
5. Kennedy, A.J., "Processes of Creep and Fatigue in Metals", John Wiley & Sons, Inc., New York, NY, 1963.

12. Appendix 1 – Fortran Setup Notes

1) Install Visual Studio 2010 Professional
2) Install Intel Visual Fortran Composer XE 2013
3) At dos prompt: c:\Program Files (x86)\Intel\Composer XE 2013\bin type **ifortvars intel 64** an hit enter.
4) Go to System Environmental Variables (System Properties-Advanced Tab). At beginning of "Path" variable, type in c:\Program Files (x86)\Intel\Composer XE 2013\bin;
5) At Start Menu->All Programs->Abaqus 6.12-2->Right click on *Abaqus Command*->Properties->Add **ifortvars intel 64** at the end of Target field (in Shortcut tab).
6) At Start Menu->All Programs->Abaqus 6.12-2->Right click on *Abaqus CAE*->Properties->Add **ifortvars intel 64** at the beginning of Target field (in Shortcut tab).
7) If Manifest errors in subroutine, then go to C:\SIMULIA\Abaqus\6.12-2\SMA\site\abaqus_v6.env, in text editor add the following three lines at very end:
```
import driverUtils
link_sl = driverUtils.substitute(link_sl, '/nologo', '/nologo /MANIFEST') link_exe = driverUtils.substitute(link_exe, '/nologo', '/nologo /MANIFEST')
```

After Step 4) we went to the working directory command prompt and typed in ifortvars intel 64. This was done to make sure the 'command prompt properties' were correctly set up and can access the compilers.

The following are my statements.

4) Variable=Path c:\Program Files (x86)\Intel\Composer XE 2013\bin;%INTEL_DEV_REDIST%redist\intel64\mpirt;%INTEL_DEV_REDIST%redist\intel64\compiler;

5) Target = C:\Windows\SysWOW64\cmd.exe /k ifortvars intel64

6) Target = "C:\Program Files (x86)\Intel\Composer XE 2013\bin\ifortvars.bat" intel64 && C:\SIMULIA\Abaqus\Commands\abq6122.bat cae || pause

To run a job from the working directory command prompt [#5 is done to permanently set Abaqus command prompt properties so that it always recognizes the compilers. So, no need to run ifortvars every time you open Abaqus command prompt.]

job=creep user=creep.for cpus=4

(creep is job name; creep.for is subroutine name and cpus=4 was added to run 4 core)

To run a job from within cae, simply add subroutine to Job-General-User subroutine file. [#6 sets Aba CAE properties to recognize compilers so that you can run any subroutine from within Abaqus/CAE.]

13. Appendix 2 – Subroutine Source Fortran Code

800H_creep_english.for

(Global Scope)

```
      SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC,ESW,P,QTILD,
     1 TEMP,DTEMP,PREDEF,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
     2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
C
      INCLUDE 'ABA_PARAM.INC'
C
      CHARACTER*80 CMNAME
C
      DIMENSION DECRA(5),DESWA(5),STATEV(*),PREDEF(*),DPRED(*),
     1 TIME(3),COORDS(*),EC(2),ESW(2)
C
C DEFINE CONSTANTS
C UNITS ARE ENGLISH -- PSI, Farenhite, Hours
C
      A=24.31D0
      B=40240.0D0
      C=7040.0D0
      TEMP_CUTOFF=1000.0D0
      T=TEMP
C     FACTOR1 AND FACTOR2 NEED TO BE COMPUTED FOR MODIFYING
C     QTILD AND T
      FACTOR1=6.8947D-3
C     T CHANGED FROM FARENHITE TO CELSIUS
      T1=(T-32.0)*5.0D0/9.0D0

C TO ADDRESS MINIMAL CREEP OCCURRING BETWEEN TEMP 900-1100
      DECRA(1) = 1.D-10
      DECRA(5) = 1.D-30
C      WRITE(6,*) 'DECRA(5), T', DECRA(5), T
      IF(T.GE.TEMP_CUTOFF) THEN
C      QTILD, NEEDS TO BE MODIFIED AS SHOWN BELOW
       IF(QTILD.LE.0.0D0) QTILD=1.D-2
       QTILD1 = QTILD*FACTOR1
C      WRITE(6,*) 'QTILD', QTILD1, QTILD
       F=A-B/T1+(C/T1)*LOG(QTILD1)
C      WRITE(6,*) 'VALUE', F
C       STOP
C      PRINT*, F
       DECRA(1) = EXP(F)*DTIME
       IF(LEXIMP.EQ.1) THEN
C        DECRA(5) = 1.D-10
C        IF(QTILD1.GE.1.0D-5) THEN
         DECRA(5) = (DTIME*EXP(F)*C/(T1*QTILD1))*FACTOR1
C        WRITE(6,*) 'DECRA(5) & 1', DECRA(5), DECRA(1), QTILD1
C        END IF
       END IF
      END IF
C
      RETURN
      END
```

14. Acknowledgement

A special thanks is given to Mr. Shashwat Sinha, Senior Technical Specialist with SIMULIA, for his assistance with the Fortran program.