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Introduction to fe-safe/TURBOlife

1.1 About fe-safe

fe-safe is a powerful, comprehensive and easy-to-use suite of fatigue analysis software for Finite Element models. It is used alongside commercial FEA software to calculate:

- where fatigue cracks will occur;
- when fatigue cracks will initiate;
- the factors of safety on working stresses (for rapid optimisation);
- the probability of survival at different service lives (the ‘warranty claim’ curve).

Results are presented as contour plots which can be plotted using standard FE viewers.

fe-safe has direct interfaces to the leading FEA suites.

1.2 About fe-safe/TURBOlife

fe-safe/TURBOlife is an add-on module for use with fe-safe fatigue analysis software, that can be used for the analysis of any engineering component, which operates hot and cyclically resulting in creep-fatigue damage. Users of fe-safe/TURBOlife are assumed to have a working knowledge of fe-safe, including such techniques as configuring a fatigue analysis and setting properties for different parts of the model, defining the fatigue loading, running an analysis and exporting fatigue results. The use and application of fe-safe is described in the fe-safe User Manual, which should be referred to alongside the fe-safe/TURBOlife manual.

fe-safe/TURBOlife is a joint collaboration between AMEC and Dassault Systèmes. fe-safe/TURBOlife performs creep-fatigue crack initiation calculations for engineering components under thermo-mechanical loading. Two methods are provided: Ductility Exhaustion and Strain Range Partitioning.

Ductility Exhaustion (DE)

This method is developed from the R5 document, volumes 2 and 3, although there are some important and significant differences and extensions.

Stress analysis for the component is performed elastically by finite element analysis to describe the load cycle or a sequence of load cycles. Plasticity and relaxation methods are then used to calculate plastic strain and creep strain at a node for the load sequence and construct the stress-strain history. Individual cycles and unmatched half cycles are identified. Fatigue endurance is calculated using a strain-life approach and creep life is calculated using a creep ductility exhaustion method. Creep fatigue-interaction is accounted for by means of a creep-fatigue interaction diagram.

Strain Range Partitioning (SRP)

This method is based on work by Manson, Halford and Hirschberg. It is aimed at separating a strain cycle into its strain component behaviours and then evaluating the damage attributable to each. The strain components are creep and plasticity.

AMEC background

Over the past twenty five years, extensive research has been undertaken collaboratively by various companies in the UK power generation sector, concerned with the understanding of thermal-mechanical and creep-fatigue...
damage mechanisms. AMEC (formerly Serco Assurance, AEA Technology Consulting and before that part of the United Kingdom Atomic Energy Authority) has contributed extensively to this research. The need was driven by incompatibilities between the type of failure observed in laboratory material tests and in plant components, along with the need for realistic estimation of thermal-mechanical fatigue damage for safe design and operation. This led to the development of a component and material specific strain based procedure, as an alternative to the time based British Standard and ASME approaches.

R5 background
The UK strain based development is the basis of both the R5 assessment procedure used extensively in the power industry and this software. The R5 assessment procedure is the only procedure used in the UK for high temperature assessments of nuclear power stations.

1.3 How to use this manual
This document describes features of the fe-safe/TURBOlife software in Chapter 2, the material property requirements in Chapter 3 and the means by which an assessment is performed in Chapter 4. Chapter 7 gives a tutorial example which can be followed using the software where the necessary finite element analysis results and material properties are included as data files. Chapter 5 covers background notes on creep-fatigue methodologies in general and Chapter 6 strain based methods in particular.

Users new to fe-safe
Because this manual assumes some familiarity with fe-safe, it will be necessary to learn a little about the main program first. Work through some of the tutorials in the fe-safe User Manual, including at least one demonstrating the use of data from your preferred FEA software, then return here.

fe-safe users new to TURBOlife
Work through the tutorial, and then follow the procedure described in Chapter 4 with your own data, referring to Chapter 2 as necessary.

Experienced users of fe-safe/TURBOlife
Experienced users are most likely to refer to Chapters 2 and 4, which provide a detailed reference, including descriptions of infrequently-used parameters.
2 Features of fe-safe/TURBOlife

2.1 Introduction

fe-safe/TURBOlife algorithms continuously assess creep and fatigue damage individually and the known effect of their interaction on a component operating with cyclic mechanical and thermal loads. The creep-fatigue damage during an operating time increment is assessed and added to the damage from the previous time increment to determine the current total damage. There is no restriction to the magnitude of the time increment that can be used and the calculation accuracy of creep strain and creep damage does not require a small time increment. However, with small time increments the damage calculation can accurately follow any component load history without the need to assume the repetition of particular cycles. On-line versions of the software are used to continuously monitor damage to power station boilers and gas turbine blades using transducer inputs that follow actual plant operation. For on-line applications the software recognises real operating cycles as they occur, thereby providing continuous information in real time on actual plant usage.

An essential element of the strain-based approach is the understanding of damage mechanisms associated with elevated temperature thermal-mechanical, creep-fatigue failure of laboratory material and feature tests. Fatigue damage concerns the initiation and growth of cracks at the free surface. Creep damage concerns the initiation and coalescence of voids to form cracks along grain boundaries, and as such affects the bulk of the material. At low strain ranges creep cracking alone can occur. At higher strain ranges, such as at stress concentrating features, surface fatigue cracks can initiate and trigger the coalescence of creep induced voids. Thus thermal-mechanical, creep-fatigue interaction can occur. This understanding of material mechanisms at a fundamental level is then reconstituted into estimates of component thermal-mechanical fatigue life. In this process it is not sufficient to perform the damage calculation for a single cycle and multiply the result by the number of cycles. This is for a number of reasons:

- Cyclic hardening changes the stress range and the instantaneous creep rate at any instant in a cycle is dependent on current stress.
- The instantaneous creep rate is also dependent on the total time since creep straining began, not simply the time period for any single cycle.
- The instantaneous creep ductility used to assess the instantaneous creep damage increment depends on the current creep strain rate.
- The fatigue damage for a cycle depends on the total strain range for that cycle, including creep strain.

Therefore, for sensible creep-fatigue damage assessments, the analysis of a full cyclic stress-strain time history is required, even though that time history may be comprised of a series of identical load cycles. To perform these calculations the TURBOlife algorithms include a number of features, most of which operate automatically but some of which have aspects that are user controlled. These are:

- materials data interpolation and extrapolation
Thus the fe-safe/TURBOlife software recognises and accounts for the total history effects, history independent state variable effects, and component specific effects, all of which are known to influence thermal-mechanical, creep-fatigue failure. These aspects are not be adequately accounted for in the more traditional phenomenological approaches, which use laboratory tests to characterise material test specimens, which are then assumed to transfer directly to component assessment. Also, these effects are not included in simplified damage methods such as time-temperature fraction accounting using the Larson-Miller parameter.

Outputs of a fe-safe/TURBOlife analysis are either in the form of creep-fatigue contours showing damage ‘hot spots’ or detailed tabular output for each nodal point of the finite element mesh.

2.2 Features

22.1 Introduction

The following text provides a general description of the fe-safe/TURBOlife software functionality. Various features of the software are described and reasons for the inclusion of these features are given. Where appropriate, limits or conditions are given that define the scope of problem that can appropriately be considered by the software. Also guidance is given on electing certain parameters controlled by the user.

22.2 Assessment point

Calculations are performed for all nodes on a finite element mesh representing the component geometry. The intention is to identify creep damage or creep-fatigue damage ‘hot spots’ due to local stress concentrating features, regions of high thermal stress or regions of high temperature. To perform this overall function expediently, it is assumed that the component has shaken down to cyclic behaviour that is essentially elastic. This means that local regions of cyclic plasticity are allowed but gross plasticity across load bearing sections of the component are beyond the scope of the TURBOlife methodology. Local cyclic plasticity is defined as extending over no more than 20% of load bearing sections. This assumption limits the extent of the plastic relaxation behaviour in plastic enclaves so that the behaviour can be described by simple methods. For pure thermal loading with no mechanical load, this 20% limit is less restrictive.
The assumption of limited plasticity is not unduly restrictive for practical purposes. This is because the endurance of high temperature components subjected to creep damage would be very low if mechanical stresses are not kept small.

The assessment points are therefore assumed to behave independently in that the stress redistribution across the entire component to account for force equilibrium and displacement compatibility are not considered. The alternative to this assumption is to perform full elastic-plastic finite element analysis for all cycles experience by the component, possibly leading to computational difficulties.

### Component loading history

Elastic finite element analysis of the component including all boundary conditions is required. Mechanical and thermal load cases may be considered separately and summed or they can be combined into a single load case. The finite element analysis must consider a full cycle of loading. The form of the finite element output is a set of six stress components, being three direct stresses and three shear stresses. Stresses are specified in time sequence where the time increment between stress sets need not be constant. There is no loss of accuracy in plasticity or creep calculations where large time steps are used.

However, the time increment must be sufficiently small that the cycle analysis adequately captures peaks and troughs. To achieve this it is recommended that elastic stress increments should usually be limited to 10 MPa or less. Where thermal analysis is included, the calculated component nodal temperatures are used to select appropriate material properties. Again the thermal time step increment need not be constant. However it is recommended that nodal temperatures changes per time increment should not normally exceed 10°C so that cyclic temperature changes are adequately described. Metal temperature change is governed by the heat transfer coefficient coupling the heat transfer fluid to the metal surface. The following table gives guidance on the maximum time increment that should be used where thermal transient loading is involved. These maximum time increments will limit the maximum surface temperature change to about 10°C or less per time increment.

<table>
<thead>
<tr>
<th>Heat Transfer Coefficient (W/m² °C)</th>
<th>Typical Heat Transfer Medium</th>
<th>Maximum Time Increment (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Cold air at 1 bar</td>
<td>45</td>
</tr>
<tr>
<td>100</td>
<td>Low velocity hot air at 1 bar</td>
<td>18</td>
</tr>
<tr>
<td>700</td>
<td>High velocity hot air at 1 bar</td>
<td>0.3</td>
</tr>
<tr>
<td>1000</td>
<td>Steam at 1 bar</td>
<td>0.19</td>
</tr>
<tr>
<td>1200</td>
<td>Steam at 150 bar</td>
<td>0.145</td>
</tr>
<tr>
<td>2000</td>
<td>High velocity hot air at 15 bar</td>
<td>0.06</td>
</tr>
<tr>
<td>25,000</td>
<td>Liquid metal cooling</td>
<td>0.0004</td>
</tr>
<tr>
<td>50,000</td>
<td>Boiling water heat transfer</td>
<td>0.000045</td>
</tr>
</tbody>
</table>

### Stress calculation

All stress concentration features should be adequately modelled and included in the elastic finite element model.
Materials data

See Chapter 3 for details on how to define the materials data described below.

Tensile Data

For a range of temperatures covering the problem, data describing Young’s modulus, Poisson’s ratio, monotonic stress-strain curves and cyclic stress-strain curves are specified by the user. For all calculations involving Young’s modulus, the software calculates and uses the effective Young’s modulus $E'$. The monotonic and cyclic stress-strain curves are given in terms of plastic strain only. A power law is fitted to the stress-strain data on a minimum error basis and the power law is used in hysteresis loop construction. Therefore, to improve the curve fit the range of plastic strain in the specified data should just exceed the maximum strain expected after plastic relaxation. At least three stress-strain data points including the origin (0,0) are needed for each curve fit. Otherwise, the curve fitting procedure cannot work. It is usually sufficient to specify tensile data at temperature increment of between 20°C to 50°C. The temperature increments need not be equal. An option exists to display the stress-strain curves together with the stress-strain data so that the accuracy of curve fitting can be considered.

Cyclic Hardening

The number of load reversals to progress fully from the monotonic stress-plastic strain to the cyclic stress-plastic strain is specified by the user. Cyclic hardening increases the stress range and decreases the strain range of hysteresis loops. The increased stress range increases the creep strain per cycle. The lower strain range decreases the fatigue damage per cycle. Therefore, cyclic hardening is important since it changes the nature of the creep-fatigue endurance problem. When designing against failure it is important to know whether the damage mechanism is creep dominated or fatigue dominated. Two options exist for the use of cyclic hardening data. Either the fully hardened curve can be used from the onset of cycling or the fully hardened curve can be introduced gradually over the specified number of load reversals. The use of gradual hardening is recommended for most cases since this has the effect of symmetrising the hysteresis loops about the strain axis. This means that the maximum tensile stress and the maximum compressive stress are of about equal magnitudes. Symmetrising occurs in plastic enclaves by shakedown when the remainder of the component is essentially elastic. The use of fully hardened behaviour will not result in symmetrising and may overestimate creep damage by over estimating the maximum stress level which occurs. The use of fully hardened behaviour from the onset of cycling should be used with care.

Creep Deformation

For a range of temperatures covering the problem, data describing creep deformation behaviour in terms of creep strain, time and temperature are specified by the user. Two options are available to do this. Either the stress to produce a specified creep strain in a specified time can be specified: these data are isochronous creep curves. Or the creep strain resulting from a steady applied stress for a specific time can be specified: these data are measured in creep tests. For both forms of data input the specified ranges of time, temperature, creep strain and stress; ranges of input data should cover the ranges expected for the specific problem under consideration. However, for any temperature it is not necessary to fully populate the creep data table. The software will automatically interpolate and extrapolate the data to cover the full ranges of creep strain, time and stress which are specified. This is done using the Larson-Miller parameter for temperature-time extrapolation together with logarithmic interpolation. The fully populated creep data tables for each temperature are curve fitted on a minimum error basis using polynomial equations; these equations are used in hysteresis loop construction.

The curve fitting procedure will adequately describe primary, secondary and tertiary creep behaviour. An option exists to display the curves and the data so that the accuracy of curve fitting can be considered.
Fatigue Endurance

For a range of temperature covering the problem, data describing the fatigue endurance in terms of strain-life are specified by the user. These data are in a form that is directly measured in strain-life fatigue tests. The software performs a fatigue crack initiation calculation including small amounts of crack growth, where both initiation and shallow crack growth are mechanistically related to strain range. The software performs no specific crack growth calculation. Where fatigue endurance data relate to test specimen failure, linear elastic crack growth considerations describing more extensive crack growth may be an important factor in the total life. Therefore in specifying fatigue endurance data, it is important to understand the definition of fatigue endurance which is implicit in the test data used. Linear elastic fracture mechanics crack growth calculations can be used to partition total life into crack initiation life and crack growth life, thereby producing an initiation endurance curve which relates better to applied strain range. Fatigue endurance data is not particularly sensitive to temperature so inputting that data at 25°C temperature increments is usually adequate.

Creep Ductility

For a range of temperature covering the problem, data describing creep rupture ductility versus creep strain rate are specified by the user. Upper bound and lower bound plateaus exist at the extents of this data where the creep ductility is independent of the creep strain rate. Only the strain rate dependent part of the data is specified. The plateaus are assumed to occur at the upper and lower extents of the specified data. Temperature increments of between 25°C and 50°C are usually adequate, depending on the particular material under consideration.

Creep Fatigue Interaction Diagram

The creep-fatigue damage envelope is specified in terms of the creep damage and fatigue damage coordinates which define the onset of cracking. For any particular material this damage envelope is taken to be independent of temperature. The damage envelope is crucial, not only in defining the onset of cracking but also whether the cracking will be creep dominated or fatigue dominated. Ideally the interaction diagram should be measured using creep-fatigue endurance experiments. In the absence of measured data, knee point coordinates of (5%, 5%) may reasonably be assumed. Such a diagram would result in a maximum fatigue life reduction factor due to creep effects of 20.

Strain Range Partitioning

As an alternative to the separate calculation of fatigue damage and creep damage which are used with the creep-fatigue interaction diagram, the method of Strain Range Partitioning can be used. This considers the creep fatigue interaction within the material endurance data so that the creep-fatigue interaction diagram is not required.

Material Data Interpolation

Young’s modulus, Poisson’s ratio, monotonic stress-strain curves, cyclic stress-strain curves, creep ductility and Strain Range Partitioning data are interpolated between data sets supplied at different temperatures to obtain the data for the assessment temperature.

226 Plastic relaxation

Three optional plastic relaxation rules can be used to estimate the actual stress and strain from the elastic stress and strain. These are the Neuber rule, the Glinka rule and the \(-\frac{E}{\epsilon}\) rule. For general application the Neuber rule will overestimate the relaxed values of stress and strain and the \(-\frac{E}{\epsilon}\) rule will underestimate them. The Glinka rule may provide an in between estimate. For any particular problem analysis, the sensitivity of the result to these three rules should be considered.
Features of fe-safe/TURBOlife

227 Creep relaxation
Forward creep, creep relaxation or any creep behaviour between these two extremes is accommodated through the use of the elastic follow-up factor Z, the value of which is specified by the user. The Z factor can be used to describe creep relaxation behaviour for a variety of conditions. When the Z factor is unity this will result in pure creep relaxation. When the Z factor is infinity this will result in forward creep with no stress relaxation. Different Z factors can be specified for different nodes or groups of nodes in the finite element mesh and Z factor is temperature independent.

228 Cycle recognition
From the elastic stress history and the user selected plastic relaxation rule, the elastic-plastic stress history is derived by the software. Creep strain determined using the appropriate Z factor is added to the elastic-plastic strain history to produce the stress versus total strain history. From the stress history, total strain history and cyclic hardening definition, and hysteresis loops are constructed. The time increment used in the elastic finite element calculation of the stress cycle should be sufficiently small to allow for peaks and troughs in the load cycle to be identified and a good definition of hysteresis loops to result.

Individual stress-strain hysteresis loops producing a cycle of fatigue damage are identified using the rainflow method of cycle counting. Complete cycles and unmatched half cycles are individually identified. Thus, identified cycles and half cycles include all the information necessary for individual creep and fatigue damage calculations including the influence of creep strain on fatigue damage through the total strain range (elastic + plastic + creep). The software is arranged to function such that all calculations are performed as the elastic stress history is read, rather than by post processing a pre-defined stress history. In this way, damage calculations can easily be extended to longer times by simply extending the stress histories. This has the advantage that residual life and total life assessments are made easier when the time to achieve 100% damage in the case that each node in the finite element mesh is different.

229 Damage calculations
The fatigue damage is calculated for each individual cycle on the basis of the total strain range for that cycle. Miner’s rule is used to sum the damage from individual cycles. Fatigue damage for unmatched half cycles is calculated as half the damage of the equivalent complete cycle. Creep damage for each time increment is calculated as the creep strain increment divided by the creep ductility where the creep ductility is a function of creep strain rate and temperature.
3 Material properties

*fe-safe* is supplied with a comprehensive database containing fatigue properties for commonly used materials. Materials data is managed within the main application environment. Functions are available for creating new material records, editing, sorting and plotting material properties and approximating fatigue parameters.

3.1 Material data requisites

*fe-safe/TURBOlife* requires that the following material parameters are defined:

- General parameters 'Young’s Modulus’, ‘Poissons Ratio’, ‘Temperature List’ and ‘Hours List’.
- Monotonic stress-strain curves (DE)
- Cyclic stress-strain curves as a function of temperature
- Number of cycles to harden. If it is non-zero then the monotonic stress-strain curve must also be defined
- Strain-life curves as a function of temperature. NOTE: b2 is not used
- Strain-life curves for plasticity, creep and their interaction (SRP)
- Either creep table A or creep table B. Creep table A defines stresses as a function of strains, time and temperature. Creep table B defines strains as a function of stresses, time and temperature
- The fatigue-creep interaction diagram. This table indicates how fatigue damage and creep damage interacts to cause failure (DE)
- Creep ductility as a function of creep strain rate and temperature. The ductility value is used to evaluate the damage due to creep (DE)
- The temperature threshold beneath which creep damage is assumed negligible.
- The creep damage endurance limit.

All parameters, with the exception of *turbo: number-of-cycles-to-Harden* and *turbo: creep-temperature-threshold* use tabular inputs. Where a table is as a function of another parameter then the parameter must be defined first, i.e. the cyclic stress-strain curve is a function of temperature, so the list of temperatures must be defined first.

Definition of these parameters is described in more detail below.

3.2 General material parameters

The temperature list (gen:TemperatureList) and hour’s list (gen:HoursList) are one-dimensional tables used to specify the values at which other parameters are defined. i.e. if you define a temperature list of 20 100 150 and 200 then any parameter that is a function of temperature will require a value specified for each temperature.

Young’s Modulus (gen:E) and Poisson’s ratio (gen:PoissonsRatio) are required as a function of temperature only.
3.4 **TURBOlife parameters**

To perform a TURBOlife creep fatigue analysis, the following additional parameters are available:

<table>
<thead>
<tr>
<th>Category</th>
<th>Displayed name</th>
<th>Units</th>
<th>Keyword</th>
<th>Definition</th>
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<td>creepStrainList</td>
<td>Strain list for creep table A</td>
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<tr>
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</tr>
<tr>
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<td>Limit</td>
<td>2nf</td>
<td>CREEP-EL</td>
<td>Pseudo endurance limit for creep fatigue</td>
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<tr>
<td>turbo : creep-temperature</td>
<td>Threshold</td>
<td>Deg.C</td>
<td>CREEP_TTHRESH</td>
<td>Threshold below which creep damage is assumed to be negligible</td>
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<tr>
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<tr>
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<td>MON_KP</td>
<td>Monotonic cyclic stress-strain curve hardening coefficient</td>
</tr>
<tr>
<td>turbo : n'(mon)</td>
<td></td>
<td>None</td>
<td>MON NP</td>
<td>Monotonic cyclic stress-strain curve hardening exponent</td>
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<td>turbo : number-of-cycles</td>
<td>to Harden</td>
<td>None</td>
<td>NHARDEN</td>
<td>Number of cycles to move from monotonic to cyclic stress-strain curves.</td>
</tr>
</tbody>
</table>

3.5 **Stress-strain and hysteresis curves and cyclic hardening**

Cyclic hardening increases the stress range and decreases the strain range of hysteresis loops. The increased stress range increases the creep strain per cycle. The decreased strain range reduces the fatigue damage per cycle. Therefore, cyclic hardening can be important as it can change the nature of the creep-fatigue endurance problem. When designing against failure it is important to know whether the damage mechanism is creep dominated or fatigue dominated.

The monotonic curve is the stress-strain curve that occurs with the first application of loading. Once the material has stopped hardening or softening the cyclically hardened curves are used. Two definitions are used in the literature to define cyclically hardened data. These are the cyclic stress-strain curve (Figure 3-1) and the hysteresis loop curve (Figure 3-2).
The cyclic stress-strain curve defines stress and strain behaviour from the origin of symmetrical cycling (Figure 3-1) where the locus of the upper tips defines the cyclic stress-strain curve. The hysteresis loop curves define the stress and strain behaviour from the origin of none-symmetrical cycling (Figure 3-2) where the loops are all adjusted so that their lower tips are at the origin. Again the locus of the upper tips defines the hysteresis loop curve. The difference between the two definitions is significant and the user must be clear which definition is used to describe data.

Both the monotonic and cyclic stress-strain curves are defined by the K and n parameters according to the equation:
The cyclic curve can be further defined in terms of stress and strain ranges:

\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K}\right)^{1/n}
\]

[Equation 3.5-2]

giving:

\[
\Delta \varepsilon = \frac{\Delta \sigma}{E} + \left(2^n \frac{\Delta \sigma}{K_{\text{hyst}}}\right)^{1/n}
\]

[Equation 3.5-3]

The hysteresis loop curve is also defined in terms of stress and strain ranges by the equation:

\[
\Delta \varepsilon = \frac{\Delta \sigma}{E} + \left(\frac{\Delta \sigma}{K_{\text{hyst}}}\right)^{1/n}
\]

[Equation 3.5-4]

Therefore, comparing Equations 3.5-3 with 3.5-4, the K value for the cyclic stress strain curve definition is related to \(K_{\text{hyst}}\) for the hysteresis loop curve by:

\[
K_{\text{hyst}} = \frac{2K}{2^n}
\]

[Equation 3.5-5]

where n is the same for both definitions. Therefore, data presented in one form can be converted to the other form.

K and n are defined for each of the temperatures in the gen:TemperatureList. The monotonic stress-strain curve is defined using the fields turbo:K(mon) and turbo:n(mon). The cyclic stress-strain curve is defined using the fields css:K' and css:n'. Whichever method is used to describe the cyclically hardened data, the values K and n describing the cyclic stress strain curve format (Figure 3-1 and Equation 3.5-1) are required for the materials database. The Material Plot dialogue allows a plot of both the cyclic and monotonic stress-strain curves and hysteresis loops at a particular temperature.

The degree of cycling to progress from the monotonic stress-strain curve to the cyclic stress-strain curve is controlled by the turbo:damage-to-Harden parameter. The hardening model is one in which the material progresses from the monotonic behaviour to the cyclic behaviour exponentially according to Equation 3.5-6. The turbo:damage-to-Harden parameter is the value D, as a fraction between 0 and 1 in Equation 3.5-6.
where:

- $h$ is a parameter which varies between 0 and 1, such that the material is fully soft for $h=0$ and fully hard for $h=1$,
- $d$ is the current fatigue damage,
- $D$ is the target fatigue damage at which the material has achieved full hardness,
- $\xi$ is a scaling factor set to 12.

For values of $h$ between 0 and 1, the stress-strain curve is linearly interpolated between the monotonic and the cyclic curves. If no hardening or softening is required then the `turbo: damage-to-Harden` parameter can be set to 0 and the monotonic curve can be omitted. For $D=0.1$, the variation of $h$ with $d$ is shown in Figure 3-3.

![Figure 3-3 Variation of the hardening parameter $h$ with accumulated fatigue damage $d$](image)

**Data Preparation**

The monotonic stress-strain curve should be measured for each temperature of interest. If this is not available the origin (0,0) and two other sets of data which are often available from materials data sheets (e.g. the 0.2% proof stress and the 1.0% proof stress) can be used to derive the monotonic stress-strain curve parameters. Other proof stress values can be used if available.

The cyclic stress-strain curve or the hysteresis loop curve should be measured for each temperature of interest. Both the cyclic stress-strain curve and the hysteresis loop curve are derived from the locus of the tips of stabilised hysteresis loops, where each loop is stabilised at a specific strain range.
ASME III (ASME, 2001, Ref. 8.1) recommends a procedure to construct the cyclic stress-strain curve when experimental data is not available. The procedure requires that the monotonic stress-strain curve is modified by repositioning the origin (0,0). This is done by adding a stress of $\sigma_{0.2\%}$ and a strain of $\sigma_{0.2\%}/E$ at slope of $E$ as shown in Figure 3-4 so that the origin becomes $(0', 0')$.

![Figure 3-4 Construction of the cyclic stress-strain curve from the monotonic stress-strain curve for rapid cycling](image)

For slow cycling where creep occurs, the creep strain acts to partially reverse the hardening. For fatigue assessment it is necessary to use an appropriate cyclic hysteresis loop curve which accounts for the net hardening and softening effects. Ideally, the appropriate cyclic hysteresis loop curve should be measured by a slow strain rate material test. In the absence of a test, the cyclic hysteresis loop curve can be constructed from the monotonic stress-strain curve and creep data. The following procedure can be used:

- Construct the monotonic stress-strain curve which is the $t_0$ curve in Figure 3-5. This is the stress versus (elastic plus plastic strain) at time = 0, i.e. no creep strain. This curve is applicable to a particular temperature.
- Construct the total isochronous stress-strain curve which is the curve for time = $t_1$ in Figure 3-4, where $t_1$ is the total service time at elevated temperature. This is done by adding the creep strain to the elastic and plastic strain for each stress level.
- Construct the pure relaxation line as a vertical line starting at a stress equal to the material yield stress $\sigma_y$ (or 0.2% proof stress) and ending at the time = $t_1$ isochronous stress-strain curve. The relaxation stress $\sigma_r$ is stress at the intersection between the vertical line and the isochronous stress-strain curve.
- Construct the cyclic hysteresis loop curve as shown in Figure 3-4 by adding a stress $\sigma_r$ and corresponding elastic strain ($\sigma_r/E$) to the origin of the monotonic stress-strain curve.
- Note that the above procedure should be followed using $E$ not $E'$. 
3.6 Strain life curve

The strain-life curves are defined in terms of $E$, $n$, $c$, $b$ and $c$, (as for the standard fe-safe analysis modules), i.e.

\[
\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f}{E} (\frac{2N_f}{b})^b + \varepsilon'_f (\frac{2N_f}{c})^c
\]

[Equation 4.5-1]

These curves are defined at a series of temperatures. The curve at a particular temperature can be plotted in fe-safe.

The fatigue calculation evaluates the life to crack initiation. No crack growth calculation is performed. The life curves should be based on this failure criterion.

Fatigue endurance data is not particularly sensitive to temperature so data at 25 degrees C temperature increments is adequate.

Data Preparation

Ideally, the fatigue endurance data should be measured using isothermal cycling for each temperature of interest and the data entered into the data entry tables. Where this is not available, a number of empirical correlations are available which enable fatigue endurance data to be derived from commonly available data.

i) Use of empirical correlation

One correlation due to Halford et al (Halford, 1968, Ref 8.2) is particularly useful for estimating isothermal endurance data. Upper bound endurance data is given by:

\[
\Delta \varepsilon = \frac{3.5 UTS}{E} N_f^{-0.12} + D^{0.6} N_f^{-0.6}
\]

[Equation 4.5-2]
Material properties

\[ D = \ln \frac{100}{100 - \% RA} \]  

[Equation 4.5-3]

where:

- \( \Delta \varepsilon \) is the total strain range for a fatigue cycle,
- \( UTS \) is the ultimate tensile strength,
- \( E \) is Young’s modulus,
- \( N_f \) is the upper bound number of cycles to failure of a specimen, typically 5 mm in diameter,
- \( D \) is the true tensile ductility
- \( \% RA \) is the percentage reduction in area of a cylindrical specimen at tensile failure.

Mean endurance data is given by \( N_f/5 \) and lower bound endurance data is given by \( N_f/10 \). Since the TURBOlife software is intended to give a best estimate of endurance, it is recommended that mean endurance data given by \( N_f/5 \) should be used.

\( \Delta \varepsilon \) in this equation is the sum of two terms which are each strains. These terms are straight lines on log-log axes as shown in Figure 3-6.

\[ \Delta \varepsilon = 3.5 \left( \frac{UTS}{E} \right) N_f^{-0.12} \quad \Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p \quad \Delta \varepsilon_p = D^{0.6} N_f^{-0.6} \]

These straight lines represent an elastic contribution to strain related to \( UTS/E \) and a plastic contribution to strain related to \( D \). From Figure 3-6 it can be seen that the \( UTS/E \) term dominates the high cycle fatigue data and the \( D \) term dominates the low cycle fatigue data. Hence the significance of the materials data \( UTS, E \) and \( D \) is related to whether the problem is high cycle fatigue or low cycle fatigue.

When a component is work hardened prior to cyclic loading, e.g. during a hydrostatic forming process, the work hardening will influence the fatigue endurance curve. This can be accounted for by reducing the true ductility \( D \) by an amount equal to the work hardening strain prior to deriving the endurance curve. The work hardening strain can
be calculated using large displacement finite element analysis or estimated from component measurements such as wall thinning.

**ii) Correcting for crack initiation**

Fatigue endurance data measured or derived for cylindrical test specimens involves a three stage process of crack initiation, crack growth and specimen fracture. The definition of what is meant by crack initiation is somewhat arbitrary and a significant number of cycles can be involved in the crack growth phase. This can introduce ambiguity into the assessment of thin walled components where crack growth is limited. A technique has been proposed (Ainsworth et al, 2001, Ref 8.3) for correcting fatigue endurance data for different definitions of crack initiation and crack growth. This technique is appropriate for ferritic steels and stainless steels and is based on combining short crack growth behaviour which is strain controlled with long crack growth behaviour which is stress controlled. For an isothermal, constant strain range fatigue test to specimen fracture, the following definitions apply:

\[ a_{lab} \] is the specimen crack depth at fracture

\[ N_{lab} \] is the number of cycles to fracture

\[ a_o \] is the specimen crack depth for which the endurance is required

\[ N_o \] is the number of cycles for a crack of depth \( a_o \)

\( a_o \) is restricted such that \( 200 \mu m \leq a_o \leq a_{lab} \)

Then, defining \( a_o \) and \( a_{lab} \) in \( \mu m \), \( N_o \) is given by:

\[ N_o = N_i + N'_g \] \hspace{1cm} [Equation 4.5-4]

\[ N_i = e^{[\ln(N_{lab}) - 8.06(N_{lab})^{0.23}]} \] \hspace{1cm} [Equation 4.5-5]

\[ N'_g = M \ N_g \] \hspace{1cm} [Equation 4.5-6]

\[ N_g = N_{lab} - N_i \] \hspace{1cm} [Equation 4.5-7]

\[ M = \frac{200 \ln(a_o/200) + 180}{200 \ln(a_{lab}/200) + 180} \] \hspace{1cm} [Equation 4.5-8]

An example of fatigue endurance data for different definitions of crack initiation, derived using the above method is shown in Figure 3-7. Significant differences are shown for low cycle fatigue.
3.7 Creep deformation tables

Data tables describing creep deformation behaviour in terms of creep strain, time and temperature are required. Two options are available to do this.

- **Table A (isochronous creep curves):** The stress to produce a specified creep strain in a specified time. Fields `turbo : creep tableA Strain List` and `turbo : creep tableA Stresses`.

- **Table B (measured in creep tests):** The creep strain resulting from a steady applied stress for a specific time at a specific temperature. Fields `turbo : creep tableB Stresses List` and `turbo : creep tableB Strains`. Editing this table displays the dialogue shown in Figure 3-8. Strain values are a fraction of 1 not a %.
For both tables the ranges of time, temperature, creep strain and stress should cover the ranges expected for the specific problem under consideration, no extrapolation is performed. The creep data table for each temperature is curve fitted to polynomial equations using a minimum error basis.

The equations are used in the hysteresis loop construction. The curve fitting procedure will adequately describe primary, secondary and tertiary creep behaviour.

If both creep tables are defined the TURBOlife options dialogue defines the table used.

**Data Preparation**

Creep deformation data may be presented as a family of curves defined in terms of the form of the Larson-Miller parameter

\[ LM = T(20 + \log_{10}t) \]

where LM is the Larson-Miller parameter, T is the absolute temperature and t is the time for creep. Each curve in the family corresponds to the achievement of a particular creep strain, say 0.5%, 1.0% etc. Thus, Larson-Miller curves can be used to partially populate the creep deformation tables in both the Option A and Option B formats. Interpolation will be required to fully populate the creep deformation tables.

### 3.8 Creep ductility damage parameters

The creep damage parameters consist of 3 items:

- Data describing creep rupture ductility as a function of creep strain rate. Upper bound and lower bound plateaux exist with this data where the creep ductility is independent of the creep strain rate. Only the strain rate dependent part of the data is required. See Figure 3-9.

![Figure 3-9 Creep ductility vs creep strain rate for 316 stainless steel](image)

Plots usually display creep ductility and strain rate as a %; the software requires these as a fraction of 1.
Material properties

The plateau are assumed to occur at the upper and lower extents of the specified data. Temperature increments of between 25 and 50 degrees C are usually adequate, depending on the particular material under consideration.

**Note:** The smaller the ductility value the greater the damage.

One set of strain rates is defined. The ductility is defined as a function of temperature and strain rate. Editing either parameter `turbo:eRate for ductility table` or `turbo:ductility for ductility table` will display the edit table shown in Figure 3-10.

![Figure 3-10](image)

- **Threshold temperature beneath which creep damage is insignificant;** Parameter `turbo:creep-temperature-threshold`. A general rule of thumb is that this should be less than half the melting point of the material in degrees Kelvin.

- **The creep endurance limit;** Parameter `turbo:creep-endurance-limit`. Due to the nature of creep damage the loading must be repeated until the combination of creep damage and fatigue damage cross the interaction diagram. A linear interpolation cannot be performed while creep damage is still accumulating. This endurance limit specifies the threshold creep damage on one iteration of the loading below which creep damage is assumed to have stabilised. This allows analysis times to be reduced. As is the custom with fatigue endurance limits this value is specified as a number of reversals (2nf). So the incremental creep damage threshold value would be

\[ \frac{2}{\text{turbo:creep-endurance-limit}}. \]
A value of $2 \times 10^7$ reversals is reasonable for this parameter.

The **Material Plot** dialogue allows a plot of strain rate versus ductility for a particular temperature to be created. In *Figure 3-11* plots at two temperatures have been superimposed.

![Figure 3-11](image)

**Data Preparation**

To perform creep damage calculations, creep deformation data (being creep strain as a function of time and stress) and some measure of the creep condition at failure are required. The latter can either be time to rupture or creep strain at rupture, both as a function of stress. All three data sets can be measured from conventional, constant stress creep rupture tests where creep strain as a function of time is recorded.

**TURBOlife** calculates the accumulation of creep strain under variable stress conditions and compares the accumulated creep strain to creep strain at failure to identify the creep failure condition. Input data required by the software are creep deformation data as a function of constant stress and time and creep strain at failure as a function of creep strain rate. The time to rupture is not required as a material data input to the software and can therefore be calculated using the software. Alternatively, the time to rupture can be specified as a problem parameter and the creep strain at rupture calculated using the software.

Clearly the time to rupture and the creep strain at rupture, where one is specified and the other is calculated, should be consistent with the material test data where both are measured. This consistency can be obtained by using *fe-safe/TURBOlife* to simulate the behaviour of constant stress, creep rupture tests in the following way. For a series of creep rupture tests at a particular temperature where the stress is constant for each test but different between tests, their times to rupture are specified as a problem input and their creep strain at failure together with the average creep strain rate calculated. These data are then used to plot a creep strain at failure versus creep strain rate curve, which is the required creep ductility input data. Each of the creep rupture tests provides a different
point on the derived creep ductility curve. The creep ductility curve is then adjusted such that the calculated creep damage, being the creep strain at failure divided by the creep ductility at the appropriate creep strain rate, is 100% for all constant stress tests with minimum error. In effect, the required creep ductility curve which results in 100% creep damage at failure for a series of constant stress, creep rupture tests is derived by trial and error. The process is repeated for creep rupture tests at each test temperature.

As noted above, the material test requirements are minimal and based on simple, uniaxial creep tests. However, for good results the material data should cover the temperature range and stress range appropriate to the component. Also the material condition covering such aspects as heat treatment and method of manufacture (i.e. casting or forging) must be appropriate since these aspects influence creep behaviour.

Example

An example is shown below where 44 creep rupture tests were performed at seven different temperatures. Figure 3-12 shows the family of seven, temperature dependent creep ductility curves calculated by the above methodology.

A significant additional benefit from this methodology is that, provided sufficient stress rupture tests are available, a cumulative probability of failure curve can easily be constructed. Figure 3-13 shows a best fit creep ductility curve which was produced in the above way such that the corresponding best fit curve to the calculated damage was 100%. From the data used to construct the best fit creep ductility curve, the corresponding probability of failure curve can be constructed as shown in Figure 3-14. Note that 100% calculated damage correlates closely with 50% calculated probability of failure.
Figure 3-12 Calculated temperature dependent creep ductility curves

Figure 3-13 Calculated best fit creep ductility curve and the corresponding calculated creep damage
### 3.9 Creep fatigue interaction diagram

The creep-fatigue damage envelope is specified in terms of the creep damage and fatigue damage co-ordinates, which define the onset of crack initiation. For any particular material this damage envelope is taken to be independent of temperature. The damage envelope is crucial, not only in defining the onset of cracking but also whether the cracking will be creep dominated or fatigue dominated. Ideally the interaction diagram should be measured using creep-fatigue endurance experiments. In the absence of measured data, knee point co-ordinates can be estimated using the fatigue life reduction data. For example, fatigue life reduction factors of 10 and 20 could correspond to knee point coordinates of (10%:10%) and (5%:5%) respectively.

The interaction diagram is defined using the fields `turbo:Interaction Creep Damage` and `turbo:Interaction fatigue Damage`. The values specified are a % not a fraction of 1.0, i.e. for pure fatigue damage failure will occur at a value of 100%.

Editing either of the fields for a material displays the dialogue show in Figure 3-15.
The Material Plot dialogue allows a plot of the interaction diagram to be created. See Figure 3-16.

When using the nodal diagnostics the actual creep and fatigue damage can be cross plotted and superimposed on this diagram.

**Data Preparation**

It may be possible to assume a linear interaction diagram, which is to say that creep damage and fatigue damage occur independently without interaction, for which no data of any sort is required. Such an interaction diagram is
adequate for many practical engineering components where creep conditions exist only to a limited extent. Otherwise, a strong creep-fatigue interaction could occur and the component endurance would be impractically low. Where it is necessary to account for a strong creep fatigue interaction, a number of options are available as follows:

i) Extensive creep-fatigue endurance test data is available in the literature from which interaction diagrams can be inferred. To do this, a symmetrical, knee shaped interaction diagram can be assumed where the coordinates of the knee point are defined from the creep-fatigue life reduction factor. For example, where the creep-fatigue life reduction factor is 10 or 20, the knee point coordinates are taken to be (10%, 10%) or (5%, 5%) respectively. Chapter 6, section 6.5.3 (taken from reference 14) gives experimentally derived creep-fatigue life reduction factors.

ii) Where component service and failure histories are known, the fe-safe/TURBOlife software can be used to reverse engineer the appropriate creep-fatigue interaction diagram. Such an approach has the advantage that the component specific manufacturing process which influences aspects such as grain size and morphology, grain boundary inclusions, heat treatment, etc, and the operating environment will be accounted for.

iii) Simple hold time, creep-fatigue endurance tests can be performed where the test cycles can be analysed using the fe-safe/TURBOlife software to determine the creep damage and fatigue damage independently and hence plot the shape of the interaction diagram.

3.10 Strain range partitioning

As an alternative to determining creep-fatigue damage using strain-life fatigue data, creep ductility data and the creep/fatigue interaction diagram, strain range partitioning can be used. Four strain-life creep/fatigue endurance curves are required. These are derived experimentally using the four specific test cycles types of :

- **pp cycle** plastic strain at the tensile part of the cycle reversed by plastic strain at the compressive part of the cycle,
- **pc cycle** plastic strain at the tensile part of the cycle reversed by creep strain at the compressive part of the cycle,
- **cp cycle** creep strain at the tensile part of the cycle reversed by plastic strain at the compressive part of the cycle,
- **cc cycle** creep strain at the tensile part of the cycle reversed by creep strain at the compressive part of the cycle.

Each of these curves is described by an equation of the form:

\[
\frac{\Delta \varepsilon}{2} = \varepsilon_f \left(2N_f \right) \]  

[Equation 3.5.11-1]
where $\Delta \varepsilon$ is the strain range, $N_f$ is the number of cycles to test specimen failure, $\varepsilon_f$ and $c$ are constants. The pp curve is identical to the plastic part of the strain life curve (Section 3.5.7) and the data is entered in the same way, i.e. for each of the temperatures in gen:TemperatureList, two constants are entered into the two fields en:c and en:Ef’. Similarly, for the cc, cp and pc curves, for each of the temperatures in gen:TemperatureList, the three exponents are entered into the three fields turboSRP:c(cc), turboSRP:c(cp) and turboSRP:c(pc) and the three coefficients are entered into the three fields turboSRP:Ef’(cc), turboSRP:Ef’(cp) and turboSRP:Ef’(pc).

Further information on the strain range partitioning method, including comment on the advantages and disadvantages compared to other method, are given in Appendix C, section C.5.5.

**Data Preparation**

Uniaxial, constant temperature tests at different strain ranges for the four cycle types are required.
Material properties
4 Creep-fatigue analysis using fe-safe/TURBOlife

4.1 Overview of analysis technique

*fe-safe/TURBOlife* algorithms assess creep and fatigue damage individually and the known effects of their interaction on a component operating with cyclic mechanical and thermal loads. The creep and fatigue damage during a time increment are assessed and added to the total damage. There is no restriction to the magnitude of the time increment that can be used and the calculation accuracy of creep strain and creep damage does not require a small time increment. However, with small time increments the damage calculation can accurately follow any component load history without the need to assume the repetition of particular cycles.

The following sections outline the procedure for performing an analysis using *fe-safe/TURBOlife*. Briefly they consist of:

- Loading definition
- Materials definition
- Analysis options
- Selecting and running a TURBOlife analysis
- Re-running and analysis to extract additional information for hot-spots

An essential element of the strain-based approach is the understanding of damage mechanisms associated with elevated temperature thermal-mechanical creep-fatigue failure of laboratory material and features tests. Fatigue damage concerns the initiation and growth of cracks at a free surface. Creep damage concerns the initiation and coalescence of voids to form cracks along grain boundaries and as such affects the bulk of the material. At low strain ranges creep cracking alone can occur. At higher strain ranges, such as at stress concentrating features, surface fatigue cracks can initiate and trigger the coalescence of creep-induced voids. In this case creep-fatigue interaction can occur. This understanding of material mechanisms at a fundamental level is then reconstituted into estimates of component thermal-mechanical fatigue life. In this process it is not sufficient to perform the damage calculation for a single cycle and multiply the result by the number of cycles. This is for a number of reasons.

- Cyclic hardening changes the stress range, and the instantaneous creep rate at any instant around a cycle is dependent on this stress.
- The instantaneous creep rate is also dependent on the total time since creep straining began, not simply the time period for any single cycle.
- The creep ductility used to assess the current creep damage increment depends on the current creep strain rate.

For sensible creep-fatigue damage assessments the analysis of a full cyclic stress-strain time history is required, even though that time history may consist of a series of identical load cycles. *fe-safe/TURBOlife* recognises and accounts for the total history effects, history independent state variable effects, and component specific effects, all of which are known to influence creep-fatigue failure. These aspects are not
adequately accounted for in the more traditional approaches. They use laboratory tests to characterise material test specimens, which are assumed to transfer directly to component assessment. These effects are not included in simplified damage methods such as time-temperature fraction accounting using the Larson-Miller parameter.

4.2 Loading

For a thermo-mechanical fatigue analysis the loading is defined as a function of time and temperature. An elastic stress sequence, a time sequence and a temperature sequence are therefore used to define the loading. The loading can be defined in the loading interface or in a .ldf file as described in the fe-safe User Manual. The stresses and temperatures are usually defined by a series of steps or increments in a FEA model, however scale and combine loading techniques can also be used (see the fe-safe User Manual for details on creating loadings). FEA strains are not used by fe-safe/TURBOlife.

Unlike the standard fe-safe modules, the Ductility Exhaustion calculation cannot be performed on a single repeat of the loading and then summed using Miners rule. The calculation must be repeated on the loading until the creep damage has stabilised. This makes this analysis technique much slower than the standard fe-safe modules and the SRP technique.

TURBOlife requires that the full loading cycle is described. To do this it is recommended that the last and first samples in the loading (and also in a block if n > 1) contain the same stress tensor.

4.2.1 FEA results

Elastic finite element analysis of the component including all boundary conditions is required. Mechanical and thermal load cases may be considered separately and combined or they can be combined into a single load case. The finite element analysis must consider a full cycle of loading. Stresses are specified in time sequence where the time increment between stress sets need not be constant. There is no loss of accuracy in plasticity or creep calculations where large time steps are used. However, the time increment must be sufficiently small that the cycle analysis adequately captures peaks and valleys. To achieve this it is recommended that elastic stress increments should normally be limited to 10 MPa or less. For thermal analysis the calculated component nodal temperatures are used to select appropriate material properties. Again the thermal time step increment need not be constant. However it is recommended that nodal temperatures changes per time increment should not normally exceed 10 degrees C so that cyclic temperature changes are adequately described.

Calculations are performed for all nodes. The intention is to identify creep damage or creep-fatigue damage hot spots due to local stress concentrating features, regions of high thermal stress or regions of high temperature. It is assumed that the component has shaken down to cyclic behaviour that is essentially elastic. This means that local regions of cyclic plasticity are allowed but gross plasticity across load bearing sections of the component is beyond the scope of this methodology. Local cyclic plasticity is defined as extending over no more than 20% of load bearing sections. This assumption limits the extent of the plastic relaxation behaviour in plastic enclaves so that the behaviour can be described by simple methods. For pure thermal loading with no mechanical load, this 20% limit is less restrictive. In this case, any section connecting two points on a free surface must always exhibit a self-balancing stress distribution that includes both tensile and compressive stress.

To summarise regions of elastic stress must always exist and gross plastic or creep behaviour cannot exist. The assumption of limited plasticity is not unduly restrictive for practical purposes. This is because the endurance of high temperature components subjected to creep damage would be very low if mechanical stresses cause full-section plasticity.
Each node is assumed to behave independently in that the stress redistribution across the entire component to account for force equilibrium and displacement compatibility is not considered. This is a standard feature with the Neuber-type elastic-plastic corrections.

422 Temperature definition

To define loading for fe-safe/TURBOlife a temperature variation must be defined as well as stress variation. This will be a list of temperature datasets extracted from the FE model - one for each time point in the loading definition. The temperature dataset is defined in a similar manner to the stress datasets.

Using the loading interface to add the temperature dataset selected in the Current FE Models window to the current block select Add... >> Temperature Dataset. If no block is selected a block will be appended with the dataset. If no temperature dataset is selected, temperature dataset 1 is used.

Using the loading definition file .ldf the temperature dataset uses the keyword dtemp instead of ds. A range of temperature datasets can be defined on a single line or each dataset can be on a separate line. In the following example, the temperature dataset sequence is built up from datasets 6 to 11 followed by datasets 17 to 20.

```
# Each load history has ten samples
BLOCK n=100, scale=1.0
lh=/data/test.txt, signum=1, ds=1
lh=/data/test.txt, signum=1, ds=2
lh=/data/test.txt, signum=1, ds=3
lh=/data/test.txt, signum=1, ds=4
dtemp=6-11
dtemp=17-20
END
```

If the defined temperature history is shorter than the loading a warning will be written to the diagnostics log and the last defined temperature will be used for all subsequent temperatures.

423 Time definition

The times associated with each of the stress/temperature increments must be defined. This can either be a list of numbers in the .ldf file / GUI loading editor or a text based data signal file. If the defined time position series is shorter than the loading, a warning will be written to the diagnostics log and the last defined time position will be used for all subsequent sequence items.
Methodologies and procedures for creep-fatigue endurance assessment

The extract below is an ASCII file containing two time definitions:

```plaintext
SafeTechnologyASCII
1 Samples
Time1  Time2
Secs   Secs
0.00   0.00
30.00  30.00
60.00  60.00
90.00  90.00
120.00 120.00
150.00 150.00
180.00 180.00
210.00 210.00
240.00 240.00
270.00 270.00
300.00 300.00
330.00 330.00
360.00 360.00
3600.00 18000.00
3630.00 18030.00
3660.00 18060.00
3690.00 18090.00
3720.00 18120.00
3750.00 18150.00
3780.00 18180.00
3810.00 18210.00
3840.00 18240.00
3870.00 18270.00
3900.00 18300.00
3930.00 18330.00
3960.00 18360.00
```

**Note:** This example contains two time definitions. Only one is required for a particular analysis. The two examples show how to define a time delay between repeats and how not to. The difference is only relevant to DE

If you wish to have a non-zero time between the last sample of one repeat and the first sample of the next repeat then the first time in the list should indicate this, i.e in Time2 above the time delay between the last sample and the first would be 5.0 seconds.

If the first sample has a time of 0 seconds (as in Time1 above) *fe-safe* will use a zero time increment between the last sample in the loading and the first when repeating the loading. In this case no creep damage will occur between these two samples.

The same comments apply if a block has a repeat count greater than one.

To add the selected history to the current block as a time definition using the loading editor select **Add... >> Time History to Block**. A time definition allows the time in seconds to be applied to each sample in the loading block.

To add a user-defined sequence to the current block as a time definition select **Add... >> User Time to Block**. The **Dataset Embedded Time History** dialogue is displayed and the dataset time intervals can be entered.

**Note:** The entered time intervals must be ascending.
Using the loading definition file .ldf the time can be defined by the \texttt{dt} parameter or by a time for each item in the sequence using the \texttt{lhtime} parameter. All time position values must be in seconds.

The \texttt{lhtime} definition overrides the block parameter \texttt{dt}, in this case the time for 1 repeat of the block will be the last value in the \texttt{lhtime} sequence.

If items in the sequence are to be equally spaced in time then the \texttt{dt} block parameter will suffice, and the \texttt{lhtime} parameter is unnecessary. In this case the time associated with the first sample is 0 seconds and the time associated with the last sample is \( \frac{dt}{n} \) seconds.

The \texttt{lhtime} time positions can be defined directly as the argument to the \texttt{lhtime} parameter (see example 1, below), or alternatively, they can be extracted from an ASCII text file, that contains a series of time positions (see example 2, below). Both of the following examples yield the same total loading for the block:

**Example 1**

\begin{verbatim}
  # Each load history has ten samples
  BLOCK n=100, scale=1.0
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=0 5 7 9 10 11 25 27 30 31
  END
\end{verbatim}

**Example 2**

\begin{verbatim}
  # Each load history has ten samples
  BLOCK n=100, scale=1.0
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=/data/test.txt, signum=1, ds=4
  lh=0 5 7 9 10 11 25 27 30 31
  END
\end{verbatim}

test.txt, column 1 defines the times for each sample in the time history loading, in seconds, for example:

0
5
7
9
10
11
25
27
30
31

*Figure 4-1* indicates the difference caused by using the \texttt{dt} parameter to define the time for a block and using the \texttt{lhtime} parameter. The block in both cases is 20 seconds long. For the \texttt{lhtime} parameter the 5 datasets are spaced at 4 second intervals.

**Using dt**

\begin{verbatim}
  BLOCK n=1, dt=20
  ds=1-5
  END
\end{verbatim}

**Using lhtime**

\begin{verbatim}
  BLOCK n=1
  ds=1-5
  lh=4, 8, 12, 16, 20
  END
\end{verbatim}
4.2.4 Complex loading

Multiple blocks can be defined. As an example a two-block .ldf file is shown below:

```
# TURBOlife sample file

# Cycle type 1, repeated 5 times, each repeat is 3960 seconds
BLOCK n=5
lhtime=Q:\data\times.txt, signum=1
dtemp=1-26
ds=1-26
END

# Cycle type 2, repeated 18 times, each repeat is 18360 seconds
BLOCK n=18
lhtime=Q:\data\times.txt, signum=2
dtemp=1-26
ds=1-26
END
```

This analysis comprises two blocks, the first repeated 5 times and the second repeated 18 times. The first block is based upon a sequence of the stresses and temperatures from the first 26 increments of the FEA analysis over a time of 3960 seconds. The second is from the same 26 increments repeated over a time of 18360 seconds.

After the .ldf file has been selected (File >> Loadings >> Open FEA Loadings File...) the loading will be displayed in the Fatigue from FEA dialogue box as shown in Figure 4-2.
The block description **Creep Block** will be displayed for each block if the loading is correct.

**Note:** The block length in the loading tree indicates how many seconds \( n \) repeats of the block will take.

### 4.2.5 Recommendations

The time increment used in the elastic finite element calculation of the stress cycle should be sufficiently small to allow peaks and valleys in the load cycle to be identified, and to give a good definition of hysteresis loops. It is recommended that nodal temperatures changes per time increment should not normally exceed 10°C so that cyclic temperature changes are adequately described. Metal temperature change is governed by the heat transfer coefficient coupling the heat transfer fluid to the metal surface. The following table gives guidance on the maximum time increment that should be used where thermal transient loading is involved. These maximum time increments will limit the maximum surface temperature change to about 10°C or less per time increment.

<table>
<thead>
<tr>
<th>Heat Transfer Coefficient (W/m² °C)</th>
<th>Typical Heat Transfer Medium</th>
<th>Maximum Time Increment (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Cold air at 1 bar</td>
<td>45</td>
</tr>
<tr>
<td>100</td>
<td>Low velocity hot air at 1 bar</td>
<td>18</td>
</tr>
<tr>
<td>700</td>
<td>High velocity hot air at 1 bar</td>
<td>0.3</td>
</tr>
<tr>
<td>1000</td>
<td>Steam at 1 bar</td>
<td>0.19</td>
</tr>
<tr>
<td>2000</td>
<td>High velocity hot air at 15 bar</td>
<td>0.06</td>
</tr>
<tr>
<td>1200</td>
<td>Steam at 150 bar</td>
<td>0.145</td>
</tr>
<tr>
<td>25,000</td>
<td>Liquid metal cooling</td>
<td>0.0004</td>
</tr>
<tr>
<td>50,000</td>
<td>Boiling water heat transfer</td>
<td>0.000045</td>
</tr>
</tbody>
</table>
Methodologies and procedures for creep-fatigue endurance assessment

4.3 Materials data

fe-safe/TURBOlife requires that the following material parameters are defined:

- Monotonic stress-strain curves (DE)
- Cyclic stress-strain curves as a function of temperature
- Number of cycles to harden. If it is non-zero then the monotonic stress-strain curve must also be defined
- Strain-life curves as a function of temperature. NOTE: b2 is not used
- Strain-life curves for plasticity, creep and their interaction (SRP)
- Either creep table A or creep table B. Creep table A defines stresses as a function of strains, time and temperature. Creep table B defines strains as a function of stresses, time and temperature
- The fatigue-creep interaction diagram. This table indicates how fatigue damage and creep damage interacts to cause failure (DE)
- Creep ductility as a function of creep strain rate and temperature. The ductility value is used to evaluate the damage due to creep (DE)
- The temperature threshold beneath which creep damage is assumed negligible.
- The creep damage endurance limit.

Definition of these parameters is described in more detail in Chapter 3 above.

4.4 Selecting analysis

To enable a TURBOlife analysis, select TURBOlife – Creep Fatigue from the Group Algorithm Selection dialogue. This dialogue is displayed by clicking on an Algorithm cell on the Fatigue from FEA dialogue for a particular element/node group, see Figure 4-3.
For the Ductility Exhaustion method two mean stress options are available: a Morrow mean stress correction or no mean stress correction.

For the Strain Range Partitioning method no mean stress corrections are provided.

Normally, stress concentration features are included in the elastic finite element model. However, this may lead to modeling difficulties where very small features are included such as an array of fine cooling holes in a gas turbine blade. To account for this, additional stress concentration factors may be specified for particular element/node groups using the surface finish effects cells.

4.5 **Analysis Options**

The analysis options are configured from the **FEA Fatigue** menu item **TURBOlife Options**, see Figure 4-4 below.

![Figure 4-4](image-url)
4.5.1 Plasticity Method

Four plastic relaxation rules can be used to estimate the actual stress and strain from the elastic stress and strain. These are Neuber’s rule, Glinka’s rule, the Negative E rule and the Vertical rule. For general application, Neuber’s rule usually overestimates the relaxed values of stress and strain. Typically Glinka’s and the Negative E rules will underestimate them. The Vertical method only modifies the stress and leaves the strain equal to the elastic strain. Neuber’s rule should generally be used as it errs on the side of conservatism. Neuber’s rule is the standard for non-TURBOlife analyses in fe-safe. Sample hysteresis loops for the 3 models are shown in Figure 4-5 for the same elastic stress loading.

4.5.2 Generalised Stress Parameter

fe-safe/TURBOlife uses a single generalised stress parameter evaluated from the stress tensors in the FEA model. This stress parameter can either be Von Mises or Tresca. Both models use an incremental technique to evaluate the stress parameter beyond the first sample.

The generalised stress parameter is used in the hysteresis loop formation, fatigue and creep damage models. Any stress or strain changes due to the creep calculations are included in the fatigue calculations.

A modification to Young’s modulus (E) is made for the hysteresis loop and strain life equations. The modification is that E is replaced by \( \frac{E}{\epsilon} \) to allow uniaxial generalised stress and strain relationships to be used for multi-axial stress-strain states.

4.5.3 Creep Table that Takes Precedence

There are two ways in which the creep behaviour tables can be defined for a material. A material can have either or both tables defined. If only one table is defined then the table will automatically be used for the calculations. If a material has both tables defined then this group of controls defines which table is used.

![Figure 4-5](image-url)
4.5.4 Elastic follow-up factor, 1/Z (0->1)

The elastic follow-up factor is used to calculate the stress associated with a creep strain value. Forward creep, creep relaxation or any creep behaviour between these two extremes is accommodated through the use of this factor, Z. When Z is unity this will result in pure creep relaxation (1/Z=1). When Z is infinity this will result in forward creep with no stress relaxation (1/Z=0). For reasons of expediency 1/Z rather than Z is defined. This removes the requirement for infinity to be defined, see Figure 4-6.

![Figure 4-6](image)

4.5.5 Maximum diagnostics table size (DE)

Sample by sample extra diagnostic tables and plot files can be created. Because of the iterative nature of fe-safe/TURBOlife these can become very large. This size limit is used to limit the total size of the tables/plots using the rules outlined below.

<table>
<thead>
<tr>
<th>Description</th>
<th>Criteria to be written to table/plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Every sample</td>
<td>Size is less than max/2</td>
</tr>
<tr>
<td>Every 20000th sample</td>
<td>Size is less than max</td>
</tr>
<tr>
<td>Last sample</td>
<td>Always</td>
</tr>
</tbody>
</table>

4.5.6 Maximum iterations of loading (DE)

fe-safe/TURBOlife iterates through the loading repeatedly until the envelope defined in the creep damage vs. fatigue damage envelope is crossed. If the creep damage stabilises then the iterative analysis stops and the remainder of the distance to the envelope is interpolated. For some nodes with small amounts of creep damage this stabilisation could take many repeats of the loading. The nodes will not be the worst case nodes on the model but they would take a disproportionate amount of time to analyse. To prevent this the Maximum iterations of loading parameter is defined. Once this number of iterations is completed the distance to the envelope will be interpolated.

*Figure 4-7 shows the interpolation and the effect of varying the Maximum iterations of loading parameter.*
For analysing full models a reasonably low value should be used (e.g: 5). When re-analysing just the nodes at the critical locations to extract extra diagnostics this parameter can be increased. A smaller value will usually give a more conservative life where creep damage is occurring slowly, and will have little effect on the life where no creep damage occurs or where creep damage occurs but failure is within the specified number of repeats of the loading.

4.5.7 Maximum iterations per FOS (DE)
This parameter is similar to the Maximum iterations of loading parameter except it is used when a FOS calculation is being performed. The FOS calculations are discussed in more detail in the fe-safe User Manual.

4.5.8 Creep contour value for 0 damage (%) (DE)
A minimum of two contour plots is created for an analysis. A contour comprises one value per node. This can be plotted in a FEA viewer. The two standard contour plots are the life in hours and the % of damage which is creep damage.

For the second contour at any node where there is no creep damage and no fatigue damage, or an overflow occurs, this value is written to the output file.

4.6 Analysing and results
Once the analysis is defined pressing the Analyse! button on the Fatigue from FEA dialogue will start the analysis. The validity of the analysis configuration will be checked. If a message box similar to that shown in Figure 4-8 appears, appropriate corrections should be made to the loading definition.
4.6.1 Ductility Exhaustion

If the validation is successful a summary of the analysis definition will be displayed as shown in Figure 4-9.

The TURBOlife parameters are highlighted in the central red ellipse.
Two outputs are always created for TURBOlife analyses. These are the life in hours (usually log10) and the percentage of damage at the node that was due to creep damage. In the special case where either an overflow occurs or there is no fatigue and no creep damage the value defined on the TURBOlife Options dialogue is stored for the % of damage due to creep (the default is 50%).

In Figure 4-10 the left-hand plot is the % damage caused by creep and the right hand one is log10 of life in hours.

For each analysis performed in fe-safe a diagnostics log file is created with the same name and in the same location as the results file, but with the extension .log. By default, this file contains the information displayed in the message log during the analysis. The full definition of the analysis parameters and all of the analysis parameter values are written to this log file. An example is shown below with the TURBOlife sections highlighted:
FATIGUE LIFE : 5.00-16 fe-safe[mswin]

Algorithm: TURBOlife: None
Material: turbolife-material-local.dbase-
Surface: User defined Kt
Kt: 1
Model File(s): P:\\data\fullmodeltests\500-16-t1lifetest03a.csv
FEA Units: S=MPa e=uE T=deg.C
Loading: Load Definition File: 500-16-t1lifetest06a.ldf, TMP/TURBOlife
Scale factor: 1
Overflow Life value: 0
Infinite Life value: Material CAEL
Elastic follow up factor: 0.33
Plasticity model: Glinka
Stress parameter: Von Mises
Precedent table: A
Exports max size: 10000
Max iterations: 20
Max FOS iterations: 10
Exports: Disabled
Output contours to: P:\data\fullmodeltests\curResults\500-16-turbolife06e.csv
Contour variables: LOGLife-Hours % Damage-Creep
....Intermediate: c:\ResultsArchive\fe-safe.fer
Influence coeff: Disabled
Gauges: Disabled

<table>
<thead>
<tr>
<th>D'set</th>
<th>Type</th>
<th>Num</th>
<th>What</th>
<th>Direct</th>
<th>Shear</th>
<th>File</th>
<th>Descr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S Elemental</td>
<td>1</td>
<td>Elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:20</td>
</tr>
<tr>
<td>2</td>
<td>S Elemental</td>
<td>1</td>
<td>elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:100</td>
</tr>
<tr>
<td>3</td>
<td>S Elemental</td>
<td>1</td>
<td>elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:700</td>
</tr>
</tbody>
</table>

% Time  Life-Hours  % Damage-Creep
20  0:00:03   1324@1.1  25@1.1   20 of 100
50  0:00:06   1324@1.1  25@1.1   50 of 100
100 0:00:12   1324@1.1  25@1.1   100 of 100

Summary
======
Worst Life-Hours: 1324.376 at Element 1.1
Worst % Damage-Creep: 24.869 at Element 1.1
Analysis time: 0:00:12

Fatigue Analysis Completed.
4.6.2 Strain Range Partitioning

If the validation is successful a summary of the analysis definition will be displayed as shown in Figure 4-11.

![Figure 4-11](image)

The **TURBOlife** parameters are highlighted in the central red ellipse.

Five outputs are always created for **TURBOlife** analyses. These are the life in hours (usually log10), and the damage due to the four components of strain.

In Figure 4-12 the first plot is the log10 of life in hours. The other 3 plots are the 3 non zero damage components.
For each analysis performed in *fe-safe* a diagnostics log file is created with the same name and in the same location as the results file, but with the extension `.log`. By default, this file contains the information displayed in the message log during the analysis. The full definition of the analysis parameters and all of the analysis parameter values are written to this log file. An example is shown below with the *TURBOlife* sections highlighted:
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FATIGUE LIFE : 5.2-05 fe-safe[mswin]

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>TURBOlife:-Strain-Range-Partitioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>turbolife-material-SRP-local.dbase</td>
</tr>
<tr>
<td>Surface</td>
<td>User defined Kt</td>
</tr>
<tr>
<td>Kt</td>
<td>1</td>
</tr>
<tr>
<td>Model File (s)</td>
<td>P:\data\fullmodeltests\500-16-thermina641.odb</td>
</tr>
<tr>
<td>FEA Units</td>
<td>S=MPa e=uE T=deg.C</td>
</tr>
<tr>
<td>Loading</td>
<td>Loading is equivalent to 6.17229 Hours</td>
</tr>
<tr>
<td>Load Definition File</td>
<td>500-16-thermina.ldf, TMF/TURBOlife</td>
</tr>
</tbody>
</table>

Scale factor 1
Overflow Life value 0
Infinite Life value Material CAEL
Temperature analysis Disabled
Elastic follow up factor 0.2
Plasticity model Neuber
Stress parameter Von Mises
Precedent table A
Histories None
Log None
List of Items 196
Histories for Items TURBOlife,
Log for Items Block lives
Output contours to P:\data\fullmodeltests\curResults\5205-thermina641R.odb
Contour variables LOGLife-Hours, Damage-PP, Damage-CC, Damage-CP, Damage-PC
....Intermediate C:\temp\fesafe.fer
Influence coeffs. Disabled

<table>
<thead>
<tr>
<th>D'set</th>
<th>Type</th>
<th>Pos</th>
<th>Num</th>
<th>What</th>
<th>Direct</th>
<th>Shear</th>
<th>File</th>
<th>Descr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S</td>
<td>Element</td>
<td>1</td>
<td>Elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:20</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>Element</td>
<td>1</td>
<td>elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:100</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>Element</td>
<td>1</td>
<td>elements</td>
<td>1 -&gt; 0</td>
<td>0 -&gt; 0</td>
<td>..csv</td>
<td>T:700</td>
</tr>
</tbody>
</table>

% Time Life-Hours Damage-PP Damage-CC Damage-CP Damage-PC
53 0:00:06 3364280200.1 0@195.1 0@1.1 0@11.1 3.053E-9@1.1 517 of 980
100 0:00:10 3364280200.1 0@195.1 0@1.1 0@11.1 3.053E-9@1.1 980 of 980

Summary

Worst Life-Hours : 336427.844
at Element 200.1
Largest Damage-PP : 6.42E-6
at Element 195.1
Largest Damage-CC : 0
at Element 1.1
Largest Damage-CP : 1.582E-5
at Element 11.1
Largest Damage-PC : 3.053E-9
at Element 1.1
Analysis time : 0:00:10

Fatigue Analysis Completed.
4.7 FOS calculations

A factor of safety calculation can be performed using TURBOlife. For FOS calculations the analysis is repeated for a series of scale factors until the life is within the range of the design life. As the creep fatigue calculation itself is iterative this can increase the time for an analysis. The Maximum iterations per FOS defined on the TURBOlife Options dialogue can reduce the time required.

4.8 Extra diagnostics

Extra information can be added to the analysis .log file as described in the fe-safe User Manual. Plot files for a node can also be created. These are both controlled from the Exports and Outputs dialogue displayed by pressing the Exports button on the Fatigue from FEA dialogue. The relevant section tabs are shown in Figure 4-13. The checked items are applicable to TURBOlife and all other check boxes shown are ignored by fe-safe/TURBOlife.

The effect of each item is discussed in the following sections. All sections below marked with ‘(plot files)’ are stored on a node by node basis in an ASCII plottable file that can be opened using the Open Data File menu option. The name of each plot file is derived from the element or node number and the output file name.

4.8.1 Load Histories (plot files)

A plot file containing stress tensors, time and temperatures is created for each of the specified List of Items when this check box is selected. The plots are for a single repeat of the loading. A data file opened into the Loaded Data Files window is shown in Figure 4-14.
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Plots of the 8 parameters are shown in Figure 4-15.

To show how a stress tensor or temperature varies with time the two data channels can be cross-plotted.
4.8.2 Export TURBOlife plots (plot files)

**Ductility Exhaustion Method**

When this check box is selected a plot file containing the total time, block number, loading repeat, block sample, temperature, stress, strain, fatigue damage and creep damage for each of the specified List of Items is created. The plots include all of the repeats of the loading performed in the calculation; they also include the interpolated values for the damage parameters if an interpolation was performed.

A data file opened into the Loaded Data Files window is shown in Figure 4-16.

![Figure 4-16](image)

The plots created are described in the table below:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total-Time</td>
<td>The total time so far in the loading in Hours is contained in this plot. This can be used for cross-plotting other parameters against time.</td>
</tr>
<tr>
<td>Block #</td>
<td>This is the block number currently being processed.</td>
</tr>
<tr>
<td>Loading Repeat</td>
<td>This is the repeat of the loading currently being processed.</td>
</tr>
<tr>
<td>Block Repeat</td>
<td>This is the repeat number of the block currently being processed; this will increase from 1 to the n value defined for the block in the .ldf file. In some cases where the creep and fatigue damage stabilise within a block some of the repeats may be omitted. This indicates a block interpolation of the damage was performed.</td>
</tr>
<tr>
<td>Block Sample</td>
<td>This is the sample number within the block. 1 is the first sample in the loading for a block.</td>
</tr>
<tr>
<td>Temperature</td>
<td>This is the current temperature in degrees C in the analysis.</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain</td>
<td>This is the calculated strain parameter in uE; this includes the creep strain. It should be noted that the creep strain component does not cause fatigue damage. Cross plotting this parameter against time shows how creep strain accumulates with time.</td>
</tr>
<tr>
<td>Stress</td>
<td>This is the calculated stress parameter in MPa; this includes the creep stress. Cross plotting this parameter against time shows how stress and creep accumulate with time.</td>
</tr>
<tr>
<td>Fatigue Damage</td>
<td>This parameter shows how the fatigue damage accumulates with time. <em>Figure 5-4</em> shows this parameter cross-plotted with the creep damage. This value is a percentage.</td>
</tr>
<tr>
<td>Creep Damage</td>
<td>This parameter shows how the creep damage accumulates with time. <em>Figure 5-4</em> shows this parameter cross-plotted with the fatigue damage. This value is a percentage. It should be noted that creep damage recovery can occur. This is where creep damage reduces with time.</td>
</tr>
</tbody>
</table>

The stress and strain data channels can be cross-plotted to display hysteresis loops as shown in *Figure 4-17*. The effect of the change in temperature around a loop can be seen as the instantaneous Youngs modulus varies.

![Hysteresis Loops](image)

*Figure 4-17*

They can also be plotted against time to show creep effects, see *Figure 4-18*. 
Strain Range Partitioning

When this check box is selected a plot file containing the total time, block number, loading repeat, block sample, ISO-temperature, stress, strain, and damage parameters for each of the specified List of Items is created. A data file opened into the Loaded Data Files window is shown in Figure 4-19.

The plots created are described in the table:
Methodologies and procedures for creep-fatigue endurance assessment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total-Time</td>
<td>The total time so far in the loading in Hours is contained in this plot. This can be used for cross-plotting other parameters against time.</td>
</tr>
<tr>
<td>Block #</td>
<td>This is the block number currently being processed.</td>
</tr>
<tr>
<td>Block Repeat</td>
<td>This is the repeat number of the block currently being processed; this will increase from 1 to the n value defined for the block in the .ldf file. In some cases where the creep and fatigue damage stabilise within a block some of the repeats may be omitted. This indicates a block interpolation of the damage was performed.</td>
</tr>
<tr>
<td>Block Sample</td>
<td>This is the sample number within the block. 1 is the first sample in the loading for a block.</td>
</tr>
<tr>
<td>ISO-Temperature</td>
<td>This is the temperature in degrees C used in the analysis. It is the average of the maximum temperature in the loading and the temperature at the maximum von Mises stress.</td>
</tr>
<tr>
<td>Strain</td>
<td>This is the calculated strain parameter in uE; this includes the creep strain. Cross plotting this parameter against time shows how creep strain accumulates with time.</td>
</tr>
<tr>
<td>Stress</td>
<td>This is the calculated stress parameter in MPa; this includes the creep stress. Cross plotting this parameter against time shows how stress and creep accumulate with time.</td>
</tr>
<tr>
<td>Damage Plasticity</td>
<td>This parameter shows how the fatigue damage due to portion of cycle cause by fully reversed plastic strains accumulates with time. This value is a fraction of 1.</td>
</tr>
<tr>
<td>Damage Plasticity-Creep</td>
<td>This parameter shows how the fatigue damage due to portion of cycle cause by tensile plastic strains reversed by compressive creep strains accumulates with time. This value is a fraction of 1.</td>
</tr>
<tr>
<td>Damage Creep - Plasticity</td>
<td>This parameter shows how the fatigue damage due to portion of cycle cause by tensile creep strains reversed by compressive plastic strains accumulates with time. This value is a fraction of 1.</td>
</tr>
<tr>
<td>Damage Creep</td>
<td>This parameter shows how the fatigue damage due to portion of cycle cause by fully reversed creep strains accumulates with time. This value is a fraction of 1.</td>
</tr>
<tr>
<td>Total Damage</td>
<td>This parameter shows how the total fatigue damage accumulates with time. This value is a fraction of 1.</td>
</tr>
</tbody>
</table>

4.8.3 Export TURBOlife tables (.log file)

**Ductility Exhaustion Method**

If the checkbox TURBOlife tables is checked then for each of the List of items a table is created. This table replicates the plots described in the previous section in tabular format. All samples used throughout the analysis are stored in the table. The table also includes the interpolated value for the damage parameters if an interpolation was performed; this will be the last sample in the table.

A table (truncated for this documentation) is shown below.
4.8.4 Block life table (.log file)

Ductility Exhaustion Method

If the checkbox Block life table is ticked then for each of the List of items a table is created. This table shows how much creep \((D(\text{creepDmg}))\) and fatigue damage \((D(\text{fatig.Dmg}))\) was caused by each repeat of a block and also by each repeat of the whole loading. For block repeats the Block number (Block) and the block repeat counter (Block Reps) are shown in the table. For repeats of the loading the loading repeat counter is shown (Loading Reps). When the incremental creep damage is zero and the incremental fatigue damage is the same as the previous repeat then the damage is assumed to have stabilised. Upon stabilisation a fatigue damage interpolation for the block or repeat of loading will be performed and column 6 (Interpolating?) will indicate a yes.
Methodologies and procedures for creep-fatigue endurance assessment

**Note:** If the Maximum iterations of loading are exceeded then an interpolation will also be performed.

TURBOLIFE BLOCK BY BLOCK INCREMENTAL DAMAGE TABLE for Element 27193.1 material index 0

<table>
<thead>
<tr>
<th>Loading Reps</th>
<th>Block</th>
<th>Block Reps</th>
<th>D(Crp Dmg)</th>
<th>D(Fat Dmg)</th>
<th>Interpolating ?</th>
<th>Time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.16E-01</td>
<td>2.88E-07</td>
<td>no</td>
<td>1.1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5.55E-02</td>
<td>2.03E-07</td>
<td>no</td>
<td>2.2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>4.09E-02</td>
<td>1.91E-07</td>
<td>no</td>
<td>3.3</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3.31E-02</td>
<td>1.81E-07</td>
<td>no</td>
<td>4.4</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
<td>2.82E-02</td>
<td>1.74E-07</td>
<td>no</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1.09E-01</td>
<td>5.46E-07</td>
<td>no</td>
<td>10.6</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>7.54E-02</td>
<td>4.81E-07</td>
<td>no</td>
<td>15.7</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5.90E-02</td>
<td>4.41E-07</td>
<td>no</td>
<td>20.8</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4.90E-02</td>
<td>4.07E-07</td>
<td>no</td>
<td>25.9</td>
</tr>
<tr>
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<td>5</td>
<td>4.23E-02</td>
<td>3.85E-07</td>
<td>no</td>
<td>31</td>
</tr>
<tr>
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<td>6</td>
<td>6</td>
<td>3.73E-02</td>
<td>3.66E-07</td>
<td>no</td>
<td>36.1</td>
</tr>
<tr>
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<td>7</td>
<td>7</td>
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<td>3.50E-07</td>
<td>no</td>
<td>41.2</td>
</tr>
<tr>
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<td>8</td>
<td>8</td>
<td>3.05E-02</td>
<td>3.36E-07</td>
<td>no</td>
<td>46.3</td>
</tr>
<tr>
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<td>9</td>
<td>9</td>
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<td>3.24E-07</td>
<td>no</td>
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</tr>
<tr>
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<td>10</td>
<td>10</td>
<td>2.60E-02</td>
<td>3.19E-07</td>
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<td>56.5</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>11</td>
<td>2.43E-02</td>
<td>3.05E-07</td>
<td>no</td>
<td>61.6</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>12</td>
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<td>66.7</td>
</tr>
<tr>
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<td>13</td>
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<td>2.89E-07</td>
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<tr>
<td>2</td>
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<td>14</td>
<td>2.04E-02</td>
<td>2.82E-07</td>
<td>no</td>
<td>76.9</td>
</tr>
<tr>
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<td>15</td>
<td>1.93E-02</td>
<td>2.76E-07</td>
<td>no</td>
<td>82</td>
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<td>16</td>
<td>1.84E-02</td>
<td>2.70E-07</td>
<td>no</td>
<td>87.1</td>
</tr>
<tr>
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<td>17</td>
<td>1.76E-02</td>
<td>2.65E-07</td>
<td>no</td>
<td>92.2</td>
</tr>
<tr>
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<td>18</td>
<td>18</td>
<td>1.69E-02</td>
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<td>no</td>
<td>97.3</td>
</tr>
<tr>
<td>1</td>
<td>.</td>
<td>.</td>
<td>9.25E-01</td>
<td>7.23E-06</td>
<td>no</td>
<td>97.3</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3.07E-03</td>
<td>1.08E-07</td>
<td>no</td>
<td>98.4</td>
</tr>
<tr>
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<td>2</td>
<td>2</td>
<td>3.04E-03</td>
<td>1.08E-07</td>
<td>no</td>
<td>99.5</td>
</tr>
<tr>
<td>1</td>
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<td>3</td>
<td>3.02E-03</td>
<td>1.08E-07</td>
<td>no</td>
<td>100.6</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3.00E-03</td>
<td>1.08E-07</td>
<td>no</td>
<td>101.7</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
<td>2.97E-03</td>
<td>1.07E-07</td>
<td>no</td>
<td>102.8</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1.56E-02</td>
<td>2.50E-07</td>
<td>no</td>
<td>107.9</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.51E-02</td>
<td>2.46E-07</td>
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<td>1.45E-02</td>
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</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
<td>1.41E-02</td>
<td>2.39E-07</td>
<td>no</td>
<td>123.2</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1.36E-02</td>
<td>2.35E-07</td>
<td>no</td>
<td>128.3</td>
</tr>
</tbody>
</table>

**Strain Range Partitioning**

If the checkbox Block life table is ticked then for each of the List of items a table is created. This table shows the damage accumulating with time.

**4.8.5 Item information and critical-plane orientation (.log file)**

A single table will be created when this check box is ticked. One entry will be added for each of the List of items. Columns 1,3 and 4 are relevant for TURBOlife analysis. This is not a critical-plane technique and no gating is performed as the whole history is required. Columns 2 and the last 5 are not applicable (they are shaded below).
The table shows the maximum temperature $T$, and the group an item belongs to $\text{Group}$. 

<table>
<thead>
<tr>
<th>Element</th>
<th>Block</th>
<th>Group</th>
<th>$T$ (degC)</th>
<th>CP Dir.</th>
<th>Tensor Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>45756.1</td>
<td>Transitions</td>
<td>Remainder</td>
<td>234 3D 1</td>
<td>...</td>
<td>-1</td>
</tr>
<tr>
<td>86859.1</td>
<td>Transitions</td>
<td>Remainder</td>
<td>234 3D 1</td>
<td>...</td>
<td>-1</td>
</tr>
</tbody>
</table>

4.8.6 Export dataset stresses (.log file)

When this check box is selected tables of the dataset stresses and temperatures extracted directly from the FEA model results for the specified $\text{List of Items}$ are created. These are the stresses before they are scaled or manipulated to create the tensor histories.

4.8.7 Loading stress, strain and temperature (.log file)

Tables of the stress tensors, time and temperatures for the specified $\text{List of Items}$ are created when this check box is selected. The tables are for a single repeat of the loading. These are the tensor histories used directly in the analysis.

4.8.8 Export FOS plane tracking table (.log file)

If a FOS calculation is enabled this table will be created for each of the $\text{List of Items}$. The table shows the iterative scaling process including the lives calculated at each scale. It should be noted that the lives shown are for repeats of the loading not hours.

ANALYSE FOS TABLE for Element 27193.1 (design life = 5.139e+000 repeats)

<table>
<thead>
<tr>
<th>FOS</th>
<th>nf(reps)</th>
<th>% Crp Dmg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>1.319e+000</td>
<td></td>
</tr>
<tr>
<td>0.100</td>
<td>9.925e+001</td>
<td>100.000</td>
</tr>
<tr>
<td>0.300</td>
<td>3.352e+001</td>
<td>100.000</td>
</tr>
<tr>
<td>0.650</td>
<td>4.948e+000</td>
<td>100.000</td>
</tr>
</tbody>
</table>

4.9 Analysis limitations

The following features are either not supported or not applicable to $\text{fe-safe/TURBOlife}$ analyses.

- Analysis of elastic-plastic FEA results
- Inclusion of elastic-plastic residuals
- Asymmetric hysteresis loops in compression and tension.
- In plane residual stress (Fatigue from FEA dialogue)
- Mixing $\text{TURBOlife}$ and non $\text{TURBOlife}$ analyses.
- Load sensitivity analyses (Export Histories and Diagnostics)
- Pre Gating of tensors.
- Nodal elimination based on material CAEL.
- Traffic Lights (Export Histories and Diagnostics)
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- Gauges and Influence Coefficients.
- All critical plane based diagnostics (Export Histories and Diagnostics)
Methodologies and procedures for creep-fatigue endurance assessment

5.1 Introduction

Engineering components operating hot and cyclically will experience creep damage and fatigue damage that can initiate cracks and ultimately lead to component failure. Fatigue damage was first recorded and investigated at the start of the railway industry and continues to be extensively studied today. Creep deformation in ice and rock under geological forces has been noted for centuries. However, creep damage in engineering materials became of significant interest at the advent of power stations since the thermal efficiency of thermodynamic cycles is directly related to the maximum operating temperature.

Creep damage and fatigue damage can occur separately and progressively during plant operation. Fatigue damage is primarily related to the magnitude and number of load cycles. Creep damage is primarily related to steady load levels and operating temperature. There are commonly occurring circumstances under which fatigue damage and creep damage can interact leading to the sudden onset of cracking and much reduced component endurances.

A common approach to managing sudden degradation due to creep-fatigue is to limit the maximum operating temperature of components. For example ASME codes (ASME NB3000, 2001, 23.1 in the User Manual) limit the operating temperature of certain classes of carbon steels and low alloy steels to 700 °F (371 °C) and to certain austenitic stainless steels and nickel based alloys to 800 °F (426 °C). Recent changes in the operating rationale of power stations have occurred due to industrial deregulation. This has meant that many power stations have changed from base load generation to demand following so that gas turbines and boilers are now operating beyond their design basis. In the automotive industry, increasingly demanding emission legislation is leading to engine and exhaust components operating hotter.

Notwithstanding the long history of creep and fatigue research, the complexity of the phenomenon and industrial changes driven by globalisation, deregulation and environmental issues means that the need now exists for validated creep-fatigue endurance methodologies linked to modern methods for stress and strain analysis. This need is set to increase in the future. Since the technical problem is now occurring in a wider range of industries, the methods should be robust for use by non-specialists.

5.2 Predictive methods for creep-fatigue endurance assessment

5.2.1 Elements of a methodology

There are three basic aspects to a creep-fatigue damage methodology. These are concerned with stress-strain behaviour of the component or structure, damage modelling and the measurement of appropriate materials data. The choice between particular methods may depend on convenience which is related to the complexity of the analytical aspects and the availability of materials data. Alternatively, the choice of method may depend on tradition within particular industries or regulatory aspects.

5.2.2 Stress-strain behaviour

Stress-strain methods can be divided into two broad categories. These are based on deformation theory of plasticity and incremental theory of plasticity. Deformation theory states that the stress-strain state depends on the total plastic deformation and not on the load history of deformation. The incremental theory of plasticity accounts for the load history. Incremental approaches can be non-unified or unified depending on how creep strain and plastic strain are combined. In a non-unified approach creep strain is added after the usual yield surface treatment.
of plastic strain. In a unified approach plastic strain and creep strain are combined prior to yield surface consideration.

5.2.3 Damage modelling

Methodologies for assessing creep-fatigue damage can generally be classified as stress based or strain based. Traditionally, stress based methods have been used because stress is easier to determine than strain. However, the application and removal of stress produces no creep or fatigue damage since the process is reversible. It is the consequential, irreversible strain which produces damage leading to cracking and failure. Stress based methods tend to be more complex than strain based methods, requiring the treatment of more parameters. This is because implicit in a stress based damage methodology must be a means of assessing strain from elastic stress analysis. A simple example of this pertains to fatigue assessment where a strain based method may relate endurance to the single parameter of cyclic strain range. A stress based method would require two parameters of mean stress and alternating stress to implicitly include the effect of strain where yielding occurs.

A well-known stress based model is due to Chaboche (Chaboche, 1976, Ref 4). Here an increment of damage is determined as the sum of the creep damage increment and the fatigue damage increment. The creep damage increment depends on stress, temperature and the current damage. The fatigue damage increment depends on the maximum and mean stresses in the cycle, the temperature and the current damage. Creep damage is based on stress and time to rupture. Fatigue damage is based on stress-life curves. The inclusion of the current damage in the damage increment summation ensures an accelerating rate of total damage accumulation.

A well-known strain based method is strain range partitioning (Manson et al, 1971, Ref 5). It is noted that the inelastic strain range associated with stress-strain hysteresis loops is related to endurance and that four possible ways exist in which a closed hysteresis loop can be formed. These are plastic strain reversed by plastic strain, plastic strain reversed by creep strain, creep strain reversed by plastic strain and creep strain reversed by creep strain. Tests are performed for each of these four cycle types to produce curves of strain range versus endurance. Where a complex cycle is comprised of two or more of these basic cycle types, the total strain range for the cycle is partitioned into that due to each basic cycle type. The damage for the complex cycle is derived as the sum of the damage from the partitioned strain ranges and their respective endurance curves.

5.3 Design and assessment procedures

5.3.1 Background

In addition to individual damage methodologies, formalised procedures exist for design or assessment purposes. These procedures are often written with particular industrial applications in mind and may include appropriate materials data. Such procedures are needed for legal and regulatory purposes and to ensure consistent standards in design and assessment. Some examples are given below.

5.3.2 ASME NH

For elevated temperature operation, ASME NH (ASME NH, 2001, Ref 2) provides rules for design by analysis of Class 1 components used in safety related structures such as nuclear power plant. The criteria on which the rules are based were published in 1974 with no significant changes since. The rules include stress limits to avoid gross plastic deformation, strain limits to avoid incremental plastic collapse due to ratcheting and stress and strain limits to avoid creep fatigue failure. Fatigue initiation damage is assessed using a strain based rule and creep initiation damage is assessed using a stress based, time to rupture rule. Crack growth aspects are not considered. For strain based aspects, rules are included to estimate plastic strain from elastic analysis. Creep-fatigue damage is explicitly accounted for by means of an interaction rule. Fully characterised material data sets for chrome steels,
austenitic stainless steel and nickel based alloys are included. These rules are intended to avoid failure in structures and so include empirical design factors in the assessment methods together with lower bound materials data.

5.3.3 RCC – MR
The French design code, RCC-MR (RCCMR, 1985, Ref 6) performs the same purpose as the American ASME NH and is structured in a very similar way. The creep-fatigue rules are based on the same methods although some differences exist in the estimation of plastic strain from elastic analysis.

5.3.4 British Standards
Some guidance on elevated temperature durability is provided by British Standards (BS, 1999, Ref 3). This guidance assumes the existence of a defect and is based on creep crack growth aspects only. Guidance is given on whether or not a component can be considered as exempt from the possibility of creep failure. Where exemption is not demonstrated, aspects which should be considered are listed such as crack propagation rates from creep and fatigue and the possibility of fast fracture. Little guidance is given on the computational aspects of creep-fatigue assessment.

5.3.5 R5 procedure
The most comprehensive and detailed guidance on elevated temperature component assessment is given in the R5 document (R5, 2003, Ref 7) which is used in the United Kingdom for assessment of nuclear reactor components. The first issue of R5 was published in 1990 although the underlying research programme started considerably before that date. Many UK companies concerned with design, construction and operation of nuclear reactors and fuel cycles have been involved in the R5 development which is ongoing. The intention of R5 is to augment and replace where necessary the provisions of ASME codes and the French RCC-MR rules. It extends the rules of these codes to consider not only crack initiation from hot, cyclic operation but also defect assessment and the treatment of weldments. Unlike ASME and RCC-MR, R5 is an assessment procedure and does not generally contain safety margins. Where necessary, safety margins can be determined by the user through sensitivity analysis.

The R5 document is written in seven volumes as follows:

Volume 1 Overview
Volume 2/3 Creep-Fatigue Crack Initiation Procedure for Defect free Structures
Volume 4/5 Procedure for Assessing Defects under Creep and Creep-Fatigue Loading
Volume 6 Assessment Procedure for Dissimilar Metal welds
Volume 7 Behaviour of Similar Weldments – Guidance for Steady Creep loading of Ferritic Pipework Components

Volume 2/3 concerning creep-fatigue crack initiation is based on the use of elastic analysis but gives guidance on the use of elastic analysis for components where shakedown to global elastic behaviour cannot be demonstrated. Fatigue assessment is based on the strain-life approach and creep assessment is based on creep ductility exhaustion.
Methodologies and procedures for creep-fatigue endurance assessment
6 Strain-based methods in thermo-mechanical creep-fatigue endurance assessment

6.1 Experimental observations of deformation behaviour

6.1.1 Engineering stress/strain curve (tensile test)

As a uniaxial test specimen is stretched its cross sectional area will reduce and its length will increase. Engineering stress $\sigma_e$ is defined as the load divided by the original cross sectional area and engineering strain $\varepsilon_e$ is defined as the extension divided by the original length. Uniaxial tensile tests described in terms of engineering stress and engineering strain are commonly used to gather data on the deformation of polycrystalline metallic materials. During such tests characteristic behaviour is exhibited. Many metals demonstrate a steep, straight line relationship between stress and strain up to a yield stress $\sigma_y$ limit (Figure 6-1).

![Figure 6-1 General form of stress-strain relationships](image)

This behaviour is elastic with a slope of E known as Young’s modulus where on removal of the load the elastic strain is recoverable back to zero strain. When loading progresses beyond the yield stress, plastic strain occurs so that the stress-strain relationship is no longer linear. On load removal the strain recovery is again elastic and the plastic strain is not recovered. This leaves a permanent plastic deformation in the material.

With continuous loading a maximum stress known as the Ultimate Tensile Stress $\sigma_{uts}$ is reached at which the slope of the stress-strain curve is zero. From this point onwards the load applied by the test machine will reduce as the plastic strain continues to increase until the specimen fractures. The strain at fracture characterises the material ductility where low strain denotes a brittle material and high strain denotes a ductile material. Young’s modulus, yield stress and UTS are traditionally considered to be material properties and are used to characterise the deformation behaviour of different materials. However the shape of the stress-strain curve between the UTS and fracture and the engineering measure of ductility depend on the length of the specimen and the control system of the testing machine. Some materials such as stainless steel do not exhibit a definite yield point at the onset of
plastic straining. Instead plastic strain occurs progressively from zero stress although plastic strain is very small in the early stages of loading. Nevertheless the above description of behaviour is still applicable.

6.1.2 True stress and strain definitions

For a cylindrical specimen tested in tension with a load \( P \) and original cross sectional area \( A_0 \), the engineering stress is given by:

\[
\sigma_e = \frac{P}{A_0}
\]  

[Equation 6.1-1]

If the original length is given by \( l_0 \) and the final length by \( l \), the engineering strain is given by:

\[
\varepsilon_e = \frac{l - l_0}{l_0}
\]  

[Equation 6.1-2]

True strain \( \varepsilon \) is defined as an increment of extension \( dl \) divided by the current length \( l \) so that an increment of true strain is given by:

\[
d\varepsilon_t = \frac{dl}{l}
\]  

[Equation 6.1-3]

Integration then gives:

\[
\varepsilon_t = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0}
\]  

[Equation 6.1-4]

Since

\[
\varepsilon_e = \frac{l}{l_0} - 1
\]  

[Equation 6.1-5]

Then

\[
\varepsilon_t = \ln \left(1 + \varepsilon_e\right)
\]  

[Equation 6.1-6]

Elastic strain produces a change in volume whereas plastic strain occurs at constant volume. When total strain is large so that elastic strain may be neglected then \( \varepsilon_t \) can be expressed in terms of \( A \) and \( R\alpha A \), the current cross sectional area and the reduction in cross sectional area respectively using the continuity of volume condition:

\[
A_0 \frac{l_0}{l} = A l
\]  

[Equation 6.1-7]

so that

\[
\frac{l}{l_0} = \frac{A_0}{A}
\]  

[Equation 6.1-8]

Therefore

\[
\varepsilon_t = \ln \left(\frac{A_0}{A}\right) = \ln \left(\frac{100}{100 - \%R\alpha A}\right)
\]  

[Equation 6.1-9]
True stress \( \sigma_t \) is defined as the current load \( P \) divided by the current area \( A \) so that:

\[
\sigma_t = \frac{P}{A}
\]  

[Equation 6.1-10]

From the continuity of volume condition:

\[
\sigma_t = \frac{P_l}{A_o l_o} = \sigma_e \frac{l_o}{l_o} = \sigma_e (1 + \varepsilon_e)
\]  

[Equation 6.1-11]

Thus true stress and true strain are defined in terms of engineering stress and engineering strain. These definitions apply up to the onset of necking. Alternatively, when \( \varepsilon \) is expressed in terms of %RA, the definition applies to pre and post necking where %RA is measured at any position along the necked section. At small strains there is very little difference between the engineering and true definitions of stress and strain. At large strains and in necked regions there is a significant difference and it is important to note the definition of stress and strain used when data is quoted. Figure 6-2 shows data for 316 stainless steel at 600 °C (UKAEA, 1976, Ref 25).

![Figure 6-2 Comparison of engineering stress-strain curves and true stress-strain curves for 316 stainless steel at 600 °C](image)

6.1.3 True stress/strain tensile curve

The stress-strain curve behaviour can be understood in terms of the true stress and true strain definitions (McClintock et al, 1966, Ref 30). As metallic materials stretch they may work harden so that further strain increments require further load increments and the stress-strain curve monotonically increases. The constancy of volume during plastic strain results in the cross sectional area reducing and the true stress becomes significantly greater than the engineering stress. A point in loading is reached at which the increment of stress required for further straining is exactly equal to the increment of stress resulting from the reducing load carrying area. Hence, plastic strain can continue to increase with no further increase in load. This is the onset of necking corresponding to the beginning of plastic instability in the test specimen. The engineering stress at the onset on necking is the UTS. Hence the UTS is a material property related to the rate at which the material work hardens.
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The load $P$ is given in terms of the current area $A$ and the true stress $\sigma_t$ as:

$$P = A \sigma_t$$  \hspace{1cm} [Equation 6.1-12]

At the onset of necking $dP = 0$ so that:

$$dP = d(A \sigma_t) = A d\sigma_t + \sigma_t dA = 0$$  \hspace{1cm} [Equation 6.1-13]

$dA$ is derived from continuity of volume:

$$Al = constant$$  \hspace{1cm} [Equation 6.1-14]

so that:

$$Adl + ldA = 0$$  \hspace{1cm} [Equation 6.1-15]

and

$$dA = -A \frac{dl}{l} = -Ad\epsilon_t$$  \hspace{1cm} [Equation 6.1-16]

Therefore:

$$Ad\sigma_t = \sigma_t A d\epsilon_t$$  \hspace{1cm} [Equation 6.1-17]

so that:

$$\sigma_t = \frac{d\sigma_t}{d\epsilon_t}$$  \hspace{1cm} [Equation 6.1-18]

In terms of the true stress-strain curve, the onset of necking occurs when the stress equals the slope. True stress-strain curves can often be described as a Ramberg-Osgood power law of the form:

$$\sigma_t = \alpha \epsilon_t^\beta$$  \hspace{1cm} [Equation 6.1-19]

$$\frac{d\sigma_t}{d\epsilon_t} = \alpha \beta \epsilon_t^{\beta-1}$$  \hspace{1cm} [Equation 6.1-20]

equating this to $\sigma_t$ gives:

$$\epsilon_t = \beta$$  \hspace{1cm} [Equation 6.1-21]

Therefore in terms of true stress strain and the Ramberg-Osgood power law curve fit, the onset of necking occurs when the strain equals the power law exponent.

The corresponding stress at the onset of necking is equal to $\alpha \beta^\beta$.

6.1.4 Stress and strain under cyclic conditions

The discussion above has considered stress and strain under a single application of loading (monotonic conditions). In some applications of the mechanics of materials, non-linear elasticity is assumed in which unloading
Strain based methods in thermo-mechanical creep-fatigue endurance assessment

exactly reverses the loading path and returns the stress-strain coordinates to the origin of the monotonic stress strain curve. More usually, metallic materials demonstrate hysteresis on unloading such that the stress and strain do not pass through the origin of the monotonic stress strain curve and hysteresis loops are formed. In addition, continuous cycling in the loading history causes the hysteresis loops to change shape in the manner of hardening (or softening) as shown in Figure 6-3.

Figure 6-3 Hysteresis loops and the definition of the cyclic stress strain curve.

Cyclically hardened hysteresis loops are formed in a single specimen material test by fixing the cyclic strain range and cycling until the stress range no longer changes. When stability is achieved, the stress range is increased and cycling continued until stability is again achieved. In this way, nested, cyclically hardened hysteresis loops are formed. For analysis purposes it is necessary to quantify the shape of hysteresis loops and the rate at which hardening occurs with continuous cycling. The shape of the hysteresis loops is defined by the cyclic stress-strain curve as defined in Figure 6-3. This takes the form of a power law and is discussed further in the fe-safe User Manual. The rate of hardening has been extensively studied by Skallerud et al (Skallerud, 1989, Ref 23.23) and considered further by Hales et al (Hales, 2002, Ref 14). Based on experimental data, Skallerud defined the hardening in terms of:

\[
\sigma_u = \sigma_0 e^{-\frac{N}{(N_{rsN})}} + \sigma_s \left(1 - e^{-\frac{N}{(N_{rsN})}}\right)
\]  

[Equation 6.1-22]

where \(\sigma_0\) is the monotonic stress, \(\sigma_s\) is the fully hardened cyclic stress, \(\sigma_u\) is the current stress, \(N\) is the number of stress reversals, \(N_{rsN}\) is the number of stress reversals to fully saturate the hardening and \(\xi\) is a scaling factor.

From the above equation:

\[
1 - \left(\frac{\sigma_u - \sigma_s}{\sigma_0 - \sigma_s}\right) = \left(1 - e^{-\frac{N}{(N_{rsN})}}\right)
\]  

[Equation 6.1-23]
Defining $h$ as a parameter which varies from 0 to 1 such that the material is fully soft for $h = 0$ \textit{i.e.} ($\sigma_a = \sigma_0$) and fully hard for $h = 1$ \textit{i.e.} ($\sigma_a = \sigma_s$), then:

$$h = 1 - e^{-\frac{N}{(N_r-N)}}$$  \hspace{1cm} [Equation 6.1-24]

The quotient $N/(N_r - N)$ is identical to $d/(D_r - d)$ where $d$ is the current fatigue damage and $D_r$ is the fatigue damage to fully harden. Therefore the hardening parameter $h$ can be conveniently expressed in terms of the fatigue damage from variable amplitude loading as:

$$h = 1 - e^{-\frac{d}{(N_r-d)}}$$  \hspace{1cm} [Equation 6.1-25]

6.1.5 Stress and strain concentration factors (elastic follow-up)

Geometric features such as holes, notches, sharp changes of section and welds result in a local increase in elastic stress above the nominal stress away from the feature. If the maximum stress at the feature remains below the yield stress then the maximum stress normalised to the nominal stress is defined as the stress concentration factor. For this condition the strain concentration factor defined as the maximum strain normalised to the nominal strain is identical in magnitude to the stress concentration factor. These factors are useful since they have specific values for specific geometric features. For a circular hole in a flat plate well away from edges and under uniaxial loading, the stress concentration factor is three. Handbooks giving stress concentration factors are available (Young, 1989, Ref 28).

It is often the case that the elastically calculated stress accounting for the stress concentration factor is above the yield stress. It is evident then that the maximum stress will be limited to a value below the elastically calculated value. The exact computation of stress and strain in this case is complex and must account for stress and strain redistribution throughout the entire component. The requirements to maintain force equilibrium and displacement compatibility must be met in accordance with the strain hardening characteristic of the material stress-strain curve.

A simple technique to estimate the maximum stress and strain under this circumstance is highly desirable. That such techniques can be developed is evident from the principle of Saint-Venant which suggests that the influence of a point force perturbation is local to the point of application of the force. Therefore, notwithstanding the requirement of force equilibrium and displacement compatibility throughout the entire component, the major effect of stress concentrating features is local to the feature. Neuber (Neuber, 1961, Ref 20) has proposed a simple rule for the tip of a slender notch where a plastic enclave exists, i.e. the plastically strained material is surrounded by elastic material. He stated that the product of the stress concentration factor and the strain concentration factor is constant and independent of the shape of the stress–strain curve. A consequence of this is that the product of stress and strain is also constant. Therefore the simple construction shown in Figure 6-4 allows notch tip stress and strain under yielding conditions to be estimated from elastic analysis.
The physical interpretation of Neuber’s rule is that once yielding, elastic strain is partly replaced by plastic strain so that the stress reduces. However, an elastic follow-up mechanism acts to reduce the load carried in the elastic region and increase the load carried in the plastic enclave region relative to the fully elastic solution. Therefore, additional stretching occurs in the plastic region and the stress relaxation does not occur at constant strain (pure relaxation) but with enhanced strain.

Neuber’s rule is widely used. Although it is strictly applicable at the tip of a slender notch only, it is sometimes applied with success throughout the entire plastic enclave region. Where the applied stress is sufficiently high such that plastic strain occurs across a significant portion of load carrying area, then Neuber’s rule does not apply. Other rules have been proposed such as that attributed to Glinka (Moftakhar et al, 1992, Ref 19). This states that plastic relaxation occurs with constant area under the stress-strain curves. In comparisons to elastic-plastic finite element analysis, Neuber’s rule tends to overestimate the plastic strain enhancement (Harkegard et al, 2003, Ref 16). Glinka’s rule produces a lower estimate of plastic strain enhancement than Neuber’s rule.

6.1.6 Time dependent behaviour

As the temperature of the tensile test increases, additional plastic strain occurs in the form of creep strain. The behaviour of creep strain is similar to time independent plastic strain in that for calculation purposes, it follows the normal flow rules and occurs at constant volume etc. The only differentiating factor is that the accumulated creep strain depends not only on temperature and stress but also on time. Some materials such as lead exhibit significant creep strain at room temperature although most engineering materials required elevated temperature for significant creep to occur. Webster et al (Webster et al, 1994, Ref 27) has given some temperatures at which creep becomes significant in the design of boiler and pressure vessel components. See Figure 6-5
Strain based methods in thermo-mechanical creep-fatigue endurance assessment

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature for significant creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon manganese steel</td>
<td>310 °C</td>
</tr>
<tr>
<td>Low alloy ferritic steel</td>
<td>420 °C</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>485 °C</td>
</tr>
<tr>
<td>Alloy 800 H</td>
<td>550 °C</td>
</tr>
<tr>
<td>Alloy 718 bolting material</td>
<td>460 °C</td>
</tr>
</tbody>
</table>

Figure 6-5 Onset of creep for design purposes

It is sometimes suggested the creep strain begins to become significant for engineering design purposes when the ratio of the metal temperature to the melting point, both in absolute terms (the homologous temperature Tm) is greater than a threshold value which is approximately 0.5. Although creep strain can certainly occur at temperatures lower than 0.5 Tm, the stress required to cause significant creep is high and possibly above the yield stress of the material (Webster et al, 1994, Ref 27). Therefore at temperatures below 0.5 Tm, plasticity considerations dominate the deformation process and life assessment procedures. On this basis the significant creep temperature for common engineering materials is as follows in Figure 6-6.

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting temperature (°C)</th>
<th>Significant creep temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrome steel</td>
<td>1250</td>
<td>488</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>645</td>
<td>186</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>1415</td>
<td>571</td>
</tr>
<tr>
<td>Nickel based alloy</td>
<td>1383</td>
<td>555</td>
</tr>
</tbody>
</table>

Figure 6-6 Significant creep temperature based on 0.5 Tm

Creep in polycrystalline materials occurs as a result of dislocation movement within grains, grain boundary sliding and diffusion. A graph of creep strain versus time for constant engineering stress and temperature will typically have the characteristic shape shown in Figure 6-7.
All of the characteristics of the curve are not necessarily exhibited in all materials in all conditions. The incubation period is a period of initial increasing creep strain rate. It is typical of single crystal materials or polycrystalline materials with a high directional orientation in the grains. The primary creep stage is a period of decreasing creep strain rate where work hardening processes act increasingly to inhibit dislocation movement and the accumulation of creep strain. The secondary creep stage, sometimes called steady state creep is a period of constant creep strain rate. It occurs when the work hardening and thermally activated softening processes are in balance. Unloading during the secondary creep phase produces a time dependent recovery of creep strain. This has been attributed (Gittus, 1975, Ref 29) to the recovery of substantial part of the primary creep which is viscoelastic rather than plastic. The tertiary creep stage is a period of accelerating creep strain rate that occurs due to a number of reasons. These include an increase in true stress due to specimen necking and grain boundary voiding or cracking, or metallurgical changes due to temperature/time exposure. Thus, issues relating to the consideration of engineering stress/strain and true stress/strain are equally as important in the understanding of creep behaviour as they are in tensile testing in the absence of creep. Tertiary creep ends in specimen fracture where the creep strain at fracture is termed the creep ductility. Creep ductility may be low or high so that materials may characterised as creep brittle or creep ductile respectively.

6.1.7 Multiaxial effects

Inevitably, practical problems will involve multiaxial loading. Uniaxial data is related to the multiaxial cases using theory developed for plastic deformation. Thus, an effective stress is defined which is related to a yield criteria such as that attributed to Von Mises or Tresca (Penny et al, 1971, Ref 21). In terms of the Von Mises definition:

$$\sigma = \frac{1}{\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yx}^2 + \tau_{zx}^2) \right]^{1/2}$$  \[Equation 6.1-26\]

where $\sigma$ and $\tau$ are direct stress and shear stress respectively. An effective strain can also be defined in terms of strain components. For cases where strain is predominantly plastic, ASME NH defines effective strain as:
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\[
\bar{e} = \frac{\sqrt{2}}{3} \left[ (\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + \frac{3}{2} (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2) \right]^{1/2}
\]  

[Equation 6.1-27]

The R5 procedure (R5, 2003, Ref 7) defines effective elastic strain and effective plastic strain using this same equation. For the elastic case, this requires an effective Young's modules \( \overline{E} \) to be defined using the elastic Poisson's ratio as:

\[
\overline{E} = \frac{3E}{2(1+\nu)}
\]  

[Equation 6.1-28]

6.2 Presentation of creep data

6.2.1 Creep curves

A common method of testing materials to determine creep behaviour involves the use of uniaxial, cylindrical specimens to measure creep strain over time for constant values of engineering stress and temperature. This results in a family of creep curves as shown in Figure 6-8.

![Figure 6-8 Influence of stress and temperature on creep behaviour](image)

The creep curves are strongly influenced by stress and temperature. Higher values of stress and temperature result in higher creep strain rates and higher creep strain at failure. Creep under constant stress is called forward creep.
6.2.2 Isochronous curves

Creep curves may be cross plotted to produce a family of creep curves giving stress versus creep strain at constant time, Figure 6-9.

![Isochronous stress-strain curves](image)

Figure 6-9 Isochronous stress-strain curves

These curves are called isochronous curves (Kraus, 1980, Ref 17). Elastic strain and plastic strain may be added to the creep strain to produce total isochronous curves (ASME NH, 2001, Ref 2). Unlike a creep curve which can be measured with a single specimen, an isochronous curve requires a multiple specimen test.

6.3 Creep under variable stress

6.3.1 Creep relaxation

If a constant temperature creep test is performed in which the total strain is also held constant, the stress will relax, see Figure 6-10.

![Stress relaxation behaviour at constant total strain](image)

Figure 6-10 Stress relaxation behaviour at constant total strain

The total strain is the sum of elastic, plastic and creep components where the elastic strain is recoverable and the plastic and creep strains are permanent. Under constant total strain conditions where the permanent strain is...
increasing due to creep, the elastic strain must reduce with a corresponding reduction in stress. A series of stress relaxation tests can be used to construct total isochronous stress-strain curves (Figure 6-11) where a vertical line represents the stress change with time at constant total strain. Creep under reducing stress with constant total strain is called pure creep relaxation.

6.3.2 Equation of state approach to variable loading

For practical creep assessments, the need arises to consider cases where stress or temperature may change according to a defined load-time history. There are two approaches to this problem (Kraus, 1980, Ref 17 and Penny et al, 1971, Ref 21). The first and simplest is the so called equation of state approach in which the current creep behaviour depends only on the current state with respect to the four controlling parameters of stress, time, temperature and creep strain. The second is the memory theory approach in which the current behaviour depends on the history of the four controlling parameters. Most work has been conducted on the equation of state approach considered further here. The equation of state is expressed as:

\[ \varepsilon_c = f(\sigma, T, s) \]  

[Equation 6.3-1]

where \( \varepsilon_c \) is the creep strain rate, \( \sigma \) is the engineering stress, \( T \) is temperature and \( s \) is the current state of the material which can typically be time \( t \) or creep strain \( \varepsilon_c \). When the current state is taken to be time related, then the so called time hardening rule results. When the current state is taken to be creep strain related then the so called strain hardening rule results.

6.3.3 Time hardening and strain hardening

A number of equations have been formulated to describe the primary and secondary phases of the creep curves. A common formulation and perhaps the simplest is the Norton-Bailey law in the form:

\[ \varepsilon_c = B \sigma^{m} t^{n} \]  

[Equation 6.3-2]

where \( t \) is time and \( B, m \) and \( n \) are constants related to temperature. In considering a variable stress problem in terms of the creep curves as shown in Figure 6-11, it is necessary to determine the position on the \( \sigma \) curve from which creep continues, following an instantaneous change of stress from \( \sigma_2 \).
It is therefore necessary to determine the new creep strain rate following a change in stress. Differentiating the Norton-Bailey law with respect to time and neglecting the time derivative of stress gives:

$$\dot{\varepsilon}_c = B\sigma_c^m n^{n-1}$$  \hspace{1cm} \text{[Equation 6.3-3]}

This is the time hardening rule which states that the current creep strain rate is dependent on the current stress, the current time and the temperature through the constants $B$, $m$ and $n$. Neglecting the time derivative of stress means that the time hardening rule is not valid when the stress is continuously changing. However it may be a good approximation when the stress is constant over time ‘blocks’. Nevertheless the time hardening rule is widely used. In terms of the creep curves (Figure 6-11), a simple construction traces the accumulation of creep strain using the time hardening rule where instantaneous changes of stress occur vertically at constant time.

Transposing the Norton-Bailey equation to give time in terms of creep strain and stress gives:

$$t = \left(\frac{\varepsilon_c}{B\sigma_c^m}\right)^{\frac{1}{n}}$$  \hspace{1cm} \text{[Equation 6.3-4]}

Substituting for $t$ in the time hardening rule gives:

$$\dot{\varepsilon}_c' = B^{\frac{1}{n}} n \sigma_c^{mn/n} \varepsilon_c^{(n-1)/n}$$  \hspace{1cm} \text{[Equation 6.3-5]}

This is the strain hardening rule which states that the current creep strain rate is dependent on the current stress, the current creep strain and the temperature through the constants $B$, $m$ and $n$. Again the time derivative of stress is neglected so that the strain hardening rule is not applicable to continuously changing stress. This rule is also used widely. In terms of the creep curves shown in Figure 6-12, a simple construction traces the accumulation of creep strain using the strain hardening rule where instantaneous changes of stress occur horizontally at constant strain.
It is evident from Figure 6-11 and Figure 6-12 that the two rules do not necessarily give the same total accumulated creep strain. Following a stress change within the primary creep phase, the predicted creep strain rates will be different. Following a stress change within the secondary creep phase, the predicted creep strain rates may be the same. Where primary creep is dominant, judgement is required as to which rule most appropriately describes the material behaviour.

The Norton-Bailey description of creep curves approximates their behaviour into a single term that describes primary and secondary creep. Many other expressions have been proposed which are based on separate formulations for primary and secondary creep strains that are added to give total creep strain. This leads to a much more complex mathematical procedure which may be best handled numerically.

6.3.4 The elastic follow-up factor

Thermal transients applied to engineering components often results in elastically calculated stresses at heat conducting surfaces where the surface stress is above the yield stress and the bulk of the component remains below the yield stress. Stress relaxation at the surface will occur in a similar manner to that discussed previously at stress concentrating features and the Neuber or Glinka rules may be applied. If hold periods at elevated temperature exist, then further stress relaxation due to creep will occur where the elastic strain is partly replaced by creep strain. However, pure stress relaxation at constant total strain is unlikely because of elastic follow-up in the structure whereby load redistribution enhances the surface strain during relaxation. The concept of the elastic follow-up factor Z (RCC-MR, 1985, Ref 6 and R5, 2003, Ref 7) is often used to account for strain enhancement under creep conditions in a very similar manner to that in which the Neuber or Glinka rules account for plastic strain enhancement.

The elastic follow-up factor Z is defined in Figure 6-13 for a creep relaxation period as the factor by which the pure relaxation creep strain is increased to obtain the actual creep strain.
Therefore a Z factor of infinity corresponds to forward creep and a Z factor of unity corresponds to pure creep relaxation. The Z factor concept can be used where a small, continuous mechanical stress is superimposed on thermal stress. As for Neuber’s rule which does not apply when significant plastic strain occurs across the load bearing ligament, then a finite value of the Z factor may not be appropriate where the mechanical stress is sufficiently high to produce significant creep strain across the entire section. In his case a Z factor of infinity may be more appropriate.

On the above basis, the Z factor is seen to be a function of the material creep behaviour, the component shape defining its stiffness, the type of loading and the types of stress in the loading. Also, it is not constant and will increase during extended periods of creep straining. Various options exist for determining the Z factor appropriate to an assessment.

i) The most conservative option is to neglect creep relaxation by assuming that Z equals infinity (forward creep). This will overestimate creep strain.

ii) The second option is applicable to components that are essentially isothermal and the mechanical stress is small compared to the thermal stress. In this case the factor is conservatively bounded by the value of Z=3.

iii) A third option is to extend the Neuber construction to intersect the time based isochronous stress-strain curves as shown in Figure 6-14.
This approach is based on recognising a close parallel between Neuber's rule and the Z factor concept and the use of isochronous curves as time dependent stress-strain curves. This approach also predicts to progressive increase in the Z factor as creep continues to long times, approaching very high values when creep strain becomes significant across the entire section.

iv) A fourth option requires the use of component finite element analysis to perform creep calculations. These calculations can be significantly simplified in that it is only necessary to model monotonic (not cyclic) conditions and the creep law can be a simplified power law. However, any non-isothermal conditions in the component should be retained and the temperature dependence of the creep law should be included. With this calculation the Z factor is determined using the construction shown in Figure 6-13.

6.3.5 Multiaxial effects

As discussed above, it is usual to obtain creep data on uniaxial specimens. Inevitably, practical problems will involve multiaxial loading. Effective stress and strain quantities defined according to last Chapters are also appropriate for creep considerations.

For creep problems where creep deformation is an issue, then a flow rule is needed to define how creep deformation is distributed amongst the three directions and consistent with the condition of constant volume. For problem where creep fracture is the issue in polycrystalline materials, a flow rule may be less important. This is because creep damage occurs at grain boundaries that face in all directions. Therefore creep damage will occur irrespective of the direction of creep flow.

6.4 Creep damage and component failure

6.4.1 Creep damage mechanisms

With continuous accumulation of creep strain specimen rupture will eventually occur. Two distinct mechanisms of rupture exist. The reason for the difference is associated with grain boundary behaviour at different temperatures (Penny, 1971, Ref 21). The transition in behaviour occurs at homologous temperatures in the range of 0.4 to 0.6.
i) At low homologous temperature the behaviour is ductile and characterised by high stress, short creep lives, transgranular failure governed by the grains themselves, with high strain at fracture and high strain rates. At lower temperatures the main cause of creep strain is slip due to the movement of dislocations through ordered molecular arrays. Grain boundaries are regions of disordered molecular arrays which form barriers to dislocation movement. Creep strain is predominantly throughout the grains causing large strain distributed throughout the section. Final fracture is by the propagation of surface cracks across grains, possibly by a single dominant crack.

ii) At high homologous temperature the behaviour is brittle and characterised by low stress, long creep lives, intergranular failure, governed by the grain boundaries, with low strain at fracture and low strain rates. Failure strain under these circumstances can be as low as 0.1%. At high temperatures the increase in activation energy encourages diffusion. Molecular disorder at grain boundaries encourages movement by diffusion resulting in grain boundary sliding. An important consequence is the formation of voids at grain boundaries, concentrating strain at the grain boundaries and leading to low overall strain at fracture. Final fracture is by the growth and linking of voids to form micro cracks and is therefore intergranular.

6.4.2 Creep strain at failure

The desirability of using strain as a means of quantifying rupture time is evident from the discussion where damage mechanisms are closely related to the manner in which creep strain accumulates and creep strain rates. Traditionally however, creep strain has not been used as a criteria for failure due to creep mechanisms. Engineering stress versus time to rupture, as shown in Figure 6-15, has usually been used as the basis for a time fraction summation rule to quantify damage (Robinson, 1938, Ref 22).

![Figure 6-15 Stress vs Time to rupture for a nickel based alloy.](image)

These data are often rationalised onto a single curve by using the Larson-Miller parameter (Kraus, 1980, Ref 17) as shown in Figure 6-16.
Strain based methods in thermo-mechanical creep-fatigue endurance assessment

The Larson-Miller parameter is a function of stress only so that it provides a convenient means of interpolating test data for different temperatures and time to rupture.

In many test programmes the only information relating to strain has been the measurement of overall specimen extension after failure. Overall elongation plotted against time to failure appears to show considerable scatter which has perhaps discouraged its use as a failure criteria. This is hardly surprising since final failure may involve necking which is a form of plastic instability similar to the tensile test (Penny et al, 1971, Ref 21). Such instabilities depend on the dimensions of the test specimen itself, as shown in Figure 6-15 for the tensile test. Total extension at failure of a creep test is not therefore a material property. It is however indicative of the margin between the onset of failure and final failure and is therefore a useful measure in avoiding rapid and perhaps catastrophic failure of components.

A different conclusion may be drawn if the creep strain at the onset of tertiary creep is plotted versus rupture time. In this case much less scatter is observed (Penny et al, 1971, Ref 21). The onset of tertiary creep is the onset of an instability that may be considered in the same way as the necking instability which begins when the UTS is achieved in a tensile test. Therefore the engineering stress to rupture and the strain at the onset of necking are uniquely related so that creep strain at the onset of necking provides a much better correlation with specimen lifetime to rupture. It has also suggested (Penny et al, 1971, Ref 21) that creep strain given by the product of minimum creep strain rate and time to rupture correlates closely with time to rupture. This strain they call the ‘true creep strain’ and the physical interpretation of this is given in Figure 6-17. It represents creep strain that would occur by neglecting part of the primary creep strain and part of the tertiary strain. The rational for neglecting part of the primary creep strain is that it is largely recoverable on unloading during a creep test (Figure 6-17) and so may be non-damaging.
The rational for neglecting part of the tertiary strain is that it may actually be additional plastic strain induced by the onset of necking at the start of the tertiary phase.

Therefore, 'true creep strain' can be considered as an estimate of creep ductility, shown in Figure 6-18

On the basis of a review which considered the modelling of a wide range of engineering components (Bretherton et al, 2000, Ref 9) it was again concluded that simple elongation is not an adequate measure of ductility in strain based methods. If data derived from stress rupture tests involving necking is to be used, this should be based on reduction of area and converted to local elongation at the neck, i.e. true strain at the neck.

6.4.3 Creep ductility versus creep strain rate

On the basis of test data analysis the use of accumulated creep strain and ductility has been proposed as a strain based creep damage summation rule (Hales, 1983, Ref 12 and Waring, 1997, Ref 26). A significant variation of creep ductility with creep strain rate as shown in Figure 6-19 may be exhibited.
Upper and lower plateaux exists corresponding to creep ductile and creep brittle behaviour respectively. The two plateaux behaviour may not always be evident and data may show the creep ductility to be independent of creep strain rate.

i) Creep ductile behaviour (upper plateaux) demonstrating high ductility occurs with high applied stress and high strain rate. Necking and localised variations in true stress at rupture may also be demonstrated. Therefore definitions of ductility should consider necking aspect.

ii) Creep brittle behaviour (lower plateaux) demonstrating low ductility occurs with low applied stress and low strain rates. Necking is small and the ductility defined as the reduction in area is the same as elongation. In the absence of necking these two definitions are very similar to ductility defined as the minimum creep strain rate multiplied by the rupture time. This last definition neglects small amounts of primary creep strain and considers secondary creep at constant rate only.

Hales has also reported that in all tests considered, the conditions that resulted in low strain, creep brittle behaviour also resulted in a propensity of grain boundary voids. Thus the upper and lower plateaux behaviour are related to the damage mechanisms discussed. Engineering components designed for durability in the creep regime usually operate at or near the lower plateaux so that creep damage is by the nucleation and growth of voids at grain boundaries and conditions pertaining to creep brittle behaviour are apparent.

### 6.4.4 Multiaxial effects

Studies concerned with the initiation and growth of grain boundary cavities have indicated that the stress state is influential. Cavity growth alone predicts only a modest influence of stress state (Hales, 1994, Ref 13). However, if cavity nucleation is also considered a stronger relationship between stress state and creep rupture is predicted. Therefore for creep brittle materials where cavity growth is strongly related to damage and rupture, all stress states need to be considered. Spindler (Spindler et al, 2001, Ref 24 and Ainsworth et al, 2001, Ref 8) has analysed biaxial...
and triaxial creep data and Type 316 and Type 304 stainless steel and produced an empirical equation relating the effective ductility under triaxial conditions to the uniaxial measured ductility. The equation is of the form:

\[
\frac{\varepsilon_f}{\varepsilon_f} = \exp \left[ p \left( 1 - \frac{\sigma_p}{\bar{\sigma}} \right) \right] \exp \left[ q \left( \frac{1}{2} - \frac{3\sigma_h}{2\bar{\sigma}} \right) \right]
\]

[Equation 6.4-1]

where \( \varepsilon_f \) and \( \varepsilon_f \) are the Von Mises equivalent and uniaxial ductilities respectively, \( \sigma_p, \bar{\sigma}, \sigma_h \) are the maximum tensile principal stress, Von Mises equivalent stress and hydrostatic stress respectively. \( p \) and \( q \) are constants. For biaxial conditions, constants of \( p = 2.38, q = 1.04 \) were obtained for materials where \( \varepsilon_f \) decreased with decreasing creep strain rate and \( p = 0.15, q = 1.25 \) were obtained for materials where \( \varepsilon_f \) was independent of creep strain rate. For triaxial conditions slightly ahead of notch tips, \( p = 1.18 \) and \( q = 1 \) were obtained. For uniaxial conditions where \( \sigma_p = \sigma \) and \( \sigma_h = \sigma_p / 3 \), the multiplication factor is unity. For other stress states considerable reductions in ductility occur leading to much reduced rupture times. Where the maximum principal stress is compressive the mechanisms for void initiation and growth do not apply so that the concept of the creep ductility reduction factor does not apply. For conservatism in engineering assessment under this circumstance, the uniaxial value of creep ductility can be used.

6.5 Influence of creep strain on fatigue damage

6.5.1 Fatigue damage mechanisms

Engineering components and structures inevitably operate with cyclic loading which results in fatigue damage which may, with sufficient cycling result in component failure. Frost, Marsh and Pook (Frost et al, 1974, Ref 11) have reviewed the mechanisms of fatigue damage.

i) Fatigue damage requires plastic straining to occur. If straining is entirely elastic, components will fully recover their size and shape on unloading and the structure of the material is unchanged.

ii) Fatigue failure is essentially a three stage process of crack initiation, the subsequent growth of a dominant crack and net section failure according to some component specific failure condition. The two processes of initiation and growth require cyclic loading and may occupy different proportions of the total life depending on the cyclic conditions. With high strain range cycling, crack initiation is rapid and most of the cyclic life is due to crack growth. For low strain range condition, crack initiation may occupy a much large proportion of total cyclic life.

iii) Cracks often initiate at free surface by a shear slip mechanism in favourably oriented grains. A series of surface intrusions and extrusions forms when plastic flow is not fully reversed during cycling. This is shown in Figure 6-20.
With continuous cycling an intrusion will grow to become a dominant crack controlled by classical linear elastic fracture mechanics mechanisms. At a free surface, one principal stress is always zero. Therefore shear slip will occur irrespective of whether the mean stress is tensile or compressive. Thus there is no marked mean stress effect in the crack initiation mechanisms. However, the subsequent crack growth phase cannot occur if the cyclic stress is entirely compressive since crack growth requires crack opening. Crack growth demonstrates some degree of sensitivity to mean stress when part of the cycle is compressive and results in crack closure. The final phase of component specific net section failure is very sensitive to mean stress.

iv) Fatigue damage away from free surfaces may not occur unless by crack propagation from a pre-existing defect or flaw.

Fatigue testing is often performed on uniaxial, cylindrical specimens which are cyclically loaded until specimen fracture occurs. The number of cycles to failure is often termed the fatigue life. From the above consideration it is evident that the fatigue life so derived is not a material property since the final phase of fracture is specimen specific. Also the total cyclic life will correlate with stress range because of the crack growth phase and the fatigue life will be mean stress dependent. If for design purposes the avoidance of fatigue crack initiation is conservatively taken as the design basis, then the fatigue life will correlate with plastic strain range and mean stress is unimportant.

6.5.2 Fatigue damage summation

When the stress and strain ranges change during a loading sequence, a means of quantifying damage to predict failure is required. This is universally performed using a linear damage summation of the form:

\[
\text{DamageFraction} = \sum \frac{n_i}{n_f} \quad [\text{Equation 6.4-2}]
\]

where \(n_i\) is the number of cycles at a specified stress or strain range and \(n_f\) is the number of cycles to failure at that stress or strain range (Miner, 1945, Ref 18). Usually the damage fraction is set to unity to predict fatigue failure. Experimental observations have indicated a wide range of damage fractions corresponding to fatigue failure.
although most observations lie within the range of 0.3 to 3.0 (Frost et al, 1974, Ref 11). When fatigue failure is dominated by the crack growth phase, a damage fraction of unity corresponding to failure is derivable from fracture mechanics crack growth considerations.

### 6.53 Experimental observations of creep-fatigue interaction

Consideration of the creep damage mechanisms as the initiation and growth of voids at grain boundaries and the fatigue damage mechanisms as the initiation and growth of cracks at free surfaces leads to the expectation that an interaction between the two mechanisms may occur. When hold periods are included in cycles at elevated temperature, the growth of surface fatigue cracks may be accelerated if they interact with creep cavities formed at grain boundaries (Wareing, 1997, Ref 26). A wide ranging review of creep-fatigue interaction has been performed by Halford and Manson (Halford et al, 1968, Ref 15). They considered experimental data from a variety of engineering materials tested under slow cycling with or without hold times at homologous temperatures in the range of 0.43 to 0.82. At these temperatures creep damage by grain boundary cavity formation is expected. Over 75 sets of data were included, comprising nearly 600 individual cyclic tests in the life range of $10^1$ to $10^5$ cycles. Five material types were included which were aluminium alloys, chromium steels, stainless steels, nickel based alloys and molybdenum steels. All tests were strain range controlled and when hold times were included, creep strain occurred under pure relaxation with a cycle of the form shown in Figure 6-21. This cycle is similar to that which would be expected in engineering components where high thermal stress relaxes during elevated temperature hold periods. However, in engineering components the accumulated creep strain is likely to be higher than that in strain range controlled tests because of elastic follow-up. From these tests, slow cycling life reduction factors have been derived as the ratio of the rapid cycling cyclic life without creep effects to the slow cycling cyclic life.

![Stress Relaxation](image)

Figure 6-21 Cycle type for strain controlled hold time creep-fatigue testing

The results are summarised in Figure 6-22. For each material type the number of tests, the range of homologous temperature, range of test frequency, the range of hold time and the range of the life reduction factor are given.

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of Tests Reported</th>
<th>Range of Homologous Temperature</th>
<th>Range of Testing Frequency (cycles/min)</th>
<th>Range of Hold Time (minutes)</th>
<th>Range of Cyclic Life Reduction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1132 aluminium</td>
<td>2</td>
<td>0.46-0.64</td>
<td>10</td>
<td>0</td>
<td>4-18</td>
</tr>
</tbody>
</table>
Large fatigue life reduction factors are indicated, particularly for hold time testing. The largest factor was 50 for 316 stainless steel with a hold time of 50 minutes. Under pure relaxation conditions the maximum creep strain that can occur is given by the stress at the start of relaxation divided by Young’s modulus. This corresponds to the stress reducing to zero during the hold time. On this basis, for the materials considered in Figure 6-22, the maximum possible creep strain which could have occurred is in the range of 0.15% to 0.4%. Thus a significant acceleration of damage by creep-fatigue interaction is demonstrated at low levels of creep strain.

For each material type, data on fatigue strength reduction factors have been collected together and plotted as histograms in Figure 6-23.
Poisson distributions are fitted to the data to better describe the variability in fatigue strength reduction factor and identify the most commonly occurring value. For molybdenum steel, the most commonly occurring value is 16. For aluminium alloys, chromium steels, stainless steels and nickel based alloys, the most commonly occurring value is between 7 and 9.
Strain based methods in thermo-mechanical creep-fatigue endurance assessment

6.5.4 Creep-fatigue interaction diagram

To account for the significant additional damage due to the interaction of creep damage and fatigue damage, the interaction diagram is often used. The form of the interaction diagram is shown in Figure 6-24.

![Creep-Fatigue Interaction Diagrams](image)

Figure 6-24 Creep-Fatigue Interaction Diagrams

Cracking will occur when the fatigue damage-creep damage coordinates are outside the envelope. Various forms of the interaction envelope have been proposed (R5, 2003, Ref 7), (RCC-MR, 1985, Ref 6), (ASME NH, 2001, Ref 2), (Clayton, 1988, Ref 10) as shown in Figure 6-24. The essential difference is the position of the ‘knee’ point which can vary significantly. The exact shape of the interaction diagram depends on many factors, in particular the definitions of creep damage, fatigue damage and the methods used to calculate them. Figure 6-25 summarises some essential differences between the four diagrams shown in Figure 6-24 although there are many detailed points of difference in the individual methodologies. The interaction diagram is an empirical correlation relating creep damage calculations and fatigue damage calculations to cracking based on experimental observations. Therefore when using a particular interaction diagram it is important to consider the methodology by which it was derived.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>CREEP DAMAGE</th>
<th>FATIGUE DAMAGE</th>
<th>CALCULATION METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCC-MR</td>
<td>Time fraction</td>
<td>Strain life</td>
<td>Approximate elastic methods</td>
</tr>
<tr>
<td>ASME</td>
<td>Time fraction</td>
<td>Strain life</td>
<td>Approximate elastic methods</td>
</tr>
<tr>
<td>R5</td>
<td>Strain fraction</td>
<td>Strain life</td>
<td>Approximate elastic methods</td>
</tr>
<tr>
<td>Clayton</td>
<td>Strain fraction</td>
<td>Strain life</td>
<td>Detailed inelastic analysis</td>
</tr>
</tbody>
</table>

Figure 6-25 Calculation basis for interaction diagram
Tutorial: Creep fatigue analysis using fe-safe/TURBOlife

7.1 Introduction
This tutorial demonstrates a TURBOlife thermal-mechanical creep and fatigue analysis of a stainless steel cylinder used in a nuclear reactor.

The sample files used for this tutorial are located in the directory \<DataDir>\Abaqus.

7.2 Preparation
The tutorial uses an Abaqus ODB model. However, the same techniques can be applied to all FE formats for which temperatures are supported, which currently include:

- I-DEAS universal (UNV) files
- Abaqus FIL files
- Abaqus ODB files
- ANSYS results (*.rst) files

This tutorial assumes that the user is familiar with the basic program operation of fe-safe. Before attempting this tutorial, it is strongly recommended that one of the introductory tutorials in the fe-safe User Manual is followed:

- Tutorial 104: Using fe-safe with IDEAS universal .unv files
- Tutorial 105: Using fe-safe with Abaqus .fil files
- Tutorial 106: Using fe-safe with Abaqus .odb files
- Tutorial 108: Using fe-safe with ANSYS .rst files

Start the program by selecting fe-safe from the Windows “Start” menu (Windows) or by running the script fe-safe (UNIX).

Select an existing project, or create a new one from the welcome page.
General FEA and analysis options

Reset any existing analysis options to their defaults in the Clear Data & Settings dialogue [Tools >> Clear Data Settings...], shown in Figure 7-2 below, by selecting the Check all option and clicking OK.

Figure 7-2

7.3 Opening the sample FE model

The component for this tutorial is a stainless steel cylinder machined into a tube/plug arrangement with a small fillet radius on the inside, blending the tube to the plug as shown in Figure 7-3. The model is the section enclosed in the (red) double lined box.

Figure 7-3
To open the model, select Open Finite Element Model... from the FEA Solutions section of the File menu. From the file selection dialogue, select the sample file thermina610.odb from the directory <DataDir>\Abaqus. The Pre-Scan File dialogue will be displayed as shown in Figure 7-4. Select Yes.

![Figure 7-4](Image)

As fe-safe pre-scans the model, information about the file is written to the file:

```
<ProjectDir>\Model\scan
```

This information is also displayed in the Message Log window.

Use the drop-down list to set the Available Position field to: Integration Points. Check the Select stresses and Select temperature boxes, click Apply to Dataset List to apply the selections, as shown in Figure 7-5. The file thermina610.odb contains many stress and temperature datasets, all of which are required for the tutorial and will be checked. Select OK to load these checked datasets.

![Figure 7-5](Image)

**Note:** If temperatures aren't available on the list it's likely because the description of the stresses show that these datasets are derived. Selecting Integration Points as the position will prevent derivation.
As *fe-safe* loads the model, information about the file and the data it contains is appended to the file:

\[<\text{ProjectDir}\>\text{Model}\text{\reader.log.}\]

This information is also displayed in the *Message Log* window.

When the model has finished loading, the *Loaded FEA Models Properties* dialogue box appears, as shown in *Figure 7-6*.

![Figure 7-6](image)

If the dialogue box does not appear automatically, then it can be displayed by right clicking on the *S?* icon in the *Current FE Models* window and selecting *Properties*.

Ensure that the stress, strain and temperature units are MPa, strain and deg.C, respectively, as shown in then click *OK*.
A summary of the open model appears in the **Current FE Models** window, showing the loaded stress increments, temperature increments and element group information. See Figure 7-7 for a partial view of the window.

![Current FE Models Window](image)

**Figure 7-7**

The dataset and group details in the tree view can be expanded to show more details by clicking on the ▶️ or ▼️ symbols.

The model contains 43 stress datasets and 43 temperature datasets. **fe-safe** also extracts element group information from the ODB file.

Datasets 1 to 11 are from step 1 and describe a thermal down shock from 600 degrees C to 400 degrees C in 0.25 seconds.

Datasets 12 to 32 are from step 2 and describe a temperature hold for 20 seconds.

Datasets 33 to 43 are from step 3 and describe a ramping up of temperature over 600 seconds.

### 7.4 Exercise 1: Using the Ductility Exhaustion method

**Objective:**

To perform a creep fatigue analysis of a sequence of stress and temperature load cases over a specified time sequence. Each load case consists of an elastically calculated FEA stress solution (i.e. a stress dataset) with a corresponding temperature dataset containing the temperature on each element.
Method:

Step 1: Define the loading

The loading consists of a single loading block, cycling around the 1st to 43rd stress and temperature datasets in the FEA model, then there is a time delay of 6 hours before repeating the loading.

The time definitions are created in a text file named thermina-times.txt.

0.00000000
0.02500000
0.05000000
0.07500000
0.10000000
0.12500000
0.15000000
0.17500000
0.20000000
0.22500000
0.25000000
0.25000100
1.25000100
2.25000100
3.25000100
4.25000100
5.25000100
6.25000100
7.25000100
8.25000100
9.25000100
10.25000100
11.25000100
12.25000100
13.25000100
14.25000100
15.25000100
16.25000100
17.25000100
18.25000100
19.25000100
20.25000100
20.25000200
80.25000200
140.25000200
200.25000200
260.25000200
320.25000200
380.25000200
440.25000200
500.25000200
560.25000200
620.25000200
620.25000300
22220.25000300

(NOT A PART OF TEXT FILE)

The times in seconds in this file denote:

Step 1 increments 0->10 over 0.25 secs

Step 2 increments 0->20 over 20 secs

Step 3 increments 0->10 over 600 secs

An example of this file can be found in the <DataDir> directory.
To create the loading:

- Select the **Loading Settings** tab from the **Fatigue from FEA** dialogue to switch to the loading tree;
- select **Clear All Loadings** from the tree context menu (right mouse click on the tree);
- click **Yes**;
- in the **Current FE Models** window, highlight any of the stress datasets next to the icon ;
- select **Add... >> Dataset**;
- edit the dataset item that appears in the loading tree;
- change the value to ‘1-43,1,1’;
- select **Add... >> Temperature Dataset**;
- edit the temperature dataset item that appears in the loading tree (double click);
- change the value to ‘1-43,1,1’ using your keyboard;
- select **File >> Data Files >> Open Data File...** menu option;
- select the file `<DATADir>\thermina-times.txt` and click **Open**;
- in the **Loaded Data Files** window, highlight the first data channel in `thermina-times.txt`;
- select **Add... >> Time History**.

The defined loading appears in the **Loading Details** list box, as shown below in **Figure 7-8**

![Loading Details](image)

**Figure 7-8**

**Note:** If the window does not appear exactly as shown in **Figure 7-8**, then expand the tree view to show more details.

- select the **Analysis Settings** tab from the **Fatigue from FEA** dialogue to switch to the main settings.
Step 2: Define the surface finish

It is assumed that the whole component has a mirror-polished surface finish, (i.e. a $K_t$ factor of 1). To define this surface finish for the whole component (i.e. all element groups):

- click on the **Group** column header to select all groups;
- double-click the **Surface** column header to open the **Surface Finish Definition** dialogue for all selected groups (i.e. all groups), as shown in Figure 7-9

![Surface Finish Definition](image)

- check the radio button **Select Surface Finish from list**;
- click on the browse button, , to open the **Select a surface finish file (*.kt) file** dialogue;
- select the surface finish database file default.kt from the <KtDir> directory;
- from the drop-down **Surface finish** list, select **Mirror Polished – Ra <= 0.25µm**;
- click **OK**.
Step 3: Select the material

- in the Open Database dialogue, select (highlight) the material **thermina-stainless-steel** from the list of available materials in the local.dbase material database;

- double-click the **Material** header in the Groups Parameter box in the Fatigue from FEA dialogue - a Change Material? confirmation dialogue box appears as shown in Figure 7-10

```
Figure 7-10
```

- click Yes;
- the material name should appear for all groups in the Material column.

Step 4: Define the analysis algorithm

Most materials in **fe-safe** are configured with an algorithm which is most applicable; this is referred to as the material's default algorithm. From the Open Databases window this is specified for a material using the gen: algorithm parameter as shown in Figure 7-11.

```
Figure 7-11
```
To use the material’s default algorithm:

- double-click the Algorithm column header to open the **Group Algorithm Selection** dialogue box for all selected groups (i.e. all groups);
- select the **Analyse with material’s default algorithm** option (*Figure 7-12*)

![Group Algorithm Selection](image)

*Figure 7-12*

- click **OK**.

**Step 5: Define the output file**

When the FE model was loaded, the output filename automatically defaulted to:

<ResultsDir>\thermina610Results.odb

Before running the analysis, change the output filename to:

<ResultsDir>\thermina610Results_ex1.odb

The output filename can be modified either by manually editing the **Output File** field in the **Fatigue from FEA** dialogue, or by clicking the adjacent browse button: ...
Step 6: Configure the TURBOlife options

To configure the extra TURBOlife options select the TURBOlife options menu item from the FEA Fatigue main menu. This displays the dialogue in Figure 7-13. Ensure the settings are:

- **Neuber Plasticity Method**
- **Von Mises Generalised Stress Parameter**
- **Table A (Stresses)** takes precedence
- **Elastic follow up factor, 1/Z** of 0.2.
- **Maximum Iterations of Loading** of 20.

Then press **OK**.
Step 7: Run the analysis

fe-safe is now configured to run the analysis.

Press the Analyse! button. A summary of analysis parameters is displayed (Figure 7-14):

Check that the analysis is configured as shown in Figure 7-14 and then click Continue.

As the analysis is being performed, the following information is written to the analysis log file. The analysis log file has the same file name as the output file, except that the extension is .log. So, for this analysis, the analysis log file is:

<ResultsDir>\thermina610Results_ex1.log

This information is also displayed in the Message Log window and includes:

Summary
========
Worst Life-Hours : 8352.63
at Element 195.1
Largest % Damage-Creep : 100
at Element 3.1
Analysis time : 0:03:24
Step 8: Reviewing the results

The analysis log shows that the worst-case life for the whole model is:

8352 hours, at element 195.

A copy of the original .odb file was created, onto which a new step containing the fatigue results was appended. In this exercise two fatigue results sets – the fatigue life and the % of damage due to creep – are exported to the appended step using the following variables:

- LOGLife=Hours
- %Damage=Creep

The results from this exercise were written to the file:

<ResultsDir>/thermina610Results_ex1.odb

The first set of exported fatigue results in the file contains the fatigue lives, which should look similar to Figure 7-15.
The second set of exported fatigue results in the file contains the % of damage due to creep, which should look similar to Figure 7-16:
Step 9: Re-running the analysis for the worst element with extra diagnostics

This section will show how to get detailed information about the creep and fatigue damage interaction for the worst case element.

Press the **Exports** button on the **Fatigue from FEA** dialogue. This will display the dialogue in Figure 7-17.

In the **List of items** type in ‘195’ to indicate that additional information should be exported for element 195. To reduce the analysis time select the **Only analyse listed items** checkbox so that only element 195 is analysed.

Ensure the checkboxes **TURBOlife plots** and **Block life table** on the **Histories for Items** and **Log for Items** tabs are selected as shown in Figure 7-17 and click **OK**.
Change the output filename from to `<ResultsDir>/thermina610R_Diag.csv`. As only one element will be analysed here, the results will be written to a text file rather than the .odb file.

Press the Analyse! button to run the analysis and click Continue.

To plot the exported results use the Open Data File option from the File menu and select the file `<ResultsDir>/thermina610R_Diag.csv_Element_195.1.txt`.

The opened file is shown in *Figure 7-18* below.

Cross plot the Fatigue Damage and Creep Damage plots by selecting them both with a CTRL key and pressing the toolbar item. This will display a plot window as shown in *Figure 7-19* below.
To plot the failure envelope for the material select the material \textit{thermina-stainless-steel} from the Material Databases window and then use the Material>>Generate Material Plot Data... menu selection. This will display the Material Plot dialogue. Check the item Creep and fatigue damage interaction diagram (*.idg) – TURBOlife and ensure all other checkboxes are cleared then press OK. A new item will be added to the end of the Generated Results in the Loaded Data Files window as shown in below.

![Figure 7-20](image)

The hysteresis loops can be displayed by cross plotting the Stress and Strain items shown in Figure 7-20 above. Additionally the variation of any of the parameters with time can be cross-plotted.

A numerical listing of the Loading Repeat item, Figure 7-21 below, shows how \textit{fe-safe} has iterated through the loading until the maximum number of iterations (20) has been reached and then an interpolation was performed. In this is shown by the straight-line section.

![Figure 7-21](image)
Nomenclature

This information can also be noted in the Block by block life table written to the .log file. Open the log file <ResultsDir>/thermin610R_Diag.log using a text editor and find a section relating to the block by block life table, which should look similar to the one below.

TURBOLIFE BLOCK BY BLOCK INCREMENTAL DAMAGE TABLE for Element 195.1 material index 0

Note: D(**Dmg) damage values are the incremental damage for the repeat of the block or loading and are a fraction of 1 NOT a percentage.

<table>
<thead>
<tr>
<th>Loading Reps</th>
<th>Block</th>
<th>Block Reps</th>
<th>D(Crp Dmg)</th>
<th>D(Fat Dmg)</th>
<th>Interpolating?</th>
<th>Time (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2.45E-03</td>
<td>9.890e-005</td>
<td>no</td>
<td>6.2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>7.06E-04</td>
<td>1.639e-004</td>
<td>no</td>
<td>12.3</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4.09E-04</td>
<td>1.394e-004</td>
<td>no</td>
<td>18.5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>4.09E-04</td>
<td>1.394e-004</td>
<td>no</td>
<td>18.5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2.82E-04</td>
<td>1.211e-004</td>
<td>no</td>
<td>24.7</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2.15E-04</td>
<td>1.066e-004</td>
<td>no</td>
<td>30.9</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1.74E-04</td>
<td>9.523e-005</td>
<td>no</td>
<td>37.0</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1.47E-04</td>
<td>8.595e-005</td>
<td>no</td>
<td>43.2</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1.27E-04</td>
<td>7.827e-005</td>
<td>no</td>
<td>49.4</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1.08E-04</td>
<td>7.154e-005</td>
<td>no</td>
<td>55.6</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>9.29E-05</td>
<td>6.603e-005</td>
<td>no</td>
<td>61.7</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
<td>8.13E-05</td>
<td>6.129e-005</td>
<td>no</td>
<td>67.9</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1</td>
<td>7.18E-05</td>
<td>5.689e-005</td>
<td>no</td>
<td>74.1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1</td>
<td>6.40E-05</td>
<td>5.327e-005</td>
<td>no</td>
<td>80.2</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>1</td>
<td>5.75E-05</td>
<td>4.981e-005</td>
<td>no</td>
<td>86.4</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
<td>5.19E-05</td>
<td>4.697e-005</td>
<td>no</td>
<td>92.6</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>1</td>
<td>4.72E-05</td>
<td>4.444e-005</td>
<td>no</td>
<td>98.8</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>1</td>
<td>4.31E-05</td>
<td>4.240e-005</td>
<td>no</td>
<td>104.9</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>1</td>
<td>3.95E-05</td>
<td>4.033e-005</td>
<td>no</td>
<td>111.1</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>1</td>
<td>3.63E-05</td>
<td>3.844e-005</td>
<td>no</td>
<td>117.3</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>3.36E-05</td>
<td>3.671e-005</td>
<td>yes (max. 1)</td>
<td>123.4</td>
</tr>
</tbody>
</table>

This shows the amount of creep and fatigue damage caused by each block and each repeat within the loading. In this example there is only one block which is repeated only once. For cases where multiple blocks or multiple repeats of a block are defined the incremental damage caused by each blocks repeat would be shown.
The **Interpolating** column shows **yes** when *fe-safe* interpolated the repeats of a block of loading. This happens when the creep and fatigue damage had stabilised or, as in this case, when the maximum number of iterations of the loading has been reached.

**Step 10: Re-running the analysis for the worst element with extra diagnostics and a higher value for the maximum iterations parameter**

To see how the maximum number of iterations of the loading affects the damage calculation the analysis will be repeated with a maximum number of iterations set to 100.

Select **TURBOlife Options** from the **FEA Fatigue** menu, change the **Maximum iterations of loading** parameter to 100, and click **OK**.

Change the output filename to `<ResultsDir>/thermina610R_Diag2.csv` and **run the analysis again**.

When finished, open the new file `<ResultsDir>/thermina610R_Diag2.csv_Element_195.1.txt`. The two open data files should appear in the **Loaded Data Files** window as shown in **Figure 7-22** below.

![Loaded Data Files](image)

**Figure 7-22**

The fatigue and creep damage interaction can be compared for the two analyses.
Exercise 2: Using the Strain Range Partitioning method

Objective:
To perform a strain range partitioning creep fatigue analysis of a sequence of stress and temperature load cases over a specified time sequence. Each load case consists of an elastically calculated FEA stress solution (i.e. a stress dataset). Each stress dataset has a corresponding temperature dataset containing the temperature on each element.

Method:
The analysis method is identical to Exercise 1 with the exception of the selected material.

Step 1: Define the loading
As defined in exercise 1.

Step 2: Define the surface finish
As defined in exercise 1.

Step 3: Select the material
- in the Open Database dialogue, select (highlight) the material turbolife-material-SRP from the list of available materials in the local.dbase material database;
- double-click the Material header in the Groups Parameter box in the Fatigue from FEA dialogue - a Change Material? confirmation dialogue box appears as shown in Figure 7-23;
- click Yes;
- the material name should appear for all groups in the Material column.

Step 4: Define the analysis algorithm
As defined in exercise 1.
Step 5: Define the output file

Before running the analysis, change the output filename to:

```<ResultsDir>\thermina610Results_ex2.odb```

The output filename can be modified either by manually editing the Output File field in the Fatigue from FEA dialogue, or by clicking the adjacent browse button:

Step 6: Configure the TURBOlife options

As defined in exercise 1.

Step 7: Run the analysis

`fe-safe` is now configured to run the analysis.

Press the Analyse! button. A summary of analysis parameters is displayed (Figure 7-24):

![Figure 7-24](image)

Check that the analysis is configured as shown in Figure 7-24, and then click Continue.
As the analysis is being performed, the following information is written to the analysis log file. The analysis log file has the same file name as the output file, except that the extension is \*.log. So, for this analysis, the analysis log file is:

<ResultsDir>\thermina610Results_ex2.log

The information is displayed in the **Message Log** window includes:

### Summary

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst Life-Hours</td>
<td>341547.25</td>
</tr>
<tr>
<td>at Element 1.1</td>
<td></td>
</tr>
<tr>
<td>Largest Damage-PP</td>
<td>6.347E-6</td>
</tr>
<tr>
<td>at Element 195.1</td>
<td></td>
</tr>
<tr>
<td>Largest Damage-PC</td>
<td>2.633E-6</td>
</tr>
<tr>
<td>at Element 104.1</td>
<td></td>
</tr>
<tr>
<td>Largest Damage-CP</td>
<td>1.597E-5</td>
</tr>
<tr>
<td>at Element 1.1</td>
<td></td>
</tr>
<tr>
<td>Largest Damage-CC</td>
<td>2.783E-9</td>
</tr>
<tr>
<td>at Element 11.1</td>
<td></td>
</tr>
<tr>
<td>Largest Temp(eval)</td>
<td>599.595</td>
</tr>
<tr>
<td>at Element 411.1</td>
<td></td>
</tr>
<tr>
<td>Largest Temp(max)</td>
<td>600</td>
</tr>
<tr>
<td>at Element 1.1</td>
<td></td>
</tr>
<tr>
<td>Largest Temp(vm-max)</td>
<td>599.19</td>
</tr>
<tr>
<td>at Element 411.1</td>
<td></td>
</tr>
<tr>
<td>Analysis time</td>
<td>0:00:01</td>
</tr>
</tbody>
</table>

### Step 8: Reviewing the results

The analysis log shows that the worst-case life for the whole model is:

341547 hours, at element 1.

A copy of the original .odb file was created, onto which a new step containing the fatigue results was appended. In this exercise four fatigue results sets – the fatigue life and the damage components – are exported to the appended step using the following variables:

LOGLife-Hours
Damage-PP
Damage-PC
Damage-CP
Damage-CC

The results from this exercise were written to the file:

<ResultsDir>/thermina610Results_ex2.odb.
The first set of exported fatigue results in the file contains the fatigue lives, which should look similar to *Figure 7-25*.
The second to fourth sets of exported fatigue results in the file contain the damage due to each of the fatigue components as shown in Figure 7-26:
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dl )</td>
<td>increment of extension</td>
</tr>
<tr>
<td>( l )</td>
<td>current length</td>
</tr>
<tr>
<td>( l_0 )</td>
<td>original length</td>
</tr>
<tr>
<td>( m )</td>
<td>Norton Bailey law constant</td>
</tr>
<tr>
<td>( n )</td>
<td>Norton Bailey law constant</td>
</tr>
<tr>
<td>( n_c )</td>
<td>number of cycles</td>
</tr>
<tr>
<td>( n_f )</td>
<td>number of cycles to failure</td>
</tr>
<tr>
<td>( p )</td>
<td>multiaxial ductility constant</td>
</tr>
<tr>
<td>( q )</td>
<td>multiaxial ductility constant</td>
</tr>
<tr>
<td>( s )</td>
<td>state in the equation of state</td>
</tr>
<tr>
<td>( t )</td>
<td>time</td>
</tr>
<tr>
<td>( A )</td>
<td>current cross sectional area</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>original cross sectional area</td>
</tr>
<tr>
<td>( B )</td>
<td>Norton Bailey law constant</td>
</tr>
<tr>
<td>( E )</td>
<td>Young's Modulus</td>
</tr>
<tr>
<td>( P )</td>
<td>current applied load</td>
</tr>
<tr>
<td>( RA )</td>
<td>reduction in cross sectional area</td>
</tr>
<tr>
<td>( T )</td>
<td>temperature</td>
</tr>
<tr>
<td>( T_m )</td>
<td>homologous temperature</td>
</tr>
<tr>
<td>( Z )</td>
<td>elastic follow-up factor</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Ramberg-Osgood constant</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Ramberg-Osgood exponent</td>
</tr>
<tr>
<td>( \sigma_e )</td>
<td>engineering stress</td>
</tr>
<tr>
<td>( \varepsilon_e )</td>
<td>engineering strain</td>
</tr>
<tr>
<td>( \dot{\varepsilon}_e )</td>
<td>creep strain rate</td>
</tr>
<tr>
<td>( \varepsilon_f )</td>
<td>uniaxial creep ductility</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>effective strain</td>
</tr>
<tr>
<td>( \varepsilon_f )</td>
<td>Von Mises equivalent creep ductility</td>
</tr>
<tr>
<td>( \varepsilon_t )</td>
<td>true strain</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Poisson's ratio</td>
</tr>
<tr>
<td>( \sigma_h )</td>
<td>hydrostatic stress</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_p$</td>
<td>maximum tensile principal stress</td>
</tr>
<tr>
<td>$\sigma_t$</td>
<td>true stress</td>
</tr>
<tr>
<td>$\sigma_x$, $\sigma_y$, $\sigma_z$</td>
<td>direct stress</td>
</tr>
<tr>
<td>$\sigma_{yield}$</td>
<td>yield stress</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Von Mises equivalent stress</td>
</tr>
<tr>
<td>$\tau_x$, $\tau_y$, $\tau_z$</td>
<td>shear stress</td>
</tr>
</tbody>
</table>
References

1 ASME NB3000, Boiler and Pressure Vessel Code, Section III, Division 1.

2 ASME NH, ASME Boiler and Pressure Vessel Code, Division 1, Subsection NH, Class 1 Components in Elevated Temperature Service, 2001.


4 Chaboche, J, L, Policella, H, Savalle, S
Application of the Continuous Damage Approach to the Prediction of High temperature, Low Cycle Fatigue, ONERA, 1976.

5 Manson, S, S, Halford, G, R, and Hirschberg, M, H


9 Bretherton, I and Hales, R

10 Clayton, A, M

11 Frost, N, E, Marsh, K, J, and Pook, L, P

12 Hales, R

13 Hales, R


14 Halford, G, R, and Manson S, S

15 Harkegard, G and Mann, T
References

16 Kraus, H
Creep Analysis, John Wiley and Sons, 1980.

17 Miner, M, A

18 Moftakhar, A, and Glinka, G

19 Neuber, H

20 Penny, R, K, and Marriott, D, L

21 Robinson, E, L

22 Skallerud, B and Larse, P, K

22 Spindler, M, W, Hales, R, and Skelton, R, P


24 Waring, J

25 Webster, G, A and Ainsworth, R, A

26 Young, Warren C

27 Gittus, J

28 McClintock, F, A, and Argon, A, S