LIFE PREDICTION OF SIMPLE STRUCTURES SUBJECT TO CYCLIC PRIMARY AND SECONDARY LOADING RESULTING IN CREEP AND PLASTICITY

N. R. OTTER, R. T. JONES

GEC Power Engineering Limited, Mechanical Engineering Laboratory,
Whetstone, Leicester LE8 3LH, United Kingdom

ABSTRACT

High temperature reactors are subject to cyclic mechanical and thermal loadings resulting from start up and shut down operations. The design must therefore guard against structural failure resulting from excessive deformation and creep-fatigue damage. Before any simplified inelastic analysis techniques can be applied, their validity needs to be examined under situations representative of the reactor. For this to be carried out it is necessary to determine the behaviour of components, initially geometrically simple, subject to loadings, cyclic primary and secondary in nature, which result in creep and plasticity. Beam-like structures have been investigated on a finite element basis with the aim of determining how cyclic plasticity, creep enhancement and plastic ratchetting vary in relationship with modified shakedown criteria, magnitude of loading and hold time.

Two levels of computation are considered. One, full history calculations in which the component's behaviour is followed through time. Two, an iterative technique which determines the steady cyclic state directly. This method assumes a short hold time during which any stress redistribution due to creep is neglected. If this steady cyclic state exists for the majority of the component's life, the total inelastic strain and creep fatigue damage can be estimated by a simple linear summation. A beam has been modelled to simulate the Bree plate under cyclic primary and secondary loading, the secondary stress corresponding to a linear temperature variation through the thickness, the primary to an axial load. A range of loading conditions with different cycle times has been applied to the beam typical of the reactor situation. The temperature during the hold time of the cycle is sufficient for creep to occur. Material properties corresponding to SS316 have been used with a point-wise temperature dependent secondary creep law and an elastic-perfectly plastic material model. Damage calculations have been carried out following ASME N47.

The full history calculations have provided the amount of accumulated inelastic strain and damage at the end of life. These have been used to construct shakedown boundaries on a Bree type diagram and have been compared with those predicted by Leckie (${}^{n}/_{n+1}\sigma_y$ where n is the secondary creep index). Leckie's boundary is shown to be conservative. The direct iteration method results compare well with the full time history calculations where the steady cyclic state has been reached. The amount of computational effort is significantly less for the iterative calculation as compared with the full time history, but any failure predictions using this method are dependent upon a steady cyclic state being achieved early in the life of the reactor.

1. INTRODUCTION

The nuclear industry in particular is faced with structural design of components subject to loadings at elevated temperature. Typical operation is cyclic in nature, periods of constant loading being followed by rapid changes, particularly in the thermal load. Normal design procedure, such as in the A.S.M.E. design codes (1), is to avoid failure by satisfying limits imposed on linearly elastically calculated stresses for a given material and situation. Essentially - with the notable exception of axisymmetric structures subject to axisymmetric loadings where the approach of O'Donnell and Porowski (2) can be applied - the A.S.M.E. combination of stresses must remain elastic, a situation unlikely in many design problems where rapid thermal changes can result in stresses in excess of yield. The work of Leckie(3) has indicated that there is a modified shakedown limit below which short term plasticity effects can be neglected. It may be possible therefore to extend the rather conservative A.S.M.E. limits to allow the elastically calculated stresses to approach this limit. Before this can be done, it is necessary to examine how cyclic plasticity, creep enhancement and plastic ratchetting vary in relationship with this modified shakedown criterion, the magnitude of loadings and hold times for representative reactor situations. To this end, the behaviour of a simple beam-like structure has been investigated subject to different combinations of cyclic primary and secondary loads. Two levels of computation have been considered, both on a finite element basis - one, full history calculations in which the components behaviour is followed through time; two, an iterative technique derived to determine the steady cyclic state directly, this being a simplified inelastic technique offering significant savings in computational effort. All calculations have been carried out using a program called PRIAM (Program for Research into Inelastic Analytical Methods) especially developed for a Hewlett Packard HP9825. It is anticipated that simplified methods should be available in the non-linear version of ASAS, ASASIN, discussed in Paper M1/6 of this conference.

2. MODEL DESCRIPTION

A beam has been idealised using one element of unit length, which is assumed fully fixed at one end and being rotationally and transversely constrained at the other end. Hence the only degree of freedom of the beam is an axial movement. The primary load system is represented by an axial (tensile) load producing a uniform membrane type stress across the beam. The secondary stress system is applied by means of a temperature distribution constant along the length of the beam and varying in a linear manner through the thickness. The application of this thermal loading is assumed to be slow so that the linear distribution is maintained as the load is applied. This model is in fact equivalent to the plate model used by Bree (4) in his analysis of a cylindrical vessel subjected to constant internal pressure and cyclic thermal load. Figure 1 shows the beam element and idealisation used and Figure 2 gives the loading history. Dwell periods of 2000 and 20000 hours have been considered, the latter being included to demonstrate the effect of large amounts of stress redistribution during a cycle. The beam has been cycled up to a maximum of 300000 hours, representative of a 30 year lifespan for a typical reactor component. For each cycle time, the different combinations of secondary and primary load shown in Figure 3 have been considered with the mean dwell temperature of the beam kept at 500^{o}C. An elastic perfectly plastic material model has been assumed with a yield stress of 150 MN/m^2, a Young's modulus of 150 x 10^3 MN/m^2 and a coefficient of thermal expansion of 2 x 10^{-5} ^{o}C.

A secondary creep law of the following form was employed:-

$$\dot{\varepsilon}_c = A\exp(-B/T)\,\sigma|\sigma|^{n-1} \quad hr^{-1}$$

where $\dot{\varepsilon}_c$ is the creep strain rate, T the temperature in °A, σ the stress in MN/m^2 and n the creep index. All material properties are thought to be representative of SS316.

3. CALCULATION PROCEDURE

In order to model the non linear variation of stress and strain across the section, the beam was divided into a number of equally-spaced through-thickness integration points. For the majority of cases 15 points were found to be adequate. The creep law was evaluated at each of these points using the local value of stress and temperature. Standard initial stress techniques were used to ensure that the stress lay on the yield surface.

3.1 Full History Calculations

All full history calculations used a time history approach where the behaviour of the beam was followed through time in a step-wise manner. At all times the requirements for equilibrium of applied loads and compatability of resulting strains are satisfied.

3.2 Direct Calculation of Steady Cyclic States

It has been noted by Frederick & Armstrong (5), that after a number of repeated load cycles the behaviour of a structure settles down to a steady cyclic nature, and after which each additional cycle results in a repeated stress and strain response. If the cycle time is short (for example greater than 100 cycles in the lifetime of the structure) the stress redistribution during a cycle due to creep can be disregarded and the stress distribution can be assumed to comprise of a constant residual plus some time varying response through the cycle. A direct iteration technique has been derived which seeks this constant self equilibriating stress, which when added to the time varying response results in a compatible creep strain integrated over the cycle. At load levels above the modified shakedown limit, where plasticity effects can no longer be ignored, an elastic plastic analysis is carried out to ensure that the stresses do not violate the yield condition. This technique has so far been applied to beam finite elements but does not depend for its working on any special property of beams. It has been used only with secondary creep laws and elastic-perfectly plastic materials. The steady cyclic states obtained involving both creep and plasticity arise therefore from a simple representation of the yield surface, any hardening effects not being considered.

3.3 Damage Calculations

The damage calculations have been carried out using the rules set down in ASME N47 (1), creep by a Robinson approach and fatigue using Miners summation rule. The combined damage should not exceed the damage envelope defined in ASME N47. It should be noted that due to the relatively small number of cycles, the fatigue damage is small. Damage values have been determined at each of the through thickness integration points using local measures of temperature and stress.

4. RESULTS

4.1 Full Time History Calculations

Figure 4 shows the total axial deformation with time for selected loading cases. In the ratchetting region R at low temperatures, the behaviour is plasticity dominated with the steady cyclic state being attained early on in the components life (resulting in the linear curves of deformation with time for both cycle times).

For lower primary loads it is the enhanced creep strain which tends to control the deformation and in general the deformation curves with time are not linear indicating the attainment of the steady cyclic state only late in the life of the component. Figures 5 and 6 are Bree type diagrams of the mean plastic strain and total membrane respectively at the end of life. Creep modified shakedown boundaries can be constructed by defining points which correspond to the maximum rate of change of plastic strain with increase in load - Figure 7. They can be regarded as load levels at which plastic strains start to predominate, either by contributing to ratchetting type deformation or to an alternating plasticity type of fatigue failure, and below which shakedown can be said to occur. Also shown is that boundary due to Leckie (3), defined at 0.9 $(\frac{n}{n+1})$ of the shakedown load with n being the creep index. This boundary is always conservative when compared to those limits derived for this problem. The amount of creep damage is particularly dependent on the actual temperature of the beam with most damage occuring on the hot side. Unit creep damage boundaries can be constructed on the Bree diagram indicating at what load unit damage is just attained. Figure 8 shows such boundaries for the two different cycle times at 500°C mean temperature. Also shown in Figure 8 are the unit creep damage limits obtained following the ASME N47 code case (1) and appear to be well below those determined here.

4.2 Direct Calculations

If the steady cyclic state is assumed to act for the whole life of a component, the total amount of accumulated strain and damage can be estimated by a simple linear sum on the number of cycles. Fundamental to this is attainment of such a state early in the design life. Figure 9 shows the number of cycles required to reach the steady cyclic state for selected loading points of Figure 3 at different mean temperatures. It can be seen that there is a strong dependence on temperature. For the cases considered, the steady cyclic state predicted by the direct method agrees well with those determined using full time/load step methods. For loading points beneath the modified shakedown of Leckie, the effect of plasticity is small and can be neglected. The problem then reduces to one of creep only and is therefore computationally easier resulting in considerable saving in computer time. Table 1 shows values of strain per cycle for selected loads above and below the modified shakedown limit. Above the limit plasticity needs to be taken into account irrespective of what type of analysis is undertaken. The computational effort is then of the same order as that for full history calculations where plasticity effects can be fully modelled. The real use of this simplified method is then below the Leckie limit.

5. CONCLUDING REMARKS

Using the results of the full time history calculations it has been possible to define a creep modified shakedown limit, below which the effects of short term plasticity are small. It has been demonstrated that the position of this limit varies with the type of loading cycle, material description and mechanical loads. The Leckie 0.9 $(^{n}/n + 1)$ limit has been shown to be conservative for all cases considered. Below this limit a method for determining steady cyclic states has been introduced which results in substantial saving of computer effort for the problems so far considered.

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REFERENCES

(1) ASME Boiler and Pressure Vessel code, Case N-47 (1592) Section III Division I March 1977.

(2) O'Donnel W.J., Porowski J. Upper Bounds for Accumulated Strains due to Creep Ratchetting WRC Bulletin 195 June 1974.

(3) Leckie F.A. A Review of Bounding Techniques in Shakedown and Ratchetting at Elevated Temperatures. WRC Bulletin 195 June 1974.

(4) Bree J. Incremental Growth due to Creep and Plastic Yielding of Thin Tubes Subjected to Internal Pressure and Cyclic Thermal Stresses. J. Strain Analysis Vol. 3 No. 2 1968.

(5) Frederick C., Armstrong J. Convergent Internal Stresses and Steady Cyclic States of Stress. J. Strain Analysis Vol. 1 No. 2 1966.

TABLE I: STRAIN PER CYCLE AT STEADY CYCLIC STATE

MEAN TEMPERATURE ^{0}C	LOAD POSITION	$\frac{\sigma_p}{\sigma_y}$	$\frac{\sigma_t}{\sigma_y}$	TIME STEP CALCULATION		DIRECT ITERATION STRAIN/CYCLE	
				CYCLES TO ATTAIN SCS	STRAIN/CYCLE	CREEP ONLY	CREEP AND PLASTICITY
500	9	0.5	0.75	150	2.6×10^{-6}	2.6×10^{-6}	2.7×10^{-6}
500	10	0.5	1.25	100	4.0×10^{-6}	2.2×10^{-6}	4.0×10^{-6}
600	9	0.5	0.75	15	5.2×10^{-5}	4.9×10^{-5}	5.3×10^{-5}
600	10	0.5	1.25	10	8.4×10^{-5}	4.4×10^{-5}	8.9×10^{-5}

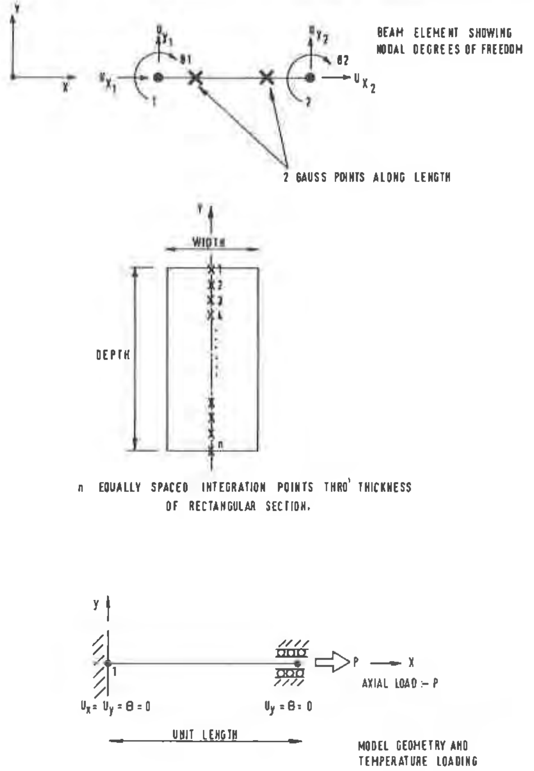

Fig. 1. Beam Element and Idealisation

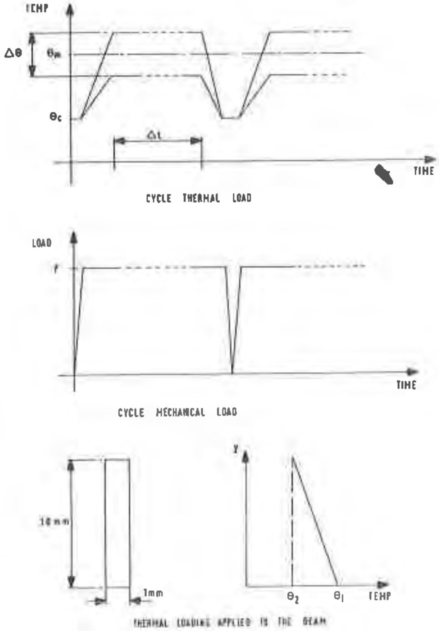

Fig. 2 Loading History

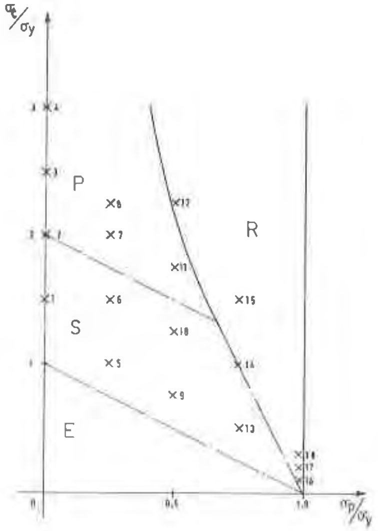

Fig. 3 Loading Combinations

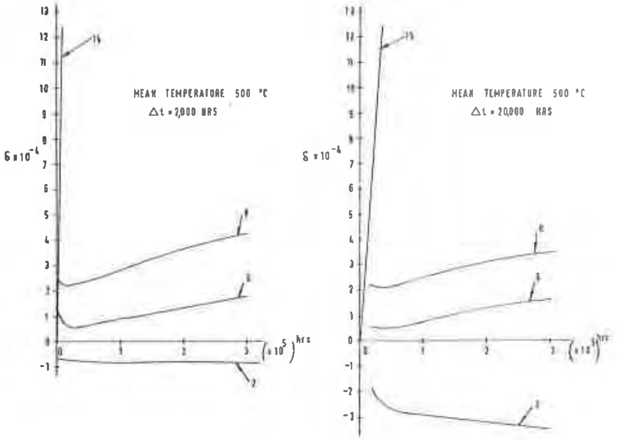

Fig. 4 · Accumulated Displacements against Time

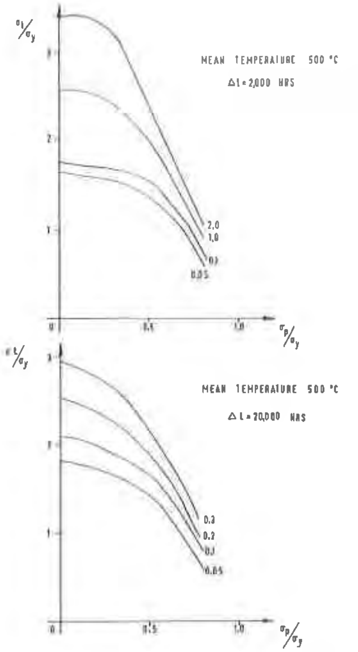

Fig. 5 · Accumulated Mean Plastic Strain Percent Contours

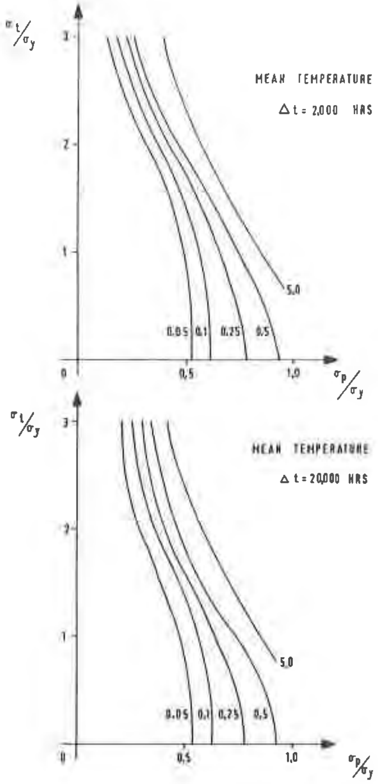

Fig. 6 Accumulated Total Mean Strain Percent Contours

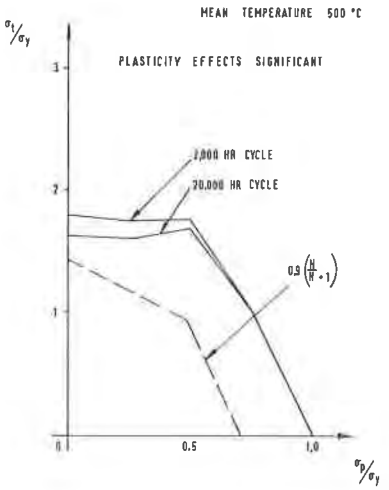

Fig. 7 Creep Modified Shakedown Boundaries

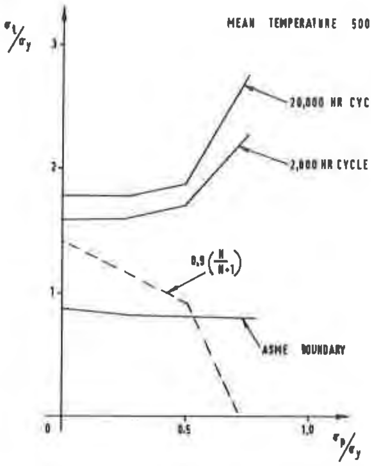

Fig. 8 Unit Creep Damage Boundaries

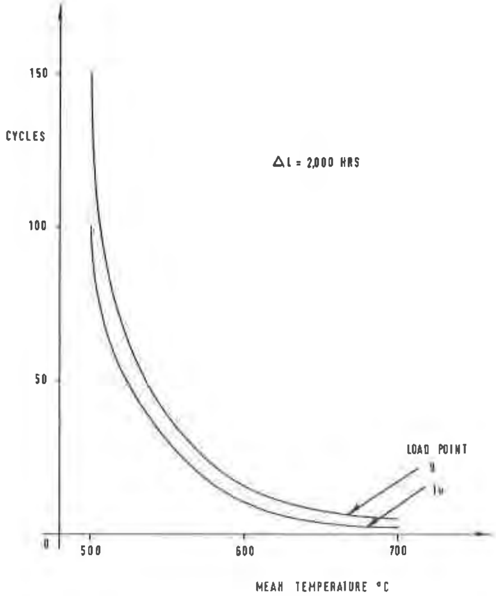

Fig. 9 Cycles to Attain Steady Cyclic State against Mean Temperature