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SHAKEDOWN ASSESSMENTS OF ELEVATED TEMPERATURE LMFBR STRUCTURES

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Introduction

The shakedown method is a powerful analytical tool which was originally developed to examine ratcheting potential in structures having completely arbitrary geometry and loading. The method and a computer program (ADAPT) which can be used to generate the required residual stress fields are described in various references including a number of papers to this and previous SMiRT conferences (references 1 to 4).

A consequence of the generation of residual stress fields in the method is that a realistic estimate of the stress in the structure is obtained for the throughout loading cycle. This can present a significant benefit in loading cycles which include a high temperature hold period since it allows an estimate of creep damage to be made. A damage assessment made by this method would be expected to be less pessimistic than an assessment carried out using more conventional elastic methods.

A further refinement of the method allows the residual stress field to be modified so as to reduce the creep damage indicated by the assessment. This optimisation of the stress field is the subject of this paper. A brief description of the reasoning underlying creep stress optimisation is given together with two examples one theoretical and one practical.

Background

The shakedown method relies on finding a constant in time residual stress field which when added to the elastically calculated stresses result in the total stress being less than the yield stress throughout the loading cycle. Except at the limit of strict shakedown the residual stress field is not unique, that is any number of different stress fields could be found that satisfy shakedown. The underlying assumptions in the method are that the stress strain behaviour is elastic-perfectly plastic, with some allowance for cyclic hardening included in the yield stress.

The effect of creep on the stress-strain history can most easily be seen by separately considering the effects in a loading cycle dominated by primary stress and in a loading cycle with only secondary stress and no elastic follow up. The case of combined primary and secondary stress may then be considered.

Figure 1 shows a typical stress strain loop for a shakedown state with a high temperature dwell at one extreme of the cycle for the case of dominant primary stress. Stress relaxation due to creep takes place over the first few loading cycles reducing the stress during the high temperature dwell which becomes asymptotic to the level of primary stress 's'. It is assumed that the secondary stress is not large enough to cause yielding at the opposite end of the cycle to the dwell.

Figure 2 illustrates the case with only secondary stresses. Again creep leads to stress relaxation during the first few cycles but in this case the relaxation takes place at constant strain. In the elastic-perfectly plastic material model, usually used in the shakedown method, the relaxation halts when reverse yielding takes place at the opposite end of the loading cycle to the dwell. This places a limit, again denoted 's' on the figure, on the final value of the stress during the dwell period. In strain hardening materials the case is as shown on figure 3. This case is analogous to the elastic perfectly plastic model and providing shakedown has been found the stress during the high temperature dwell will be gradually reduced. The extent of this reduction is limited by yielding at the opposite extreme of the loading cycle.

The case of combined primary and secondary stress (or of secondary stress with a significant amount of elastic follow up) is shown on figure 4. This case is similar to that illustrated in figure 2 but with the addition of forward creep strain. Again the stress at the beginning of the dwell is reduced until there is yielding at the opposite extreme of the loading cycle.

It can be seen by examination of figures 1 to 4 that the stress state at the end of the creep phase of the cycle can be enforced by introducing a fictitiously low value of yield stress for the time point corresponding to the high temperature dwell period. In practice it is not always necessary or desirable to try to reduce the stress at the start of the dwell to its theoretical minimum. Instead it is often reduced to some higher value related to some limit determined from design considerations.

Theoretical Problem

Consider a thin walled cylinder of type 316 stainless steel. The cylinder has sodium on both sides. On one side of the cylinder the sodium temperature is constant at 450°C and on the other side it varies between 450°C and 550°C as shown on figure 5. The change in temperature is slow enough to ensure that the through wall temperature gradients developed are a good approximation to linear.

The through wall temperature difference gives rise to an equibiaxial pure bending stress (figure 6). The maximum value of this stress can easily be calculated as 198MPa (using $E = 150000$MPa and $\alpha = 18.5\times10^{-6}$). This stress is clearly in excess of the yield stress which would typically be 113MPa at 550°C.

A residual stress field to obtain shakedown can be obtained by noting that residual and thermal stress fields have similar characteristics and that a thermal stress field or a constant multiple of a thermal stress field can be used as a residual stress field. The residual stress thus chosen is a pure bending stress of opposite sign to the thermal stress field and with a maximum value of 85MPa. When the thermal and residual stress fields are added the resulting stress has a maximum value of 113MPa with the full through wall temperature difference and 85MPa with no temperature difference. This loading is clearly within strict shakedown.

The optimisation of the residual stress field starts by noting that the yield stress at 450°C is 139MPa. Comparing this with the elastic plus residual stress of 85MPa when the cylinder has a uniform temperature of 450°C shows that the stress at this extreme of the cycle may be increased by up to 54MPa before the yield stress is exceeded. This is achieved by increasing the maximum stress in the residual stress field by 54MPa to 139MPa. The effect of such an increase is shown on figure 7. The benefit of this change in the residual stress field can also be seen on figure 7: the stress during the hot dwell is reduced to 59MPa. This reduction would lead to a large decrease in calculated creep damage.

Practical Example

This example is a 3.5m diameter 20mm thick cylinder of type 316 stainless steel (figure 8). The cylinder is partially immersed in sodium at a temperature of 485°C. Above the sodium there is a gas blanket at a temperature of 440°C. The level of the sodium pool rises by approximately 290mm over a time of 840s and at the same time the temperature of the sodium increases steadily to 565°C. The temperature of the gas remains constant. The higher sodium level and temperature are maintained for a period of 24 hours after which they return slowly to their original values.

A stress analysis followed by a shakedown analysis using the ADAPT post processor to generate residual stress fields indicated that most of the structure would be within strict shakedown but that there would be a small area, between 20mm and 40mm below the position of the sodium surface during the high temperature dwell, where cyclic plasticity was predicted for one surface of the cylinder.

From design considerations it was necessary to limit the stress during the 24 hour dwell at 565°C to 70MPa. The shakedown analysis predicted stresses in excess of this value (up to 85MPa) in an area between the zone of cyclic plasticity described above and the position of the sodium surface during the high temperature dwell. The stress trajectory at a typical point in this area is shown on figure 9. It can be seen that there is some margin between the stresses at the extremes of the loading cycle and the appropriate yield stresses. It was therefore decided to attempt to reduce the highest stresses by optimising the stresses during the dwell period. Note that in this case the high temperature dwell period does not lie at either extreme of the stress cycle. A second shakedown analysis was therefore carried out with some adjustment to the input yield stress at the time corresponding to the high temperature dwell. In view of the fact that an area of cyclic plasticity had been indicated by the initial shakedown analysis it was considered inappropriate to reduce the yield stress over the full height of the cylinder. A fictitious yield stress of 70MPa was therefore imposed over a region extending from about 15mm below the sodium surface during the hot dwell, to the top of the cylinder.

The second analysis converged with the same small region of non shakedown as found in the first. The maximum stress during the hot dwell in this case was 69MPa. Figure 10 shows the modified stress trajectory for the same point as figure 9.

Conclusions

The theoretical background behind creep optimisation in the shakedown method has been described and two examples of the method have been presented.

The shakedown method is a very powerful tool in cases where there is potential for creep damage as it provides, by elastic means, a reliable and conservative assessment which may be considerably less pessimistic than conventional assessment techniques.

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References

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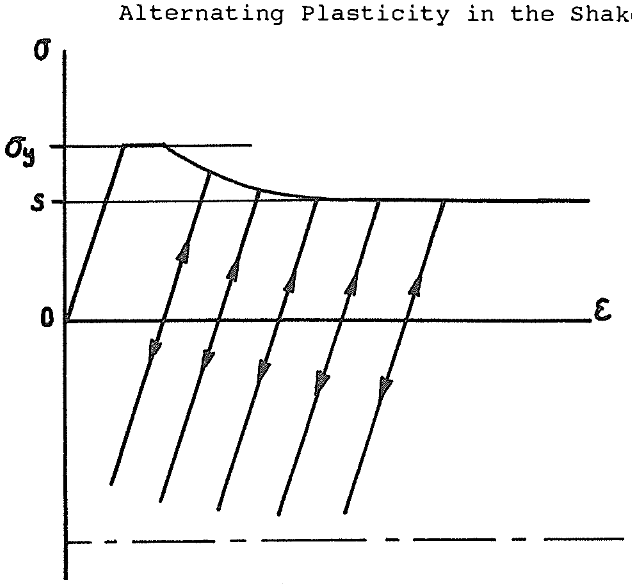

Figure 1

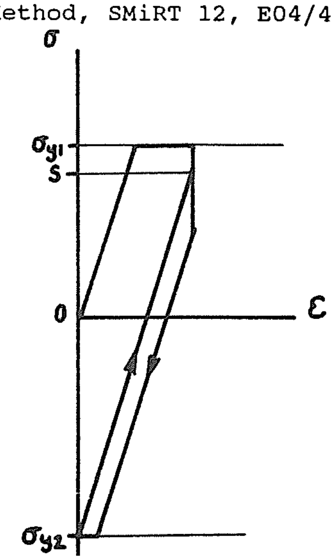

Figure 2

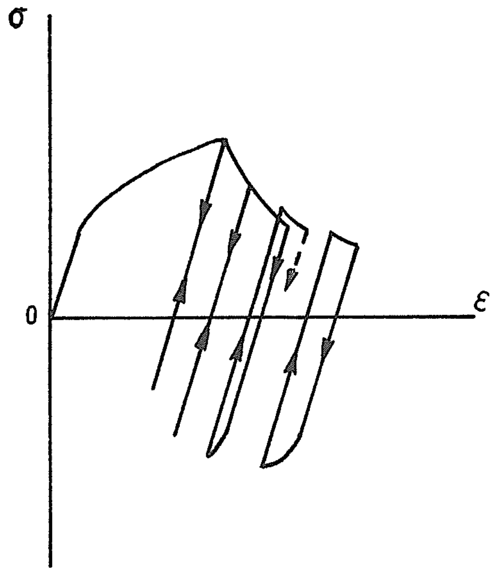

Figure 3

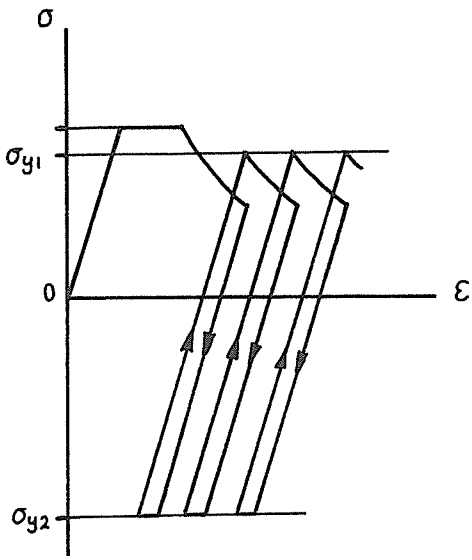

Figure 4

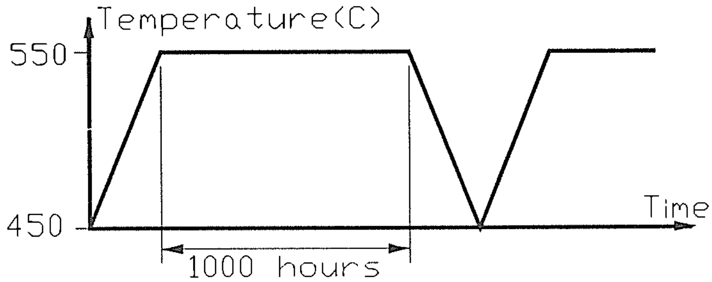

Figure 5

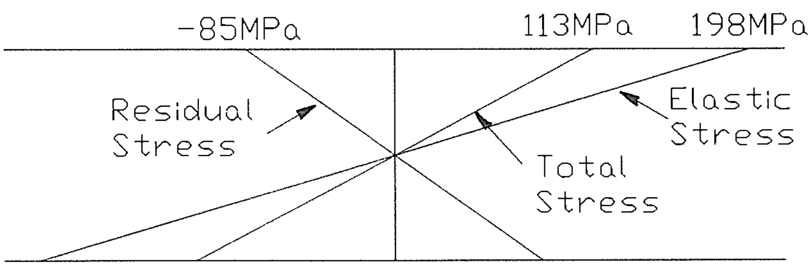

Figure 6

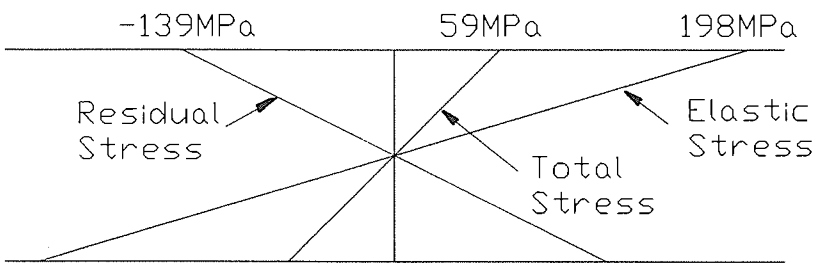

Figure 7

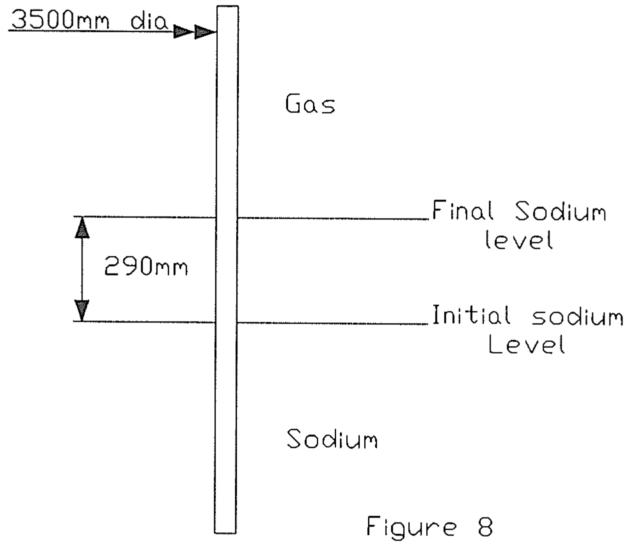

Figure 8

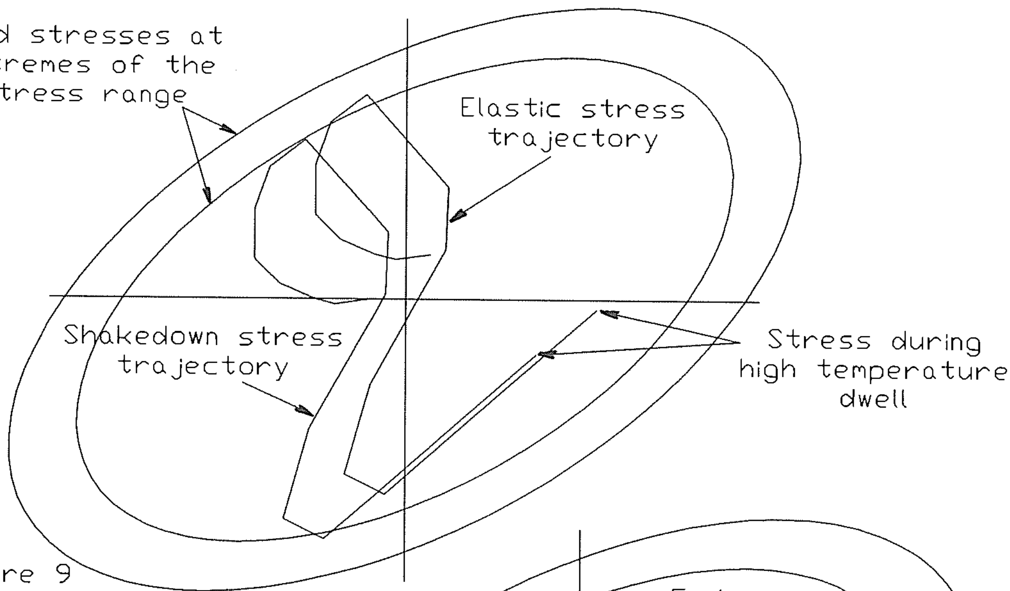

Figure 9

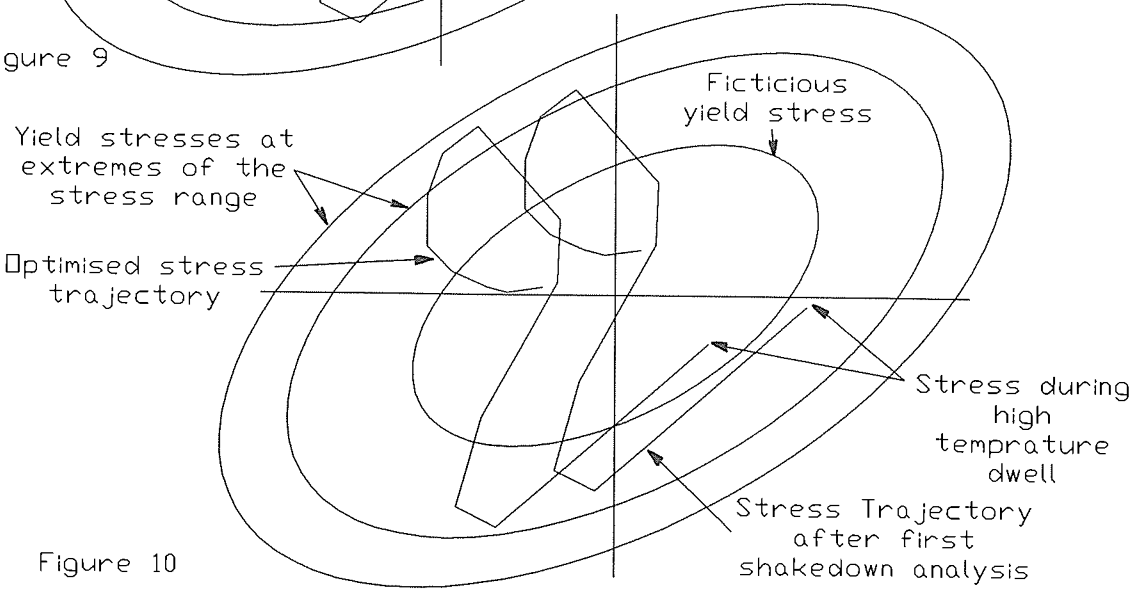

Figure 10