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Development of Inelastic Design Method for Liquid Metal Reactor Plants

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ABSTRACT

Effective utilization of inelastic analysis in structural design assessment is expected to play an important role for avoiding too conservative design of liquid metal reactor plants. Studies have been conducted by the authors to develop a guideline for application of detailed inelastic analysis in design assessment. Both fundamental material characteristics tests and structural failure tests were conducted. Fundamental investigations were made on inelastic analysis method and creep-fatigue life prediction method based on the results of material characteristics tests. It was demonstrated through structural failure tests that the design method constructed based on these fundamental investigations can predict failure lives in structures subjected to cyclic thermal loadings with sufficient accuracy.

1. INTRODUCTION

In some of the components of liquid metal reactor plants, thermal stresses become so large that the design criterion based on elastic stress analysis is sometimes hard to comply with. In such cases, application of detailed inelastic stress analysis will be required as an alternative measure for assessing integrity of structural components. Studies have been conducted by the authors to develop a guideline for application of detailed inelastic analysis in design assessment. Investigation has been made on the following items.

(1) Inelastic analysis method (constitutive equations)
(2) Creep-fatigue failure criterion for base metal and weldments
(3) Verification of design method through structural failure tests

This paper describes an outline of these studies, while the details of each study will be given elsewhere (Takahashi 1991, Takahashi et al. 1991, Kaguchi et al 1991).

2. STUDY ON INELASTIC ANALYSIS METHOD

2.1 Development of constitutive models (Takahashi, 1991)

A temperature-dependent plastic constitutive model was developed by one of the authors for type 304 stainless steel between room temperature and 650°C by modifying the model proposed by Ohno and Kachi (1986). Now the standard numbers for type 304 stainless steel are given for all constants involved in the model. Variation of material property can be taken into account by

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changing the number of a few constants. Some examples of comparison between model prediction and test data are given in Figure 1.

Based on the comparison of predicted and measured stress relaxation behavior during strain-hold creep-fatigue tests, and also directly from the results of failure life prediction shown in Figure 2, it was judged that the PNC creep equation can be used for the prediction of time-dependent inelastic deformation with the modified strain-hardening theory proposed by the researchers in Oak Ridge National Laboratory (Pugh 1983, Corum and Sartory 1987). Interaction between plastic and creep constitutive models was also introduced along the lines of the method suggested by them.

2.2 Procedure for application to design assessment

The recommended plastic constitutive model can describe cyclic hardening behavior of 304 stainless steel fairly accurately but this means that more than a hundred cycles of calculation are necessary to reach stabilized stress-strain locus. To overcome this disadvantage, a method for accelerating cyclic hardening is given for application to design assessment. This is done by changing a few constants of the model after a few cycles. Effectiveness of this procedure was studied by comparisons of the results obtained by accelerated and non-accelerated analyses.

As for material property variation, it was judged that minimum, rather than average, property should be used for estimation of ratcheting and fatigue damage. This judgement was made based on the results of parametric study on the effect of material property. Particularly for ratcheting, results were very sensitive to variation of yield stress level and a universal constant which can describe the difference between average and minimum properties could not found.

However, this choice of minimum property gives us smaller creep damage than the evaluation with average property in many cases. It is possible to get rid of this unconservativeness by adding a fraction of maximum equivalent stress value experienced during the cycle to the equivalent stress during hold period in creep damage evaluation.

3. STUDY ON CREEP-FATIGUE EVALUATION METHODS (Takahashi et al. 1991)

3.1 Base metal

For one 50mm-thick plate product of type 304 stainless steel, various types of tests have been conducted. It was found by conventional creep and fatigue tests that the material used in this study has average creep and fatigue characteristics described reasonably well by the equations developed by Power Reactor and Nuclear Fuel Development Corporation (PNC) for design of the prototype reactor, Monju (Wada et al. 1987, Yoshitake et al. 1986).

A number of uniaxial creep-fatigue tests have been conducted for small solid-bar specimens. A strain hold period between 1hr to 240hr was introduced at tensile strain peak. Stress relaxation behavior during strain holding was measured and compared with the estimation by the creep strain equation with the assumption of strain-hardening law. Reasonable agreements were obtained between the calculated and observed stress relaxation curves.

Figure 2 shows the results of damage evaluation for the tests with hold time up to 10hr. In the left figure, creep damage was calculated from measured stress relaxation curves, while "analytical" relaxation curves calculated by the PNC creep equation with strain-hardening law were used in the right figure. It can be seen that both results are similar and that the data points are within the scatter of a factor of two from the criterion used in ASME Code Case N-47 and others. It was judged based on this result obtained so far, that the creep-fatigue damage assessment method in the present design codes is appropriate.

3.2 Weldment

A number of tests have been conducted for 304-308 TIG welded joint specimens as well as the tests for weld metal itself. The results of fatigue tests for various types of test specimens are shown in Figure 3 in terms of strength reduction factor applied to strain range (not to life). It can be seen that the reduction of strength of welded joints largely depends on the loading direction and loading type, but not on amplitude of loading. The largest strength reduction of the value of about 1.6 was obtained for traverse joints under axial loading.

Moreover, creep tests for traverse joint specimens indicated the creep strength reduction factor of about 1.1 in terms of stress. In Figure 4, the results for life prediction using these reduction factors are compared with observed failure lives in creep-fatigue tests for traverse joint specimens with 30 minute hold time. Also shown in the figure are the estimations by the method given in the latest version of ASME Code Case N-47(1988), whose background was described by Corum(1989). In both cases, fatigue and creep rupture curves in the design code were used. It can be seen that the present method gives a little more conservative results than N-47. However, test results with longer hold time are indispensable for judging the transferability of the methods to actual plant conditions.

4. VERIFICATION BY STRUCTURAL FAILURE TESTS (Kaguchi et al. 1991)

4.1 Outline of tests

Two kinds of structural tests have been conducted for assessing the design method in conditions similar to actual plants. They are called free surface model and ring cylinder model, here. Approximate elastic stress intensity range and hold time are summarized in Table 1. As indicated in the table, an axial weld line was included in some of the test specimens.

In the free surface model, a smooth hollow cylinder of 155mm diameter was cyclically stressed by its vertical movement in the test apparatus consisting of a water pool and an induction heating coil. Main origin of stresses is axial temperature gradient generated between the water pool and the coil.

In the ring cylinder model where smaller specimens were used, temperature difference between thick and thin portions during up- and down-thermal transients generated large thermal stresses around the boundary between them.

The definition of failure life in these, and other similar tests (Corum and Sartory 1987), is somewhat ambiguous. In this study, detection of small visible cracks through dye penetration inspection was defined as 'failure'. This obviously does not consistent with the definition of failure points in the 'material' tests using solid-bar test specimens, because the latter involves a larger fraction of crack propagation process. This inconsistency tends to lead apparent unconservativeness of the failure life prediction based on inelastic analysis.

4.2 Inelastic analysis and failure life prediction

Inelastic analysis was carried out by a finite element code, FACE (Finite Element Analysis Code with Advanced Constitutive Equations) developed by CRIEPI. Axisymmetric finite element models were constructed for both test models using 8-noded isoparametric elements. The recommended constitutive model whose outline is given in the above section had been introduced into the code and was used in the present analysis. In some cases, acceleration of cyclic hardening was applied after several thermal cycles.

Prediction of failure lives was conducted for all the test conditions according to failure criterion used in the current design codes(lines in

Figure 3). Fatigue and creep rupture properties obtained for the test material were used without an addition of any safety factors. Strain-rate effects were taken into account in fatigue damage calculation. No strength reduction factors were introduced for weldments in the evaluation.

4.3 Comparison between predictions and test results

Figure 5 shows comparison between predicted and measured thermal ratcheting deformation. Predicted deformation in the early few cycles is in good agreement with the test result but tends to be larger in the later cycles. This tendency is similar to that observed in mechanical ratcheting condition and improvement of plastic constitutive model is desirable.

Figure 6 shows the results of failure life prediction according to the method described above. In spite of the ignorance of strength reduction for weldments and the problem pointed out in 4.1, all predictions are within a factor of two from the observed failure lives. This result indicates that strength reduction at welds in the present test models was milder than that in the solid-bar test specimens.

5. CONCLUSION

In this paper, an outline of our studies for developing a rationalized structural design method based on detailed inelastic analysis for liquid metal reactor plants has been described. Structural model tests showed that the present design method have large margin against failure especially when considering large safety margin introduced in fatigue and creep rupture design curves. A guideline is being constructed integrating the results of these studies.

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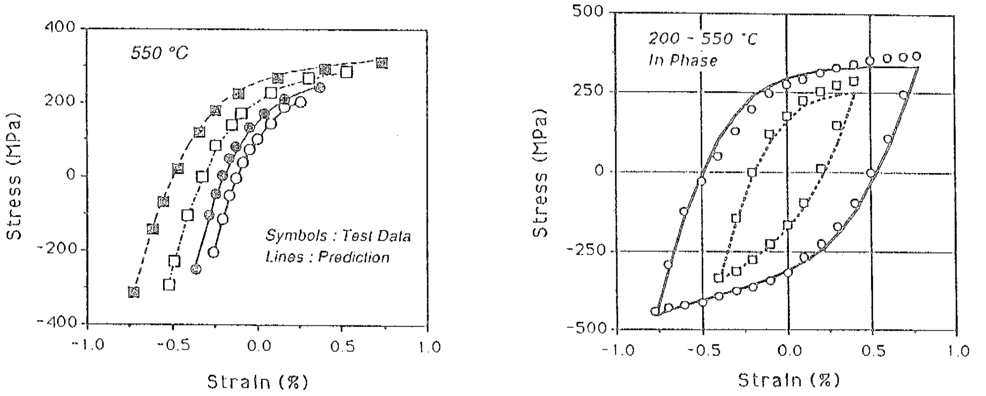

Isothermal Fatigue Condition　　Thermo-mechanical Fatigue Condition

Figure 1 Comparison of Prediction by Developed Plastic Constitutive Model with Test Results -Stabilized Hysteresis Loops

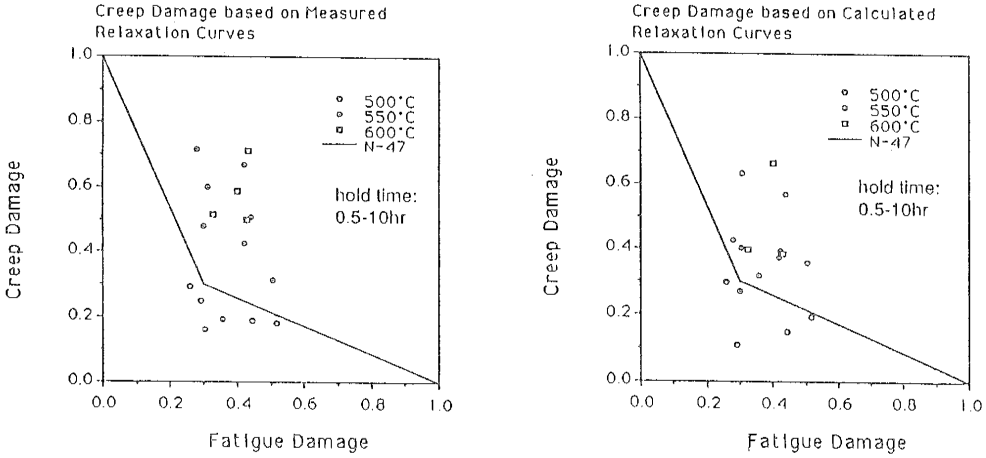

Figure 2 Result of Creep-Fatigue Damage Assessment for Creep-Fatigue Tests

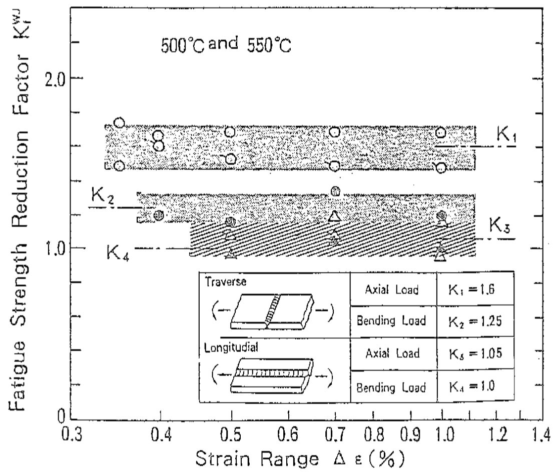

Figure 3 Fatigue Strength Reduction Factors for Welded Joint Specimens

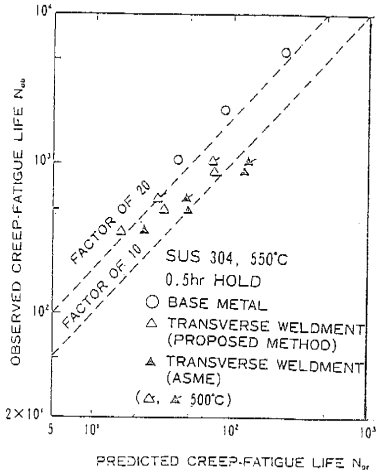

Figure 4 Result of Creep-Fatigue Life Estimation for Welded Joint

Table 1 Conditions of Structural Failure Tests

Model	Case No.	$\Delta\sigma$max 1) (MPa)	Hold Time (h)
1. Free Surface Model	1-A	1000	0
	1-B	1000	1
2. Ring Cylinder Model	2-A	1000	0
	2-B	1500	0
	2-C	1500	1
	2-D 2)	1500	0
	2-E 2)	1500	1

1) Approximate Maximum Elastic Stress Range
2) Specimen with Axial Weld

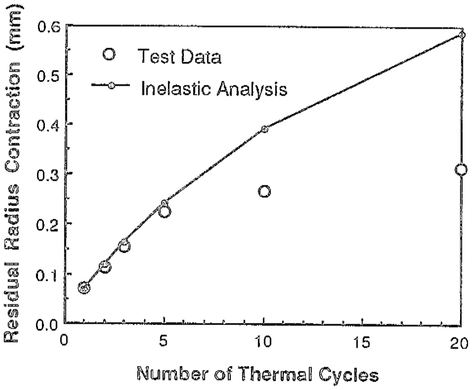

Figure 5 Comparison of Calculated and Observed Ratcheting Behavior

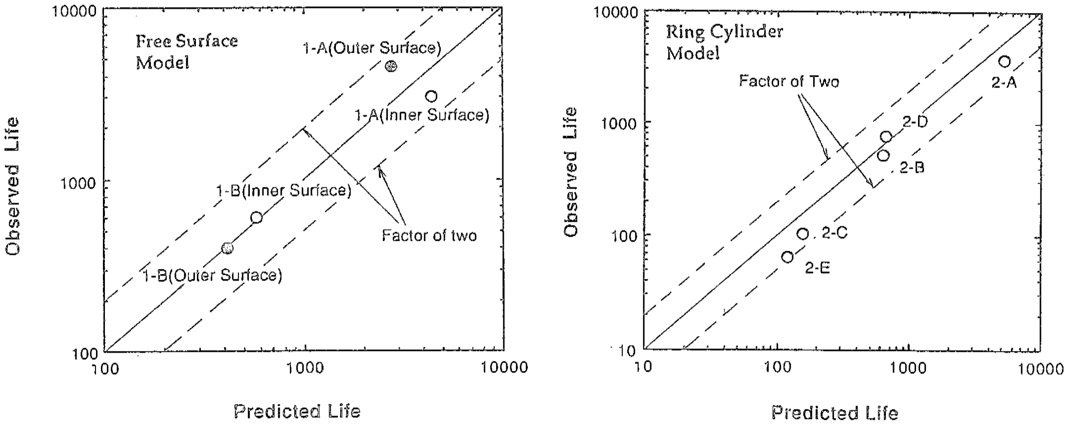

Figure 6 Comparison Between Predicted and Observed Failure Lives for Structural Failure Tests