Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

F06/5

Application of viscoplastic theory to high temperature design of fast breeder reactor components

Chellapandi P., Chetal S.C., Bhoje S.B.
Indira Gandhi Centre for Atomic Research, India

ABSTRACT: 23-Parameter Chaboche model for SS 316 LN is simplified to have only 13 material parameters which are found to be sufficient for FBR applications. The model, thus derived is termed as 'Reduced Chaboche Model' which involves only 6 temperature dependent material parameters. Further for reducing the computer time, an efficient and non-iterative self correcting solution technique is implemented. The prediction capability of thermomechanical behaviour is also improved by a novel way of interpolating the internal variables at intermediate temperatures using the material parameters at the discrete temperatures. A few interesting validations are shown. Finally it is shown that the use of the viscoplastic model helps to opt for higher operating temperature and / or a longer life for an FBR.

1.0 INTRODUCTION

The existing Fast Breeder Reactors (FBR) in the world are operating in the temperature range of 800-835 K with design life of about 30 years. Towards making FBR commercially viable FBR designers are investigating the cost effective component design, higher operating temperatures and longer design life. Since the boiling point of sodium which is the coolant in FBR, is about 1200 K, the reactor outlet temperature can be up to 870 K even with the convenient safety margin between boiling point and operating temperature. As much as 60 years are being considered as the design life for future reactors. To introduce such innovations in the FBR design, it is essential to accurately assess structural integrity of the components for long-term elevated temperature service and thereby to reduce the unduly overconservatism in the design. In this process it becomes necessary to follow the 'inelastic analysis route' of the design codes like, RCC-MR (1987)[1] and ASME-CC N47[2]. In order to satisfy these code rules, particularly for the creep-fatigue damage and cumulative inelastic strains, it is required to perform detailed inelastic analysis for predicting accurately the stress/strain history taking into account both time independent and time dependent material deformation behaviour. Since the stress/strain response of the components is closely related to life prediction, the reliability of life prediction depends strongly on the adequacy of the constitutive models employed in the analysis. As regards to the materials, austenitic stainless steel type 316 LN (for reactor assembly components, indicated in Fig 1) and mod.9Cr-1Mo grade T91 ferritic steel (for steam generator) are used.

Among various viscoplastic models available in literature, the '23-parameter Chaboche viscoplastic model' is found to be superior for FBR applications because of its ability to simulate, with reasonable accuracy, all the essential mechanical behaviour of austenitic stainless steels in the temperature range 300-900 K under monotonic and cyclic loading conditions [3]. However, one major limitation of this model is that it has too many material parameters and accordingly a lot of material data is required to identify them. Hence it is required to simplify the model probably with a lesser number of material parameters. With this object, research has been carried out and the outcome of the research is a 'Reduced Chaboche Model'. This paper deals with the application of this model in the high temperature design of critical FBR components. This paper also includes the assessment of accuracy of more commonly used 'ad-hoc' material model developed by Oak Ridge National Laboratory (ORNL)[4], with a reference to 'Reduced Chaboche Model'.

2. REDUCED CHABOCHE MODEL

2.1 *Viscoplastic Theory*

The viscoplastic behaviour is seen in certain metal alloys, especially under extreme thermomechanical loadings. To illustrate this, with reference to FBR situation, a deformation mechanism map (inter-relationship between temperature, stress, strain rate and possible deformation mechanism) developed by Frost and Asby[5] for SS 316, is reproduced in Fig 2 highlighting only the relevant aspects. Basically there are three regions marked in the figure, which are separated by two solid lines, corresponding to infinitely small strain rates and extremely high strain rates respectively.

In region I and region II, time independent deformation mechanisms, viz. elasticity and plasticity, occur. The region III is the domain of viscoplasticity wherein material response is function of time i.e., the response continues even after loading/unloading. For metals loaded at temperatures lower than about 0.3 times of their absolute melting temperature (Tm), the viscoplastic region III in between the above two lines are absent. But, for the higher temperatures , the width of this region which represents the viscous stress, increases significantly with the temperature. For the given temperature, the total internal stress developed may be decomposed into elastic, plastic and viscous contributions. At the higher temperatures (> 0.6Tm), the elastic contribution is even absent and so the viscous flow starts at zero stress itself.

It is to be emphasised that the viscous stress is responsible for the subsequent time and rate dependent behaviour. It is seen in Fig 2 that FBR components operate in the domain of viscoplasticity. Since viscoplasticity mimics both plastic and creeping behaviour, many unified creep-plasticity (UCP) theories have been developed to model these complex processes in a constitutive model. UCP theories have been broadly classified as hereditary or memory theories and state variable theories. The state variable theories are formulated either with or without the use of yield criteria.

2.2 *Chaboche Viscoplastic Theory*

Chaboche theory is a yield-based state variable unified creep-plasticity theory that has been developed and improved considerably since it was introduced in 1977[6]. This theory fits well into a general thermodynamic frame work that uses internal variables to express the irreversible processes. The current version of Chaboche model has 23 material constants [7] by which it is possible to simulate many complex behaviour of SS 316 LN at elevated temperature (about 900K).

2.3 Simplification of Chaboche Model

One major limitation of 23-parameter Chaboche model is that it has too many material parameters and accordingly a lot of material data is required to identify them. Hence this 'complete Chaboche Model' is simplified and a 'Reduced Chaboche Model' is derived based the physical interpretations that are associated with the parameters. This 'Reduced Chaboche Model' is defined with only 13 material parameters which need to be identified from the experimental material data. Out of 13, only 6 parameters are function of temperature. An elegant approach is also found out to reduce the number of iterations required in the process of identifying the parameters. More details of this work are given in ref[8].

3. NUMERICAL INTEGRATION OF CHABOCHE MODEL

In the overall solution procedure, a considerable percentage of computation time is devoted to the integration of the constitutive model because the system of partial differential equations related to a specific constitutive model becomes very stiff in the mathematical sense, in certain regimes. Hence the implementation of an efficient numerical solution technique in the finite element analysis is very much essential for the use of a viscoplastic model for the practical applications. For this the NONSS algorithm developed by Tanaka and Miller[9] has been modified and implemented in an in-house FEM code 'CONE'. Many novel features have been adopted in the implementation so as to reduce the overall computer time.

In order to demonstrate the computational effectiveness of this method, many bench mark problems covering a wide range of strain rate sensitivity regions, complex monotonic and cyclic loading conditions have been solved[10].

4. SIMULATION OF THERMOMECHANICAL BEHAVIOUR WITH CHABOCHE MODEL

FBR components are subjected to severe through wall temperature gradient during normal as well as transient conditions. This means that each material point of the structure will see different temperature in the course of operation. Since some of the material parameters that are associated with a viscoplastic model are strong function of temperatures, the difficult task in the analysis is to define the material parameters at each and every material point (Gaussian integrating point) depending upon its status of temperature. The conventional technique to handle such a situation is, first to generate material parameters at discrete temperatures of interest based on isothermal data and then determine the parameters at intermediate temperatures by linear interpolation in the analysis. Such a technique is found to give ambiguous results. To overcome this, a temperature-rate term is introduced in Chaboche model to extend the prediction capabilities with respect to non-isothermal behaviour. According to this, a temperature-rate term (T-term) has been supplemented to the isotropic hardening evolution equations in the isothermal Chaboche model.

An alternate methodology has been proposed[11]. As per this, instead of interpolating material parameters at intermediate temperatures, the state variables are interpolated using the corresponding values, computed at discrete temperatures. This new proposal has been demonstrated for some complex thermo-mechanical cyclic loading situations and results are compared with both experimental data and also with those predicted after introducing temperature-rate term (Fig 3).

5. SIMULATION OF CONTINUOUS FATIGUE CYCLES

The prediction capability of Reduced Chaboche model is illustrated with reference to experimental prediction (experiments have been done at IGCAR) in Fig 4 for the transient cyclic hardening and the shape of the hysteresis loops under strain controlled cycles with strain range of ±0.6 %. In the same figure the prediction by ORNL model is also included. It is very clear from the figure that the Chaboche model is simulating the stress-strain responses cycle by cycle.

6. PFBR ANALYSIS

The critical out of core components, viz. Control Plug (CP), Inner Vessel (IV), Intermediate Heat Exchanger (IHX) have been analysed for estimating their life at various operating temperatures in compliance with RCC-MR. Viscoplastic analysis has been done for CP and IV. For IHX, considering the convenient safety margins with inelastic analysis with ORNL model itself (ORNL gives conservative result), viscoplastic analysis has not been done. The summary of results are depicted in Table I. Details of analysis can be found in ref[11].

Table I Allowable cycles for the design limit of 1000 cycles

Reactor Outlet Temp. (K)	Elastic			Inelastic (ORNL)			Chaboche	
	CP	IV	IHX	CP	IV	IHX	CP	IV
793	285	1033	8716	3028	5466	48092	4095	18395
803	177	427	3398	2000	7592	18906	2647	11867
813	108	208	1490	1217	4717	7700	1633	7472
823	68	106	718	728	2890	3523	1048	4508
833	42	58	365	500	1670	1670	773	2907

CP and IV cannot meet RCC-MR 93 code rules by elastic analysis route for temperatures above 775 K. CP is the most critical component. For the design requirement of 1000 cycles which corresponds to the reactor design life of 30 years, maximum permissible reactor outlet temperature can be 823 K. This corresponds to a steam temperature of 763 to 773 K. Thus, by way of performing a detailed analysis with realistic material model, it is demonstrated that 50 K increase is possible in the steam temperature which inturn results in 1 % increase in plant efficiency. This increase in efficiency represents an additional energy of 12.5 MWe during entire service life of the plant. This is the benefit of performing detailed inelastic analysis.

However, it is to be mentioned that in the above analysis, the thermal transient following a reactor scram without any sympathetic safety actions is considered. Noting that the creep-fatigue damage is severe during this transient following a reactor scram, analysis has been carried out to estimate the upper bound creep-fatigue damage values. As a step towards reducing the thermal load, lesser number of reactor scrams, i.e. 500 scrams instead of 1000 and a scram with core flow coast down to 20% are considered in the analysis. While the case of a scram without flow reduction, based on viscoplastic analyis, permits 1064 reactor scrams to meet the RCC-MR code rules for 823 K, the flow coast down to 20% following a scram reduces thermal shock significantly. With this, it is possible to meet the code rules via elastic route itself. The allowable number of scrams with flow coast down is 1192 at 820 K with elastic analysis itself. This will be much higher (atleast 3 times the life) if an inelastic analysis route is followed. Reduction of creep-fatigue damage due to a lesser number of reactor scrams, i.e. 500 instead of 1000, is marginal (8 K higher operating temperature) because the change in the creep damage which is dominant in this structure, is negligible and reduction of fatigue damage by 50% has not changed the overall creep-fatigue damage, significantly. Based on studies reported, it is recommended to have sympathetic safety action of core flow coast down to 20% in case of a scram.

7. CONCLUSION

In this paper efforts made to use the Chaboche viscoplastic theory for the life prediction calculations of FBR components are highlighted. This includes simplification of 23-parameter Chaboche model to derive a 13-parameter model, called 'Reduced Chaboche Model', implementation of non-iterative & self correcting solution method for integrating the constitutive model in the finite element analysis and improvements made in the interpolation of internal variables of the model at the intermediate temperature from the material parameters defined at the discrete temperature intervals to predict the thermomechanical behaviour realistically. Further an example on the PFBR analysis for life assessment has been dealt in this paper. The benefits of detailed viscoplastic analysis with Reduced Chaboche and ORNL material models in demonstrating higher operating temperature and longer design life have also been demonstrated.

REFERENCES

1. Design and Construction Rules for Mechanical Components of FBR Nuclear Islands (RCC-MR), 1993, AFCEN, Paris, France.

2. ASME Boiler and Pressure Vessel Code Case N-47, 1992, Class 1 Components in Elevated Temperature Service, Sec.III, Div.1, American Society of Mechanical Engineers, NewYork.

3. Chaboche, J.L and D.Nouailhas, 1989. A Unified Constitutive Model for Cyclic Viscoplasticity and its Applications to Various Stainless Steels, ASME Journal of Engineering

Materials and Technology, Vol.111.

4. C.E.Pugh 1972. Currently Recommended Constitutive Equations for Inelastic Design on FFTF Components, ORNL-TM-3602.

5. Frost, H.J. and M.F.Ashby, 1982. Deformation-Mechanism Maps - The Plasticity and Creep of Metals and Ceramics, Pergaman Press.

6. J.L.Chaboche. 1977. Viscoplastic Constitutive Equations for The Description of Cyclic and Anisotropic Behaviour of Metals, Bulletin De L'Academie Polanaise des Sciences, Vol.25.

7. Chaboche,J.L. and G.Rousselier, 1983. On the Plastic and Viscoplastic Constitutive Equations: Part I-Rules Developed with Internal Variable Concept, ASME Journal of Pressure Vessel Technology, Vol.105.

8. Chellapandi, P. and R.S. Alwar, 1997. Simplification of Chaboche Viscoplastic Model with Reference to LMFBR Applications, to appear in ASME Journal of Engineering Materials and Technology.

9. Tanaka,T.G. and A.K.Miller, 1988. Development of a Method for Integrating Time-Dependent Constitutive Equations with a Large, Small or Negative Strain Rate Sensitivity, Int.J.Numerical Methods in Engineering, Vol.26.

10. Chellapandi,P. and R.S.Alwar, 1997. Development of Non-Iterative and Self-correcting Solution (NONSS) Method for Viscoplastic Analysis with Chaboche Model, to appear in Int. Journal for Numerical Methods in Engineering.

11. P.Chellapandi, 1995, Application of Viscoplastic Theory to High Temperature Design of Fast Breeder Reactor Components, PhD thesis.

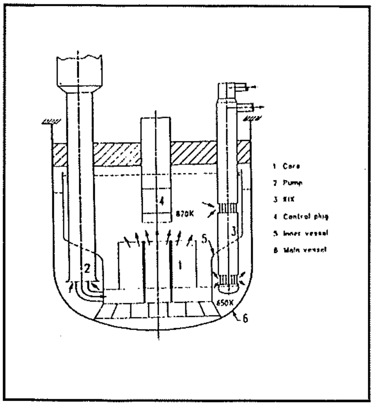


Fig.1 Schematic of FBR vertical section

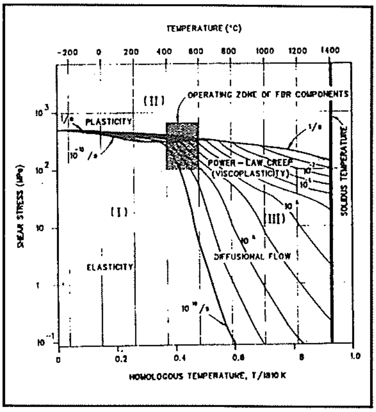
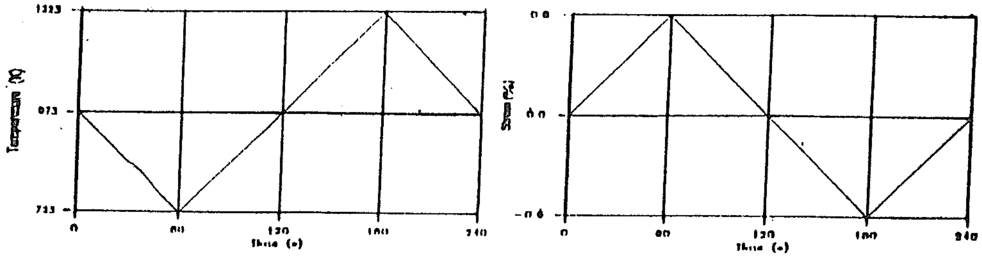
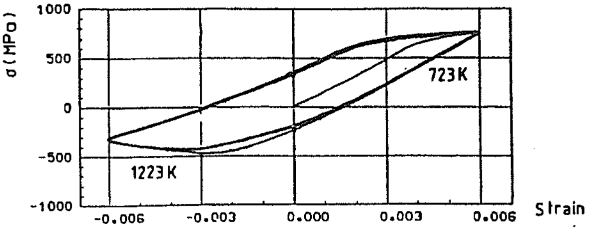


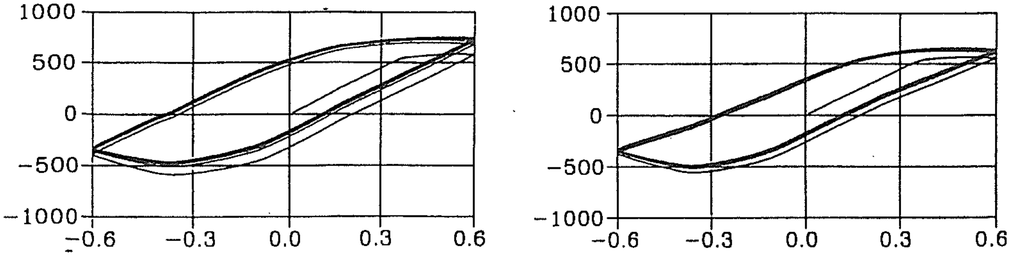
Fig.2 Deformation mechanism map for SS 316



Loading Detail for Uniaxial non-Isothermal Test



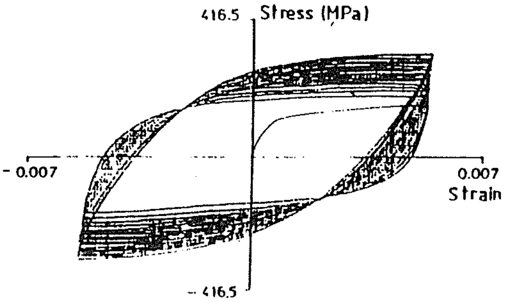
Experiment [1]



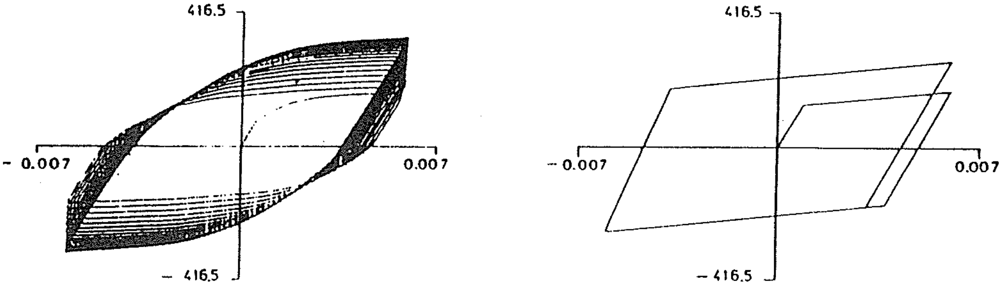
Simulation [1]

Simulation (authors)

Fig.3 Uniaxial thermomechanical out-of-phase test: experimental data and simulation



Experiment



Predicted by Chaboche

Predicted by ORNL

Fig. 4. Complete simulation of cyclic test on SS 316LN at 873 K Stress verses total Strain