Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 55 (2013) 309 – 313

Procedia Engineering

www.elsevier.com/locate/procedia

6th International Conference on Creep, Fatigue and Creep-Fatigue Interaction [CF-6]

Creep-Fatigue Evaluation Methodologies and Related Issues for Japan Sodium Cooled Fast Reactor (JSFR)

Tai Asayama*, Shigeru Takaya, Yuji Nagae, Masanori Ando, Kazuyuki Tsukimori

Japan Atomic Energy Agency, Ibaraki, Japan

Abstract

This paper describes the main topics on creep-fatigue evaluation methodologies for the Japan Sodium Cooled Fast Reactor (JSFR). JSFR's operating temperature is 550C and design life is 60 years with key technologies in terms of creep-fatigue being the adoption of new materials, 316FR and Mod.9Cr-1Mo steel, and the development of evaluation methodologies for those materials: 316FR is low-carbon nitrogen-added 316 steel which has superior creep properties and will be used for the reactor vessel and internal structures. Mod.9Cr-1Mo steel will be applied to most of the coolant systems including primary piping, intermediate heat exchangers, secondary piping and steam generators. Creep-fatigue evaluation methodologies for those materials are being developed concentrating on capturing long-term materials behavior and strength so that the evaluation of 60-year design is justified, and simplified evaluation methods for strain ranges and stress relaxation behaviors applicable to JSFR structures which have various configurations and loading conditions are also being developed. The results of R&D will be incorporated in a JSME (Japan Society of Mechanical Engineers) code for the design and construction of fast reactors.

Selection and peer-review under responsibility of the Indira Gandhi Centre for Atomic Research.

Keywords: Fast breeder reactors; structural materials; 316FR; Mod.9Cr-1Mo steel; creep-fatigue evaluation

1. Introduction

Japan Sodium Fast Reactor (JSFR) is a demonstration reactor which is being developed as a reactor that follows the prototype reactor Monju in Japan. JSFR's operating temperature is 550 C and the design life is 60 years. 316FR, a material developed in Japan whose creep properties are improved based on Type 316 Stainless Steel by optimizing chemical compositions, is to be applied to the reactor vessel and internal structures of JSFR. Also, Mod. 9Cr-1Mo steel, which is basically Grade 91 steel in ASME Boiler and Pressure Vessel Code, is to be used for most of coolant systems including primary and secondary piping, internal heat exchangers and steam generators to realize a shortened piping system and compact component design taking advantage of the excellent combination of thermal conductivity and elevated temperature strength of this material.

---

* *Corresponding author:*
E-mail address: asayama.tai@jaea.go.jp

Selection and peer-review under responsibility of the Indira Gandhi Centre for Atomic Research.
doi:10.1016/j.proeng.2013.03.259

For the design and construction of JSFR, the JSME Code [1] is to be used. The 2012 edition of the Code incorporates 316FR and Mod.9Cr-1Mo steels with allowable stresses up to 300,000h. These are to be extended to 500,000h in the 2016 edition to realize 60-year design life.

One of the most important failure modes to be prevented in the design of sodium cooled fast reactor is creep-fatigue. Accurate prediction of creep-fatigue life in long-term regions is of particular importance when design life is extended to 60 years. Therefore, a number of uniaxial creep-fatigue tests have been conducted and the validity of the creep-fatigue evaluation method provisioned in the JSME code in long-term regions was demonstrated.

Another important point is to enhance the applicability of simplified evaluation method of strain range, which is used as input to creep-fatigue life evaluation, to structures with complex geometries subjected to thermal gradients such as tubesheets of steam generators so that the extent of conservatism in evaluation may not be excessive.

2. Creep-fatigue damage evaluation based on material tests

The creep-fatigue evaluation method implemented in the JSME code [1] is based on the time fraction rule, in which accumulated fatigue damage and accumulated creep damage are evaluated by Equations (1) and (2), respectively, and the failure criteria is described by Equation (3) using these quantities.

$$D_f = \sum \frac{n|_{\Delta\varepsilon_{ti}}}{N_f(\Delta\varepsilon_{ti})} \tag{1}$$

$$D_c = \sum \int \frac{dt}{t_r(T, \sigma(t))} \tag{2}$$

$$D = f(D_f, D_c) \tag{3}$$

Where, D_f and D_c are accumulated fatigue damage and creep damage, respectively. D is the criteria value for creep-fatigue damage. N_f is fatigue life, t_r is time to rupture, $\Delta\varepsilon_t$ is strain range, T is temperature and $\sigma(t)$ is stress at time t.

This method is very conventional and commonly used but when applying to 60-year design, detailed investigation focusing on the predictability in long-term regions is necessary.

Equation (1) is the Minor's rule and there is no question on the validity of the rule itself. However, when it is applied to creep-fatigue evaluation, errors or scatter associated with Equation (1) can emerge as mismatch between calculated creep-fatigue damage and the damage envelope represented by Equation (3). Suppose a situation where creep damage is underestimated; When fatigue damage is overestimated simultaneously, then resultant combination of accumulated fatigue damage and creep damage could fall just on the damage envelope. In this case, the result would appear to be good but in reality it is just a superposition of two errors that could lead to incorrect creep-fatigue life prediction. So, particularly in code provisions where fatigue curves that represent several heats or materials are used rather than precise reproduction of fatigue properties of individual heat, it is necessary to grasp the conservatism or unconservatism associated with the provisions.

With regards to Equation (2), one of the problems associated with formulating the stress-strain curves and creep equations to evaluate stress relaxation behaviors is that accurate reproduction of actual behavior in experiments does not necessarily lead to appropriate prediction of creep damage in light of the creep-fatigue damage envelope. Appropriateness of creep damage evaluation can only be discussed in terms of the consistency with the creep-fatigue damage envelope described by Equation (3). Generally, observed trend is that if measured stress relaxation histories obtained in experiments are used, creep damage is underestimated

[2]. Therefore, in code provisions, maneuvers to compensate this issue are necessary. How stress-strain curves and creep strain equations are formulated could affect the values of evaluated creep damage significantly, and formation should be done in a manner that the prediction of creep-fatigue damage in long-term regions maintains the same level of margins as in short term regions in combination with Equation (3).

As for a creep-fatigue damage envelope itself, there could be two choices: one is to use an identical envelope for all the conditions, which is a normal practice. An example of the diagram is the one provisioned in the JSME Code, which the Campbell diagram that connects points (D_f, D_c)=(1.0, 0), (0.3 0.3) and (0, 1.0). The other option is to establish appropriate envelopes newly which may be a function of material, temperature, strain range, strain hold time, etc. Although the latter approach might be desirable in light of reproducing what is happing in materials in reality but is not practical for code use at this point in time. Therefore, we still stick to the former option. It was confirmed by detailed investigation that the stress-strain curves and creep strain equations are determined for both materials in such a way that creep-fatigue evaluation in long-term regions maintain a same or higher level of margins compared to short-term regions.

The above point was verified by creep-fatigue life prediction of material tests accumulated in our databases. The data of 316FR covered temperature range of 500 to 600 C, strain range of 0.35 to 1.0%, hold time up to 100hours and the maximum time to failure was approximately 60,000 hours. The ratio of predicted life to observed life was almost constant irrespective of time to failure. The data of Mod.9Cr-1Mo steel covered temperature range of 482 to 650C, strain range of 0.35 to 2.0 %, hold time up to 10 hours and the maximum time to failure was approximately 30,000 hours. The ratio tended to decrease as time to failure increased.

3. Evaluation of strain range in structures subjected to creep-fatigue

A creep-fatigue evaluation procedure provisioned in the JSME Code [1] is based on elastic analysis. Plastic and creep deformation is evaluated using the result of elastic analysis along with stress-strain relationship and creep strain equations by utilizing the elastic follow-up concept. A typical method adopted in the JSME code is to start with stress intensity S_n obtained from elastic analysis which accounts for membrane and bending stresses. Then, strain range is determined considering an elastic follow-up factor and stress-strain curve that reflects inelastic deformation of material being evaluated. In this procedure, an elastic follow-up factor of 3 is normally used to encompass various geometries in components and variations in loading conditions encountered in fast reactors. It has been demonstrated that this method could have a large extent of conservatism in some cases. Therefore, a method with more accurate prediction with less conservatism is desirable and a new method based on "stress relaxation locus method" was investigated [3]. A schematic illustration of this method is shown in Fig. 1. Equations (4) to (6) represent a stress relaxation locus. The locus can vary according the value of κ, which represents the character of the geometry, where ε_0 and σ_0 correspond to elastically obtained strain and stress, respectively. $\kappa = 1.0$ represents the Neuber hyperbola.

$$\tilde{\varepsilon} = \frac{1}{\kappa}\left[\frac{1}{\tilde{\sigma}} + (\kappa - 1)\tilde{\sigma}\right] \tag{4}$$

$$\tilde{\varepsilon} = \frac{\varepsilon_t}{\varepsilon_0} \tag{5}$$

$$\tilde{\sigma} = \frac{\sigma_t}{\sigma_0} \tag{6}$$

Where, κ is constant, ε_t and σ_t are strain and stress at time *t*, respectively.

To verify the above method and to find the optimum value of κ, a series of stroke controlled uniaxial push-pull creep-fatigue tests using specimen with notches of various radius were performed with Mod.9Cr-1Mo steel at 550C. The radius of notches corresponded to stress concentration factor of 1.08 to 2.74. Also, to ensure the applicability of the method to more general loading conditions, a structural thermal creep-fatigue test using a plate with notches was performed. Temperature range was 550 to 200C and the radius of the plate is 220mm. On the edge of the plate were notches of which radius varied from 3 to 8mm.

In order to compare the results of push-pull and thermal creep-fatigue tests, creep-fatigue life was defined as a point when a crack of which length is 1mm is observed at the surface of a specimen. As a result, it was concluded that most relevant life prediction was possible when $\kappa = 1.6$ was assumed.

4. Discussion

ASME Boiler and Pressure Vessel Code Section III Division 1 Subsection NH [4] adopts a creep-fatigue damage envelope with an interception of (0.1, 0.01) for Mod. 9Cr-1Mo steel which is more restrictive than the one we are going to adopt in the JSME Code. However, based on the same line of investigation as the discussion in Chapter 2 of this paper which was led by the authors in the ASME Boiler and Pressure Vessel Code Committee, a Code Case for Mod.9Cr-1Mo steel has been published that allows the use of an alternative damage envelope whose interception is (0.3, 0.3) instead of (0.1, 0.01) [5]. It is to be noted that the use of this envelope will only be allowed when strain range is evaluated through elastic analysis and the isochronous stress-strain curves are used for creep damage estimation. This limitation is made from the viewpoint of ensuring sufficient conservatism.

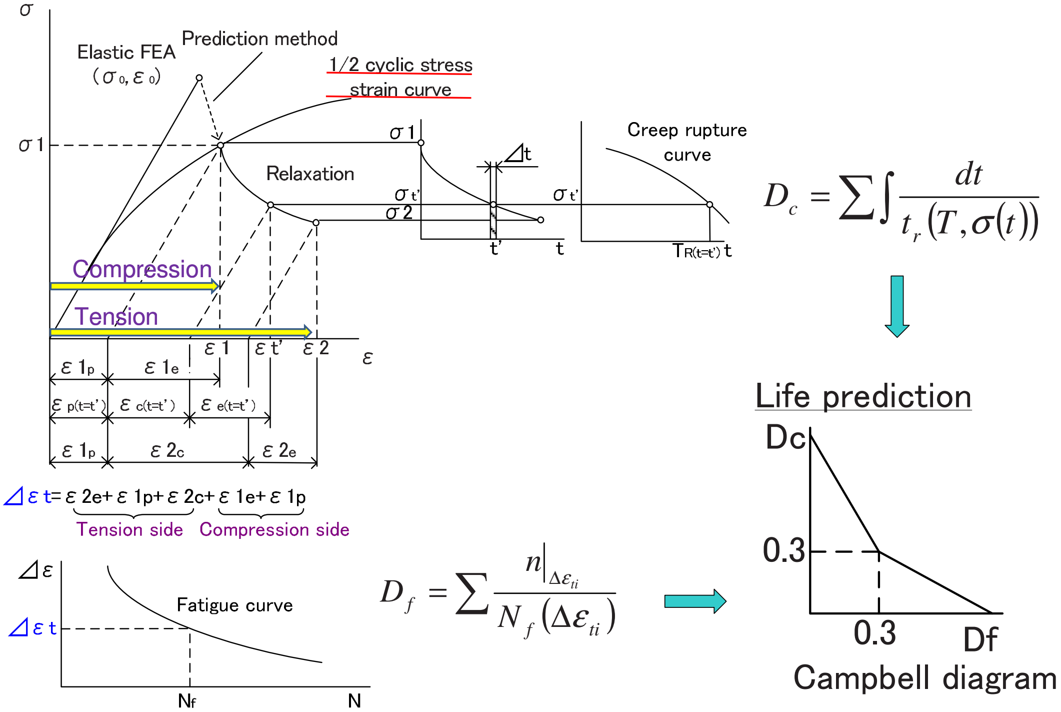

Fig. 1. Schematic illustration of creep-fatigue evaluation method.

One point to be kept in mind is that methods for estimating input for creep-fatigue damage evaluation such as strain range and stress relaxation history will be continuously improved and ultimately use of full inelastic analysis will be allowed. If the improvement is within the scope of elastic analysis route, of which example is presented in Chapter 3 of this paper, the strategy described in Chapter 2 is still applicable. However, when a full inelastic analysis route is permitted, which would allow estimation of material behaviors without any “margins”, the current strategy becomes inappropriate as is because keeping the necessary level of conservatism in creep damage evaluation by means of conservative formulation of stress-strain relationship and creep strain equations is no longer valid. A more comprehensive strategy for allocating margins would be required in this case. When utilizing a full inelastic route, the accuracy of constitutive equations should be validated by comparison with material tests and also structural tests that adequately represent actual deformation and failure in components.

5. Conclusions

For the 60-year design of Japan Sodium Cooled Fast Reactor (JSFR), the applicability of the creep-fatigue rules provisioned in the JSME code has been demonstrated for new materials to be incorporated in the code, 316FR and Mod.9Cr-Mo steel by showing that conservatism in prediction is maintained in long-term regions as well. Moreover, a simplified method for the evaluation of strain range to be used in creep-fatigue evaluation based on peak stress value and the locus of stress relaxation was proposed. These results will be implemented in the JSME Code for Nuclear Power Generation Facilities, Rules on Design and Construction for Nuclear Power Plants, Section II Fast Reactor Standards.

References

[1] Japan Society of Mechanical Engineers, *Codes for Nuclear Power Generation Facilities, Rules on Design and Construction for Nuclear Power Plants*, Section II Fast Reactor Standards, 2012 edition (2012), JSME S NC2-2012 (in Japanese, to be published)
[2] T.Asayama and R.Jetter., An Overview of Creep-Fatigue Damage Evaluation Methods and an Alternative Approach, *Proceedings of ASME PVP 2008*, Paper # PVP2008-61820
[3] M.Ando, Y.Hirose, T.Karato, S.Watanabe, O.Inoue, N.Kawawaki and Y.Enuma, Comparison of creep-fatigue evaluation methods with notched specimens made of Mod.9Cr-1Mo steel, *Proceedings of ASME PVP 2011*, Paper # PVP2011-57532
[4] *American Society of Mechanical Engineers, Boiler and Pressure Vessel Code Division 1 Subsection NH*, 2010Edition
[5] *American Society of Mechanical Engineers, Code Case N-812*, Alternate Creep-Fatigue Damage Envelope for 9Cr-1Mo-V Steel, 2011.