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Effect of frequency of free level fluctuations and hold time on the thermal ratcheting behavior

A. Mishra [a,*], P. Chellapandi [a], R. Suresh Kumar [a], G. Sasikala [b]

[a] Reactor Design Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, 603102, India
[b] Metallurgy & Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, 603102, India

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ABSTRACT

Investigation of cyclic strain accumulation behavior of a thin cylindrical shell (SS 316L) due to thermal ratcheting, in the framework of time independent (*Model-1*) and dependent formulations (*Model-2*) is carried out. The effect of frequency of free level fluctuations by varying cycle time (CT) is compared for *Model-1* and *Model-2*. Contribution of strain due to high frequency and low frequency level fluctuations is quantified. Further, the contribution of ratcheting strain with hold time is evaluated to highlight the effect of free level hold on radial deformation of the cylinder. Improvement in predicting ratcheting strain is observed using semi-implicit plasticity integration method. Implicit plastic increment formulation is derived using Newton's method. Validation of code for *Model-1* is done by comparing the results with the existing experimental results. Strain controlled cyclic characteristics and uniaxial monotonic loading at different strain rate is analyzed to validate the code for *Model-2*.

1. Introduction

Components and structures operating at high temperature conditions as in nuclear application have to be designed as per nuclear design codes for their safe functioning. The phenomenon of inelastic material behavior due to thermal loading, as in the main vessel of pool type nuclear reactors results into thermal ratcheting. It is a critical phenomenon, which should be considered while designing a reactor main vessel to limit the radial deformation within acceptable values as per design codes [1–3]. However, these codes discuss the basic elastic approach to evaluate such type of deformation, which involves higher safety margins to take care of several possible uncertainties due to inelastic material deformation behavior. Many researchers [4–8] have studied ratcheting phenomenon for various steels under uniaxial and multiaxial loading cases. These studies have shown that different materials exhibit different ratcheting behavior (hardening/softening). The cyclic hardening behavior of austenitic steels employing nonlinear constitutive model has been analyzed in detail and provided a good insight of ratcheting phenomenon [9–11]. As discussed by Bari and Hassan [12], kinematic hardening rules considering Chaboche model can be suitably used to predict nonlinearity due to yield surface translation in multi-axial ratcheting. Portier and co-authors [13] studied ratcheting behavior of SS 316 following five sets of constitutive models. They performed several tests to generate an experimental database for mechanical behavior under uniaxial and multiaxial loadings. Investigation of different type of models for damage evaluation is of high importance for the nuclear industries to achieve high reliability and safety levels during operational life.

Ratcheting studies by Bree [14], under the combination of both primary and secondary stresses, neglected the Bauchinger effect. Roche et al. [15] later provided insight of combined hardening behavior in ratcheting phenomenon for nuclear components. Moreover, the effect of employing different kinematic hardening rule for predicting thermal ratcheting due to moving temperature front shows importance of material model selection [16]. Ratcheting following inelastic analysis route for different combination of loads [17] is explained in DDS (Demonstration plant Design Standard). Japanese LMR (Liquid Metal Reactor) design code DDS [18] implemented methods to evaluate ratcheting strain considering combinations of primary and secondary stresses with imposition of secondary membrane and bending stresses. Igari [19] discussed time independent analysis of thermal ratcheting due to moving temperature front, implementing different hardening rules superposing creep effect independently. Time independent progressive deformation and the effect of loading method on the progressive

* Corresponding author. Tel.: +91 44 27480500x21176.
E-mail address: ashutoshjssate@gmail.com (A. Mishra).

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deformation behavior of a thin cylinder (SS 316L) are studied by Mishra et al. [20].

It is worth noting that progressive deformation behavior requires incorporating time dependent formulation to include visco-plasticity/rate dependence, which may significantly affect ratchet strain [21]. In the framework of rate-dependent plasticity, researchers [22] adopted a visco-plastic model for mechanical ratcheting and verified it by simulating the uniaxial/multiaxial ratcheting of U71Mn rail steel at room temperature. Thus, significance of rate dependence is observed in these literature using different time dependent constitutive models. It was reported that plasticity-creep superposition model (SPC) is suitable when hold time/creep effect is to be accounted while unified visco-plastic constitutive model (UVP) is preferred to account visco-plastic behavior (without hold time/creep) [23].

Structures used in nuclear application such as PFBR main vessel, experience loading at various strain/stress rates due to sodium free level fluctuations at different frequencies. In addition, sodium free level hold at different elevations, under various operating conditions, effect radial deformation due to creep. The literature on strain accumulation behavior of steels considering time independent and dependent formulations separately for mechanical ratcheting is large. In contrast, literature covering comparative studies of ratcheting behavior with strain/stress rate contribution and the contribution of ratcheting stain with hold time under cyclic mechanical loading are few [21]. As far as the authors have been able to discover, studies which address the relative contribution of these effects for cyclic thermal loading, are not presented earlier and hence valuable. In view of this, effects of sodium free level (Fig. 1) fluctuations in the main vessel of pool type nuclear reactor should be analyzed using time independent and dependent formulations for ratcheting. This may reveal the contribution of visco-plasticity in radial strain accumulation during level fluctuations at different frequencies. Similarly, the contribution of hold time on thermal ratcheting deformation due to free level hold during reactor operation/shutdown conditions is needed to be studied.

Present work first describes the ratcheting formulations based on two constitutive models to compare the thermal ratcheting behavior with and without considering rate effect at some frequency of free level fluctuations. The strain rate effect under such loading condition is highlighted in section 3.3.1. Afterwards, the study is extended in section 3.3.2 to predict the effect of frequency of free level fluctuations by changing the cycle time for the considered models. Thus, the section 3.3.2 presents a comparative approach to discover the contribution of visco-plasticity in ratcheting due to secondary stresses alone. Section 4 presents the validation of the ratcheting formulation with visco-plastic creep superposition model and the effect of short duration free level hold on thermal ratcheting deformation. The significance of ratcheting with hold time and without hold time is revealed in section 4.2 by comparing the thermal ratcheting deformation with and without hold times.

2. Description of constitutive models and material parameters

Constitutive models such as in Refs. [24,25], discussed ratcheting with time independent formulation. The effect of time dependence in ratcheting models is discussed in literature [26,27]. For the present analysis, the constitutive models for *Model-1* and *Model-2* are discussed in the following sections.

2.1. Time independent formulation: Model-1

The combined hardening model with the normality hypothesis and associated flow rule obeying the von Mises yield criteria is reproduced with material parameters (Table 1) as reported in the literature [28].

$$d\varepsilon^P = d\lambda \frac{\sigma' - X'}{J_2(\sigma - X)} \tag{1}$$

$$d\lambda = \frac{H(f)}{h} \left\langle \frac{3}{2} \frac{\sigma' - X'}{J_2(\sigma - X)} d\sigma \right\rangle \tag{2}$$

$$J_2(\sigma - X) = \sqrt{\frac{3}{2}(\sigma - X) : (\sigma - X)} \tag{3}$$

$$f = J_2(\sigma - X) - R - k \tag{4}$$

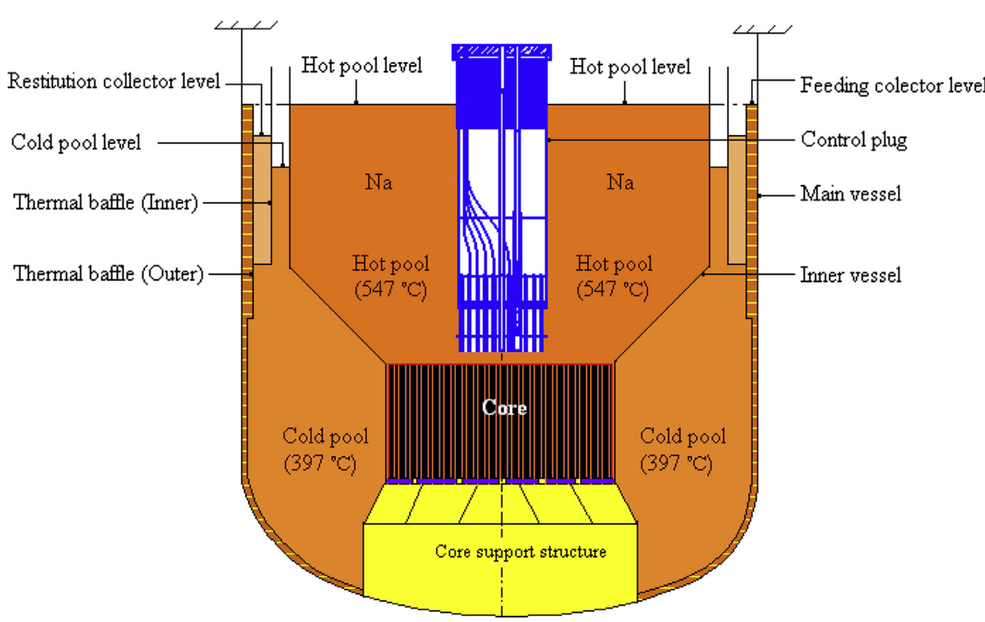

Fig. 1. Typical sodium free levels in main vessel of PFBR.