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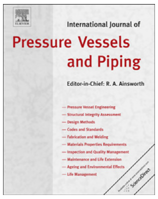

Assessment methods for Bree-type ratcheting without the necessity of linearization of stresses and strains

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ABSTRACT

This paper proposes methods for assessing Bree-type ratcheting in a cylinder subjected to constant internal pressure and cyclic thermal loading. The proposed methods are elastic analysis-route and elastic–plastic analysis-route. The former is based on the polynomial approximation of the elastic stress distributions for thermal stresses and the reference stress concept for estimating primary stress. The latter elastic–plastic route method is based on the concept of relative elastic core size. The methods proposed were validated by performing elastic–plastic finite element analyses of a smooth cylinder that exhibited Bree-type ratcheting.

1. Introduction

Current pressurized power component design codes based on design-by-analysis require the evaluation of the thermal ratcheting produced by a combination of primary and cyclic secondary stresses. In the design codes for low-temperature nuclear power components [1,2], the domain categorization approach using Miller's [3] or Bree's diagram [4] is used to assess the acceptability of given stress conditions. This elastic-route method requires stress linearization (referred to as stress classification procedure). This type of ratcheting is still interested in, and improvements for the conventional approach are proposed in Refs. [5,6] by considering realistic cycling primary load.

The elevated temperature design codes for fast reactors [7,8] employ the quantitative limitation of the principal strains, which requires strain linearization. It is sometimes difficult to apply these linearization procedures to general three-dimensional geometries because of the ambiguity in defining the cross section to be evaluated.

This paper describes new methods to assess the allowable limit of Bree-type ratcheting together with numerical validations made in this study by performing elastic–plastic FEAs of a thermally-stressed cylinder. The proposed methods are elastic- and inelastic-routes, and are consistent with the current design methods in terms of allowable stress levels.

2. Ratcheting evaluation methods in design codes

2.1. Domain categorization approach using Bree's diagram

Based on theoretical investigations of a smooth, ideally thin cylinder (plate) of an elastic-perfectly-plastic (EPP) body subjected to combination of constant internal pressure and cyclic thermal stresses, Bree proposed a diagram in which the two-dimensional space was divided into six regimes as shown in Fig. 1. The two parameters of the space were the primary stress parameter X and the secondary stress parameter Y, which are defined as.

$$X = P/\sigma_Y \tag{1}$$

$$Y = Q/\sigma_Y \tag{2}$$

where P is the primary stress, Q is the secondary stress range, and σ_Y is the yield strength of the EPP material.

The six regimes in Fig. 1 are.

E: the elastic regime where no yielding occurs
S_1, S_2: the shakedown regimes where no yielding occurs after the initial thermal cycle involving yielding
P: the plastic cycle regime where the strain is not progressive in spite of cyclic yielding
R_1, R_2: the ratcheting regimes where stable strain progression occurs.

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Nomenclature

E	elastic modulus [MPa]
K_S	factor for obtaining material ratchet limit
P	primary stress [MPa]
Q	secondary stress range [MPa]
R_{in}	inner radius of cylinder [mm]
$S_{ij,n}$	nominal stress component obtained by stress linearization [MPa]
S_n	nominal equivalent stress for $S_{ij,n}$
T	temperature [°C]
$T_{\max}$	maximum temperature [°C]
X	primary stress parameter
Y	secondary stress parameter
p	internal pressure [MPa]
p_L	limit pressure [MPa]
w	cylinder wall thickness [mm]
α	thermal expansion coefficient
ν	Poisson's ratio
ρ_e	relative elastic core size
σ_{ij}	stress component
$\sigma_{ij,m}$	membrane stress component
$\sigma_{ij,b}$	bending stress component
σ_{ref}	reference stress [MPa]
σ_Y	yield strength [MPa]

The E, S_1, S_2, and P regimes are categorized as non-ratcheting domains, and the R_1 and R_2 regimes as ratcheting domains. The same categorization was proposed by Miller based on theoretical investigations of a simplified uni-axial stress model [3]. Bree also proposed equations to estimate the incremental strain per cycle using Tresca-type equivalent stresses and a bi-axially stressed plate model [9]. The diagrams of Miller and Bree are equivalent in terms of acceptability conditions for preventing ratcheting.

In the non-ratcheting regimes, an elastic core in which no yielding occurs during a thermal cycle, commonly exists within the wall. The existence of the elastic core after a few thermal cycles indicates that the stress conditions are within the non-ratcheting domain.

In producing Fig. 1, Bree assumed a constant primary load. This may be realistic for nuclear fuel tubes subjected to a constant pressure and fluctuating temperatures, but can be too conservative for actual pressure vessels where internal pressure changes in-phase with thermal loading. In Refs. [5,6], improvements for this conservatism have been made by considering cycling primary stresses.

2.2. Inelastic-route strain limit in high temperature design codes

For base metal portions, French [10] and Japanese [8] fast reactor design codes employ the following general limitations on the principal strains:

Averaged principal strain ≤ 0.01.
Linearized surface principal strain ≤ 0.02.

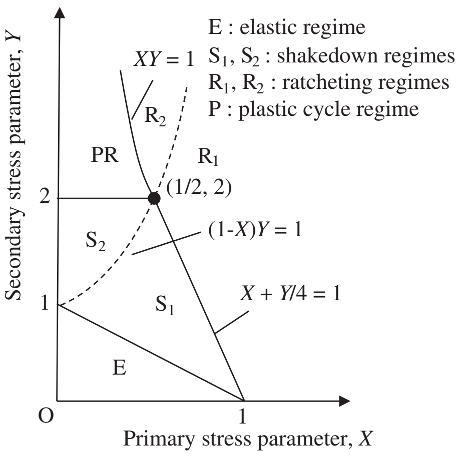

Fig. 1. Bree's diagram employed in the elastic-route design method.

The limits for welded portions are half of the above upper bound values. In addition to the above two limits, ASME Section III SS-NH [7] requires the peak surface principal strain to be ≤ 0.05.

The above limit of the linearized surface principal strain requires a linear approximation of the strain components, which creates the same difficulty as the stress classification approach.

2.3. Cyclic stress limit as the premise of simplified elastic-route approaches

The British high temperature structure assessment guideline, R5 [11] employs a simple shakedown criteria based on the relative size of a continuous ligament subjected to a cyclic secondary stress range within the shakedown limit of the material. The maximum acceptable limit of the ligament required by R5 [11] is 80% of the wall thickness. The upper limit before shakedown is given by $2K_S\sigma_Y$, where K_S is an experimentally determined factor and σ_Y is the 0.2% proof strength of the material. The values of K_S are given in R5 (e.g. 0.7 to 1.3 for type 316 cyclic hardening stainless steel, and 0.7 to 0.9 for ferritic steels (cyclic softening)). Using the R5 method, the relative size of a lowly stressed ligament in the wall thickness can be correlated with the occurrence of gross plastic deformation.

The low temperature design codes [1,2] permit the use of the purely elastic method of fatigue evaluation when the primary-plus-secondary stress $P + Q$ is less than twice the design yield strength. If the $P + Q$ limit is not satisfied, the elastic strain invariance may not be valid. The strain concentration factors including plastic strain effects (simplified elastic–plastic analysis) should therefore be used for the fatigue evaluations. To apply the current simplified elastic–plastic analysis [3,4], the satisfaction of the ratcheting limit is required. Ratcheting evaluation is not exemptible even if the limitation of $P + Q$ is satisfied. This $P + Q$ limit should be examined based on strain ranges rather than shakedown response related to ratcheting. Reference [12] proposed a method to replace the current $P + Q$ limit mostly based on ratcheting response, and the method leads to non-conservative estimate of strain ranges for fatigue assessment [13].

3. Evaluation methods without the necessity of linearization

3.1. Estimation of primary stress parameter by elastic–plastic FEA

Based on the equivalence between primary stress and reference stress [14], R5 describes the following equation to estimate the primary stress parameters in Fig. 1:

$$X = \sigma_{\text{ref}} / \sigma_Y \tag{3}$$