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Original Article

Proposal of the Penalty Factor Equations Considering Weld Strength Over-match

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ABSTRACT

This paper proposes penalty factor equations that take into consideration the weld strength over-match given in the classified form similar to the revised equations presented in the Code Case N-779 via cyclic elastic-plastic finite element analysis. It was found that the K_e analysis data reflecting elastic follow-up can be consolidated by normalizing the primary-plus-secondary stress intensity ranges excluding the nonlinear thermal stress intensity component, S_n to over-match degree of yield strength, M_F. For the effect of over-match on $K_n \times K_\nu$, dispersion of the $K_n \times K_\nu$ analysis data can be sharply reduced by dividing total stress intensity range, excluding local thermal stresses, $S_{p\text{-}lt}$ by M_F. Finally, the proposed equations were applied to the weld between the safe end and the piping of a pressurizer surge nozzle in pressurized water reactors in order to calculate a cumulative usage factor. The cumulative usage factor was then compared with those derived by the previous K_e factor equations. The result shows that application of the proposed equations can significantly reduce conservatism of fatigue assessment using the previous K_e factor equations.

1. Introduction

Fatigue is one of several potential aging-related damage mechanisms in nuclear components. It has also been reported that some fatigue failures in piping and other components of nuclear power plants have occurred, and light water reactor environments can accelerate the fatigue damage. Thus, nuclear components should be designed to ensure structural integrity against fatigue damage during design lifetime.

The design-by-analysis concept was first introduced in 1963 in the publication of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessels (B&PV) Code, Section III [1]. The vessel and piping rules were published together in 1971 when the ASME B&PV Code, Section III was revised to include rules for all nuclear components. At the time, the design–by-analysis criteria were revised to include "simplified elastic-plastic analysis" rules [2]. In the Section III design-by-analysis criteria, a prerequisite for fatigue analysis

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is that the primary-plus-secondary stress intensity range should not exceed $3S_m$, where S_m is the design stress intensity. If this limit is exceeded, the code provides a simplified elastic-plastic analysis approach for fatigue evaluation. A K_e penalty factor is applied to the elastically predicted alternating stress to reflect strain concentration. The maximum values of K_e are 5 for carbon steel and low alloy steel and 3.3 for austenitic stainless steel [3].

It is widely recognized that the K_e factor calculated from current code equations can be overly conservative for some conditions such as thermal stratification, and can subsequently cause serious limitations in design [4, 5]. In an attempt to reduce this conservatism, the Electrical Power Research Institute [5] compared K_e factors calculated directly from the elastic-plastic finite element analysis (FEA) to those calculated from approaches in the Welding Research Council Bulletin 361 [6] and the ASME B&PV Code. Electrical Power Research Institute then developed a unified approach to calculate a more realistic and less conservative K_e factor. Using analytical results, Asada et al. [7] evaluated the conservatism of the simplified elastic-plastic analysis in the current ASME B&PV Code, Section III and proposed new K_e factors to replace those found in the ASME B&PV Code and in the Ministry of International Trade and Industry Code [8]. The new K_e factors were adopted in the “Rules on Design and Construction for Nuclear Power Plants” published by the Japan Society of Mechanical Engineers in August of 2001 [9]. Hélder et al. [10] performed a preliminary study on the K_e factor proposed in Part 3-Clause 19 of the European Standards (EN)13445 [11] for correction of elastic stress ranges exceeding twice the yield stress from mechanical loading. Slagis [2] described the meaning of K_e in design-by-analysis fatigue evaluation in detail. Gurdal and Xu [12] assessed the conservatism of the K_e procedure in the current ASME B&PV Code, Section III, NB-3228.5 and, through a comparative study, evaluated the two proposed alternative ASME B&PV Code K_e procedures [13,14]. The ASME B&PV Code Committee revised the K_e equations by classifying the existing K_e factor, Poisson’s ratio factor K_ν, and plastic strain redistribution factor in a notch, K_n, then published the Code Case N-779 [15]. In general, for safety considerations, the nuclear industry is likely to design and manufacture safety class components with weld strength over-match [16]. In some cases, significant CUFs can be derived at the locations of welds, e.g., the weld between a safe end and a surge pipe on a pressurizer surge nozzle in a pressurized water reactor (PWR) [17]. In addition, because effects of light water reactor environments on fatigue need to be considered at the design and license renewal stages, these significant CUFs can be one of several fundamental and practical problems for new plants under design and currently operating plants considering applying for life extension. However, the proposed or revised equations may still have excessive conservatism because they don’t include the effect of weld strength over-match.

This paper investigated the effect of weld strength over-match on the penalty factors via parametric studies considering elastic follow-up, plastic strain redistribution in a notch, and Poisson’s ratio variation by using cyclic elastic-plastic FEA. As a result of the parametric studies, penalty factor equations that account for weld strength over-match were proposed in a classified form similar to the revised equations presented in the Code Case N-779. Finally, the proposed equations were applied to the weld between the safe end and the piping of a pressurizer surge nozzle in a PWR to calculate a CUF. This CUF was then compared with those derived by the previous penalty factor equations to assess the reduced degree of conservatism in fatigue evaluation.

2. Previous penalty factor rules

This section summarizes the simplified elastic-plastic analysis rules and penalty factor equations presented in ASME B&PV Code, Section III, NB-3228.5, and Code Case N-779.

2.1. ASME B&PV Code, Section III, NB-3228.5

It is said that the K_e factor in the ASME B&PV Code, Section III is based on the study made by Tagart [18], which has been modified according to Langer’s work [19] with regard to the upper limit, $1/n$. The following requirements are given in the ASME B&PV Code, Section III, NB-3228.5 [3]:

The $3S_m$ limit on the range of primary plus secondary stress intensity (NB-3222.2) may be exceeded provided that the requirements of (a) and (b) below are met.

(a) The range of primary plus secondary membrane plus bending stress intensity, excluding thermal bending stresses, shall be $\leq 3S_m$.
(b) The value of alternating stress S_{alt} used for entering the design fatigue curve is multiplied by the factor K_e, where:

$$\begin{array}{rll} K_e & = 1.0, & \text{for } S_n \leq 3S_m \\ & = 1.0 + [(1-n)/n(m-1)] \times (S_n/3S_m - 1), & \text{for } 3S_m < S_n < 3mS_m \\ & = 1/n, & \text{for } S_n \geq 3mS_m \end{array} \quad (1)$$

S_n = range of primary plus secondary stress intensity.

The values of the material parameters m and n for the various classes of permitted materials are as given in Table NB-3228.5(b)-1 [3].

2.2. ASME B&PV Code, Section III, Code Case N-779

The ASME B&PV Code Committee published Code Case N-779 because of the need to revise NB-3228.5. The following requirements are given in Code Case N-779.

The $3S_m$ limit on the range of primary plus secondary stress intensity may be exceeded provided that the following rules are met:

(1) The component meets the requirements of subparagraphs (a), (c), (d), (e), and (f) of NB-3228.5.
(2) The value of S_{alt} used for entering the design fatigue curve is one-half of the stress intensity range calculated by the combination of the terms in (3), (4), and (5) below.
(3) The total stress intensity ranges, excluding both thermal bending stress caused by linear through–wall thermal gradients and local thermal stresses, shall be multiplied by the factor K_e given in NB-3228.5(b).

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