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Review

Proof of fatigue strength of nuclear components part II: Numerical fatigue analysis for transient stratification loading considering environmental effects

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A B S T R A C T

For the construction, design and operation of nuclear components and systems the appropriate technical codes and standards provide detailed analysis procedures which guarantee a reliable behaviour of the structural components throughout the specified lifetime. Especially for cyclic stress evaluation the different codes and standards provide different fatigue analyses procedures to be performed considering the various mechanical and thermal loading histories and geometric complexities of the components. To consider effects of light water reactor coolant environments, new design curves included in report NUREG/CR-6909 for austenitic stainless steels and for low alloy steels have been presented. For the usage of these new design curves an environmental fatigue correction factor for incorporating environmental effects has to be calculated and used. The application of this environmental correction factor to a fatigue analysis of a nozzle with transient stratification loads, derived by in-service monitoring, has been performed. The results are used to compare with calculated usage factors, based on design curves without taking environmental effects particularly into account.

1. Introduction

The basis for construction, design and operating nuclear systems, structures and components are national technical codes and standards like the ASME-BPVC Section III [1], the French RCC-M Code [2] or the German Nuclear Safety Standards KTA [3]. Reviewing national fatigue codes and standards for nuclear pressure vessels and pipings show, that the majority are similar with those in [1]. It is possible to prevent failure modes caused by fatigue by imposing distinct limits on the peak stresses at the highest loaded region since fatigue failure is related and initiated by high local stresses and respective strains. Different procedures with varying complexity levels to prevent failure modes by fatigue are available. If elastic–plastic deformation is expected, non-linear Finite Element (FE) calculations have to be carried out. Under specific conditions a simplified elastic–plastic fatigue analysis can be performed using a plastification factor K_e. This approach to calculate equivalent stress amplitudes S_a is based on a linear-elastic analysis. If the range of primary plus secondary stress intensities S_n exceeds a material-specific value, the calculated equivalent stress amplitude is multiplied by the plastification factor. Compared to experimental data the calculation of the plastification factor K_e according to ASME/KTA is mostly very conservative [4].

The ASME design fatigue curves for carbon and low alloy steels as well as austenitic stainless steels are based on best fit curves of experimental investigations. The data were obtained from unwelded small smooth-machined specimens tested with a strain controlled fully reversed loading at room temperature and air environment [5–7]. The total strain range $\Delta\varepsilon_{at}$ is converted to nominal stress range by multiplying the strain range by the modulus of elasticity at test temperature. The design curves in ASME BPVC (ed. 2007 and before) are derived from the mean data curves by introducing factors of 2 on stress and 20 on cycles, whichever give the lowest curve. These factors do not represent a safety margin, but account for real effects, i.e. “scatter of data and material variability”, “size effects”, “surface finish and environment” [7,8]. During the last three decades great endeavours have been made to investigate the influence of the coolant environment on fatigue life [9–12]. Light Water Reactor (LWR) environment can have a significant impact on the fatigue life and has to be involved in cumulative fatigue life considerations. U.S. Nuclear Regulatory Commission (NRC) has recently issued the Regulatory Guide 1.207 “Guidelines for Evaluating Fatigue Analyses Incorporating the Life

Abbreviations: E, young’s modulus; ε, strain; $\dot{\varepsilon}$, strain rate; $\Delta\varepsilon_{eq}$, equivalent strain range; $\varepsilon_{a,thres}$, threshold strain amplitude; F_{en}, environmental correction factor; K_e, plastification factor; N, number of cycles; σ, stress; σ_i, principal stress; σ_{ij}, component stress; $\Delta\sigma_{eq}$, equivalent stress range; S_a, elastic stress amplitude; T, temperature; ΔT, temperature range; U, usage factor.

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Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors" [13]. This Guide is based on the research work and publications by Argonne National Laboratory (ANL) [14], which provides equations for mean fatigue life curves in air and LWR environment of carbon steels, low alloy steels and austenitic stainless steels. The ANL fatigue life model includes parameters for the effects of temperature, strain rate, dissolved oxygen content in water, and in the case of carbon and low alloy steels, sulphur content of the steel. In this approach the environmental effects are expressed in terms of an environmental correction factor F_{en} as the ratio of fatigue life in air environment at room temperature to fatigue life in LWR coolant environment at operating temperature. The corresponding new fatigue design curve is based on the new ANL best fit curve with introduced factors of 2 on stress and 12 on cycles. Environmental effects are considered by calculating F_{en}-factors, which are multiplied with the calculated usage factor of a given stress amplitude, derived from the new ANL mean air curve, to get the usage factor in LWR coolant environment.

2. Thermal and mechanical loading conditions

The development of thermal stresses in components is linked with external restraints and or due to materials with different thermal expansion coefficients. In piping systems thermal loading occurs as transient thermal shock or transient thermal stratification loadings.

If water injection with a high flow rate takes place in a piping system with low or high temperature in its initial state, a temperature gradient will develop along the axial direction of the piping system and result in a thermal transient loading. In the cross-section of the piping the flow velocity as well as the temperature is assumed to be constant apart from the areas closed to the wall of the pipe.

A change in temperature causes a change in the density of solid, liquid and gaseous materials, where an increase in temperature means a reduction in the density. If a piping is filled with hot water and cold water is injected with a low flow rate, a thermal stratification will develop due to the difference in density, e.g [15–18]. Different temperatures of the medium in the piping, a reduced flow velocity as well as certain constructive and geometrical conditions are responsible for the occurrence of a thermal stratification flow. The extension of the mixing layer between hot and cold medium usually depends on the mass flow rate and the difference in temperature.

In this paper a nozzle of the Pressurized Water Reactor (PWR) Surge Line (surge line connected to pressurizer) with a thermal stratification load was examined by FE calculations. The base material of the nozzle, used in the calculation is low-alloy ferritic steel 1.6310 (20 MnMoNi 5-5). The cladding and the connection to the piping system is made of Nb-stabilized austenitic stainless steel 1.4550 (X 6 CrNiNb 18-10),Fig. 1. To reduce the impact of thermal induced stresses to the nozzle wall a isolating thermo-sleeve is used. The usage of a thermo-sleeve significantly reduces thermal loadings of nozzles due to the isolating gap between sleeve and nozzle [18].

Measured temperature data from in-service monitoring during operation were used and a rainflow analysis was performed to obtain thermal transients (ΔT). On the PWR Surge Line three locations are instrumented with seven thermocouples at the outer surface of the pipe each. The maximum thermal stratification load, measured at the outer surface of the pipe within the period of 1988–2005 was used to define an envelop transient as a combination of the maximum temperature change, maximum temperature gradient and the given design temperature of $T = 350$ °C. The highest temperature change measured by in-service monitoring at the outer surface of the piping system is shown in Fig. 2.

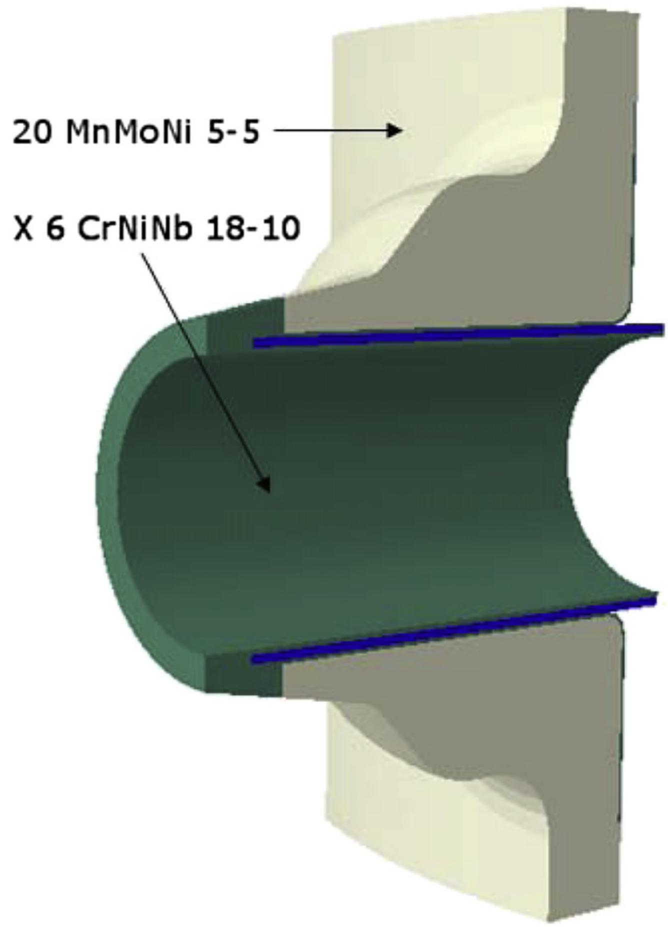

Fig. 1. Used model of the nozzle with material assignment (20 MnMoNi 5–5/X 6 CrNiNb 18–10).

With this data a envelop thermal stratification load with respect to maximum stress- and strain amplitudes as a combination of maximum measured temperature difference ΔT_{max} found as 163,7K and maximum measured temperature gradient $(dT/dt)_{max}$ found as 0.37 K/s was adopted. The procedure to define an envelop transient including the shift to design temperature is shown in Fig. 3.

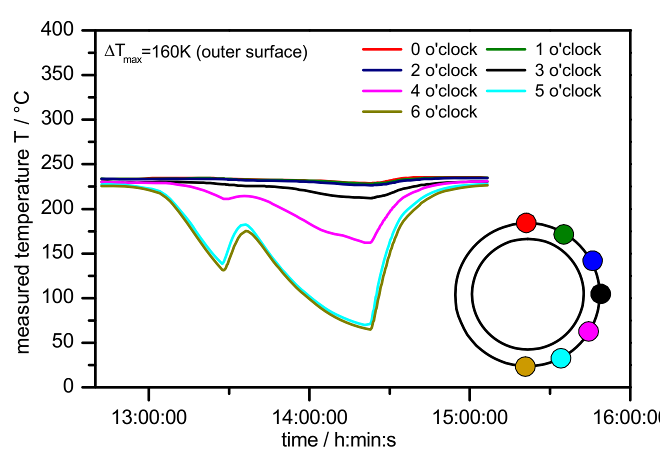

Fig. 2. Temperature vs. time at the outer surface as a result of in-service monitoring.