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Safety assessment of austenitic steel nuclear power plant pipelines against stress corrosion cracking in the presence of hybrid uncertainties

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Abstract

Stress corrosion cracking (SCC) is an important degradation mechanism to be considered for safety assessment of nuclear piping components made of austenitic steels, especially in the heat-affected zones. Damage due to SCC occurs in a susceptible material, in a corrosive environment, in the presence of high temperature and high applied/residual stresses. The operating conditions and the environmental conditions show variations during the lifetime of the power plant. Also, there will be variations in micro-structural properties of the material of piping components. These variations should be taken into account while assessing the safety of the piping component against SCC. This can be accomplished by treating the relevant variables as random or fuzzy depending upon the source and type of uncertainty. In this paper, an attempt has been made to compute the fuzzy failure probabilities of a piping component against SCC with time, using an approach combining the vertex method with the Monte Carlo simulation technique. The initiation and propagation stages of stress corrosion cracks are modelled using a modified PRAISE approach. The degree of sensitisation, material fracture toughness, yield strength, ultimate strength and applied stress are considered as random variables, while operating temperature and oxygen concentration are considered as fuzzy variables. The R6 procedure is used in the computation of the fuzzy failure probabilities. The usefulness of the approach is demonstrated through an example problem.

Keywords: Safety assessment; Piping component; Stress corrosion cracking; Failure probability; Fuzzy sets; Monte Carlo simulation

1. Introduction

Austenitic stainless steels are commonly used in power-generating industries due to high ductility and fracture toughness [1]. This type of steel is used in applications where corrosion resistance is an important characteristic. However, under specific conditions (which are typical of weldments in reactor recirculation, reactor water clean-up, residual heat removal, core spray and feed water pipes [2]), localised attack in the form of pitting or stress corrosion cracking (SCC) may occur. Even though failures of piping components due to SCC are rare compared with failures due to other degradation mechanisms such as erosion–corrosion, vibration fatigue and thermal fatigue, they can be costly and destructive when they do occur. Also, SCC in a piping component is difficult to detect. Considering the consequences, SCC has been identified as an important degradation mechanism to be considered for safety assessment of piping components made of alloyed steels, especially austenitic steels, in nuclear power plants [3].

A fundamental component of analysis of complex engineering facilities, such as nuclear power plants, is the appropriate representation and incorporation of uncertainty [4]. Uncertainty can be classified into two main types, namely, aleatory (or random or irreducible or Type A) uncertainty and epistemic (or reducible or Type B) uncertainty [5]. Aleatory uncertainty arises due to inherent randomness in physical phenomena or processes, and epistemic uncertainty arises due to lack of knowledge about the quantities. While probability theory has been traditionally used to represent both these types of uncertainty, various researchers have pointed out that it may not be proper to use probability theory to represent

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epistemic uncertainty in the presence of limited knowledge [4,6]. A number of alternative theories to probability theory, for modelling epistemic uncertainties, have been proposed by various researchers. These include fuzzy set theory, evidence theory, interval analysis and convex modelling [4]. In particular, fuzzy set theory provides a more rational framework for handling uncertainties arising from *vagueness*, namely, imprecision of definition or use of linguistic terms in a natural or artificial language [7]. The benefits of fuzzifying uncertain variables include greater generality, higher expressive power, an enhanced ability to model real-world problems and a methodology for exploiting tolerance for imprecision [7]. In cases where both types of uncertainty exist, there is a need to develop special techniques, for carrying out the safety assessment, which can handle hybrid uncertainties (i.e. fuzzy and random).

Different methods have been proposed by various researchers for handling fuzzy and random uncertainties together [8–12]. One method is to convert all probabilistic information into fuzzy sets (or vice versa) and carry out the analysis in the framework of the fuzzy set theory (or probability theory) [10–12]. The major criticism against this approach is that since fuzziness and randomness represent different kinds of uncertainty, it is not proper to convert one to another. In the present study, an approach that combines the vertex method [7] with the Monte Carlo simulation (MCS) technique is proposed for computing the fuzzy failure probabilities of a piping component against SCC with time. The initiation and propagation stages of stress corrosion cracks are modelled using the PRAISE approach with the modification proposed by Priya et al. [13]. The degree of sensitisation, material fracture toughness, yield strength, ultimate strength and applied stress are considered as random variables, while operating temperature and oxygen concentration are considered as fuzzy variables, in the analysis. The R6 failure assessment procedure [14–16] is used in the computation of fuzzy failure probabilities.

The paper is organised as follows. In this study, initiation and propagation of stress corrosion cracks are modelled using the methodology recommended in PRAISE [17], which is explained briefly in the next section. The proposed fuzzy-probabilistic analysis procedure for safety assessment of nuclear power plant pipelines against SCC is outlined in Section 3. Details of an example problem considered to demonstrate the usefulness of the proposed procedure are presented in Section 4. Results and discussions are given in Section 5, followed by conclusions in Section 6.

2. Modelling of stress corrosion cracking

SCC occurs when the following three conditions occur simultaneously [1,3]:

(a) susceptible material,
(b) tensile stress (applied and residual),
(c) an environment that can provide the chemical driving force for the corrosion reaction.

The methodology recommended in PRAISE [17] for modelling SCC in pipes is followed in this study. PRAISE analysis usually concentrates on girth welds in the pipe and axial stresses are considered, since axial stresses have the major influence on crack growth in circumferential girth butt welds. In PRAISE, occurrence of SCC is modelled by considering it as a two-stage process, namely, (1) crack initiation and (2) crack propagation. The methodology recommended in PRAISE for modelling SCC is described briefly below.

2.1. Time to initiation

The time to initiation of SCC is considered as a function of a damage parameter, D, which represents the effects of loading, environment and material variables on SCC. The damage parameter is given by

$$D = f_1(\text{material}) \cdot f_2(\text{environment}) \cdot f_3(\text{loading}), \tag{1}$$

where f_1, f_2 and f_3 are given by

$$f_1 = C_1(Pa)^{C_2}, \tag{2}$$

where Pa is a measure of degree of sensitisation, given by electrochemical potentiokinetic reactivation (in C/cm^2).

$$f_2 = \mathrm{O}_2^{C_3}\,\exp[C_4/(T+273)]\log(C_5\gamma^{C_6}), \tag{3}$$

where O_2 is the oxygen concentration in ppm, T is the temperature in degrees centigrade and γ is the water conductivity in μs/cm.

The loading term f_3 is considered to be a function of stress. For constant applied load, f_3 is given by

$$f_3 = (C_8\sigma^{C_9})^{C_7}, \tag{4}$$

where σ is the stress in ksi.

C_1–C_9 are constants whose values depend on the type of material, and are evaluated by applying curve-fitting procedures to laboratory and field data. For AISI 304 austenitic stainless steel, values of these constants are given by $C_1 = 23.0$, $C_2 = 0.51$, $C_3 = 0.18$, $C_4 = -1123.0$, $C_5 = 8.7096$, $C_6 = 0.35$, $C_7 = 0.55$, $C_8 = 2.21 \times 10^{-15}$ and $C_9 = 6.0$ [17].

In order to cater for the observed scatter in experimental data of initiation time, time to initiation (t_I) for a given D is considered as a random variable following a lognormal distribution. The mean and standard deviation of $\log(t_\mathrm{I})$ are given by

$$\begin{aligned}&\text{Mean value of } \log(t_\mathrm{I}) = B_0 + B_1 \log(D),\\ &\text{Standard deviation of } \log(t_\mathrm{I}) = B_2 + B_3 \log(D),\end{aligned} \tag{5}$$

where B_0, B_1, B_2 and B_3 are constants whose values depend on the type of material and the loading conditions (i.e. constant load or changing load), and are evaluated by applying curve-fitting procedures to laboratory and field data. For AISI 304 austenitic stainless steel under