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Combining discrete-time Markov processes and probabilistic fracture mechanics in RI-ISI risk estimates

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ABSTRACT

Based on the research conducted in the Finnish SAFIR project, which is a national nuclear energy research program, discrete-time Markov processes and probabilistic fracture mechanics (PFM) methods are further developed and applied in this paper. The purpose of this work is to increase the accuracy of risk estimates used in RI-ISI, and to quantitatively evaluate the effects of different inspection strategies on risk. Piping failure probabilities are obtained by using PFM analyses. PFM has the advantage that its results are not affected by existing in-service inspection (ISI) activities at the nuclear power plants (NPPs), unlike failure probabilities assessed from existing failure data. The PFM results for crack growth are used to construct transition matrices used in a discrete-time Markov process. The application of Markov process allows the examination of effects of inspections on the failure probabilities. Finally, the developed method and results are showcased by applying them to a selected piping system in an existing Finnish NPP.

1. Introduction

Advances in probabilistic safety assessment (PSA) methodology in the 1990s have created increased possibilities for risk informed in-service inspections (RI-ISI). RI-ISI has been recognised as a viable method for increasing efficiency in in-service inspection tasks, without sacrificing plant safety. The basic idea for any RI-ISI method is to prioritize the inspections of piping sections according to their risk importance. Risk combines two factors in case of NPP piping; the probability of a pipe leak/break and the consequences of the leak/break. The two widely applied RI-ISI approaches are the EPRI RI-ISI method [1] and the WOG (Westinghouse Owners Group) method, which are included in the ASME Boiler & Pressure Vessel Code [2]. This paper presents a quantitative RI-ISI method where both the probabilities and consequences are assessed numerically. The consequence assessment follows similar principles as the EPRI methodology, while the failure probability assessment is supported with PFM calculations.

In any complete RI-ISI scheme, methods are needed to assess both the probability and the consequences of a pipe leak/break with an adequate accuracy. The probability of a pipe leak/break can be estimated from existing data from NPPs, soliciting expert opinions, identifying dominant degradation mechanisms, or by using PFM. The latter method has the advantage of providing data that is free from the effects of any existing inspection activities. Simulation data resulting from PFM analyses are used in this paper because one of the aims is to compare different inspection strategies. The consequences are assessed with a PSA model, using the conditional core damage probability (*CCDP*) as the importance measure.

The aim of this paper is to present and demonstrate a quantitative RI-ISI method that allows the comparison of different inspection strategies in regard to their effect on overall plant risk. To achieve this, three effects need to be modelled: the phenomena of crack initiation and growth until failure, the activity of inspecting and repairing the pipes, and the PSA consequences of pipe breaks. The solution presented in this paper uses a combination of PFM crack growth simulations and Markov matrices to model the crack initiation and growth and the inspections, while the PSA model is used to assess the consequences. The use of Markov process in RI-ISI was first presented by Fleming [3], and has been refined later [4]. Fleming used a continuous Markov process, while the method in this paper utilizes a discrete-time Markov process.

Application of the method is also presented, the object here being the Shut-down cooling system of the Olkiluoto 1 NPP unit. This method was developed within the Finnish nuclear energy research program SAFIR, with a more detailed report available [5].

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2. RI-ISI analysis method

2.1. Overview

An analysis method that allows a fully quantitative risk analysis of a piping system needs to yield the probability of a pipe break at time t when subject to inspection strategy s for any weld included in the analysis *and* the consequences of the pipe break. To calculate the rupture probability, two distinct parts of ISI are modelled: the phenomenon of crack growth and the activity of inspecting the pipes. These both affect the probability or frequency of pipe rupture. In addition to this, PSA is used to evaluate the consequences of pipe rupture. The focus of this paper is on the pipe rupture probabilities, since the piping inspections cannot affect the consequences.

The goal of crack growth modelling is to calculate rupture probability densities for a pipe segment, depending on the degradation mechanisms affecting the segment in question. This information is used to determine the state transition matrices for a Markov model where the different distinct states correspond to different depths of the crack growth process. A discrete-time Markov procedure was chosen for easier applicability when comparing different inspection strategies, by using two different Markov matrices; one for crack growth and another one for inspection activities. The overall method can be summarised in six steps:

1) Crack growth simulations based on PFM
2) Construction of degradation matrix transition probabilities from PFM simulations and database analysis of crack initiation frequencies
3) Model for inspection quality, which is used to construct inspection matrix transition probabilities
4) Markov model to calculate pipe rupture probabilities for chosen inspection schemes
5) Assessment of pipe rupture consequences from PSA
6) Comparison of results for different inspection strategies. Measures of interest include yearly rupture probability, yearly core damage probability and average values for both of these over operational plant lifetime

In step 6 the RI-ISI risk classification principle as further developed by VTT is applied, see Ref. [5]. This methodology is a modification of the EPRI risk matrix [1], and includes quantified classes for both probabilities and consequences of the pipe rupture.

2.2. PFM procedure

The probabilistic crack growth analyses were carried out with a modified version of analysis code VTTBESIT, developed by the Fraunhofer-Institut für Werkstoffmechanik (IWM), Germany and by VTT. With the VTTBESIT it is possible to quickly compute the mode stress I intensity factor (SIF-I) values along the crack front and based on this simulation data the crack growth [6]. The calculation of the SIF-I values is based on a set of influence functions fitted to a sufficient range of 3D finite element method (FEM) analysis results, see Refs. [7–9]. For cracks with depth up to 80% of the wall thickness the approximation error of the interpolated SIF-I values is less than 3% within the wall, and for locations in the free surface less than 7%. For deeper cracks the SIF-I solutions are extrapolated, resulting with more altering but still at least reasonable good accuracy, with involved plasticity effects incorporated from the corresponding 3D FEM results. The modifications concerning VTTBESIT and performed within this study deal with the addition of probabilistic capabilities to the code, which is originally intended for deterministic fracture mechanics based crack growth analyses.

The analysis procedure of the probabilistic version of VTTBESIT is as follows [5]:

- reading of the deterministic input data
- random sampling of certain input data parameters from the specified distributions: exponential distribution for initial crack depth, exponential distribution for initial crack length and Poisson distribution for thermal load cycle frequency
- crack growth analysis: the amount of crack growth in each time step is calculated from the respective crack growth equation ⇒ the ending criterion of the analysis is that crack depth reaches the outer pipe surface
- for each analysed piping component location 5000 separate simulations were calculated, and for each of these, values of the above mentioned distributed input data parameters/variables are sampled at random from the respective probabilistic distributions
- the degradation state to which the crack has grown is calculated for each year of the estimated time of operation and for each simulation ⇒ these results are used in the consequent Markov system probabilistic degradation analyses performed with a Matlab application developed in the project

2.3. Markov process for pipe degradation and inspection modelling

Most of the piping inspections in a NPP are conducted during the yearly refuelling and maintenance outages. Thus, the use of a discrete-time Markov model with one-year intervals is justified.

The basic discrete-time Markov Eq. (1) is:

$$\overline{p}_t = \overline{p}_{t-1} \times M, \tag{1}$$

where $\overline{p}_t$ is probability vector $[p_0, p_1, p_2, p_3, p_4, p_5]$ the elements of which contain the probability for each system state at time t, and M is the transition matrix that contains the transition probabilities to each state. Due to Markov property the probability vector can be calculated after any number of steps with Eq. (2):

$$\overline{p}_t = \overline{p}_0 \times M^t, \tag{2}$$

where $\overline{p}_0$ is the vector containing the probabilities of different degradation states in initial condition. It is assumed that the probability of detectable flaws or other degradation conditions is initially zero, i.e. the pipe is in as good as new condition. Six states are used for the Markov process, each corresponding to a different crack depth as seen in Table 1.

The Markov process presented above models the crack growth. Another Markov matrix is needed to model the inspections. Crack or leak detection probabilities are used as elements in this matrix, i.e. the probabilities are for transitions from each degraded state (states 2–4 in this application) to the undamaged state (state 0).

When applied, the end result from the Markov process is a vector whose elements are the probabilities that the crack is in certain state at each discrete-time step t in Eq. (3):

$$\overline{p}_t = \overline{p}_{t-1} \times M_{\text{deg}} \times I(t) \cdot M_{\text{ins}} \tag{3}$$

where M_{deg} is the degradation matrix, M_{ins} is the inspection matrix and $I(t)$ is a Boolean function with value 1 if inspections are performed at time step t and 0 if no inspections are performed at time step t.