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Development of Deterministic and Probabilistic Fracture Mechanics Analysis Code PROFAS-RV for Reactor Pressure Vessel – Progress of the Work

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1. Introduction

Since the 1980s, a number of computer codes have been developed to perform the probabilistic analysis of reactor pressure vessel (RPV) [1-2]. Recently, applications of some new radiation embrittlement model, material database, calculation method of stress intensity factors, and others which can improve fracture mechanics assessment of RPV are introduced. The purpose of this study is to develop a probabilistic fracture mechanics (PFM) analysis program for RPV considering above modification and application of newly developed models and calculation methods. In this paper, it deals with the development progress of the PFM analysis program for RPV, PROFAS-RV.

2. Development of DFM/PFM Analysis Code

The PROFAS-RV follows the general procedures such as existing PFM evaluation codes, VISA-II and FAVOR [3]. Differences of PROFAS-RV are K_I calculation method, RT_{NDT} shift model, graphic user interface (GUI) and message passing interface (MPI). Moreover, it is available to revise the calculation methods and latest database & models by having own original code.

2.1 Calculation Methods and Performance

Finite difference method (FDM, 1-D) was used to calculate the temperature and thermal stress distributions through the vessel wall during given transient conditions in PROFAS-RV. The distribution of stress from pressure is separately calculated, then, the stress intensity factor (SIF) corresponding to a given crack is calculated by influence coefficient method based on flaw evaluation procedures, both ASME Sec. XI App. A and RCC-MRx codes [4-5] since it was reported that AFCEN code provide relatively correct estimation of SIF to the FE reference solution through the international joint research in which authors have participated [6]. And new radiation shift correlation in the 10CFR50.61a is added with the existing RT_{NDT} shift equation of RG-1.99 rev. 2 to the PROFAS-RV [7]. In 2010, based on newly reported large amount of fracture toughness data, index temperature screening limits are established by NRC's PTS re-evaluation effort. This result was adopted in 10CFR50.61a as the alternative index temperature screening limits. The calculation methods of RT_{NDT} shift model were separately proposed for the axial weld, circumferential weld, plate and forging based on state-of-the-art knowledge which overcomes conservatism in RT_{NDT} shift equation of RG-1.99 rev. 2.

The parallel programming for multi-core processors with MPI is applied in the code to reduce the computing time of Monte-Carlo simulation. The PROFAS-RV is being tested with other codes, and it is expected to revise and upgrade by reflecting the latest model and calculation method continuously.

2.2 The Construction of the Code

The PROFAS-RV is developing for the DFM/PFM failure analysis of reactor pressure vessel and consists of input module and output module. The user interface module is developed under Windows environment to connect the user and the execution module effectively. Fig. 1 shows the initial screen of PROFAS-RV. The input module consists of five sub-modules, analysis model, material property, transient state, weld data and simulation for PFM. The output module is composed of the three sub-modules, PFM result summary, view result file and graphic display. The Monte-Carlo simulation is performed by following general procedure. The applied stress intensity factor, K_I, at the crack tip is calculated by using temperature and stress distributions. The value of the RT_{NDT} shift is taken from one of the shift models which is selected by the user. And then the values of fracture toughness, K_{IC}, are estimated and compared to the K_I to determine crack initiation. Once crack initiates, the crack is extended 1/4 in. (or selection) and the crack arrest (K_{IA}) is checked at the extended location. If arrest occurs, the simulation moves to the next time step, if not, the crack is continued to extend until either crack is reached outside of the wall or K_I is less than K_{IA}. This process continues until either the vessel fails or the transient time is ended as shown in Fig. 2. Additionally, residual stress and warm pre-stressing (WPS) were considered in the PROFAS-RV.

2.3 Preliminary Analysis

The PROFAS-RV program is on the way of the validation and verification process. The RT_{NDT} shift model of 10CFR50.61a and stress intensity factor calculation method of RCC-MRx code are included. The failure probabilities of two RT_{NDT} shift equations with respect to the fluence for the Linde80 weld (Cu: 0.29 wt%, Ni: 0.68 wt%) and SBLOCA transient of sample problem was compared. The probability of failure of 10CFR50.61a is lower than that of RG-1.99 rev. 2. The effect of difference on the failure probability is more significant for the lower fluence region. The probabilities of failure due to the difference in the stress intensity factor calculation method were also evaluated.

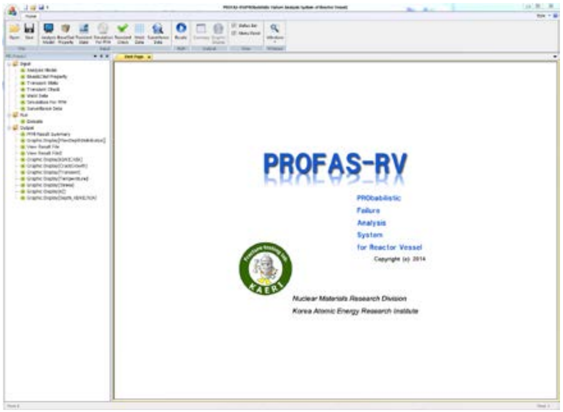

Fig. 1. Initial Screen of the PROFAS-RV.

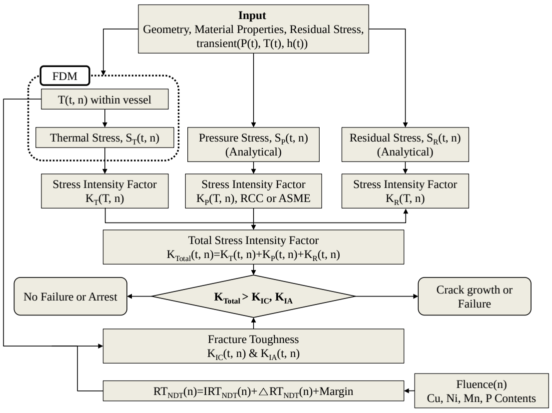

Fig. 2. The Flowchart of DFM/PFM Fracture Mechanics Analysis for RPV.

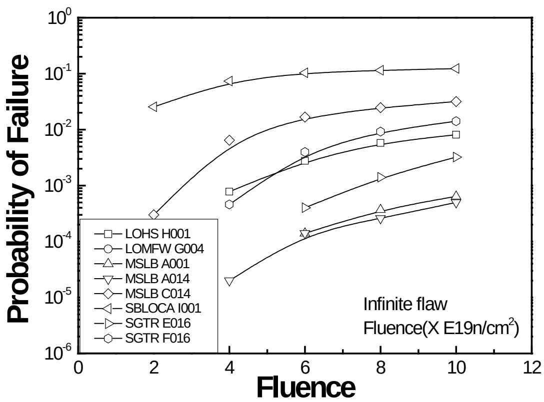

Fig. 3. Comparison of the Failure Probabilities for 8 Sample Transients.

The failure probability of ASME code gave a more conservative result than that of RCC-MRx code for sample cases. For the verification and validation of PROFAS-RV, parametric studies were carried out. The failure probabilities for 8 sample transients were evaluated, and the effects of initial RT_{NDT}, Cu and Ni contents on the failure probabilities are also analyzed. SBLOCA transient gave higher probability of failure than MSLB transient as shown in Fig. 3. As the initial RT_{NDT} increase, failure probability increase linearly. The effect of initial RT_{NDT} on the probability is more significant for the lower fluence region. Failure probability increases with increasing the content of Cu and Ni. Increasing rates are almost the same for the all fluence ranges, and effects of Ni are lower than that of Cu for increasing failure probability.

3. Conclusions

In this study, a deterministic/probabilistic fracture mechanics analysis program for reactor pressure vessel, PROFAS-RV, is developed. This program can evaluate failure probability of RPV using recent radiation embrittlement model of 10CFR50.61a and stress intensity factor calculation method of RCC-MRx code as well as the required basic functions of PFM program. Moreover, parallel programming for multi-core processors with MPI is applied in the code for the improvement of calculation performance. The PROFAS-RV is being tested with other codes, and it is expected to revise and upgrade by reflecting the latest model and calculation method continuously. These efforts can minimize the uncertainty of the integrity evaluation for the reactor pressure vessel.

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