17th International Conference
ENGINEERING MECHANICS 2011
Svratka, Czech Republic, 9 – 12 May 2011

APPLICATION OF THE SIMULATION BASED RELIABILITY ANALYSIS ON THE ASSESSMENT OF THE CRITICAL THROUGH WALL CRACK STABILITY

L. Pečínka*, M. Švrček*

Abstract: *Specific feature of the nuclear power plants is in comparison with coal fired plants the break postulation of each high energy piping. Fluid system is considered as high-energy piping if the maximum operating temperature exceeds 100°C and the maximum operating pressure exceeds 2MPa. Based on the progress of the linear fracture mechanics US NRC approved deterministic „leak before break" methodology. If the defined requirements are met, the break postulation may be canceled. The first step is the assessment of the through wall critical length lcrit. Using the Simulation Based Reliability Analysis approach all uncertainties in the input data of lcrit are in the paper analyzed and the related probability of pipe failure is predicted.*

Keywords: ***Leak-before-break, probabilistic calculations, crack.***

1. Historical Background

Break postulation of the primary piping of PWR type reactors has been established in 1959 as the part of the US NPP Shipping port design. In 1975 US Nuclear Regulatory Commission (NRC) explained their position on the determination of break locations and dynamic effects associated with the postulated rupture of piping in the Standard Review Plan 3.6.2 (SRP 3.6.2). The basis for postulating pipe breaks inside containment were at that time expressed in the Regulatory Guide 1.46 while the rules for postulating pipe breaks outside containment were summarized in the SRP 3.6.2, part Mechanical Engineering Branch 3-1. This version of S.R.P. was updated in 1981 (US NRC, 1981). One of the major modifications was the extension of the MEB 3-1 from break locations outside containment to break location inside and outside containment.

In 1987 MEB 3-1 again went through some substantial changes. The US NRC recognized that the need for two intermediate breaks in a pipe line, that respects the imposed stress criteria, is no longer required. And in parallel with the changes in the ASME Code, they also updated the stress criterion in accordance with these changes (US NRC, 1987).

Based on the advanced fracture mechanics technology Westinghouse submitted in 1982 to the NRC staff topical reports "Mechanistic Fracture Evaluation of Reactor Coolant Pipe Containing a Postulated Circumferential Through Wall Crack" (WCAP 9558, Rev. 2) and "Tensile and Toughness Properties of Primary Piping Weld Metal for Use in Mechanistic Fracture Evaluation" (WCAP 9787). The NRC staff concluded that large margins against unstable crack extension exist postulated to have large flaws and subject to the safe shutdown earthquake (SSE) in combination with the loads associated with normal plant conditions. This approach has been called "leak-before-break" and US NRC issued in October 1986 the S.R.P. 3.6.3 "Leak-Before-Break Procedures" where explained their position to elimination of pipe ruptures and also elimination of pipe whipping dynamic effects (US NRC, 1986).

2. Deterministic LBB approach

The potential users of the LBB approach shall submit to NRC staff the following calculations

– length of the circumferential through wall crack with leak rate 38 l/min.,

* Ing. Ladislav Pečínka, CSc. and Ing. Miroslav Švrček: Nuclear Research Institute Rez, Husinec-Rez, čp. 130, 250 68 Rez, CZ, e-mails: pel@ujv.cz, smi@ujv.cz

- length of the critical through wall crack,
- to demonstrate that there is a margin of at lest 2 between the leakage size flaw and the critical size crack to account for the uncertainties inherent in the analyses and leak detection capability,
- determine margin in terms of applied loads by a crack stability analysis. Demonstrate that the unstable crack growth of leakage cracks will not occur. Or demonstrate that crack growth is stable and the final crack size is limited such that a double–ended pipe break will not occur.

3. Probabilistic LBB

Probabilistic LBB is essential to highlight effects of uncertainties around the deterministic criteria of LBB. All of them have a key request-good under standing of the different degradation mechanism. The level of integration in the decision process of probabilistic considerations on structural integrity of piping as passive component

- is different by country (from decision based on risk level in some countries to no consideration in few other countries),
- need a large investment from all partners (Utilities, Safety Authorities and Technical Support Organizations) to obtain conclusion acceptance,
- can be completed by "economic" considerations.

In NRI the probabilistic approach is based on the Simulation Base Reliability Analysis (SBRA) (Marek, 2003). The key elements are as follows

- the probability of pipe failure is calculated based on the theory of limit states,
- all random input quantities as loadings, mechanical and geometrical properties etc. are transformed on the output quantities which express effects of loadings and resistances,
- using Monte-Carlo simulation the empirical distribution of this output quantities is obtained,
- the reliability function of solved problem is developed and the region of interest is divided on the reliable and the failure parts,
- finally the probability of pipe break as a needed parameter of reliability is calculated.

All this calculations are based on the computer code Anthill (Guštar). In the next chapter the application on the critical circumferential through wall crack length l_{crit} is demonstrated.

4. Application of the SBRA methodology to the l_{crit} calculations

According (ČSKAE, 1991; Pečínka, 2010) the master equation for calculation of the critical through wall crack (TWC) takes the form

$$\frac{2\sigma_f}{\pi}\left(2\sin\beta - \sin\theta\right) + M\left(\sigma_{red}\right)_m = M\left[\left(\sigma_{red}\right)_m + \left(\sigma_{red}\right)_b + \left(\sigma_{red}\right)_c\right]Z \qquad (1)$$

where

θ half angle of the postulated TWC

$\left(\sigma_{red}\right)_m$ effective primary stress induced by internal pressure, sustained loads and safe shutdown earthquake (SSG)

M prescribed safety coefficient (Pečínka, 2010)

σ_f flow stress of the pipe material

$\beta = 0{,}5\left[\left(\pi - \theta\right) - \pi\left(\sigma_{red}\right)_m / \sigma_f\right]$

$\left(\sigma_{red}\right)_b$ effective bending stresses at normal operational mode

$(\sigma_{red})_c$ thermal expansion stresses at normal operational mode

Z Z factor according ASME Code Section XI

It is possible to use equation (1) for the definition of the reliability function RF, but more advantageous seems to apply modification according (ČSKAE, 1991) where is defined that the allowable values of $\theta = l_{crit} / 2R$ shall met the conditions (Pečínka, 2010).

$$S = \frac{2\sigma_f}{\pi}\left\{cos\ \frac{l_{crit}}{4R} \times cos\ \frac{\pi}{2}\frac{(\sigma_{red})_m}{\sigma_f} - sin\frac{l_{crit}}{4R}\ sin\ \frac{\pi}{2}\frac{(\sigma_{red})_m}{\sigma_f} - sin\frac{l_{crit}}{4R}\right\} > 0 \qquad (2)$$

or

$$S = \frac{2\sigma_f}{\pi}\ sin\left[-\pi\frac{(\sigma_{red})_m}{\sigma_f}\right] > 0 \qquad (3)$$

where R denote mean radius of the pipe.

For the application of the SBRA the reliability function shall met the condition $RF = S > 0$ and we shall search the cases at which $RF > 0$. As the independent coordinates will be chosen $l_{crit}/2\ R$ and $\pi\,(\sigma_{red})_m / 2\sigma_f$, and using computer code Anthill we will search regions where condition $RF > 0$ will be met together with related probability.

5. Numerical example

Numerical example will be demonstrated on the primary circuit of Armenia NPP primary circuit, see Fig. 1. The critical cross section is marked as O.

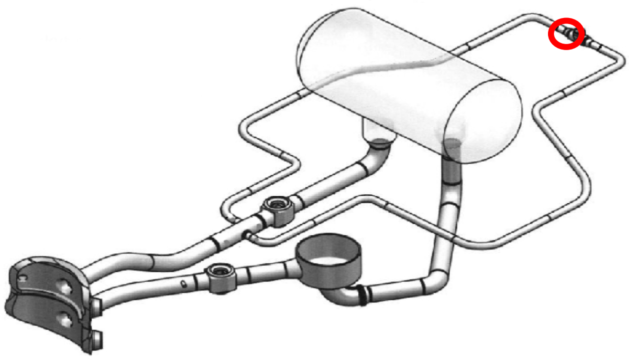

Fig. 1: Primary circuit of the Armenia NPP Metsamor.

Results of the deterministic calculations are as follows: $l_{leak} = 156.7$ mm, $l_{crit} = 450$ mm, $l_{crit}/l_{leak} = 2.9$, $M_{nom} = 3\ 037$ Nm, $F_{nom} = 433\ 130$ N, $M_{SSE} = 44\ 850$ Nm, $F_{SSE} = 10\ 084$ N. As the variable input quantities are chosen: diameter D and wall thickness t of the pipe, loadings (M_{nom}, F_{nom}, M_{SSE}, F_{SSE}) and material properties ($R_{p0.2}$, R_m and relater σ_f). Histograms are illustrated in the Figs. 2 - 4.

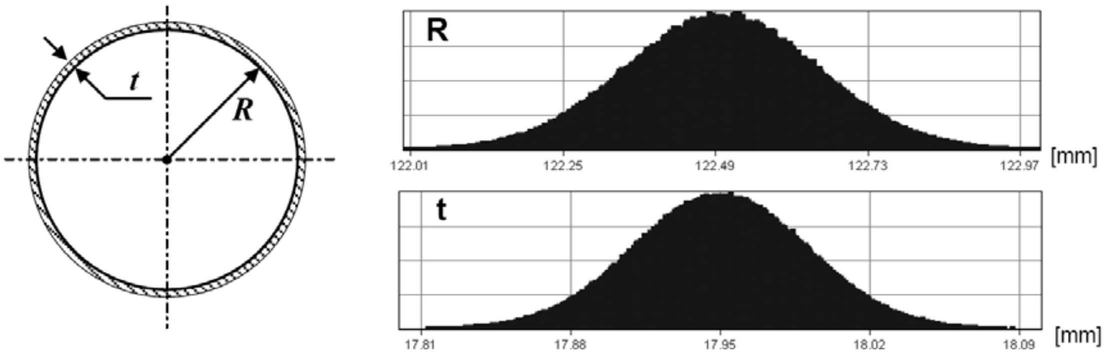

Fig. 2: Histograms of pipe parameters.

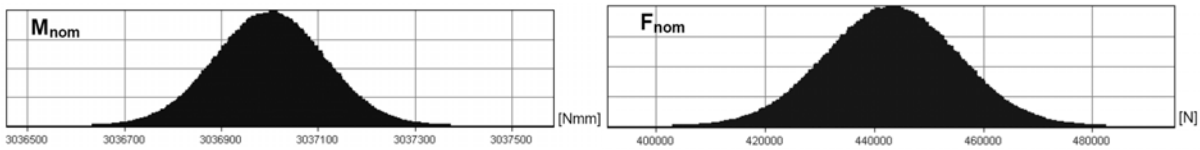

Fig. 3: Histograms of $_{nom}$ and F_{nom}.

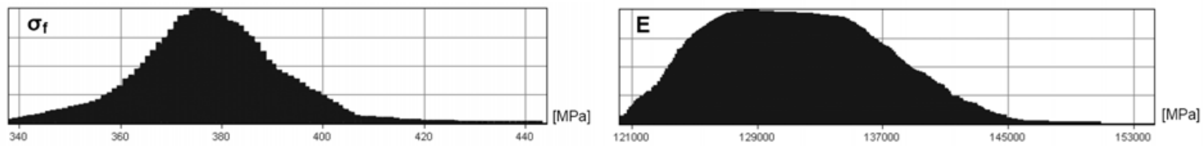

Fig. 4: Histograms of material parameters.

We will suppose in the next the random variability of the crack length l_{leak}. The normal distribution function and the variability ± 10% are supposed. The numerical calculations are performed for l_{leak} = (311 ± 10%, 370 ± 10%, 405 ± 10% and 415 ± 10%,)mm. Using Anthill computer code the result are illustrated in the form of pseudo-2D diagrams $l_{crit}/2R$ and $\pi\left(\sigma_{red}\right)_m/2\sigma_f$, see Fig. 5. Each point of the diagram represents one step of the simulation. Red color represents the region with most density of probability. Orange color represents those steps of simulation, where reliability function do not met the requirement $RF > 0$.

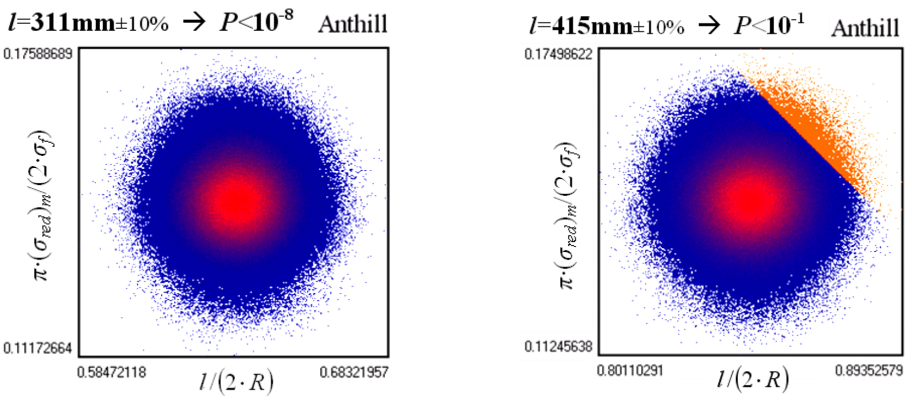

Fig. 5: 2D diagrams representing results of all simulation steps.

6. Conclusions

As mentioned in chapter 3 the probabilistic LBB is essential to highlight the effects of uncertainties around the deterministic criteria of LBB. The most important deterministic criterion takes the form $l_{crit}/l_{lead} \geq 2$. The probabilistic approach proved that the corresponding probability of pipe rupture is lesser than 10^{-8}. If the probability 10^{-7} would be accepted then the ratio l_{crit}/l_{lead} should be lesser than 2.

References

US NRC: Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, Chapter 3.6.2, NUREG 0800, 1981.

US NRC: Relaxation in Arbitrary Intermediate Pipe Rupture Requirements, Generic Letter 87-11, 1987.

US NRC: Leak-Before-Break, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, Chapter 3.6.3, NUREG 0800, 1986.

Marek, P. et al., (2003) Probabilistic Assessment of Structures Using Monte Carlo Simulation, TeReCo, 2nd Edition, Prague.

Guštar, M., Marek, P.: Windows help file of program Anthill™ 2.5.0.1 Professional.

ČSKAE: Požadavky pro sestavení a obsah bezpečnostních zpráv a jejich dodatků: Postup pro stanovení průkazu únik před roztržením, № 1, 1991.

Pečínka, L., Švrček, M. (2010) Application of the Simulation Based Reliability Assessment Method on the Assessment of the Critical Circumferential Through Wall Crack Length, Report NRI, № DITI 2300/21.