On the Failure Probability of Pipings

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ABSTRACT

Various methods to calculate failure probabilities of piping systems of NPP′s are discussed in view of their accuracy, efficiency and possibility of practical application. Ultimate load as well as fatigue failure modes - including corrosive effects - are considered in the analysis. The time variant reliability problem is solved by utilizing advanced simulation procedures.

INTRODUCTION

Piping systems are part of the most sensitive structural equipments of power plants. Therefore the analysis of these complex systems and the quantification of their fragility in terms of failure probabilities or reliability estimates are of paramount interest. This requires the combination of a number of methods of analysis. In a first step a structural model of the entire system has to be developed. This necessarily includes the modeling of the nonlinear soil structure interaction, especially with respect to the consideration of the earthquake loading case. The external loading events must be combined with the internal loading conditions, which may be due to normal operational and/or accidental loading conditions. Static loading, as well as in the case of cyclic loading the deterioration process of fatigue, may cause a crack growth of the inevitably occurring faults within the material or especially within the welds. The crack growth behavior can be treated by applying various methods. These methods, however may be limited by the respective characteristics of the structural or loading conditions.
To estimate the fragility of piping systems a number of approaches, based on fracture mechanical considerations have been developed. Of course, the estimates of the crack growth rates must take into account the statistical and stochastic properties of all important uncertainties that, for example may be due to installation or manufacturing processes. Uncertainties are inherent in the material properties, such as the yield strength, as well as in the initial state of the structure.

METHODS OF ANALYSIS

General

The great variety of effects influencing the fragility of piping systems as well as their structural complexity require an extensive analysis. The methods to be applied range from structural modeling - including soil structure interaction of the entire reactor building -, to load modeling, failure analysis - including deterioration processes, e.g. due to fatigue and/or corrosion -, reliability analysis, etc.

Structural Modeling

The piping systems of large power plants are complex systems with a large number of branches. For example the primary piping (PP) of a PWR is illustrated schematically in Fig.1. This system consists of four redundant loops.
The structural analysis of the system as illustrated in Fig.1, as well as for secondary systems, is most advantageously carried out by utilizing Finite Element procedures. The structure is mainly modeled applying beam elements, that allows to consider the internal pressure affecting the structural stiffness. The masses, e.g. of the steam generator (SG) or the main coolant pump (MCP), are generally discreticed by lumped masses, while their structural properties are reflected by weightless beam elements. The supports of the system are generally idealized by linear elastic springs.

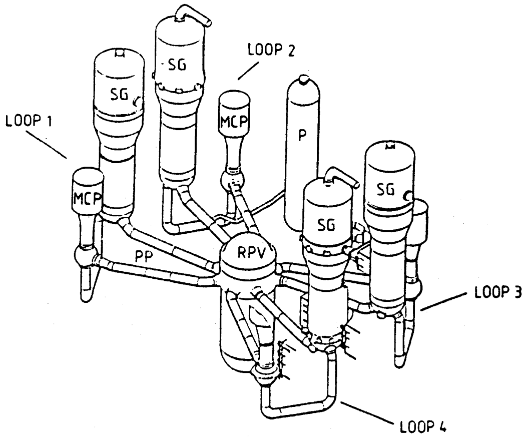

Fig. 1 Schematic sketch of the primary piping of the nuclear power plant BIBLIS B (FRGermany) (Deutsche Risikostudie, 1979)

Naturally a more sophisticated modeling of the structural behavior will be achieved by considering the nonlinear soil structure interaction of the entire building - including the containment structure (Schuëller et al, 1988). For the analysis of secondary systems their interaction with the primary systems has to be included.

Loading Conditions

During its design life the piping structure is expected to experience various internal and external loading conditions, a number of them associated with uncertainties in frequency of occurrence as well as magnitude. Internal loading conditions are due to normal operation (e.g. start up or load ramp cases, etc.) as well as accidental loading (such as shut down, scram, etc.). External loading conditions may be due to accidental aircraft impact, earthquake, etc.. All these loading conditions have to be combined. Due to the generally large number of possible load cases, the generation of a "most likely" load history (by simulation) is recommended.

Structural Analysis

Based on the respective structural models and the load analyses, the structural analysis - in the linear as well as nonlinear range - can be carried out by utilizing appropriate methods.

Reliability Analysis

Possible failure of the piping system under the loading conditions described above may be due either to brittle and/or ductile failure. The so called *Two*

Criteria approach allows to distinguish between these two failure mechanisms (see Fig.2).

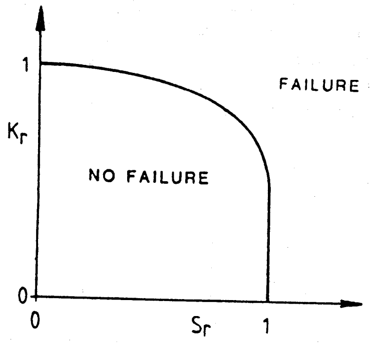

Fig. 2 Schematic sketch of the "Two Criteria Approach"

Brittle failure is defined by $K_I \geq K_{IC}$, i.e. the stress intensity factor exceeds a critical value, whereas ductile failure occurs if the stress $\sigma > \sigma_{fail}$, i.e. the stress exceeds a value, at which failure is assumed (e.g. yield stress, rupture stress, etc.). Note, that the mixed failure mode may also be treated by this approach. From Fig.2 it can be seen clearly that failure is expected to occur when the fracture checking point lies outside the so called safe, i.e. no failure region. Various suggestions may be found in the literature (see e.g. Schwalbe, 1980) to define this region. Most frequently the so called Burdekin/Stone relation (Burdekin and Stone, 1966) is utilized:

$$K_r = S_r \Big/ \sqrt{\frac{8}{\pi^2} \ln \sec \left(\frac{\pi}{2} S_r \right)} \quad , \tag{1}$$

where $K_r = K_I / K_{IC}$ and $S_r = \sigma / \sigma_{fail}$.
It is interesting to note that eq.(1) defines the *limit state function* as utilized for reliability analyses.
It is a well known fact, that most of the parameters involved in the analysis of structural systems - in the present case piping systems - show uncertainties of such a magnitude which must not be neglected anymore. A rational treatment of these uncertainties provide the possibility to *quantify* the safety, i.e. reliability of these systems. These uncertainties refer not only to loads, but also to material properties, the manufacturing process, etc.. The uncertainties may be modeled by random variables and processes, respectively. To determine the time invariant failure probability p_f of the structure - which is in fact the complement of the reliability r, i.e. $r=1-p_f$, the following multi-dimensional integral has to be solved (see e.g. Schuëller, 1987)

$$p_f = \int \cdots \int_{\underline{X} \in D_f} f\,(\underline{X}\,|\underline{X}_0)\; d\underline{X} \quad , \tag{2}$$

where $\underline{X}$ denotes the vector of the random variables. The integration must be performed over the failure domain D_f. In practical application a large number of variables are involved. Hence, the solution of the integral for higher dimensions is required. For this purpose a number of methods, such as approximate methods (of first and second order), as well as exact and accurate methods (e.g. adaptive integration, advanced simulation, etc.) are available. For a discussion of their accuracy and effiency it is refered to the pertinent literature (see e.g. Schuëller and Stix, 1987; Schuëller et al, 1989). In this context it is worth mentioning, that the appropriate software for most accurate and efficient procedures is already available (see e.g. Bourgund and Bucher, 1986; Bucher et al, 1989).

Deterioration Processes

In-service conditions of structural piping systems may cause their deterioration. Depending on the respective environmental conditions, this effect may be due to fatigue, corrosion, aging, etc.. Naturally, the deterioration effects reduces the lifetime of a system - in some cases considerably. In the following two types of deterioration effects are discussed, i.e. fatigue crack growth and corrosion.

Fatigue Crack Growth Behavior

Since all piping systems in nuclear power plants - primary as well as secondary piping systems - contain weldings, their fabrication procedures, i.e. quality, inspection, etc., are of great interest for reliability estimation, both for fatigue and ultimate load failure modes. It is a well known fact, that despite most stringent quality control, it is not possible to avoid faults (e.g. flaws, gas inclusions, etc.) in welds during the fabrication process. In fact, generally welding faults exceed respective faults in base metal both in size and frequency of occurrence. Hence, attention is generally focused on welding faults.

Under static as well as cyclic loading of respective stress amplitudes, crack growth has to be expected. A large number of models are available to describe and estimate the crack growth rate under cyclic loading (see e.g. Hoeppner and Krupp, 1974). For the linear range the most frequently applied models are due to the Paris-Erdogan as well as Forman. For the nonlinear range the Coffin-Manson relation is frequently utilized. Due to the uncertainties in the material properties, reflected by the respective random parameters in the crack growth relations, the crack growth rate is also a random quantity. Based on this, the crack growth equations, and hence the crack growth behavior, can be solved in various ways, i.e. by simulation and numerical integration (see e.g. Oswald and Schuëller, 1984) or by solving the diffusion equation (see e.g. Tsurui and Ishikawa, 1986).

Numerical integration must be performed for every combination of simulated values of the random variables within the reliability analysis, whereas the solution of the diffusion equation leads directly to a probability density distribution of the crack length after a specified number of load applications. For an overview of respective methods as utilized for the analysis of NPP-components it is referred e.g. to (Dolinski and Schuëller, 1985).

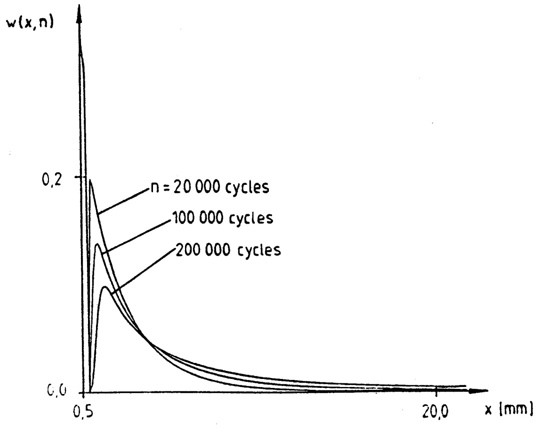

Fig. 3 Crack growth distribution (Tsurui et al, 1989)

As an example Fig.3 illustrates the crack growth distribution of a crack in a rectangular plate under cyclic loading described by a Rayleigh distributed stress amplitude after different numbers of load applications. The initial crack size is assumed to follow a shifted exponential distribution with a mean value of 2.5 mm and a standard deviation of 2.0 mm. The threshold value of crack growth is assumed to be 0.8 mm. The figure illustrates clearly the increasing probability of occurrence of larger cracks with an increasing number of load applications.

This method, however is restricted by a number of assumptions, that are necessary to derive a closed form solution of the Fokker-Planck equation, resulting from the diffusion equation (Tsurui and Ishikawa, 1986). The most restricting assumption refers to the loading process. Hence, this method can not be applied to all the loading conditions mentioned above. Nevertheless, the applicability of this method of solution is shown for the one dimensional crack growth in (Tsurui et al, 1989), and for the two dimensional crack growth model of semi-elliptical shape in (Nienstedt et al, 1988).

It is shown for example by (Schäfer et al, 1984), that the estimates of the failure probability within the design life of 40 years of a typical primary piping are 5.10-6. For this analysis the limit state function as defined by eq.(1) has been utilized. The results - which refer to the most critical (welded) cross section of the pipe - have been obtained by applying numerical integration to evaluate the crack growth behavior.

In another investigation the diffusion equation has been utilized to solve the two-dimensional crack growth behavior, which allows the identification of the sensitivities of pipes with respect to the leak before break (LBB) and break before leak (BBL) failure (see Fig.4). The results of the respective example show that the differences may be as large as four orders of magnitude.

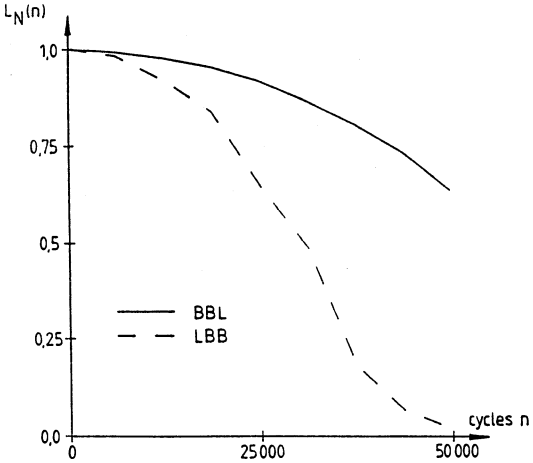

Fig. 4 Reliability estimates of a pipe (Nienstedt et al, 1988)

Corrosion

An additional deterioration process influencing the crack growth behavior may be due to corrosion. This process - due to cladding - can be neglected when considering primary piping systems, but it might be of interest for the secondary pipings. The effect of corrosion can be modeled utilizing a multiplicative factor within the crack growth laws. This corrosion factor, however is generally a function of the loading conditions, like the loading stress amplitude and the frequency (see e.g. (Schmelzer and Schmitt, 1981; Helms et al, 1985)). First estimates of the corrosive effects of structural steel in saline water environment show a significant decrease of the structural reliability due to corrosion (Nienstedt, 1989).

CONCLUSIONS

The methods as discussed here to analyse the fragility of piping systems are shown to be efficient tools to quantify the various influences affecting their structural reliability. These methods, besides their capability to estimate the structural failure probabilities of pipings, provide also the possibility to identify the most critical parameters influencing the failure rates of the system.

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