SOME ASPECTS OF THE INTERACTION BETWEEN SYSTEMS- AND STRUCTURAL RELIABILITY

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ABSTRACT

The purpose of this paper is to study the interaction between systems- and structural reliability analysis with reference to the design of structural components of LWR. Presently the evaluation of systems reliability is carried out apart from structural reliability analysis. Moreover, two basically different methodologies are used for analysis. While in systems analysis the simplified binary approach is still generally accepted, in structural reliability one has to resort to more sophisticated procedures to obtain realistic results. The interactive effect may be illustrated as follows: For example, the integrity of the primary circuit interacts with the integrity of the containment structure. This means that the probability of occurrence of the pipe rupture which may cause a LOCA and consequently leads to a build-up of temperature and pressure within the containment affects directly its structural reliability. The piping system, particularly the primary piping, in turn interacts with the protective system, which is part of the safety system. This piping structure is also subjected to various operational loading conditions. In a numerical example dealing with leakage probabilities of pipes it is shown how methods of structural reliability may be used to gain more insight in the estimation of failure rates of system components.

1. Introduction

Nuclear Reactors are considered to represent one of the most advanced, technological systems of our times. Their functioning is based on the interaction between electronic, mechanical and structural components. As society in general is very much concerned with the risk involved with these sophisticated technological systems, such as chemical plants, large airplanes and in particular with nuclear power plants one might think the method of determining their reliability takes into account the interactive effect between the different components. Surprisingly enough very little is found in the existing literature which approaches this problem in a systematic manner. Risk studies of nuclear power plants carried out so far - for example the "Rasmussen Report" [1] and the German Risk Study [2] - concentrate more on the systems reliability aspect, an expression which is used to denote the reliability analysis of the electronic and mechanical components. However the necessity to include the structural reliability aspect in the analysis receives increasing attention [3].

The purpose of this paper is first to point out some difference in approach of presently used methods of systems and structural reliability analysis respectively, and secondly to give some examples where the interactive effect between these two approaches is of particular importance. Finally to exemplify the arguments a numerical example with reference to the reliability of the hot leg of the main coolant pipe of a PWR is carried out.

2. Approaches to Systems- and Structural Reliability Analysis

2.1 General

There is a distinct difference in the approach of performing on one hand reliability analyses of electronic and mechanical systems and on the other hand the reliability analysis of structural components. In the first case the elements are assumed independent while in the second case they are assumed to interact mutually. The following the discussion on systems and structural reliability is confined to those aspects which are needed for the interaction problem. For a more general and thorough treatment of the subject it is referred to the pertinent literature [4, 5].

2.2 Systems Reliability

Generally, electronic and mechanical systems are modeled as networks which are analyzed by using the event tree and the fault tree methods respectively. The event tree method is utilized to analyze, i.e. predict a likely sequence of undesired events or operational states of the system, including all possible branches. The event tree analysis is based on the binary approach by which only conservative discrete states are considered. In other words, the states are labled with "non-failure" or "failure". For example a pump is considered to work either with 100 % capacity or none at all. The spectrum of the possible different states inbetween is neglected. It is quite obvious that a valve which due to some defect may open partially therefore allows only a fraction of the full flow capacity of a pipe to go through.

A typical event tree for three initiating events is shown in Fig. 1 (LOCA stands for the loss of coolant accident). The fault tree analysis is then used to analyze the sequence and associated occurrence probabilities of the undesired events at those locations, at which alternative possiblities of sequences do exist. Depending on the fulfilment or non-fulfilment of certain requirements of a unit under consideration, the initiating event has different consequences. With respect to the nomenclature of Fig. 1 the mean value of the frequency of each accident consequence within a certain time interval is denoted with p_{ij}. It can be obtained from the product of $H(E_i)$ and $W(A_{ij})$ where $H(E_i)$ is the mean value of the number of occurrences of the initiating event E_i per unit time and $W(A_{ij})$ the conditional probability for the consequences A_{ij}, given the occurrence of the initiating event E_i. If $S(A_{ij})$ is defined as the magnitude of the corresponding damage consequence, p_{ij} might also be interpreted as the mean value of the number of the occurrence of accident consequences $S(A_{ij})$ per unit time. Let e be the input event, a the output event and w the conditional probability in such a way that

$$e \begin{cases} a_1 \ \ldots\ldots \ \text{yes (available)} \\ \\ a_2 \ \ldots\ldots \ \text{no (not available)} \end{cases}$$

then the following relations hold

$$w(a_1) = w(e) \cdot w(\text{yes})$$
$$w(a_2) = w(e) \cdot w(\text{no})$$
$$w(\text{yes}) + w(\text{no}) = 1$$

If these relations are, for example, applied to the large LOCA - which is defined as the occurrence of a rupture area of the main coolant pipe $> 1000\ \text{cm}^2$ - the results as shown in Fig. 2 are obtained. For these calculations the probability of the initiating event of 10^{-4}/year was taken from ref. [1]. At this point it should be stated that the accident consequences, i.e. mean failure rates are determined or estimated in the statistical sense from observed (empirical) data. The operation of plants are observed for many years from which (hourly) mean failure rates are calculated [6]. One of the major drawbacks is the fact that in view of scarce data these rates are estimated from samples drawn from various populations. A method of improvement of the failure analysis is suggested in [7].

Systems reliability in connection with thermodynamic analysis produces predictions of frequencies of occurrence and associated intensity distributions of resulting loads for the structural components, such as pressure vessel, containment, etc..

2.3 Structural Reliability

It has been indicated before, that the binary approach of discrete states does not resemble physical reality of structural components. In this case the elements posess probabilistically dependent and continuous states. Depending on the problem the determination of the reliability of structural components may be carried out at various levels of sophistication [8]. In structural reliability loads (i.e. demands) as well as structural resistances (i.e. capacities) are considered to be random variables. The probability of failure of a structural component is obtained by the well known convolution integral between the distribution and density functions of these variables. Great emphasis is put on the choice of appropriate probability distributions which should be based on a combination of physical and statistical reasoning. To determine the total structural failure various failure modes, i.e. yield, fracture, buckling, etc., have to be analyzed. Realistic structural reliability analysis of multimember systems consisting of ductile materials must be based on methods which are bounded by the chain and the parallel model respectively. The inclusion of the time dependency can be achieved by applying the theory of stochastic processes.

3. Interaction between Systems and Structural Reliability

In the previous section it was pointed out, that advanced systems analyses are capable of predicting occurrence probabilities of failure events along with its intensity distributions. This information may then be used as input for the performance of structural reliability analysis. In the following, two examples are stated where the interacting effect between system and structure becomes particularly obvious.

First it is referred to the interaction between the Protective Systems (PS) and the pressure vessel (PV) [9]. The purpose of the PS is to protect the plant from unacceptable loading conditions and to limit the environment and the plant itself to those limits which are outlined in the specifications. It should be stated, that the PS is part of the Safety System. Based on measurements of different parameters such as temperature, pressure, neutron flux etc. it decides if safety features, such as the Scram System, the Emergency Core Cooling Systems, the Emergency Feedwater Systems, the Emergency Power System and the Containment System, are to be initiated. In this way the PS indirectly interacts with the integrity of the PV. For example the Emergency Core Cooling System is designed to cool the core when normal cooling is insufficient i.e. to avoid an increase of thermal stresses and pressure loading to unacceptable high magnitudes which means to reduce the failure probability.

The second example refers to the interaction of the primary system and part of the secondary system with the containment. In section 1 it has been mentioned that under certain conditions pipe rupture in the primary system can lead to a LOCA by which the containment may receive significant loading from internal pressure and temperature build up. This example has been well documented in [10, 11] and will therefore not persued here any further.

In summary, systems reliability should provide the estimates of probabilities for the malfunctioning of the PS or the primary system and the associated hardware. These malfunctions produce transients or LOCA. Utilization of thermohydraulic analysis converts these transients into temperature gradients and pressures. Taking into account all uncertainties in the performance of the hardware and the physical model, this information is the transformed in load probability distributions by means of a stress analysis. The analysis of the material properties yields the probability distribution of the structural resistance. For the choice of the appropriate types of probability distributions to model loads as well as for the resistance and the determination of its parameters - and thus the failure probability - the following points must be considered:

- the physical properties of the component (size, thickness, method of manufacture, etc.)
- the description of the transient (temperature versus time, pressure versus time etc.)
- division of the component into parts with respect to loading, manufacturing, defects, inspection
- failure mode
- failure criteria
- governing parameters for the particular failure criteria

4. Numerical Example

In the previous sections it has been pointed out that under the condition of failure, systems, such as the primary system for example may lead to serious increase in structural loading and therefore endanger its integrity. It has also been shown, that the parameters used in systems analysis, such as the mean failure rate, are statistically estimated from (empirical) observations. This numerical example is meant to point out, that presently used procedures of structural reliability may be used to predict these estimates of failure rates by analytical means and therefore is capable to provide additional, extremely valuable information with respect to the production process, inspection procedures, quality control, etc.. The example deals with the important problem of the prediction of the leakage probability of circumferential defects in a shop weld of the hot leg of the main coolant pipe. It is obvious that the fracture failure mode governs the problem.

With respect to the determination of the distribution of defects in the following analysis only semi-elliptical circumferential surface flaws at the inside of the pipe are considered. The corresponding initial crack distribution is modelled by assuming that the welder (or welding machine) will make between 1 and 10 faults of length 2c = 24 mm during each weldbead. Another assumption has to be made concerning the shape of the resulting cracks: either the depth/length ratio of the crack (a/2c) is constant for all cracks or it is increasing with the depth of the crack, this means that the length of all cracks (2c) is constant. The constant depth/length ratio for all cracks will lead to a very conservative crack distribution, while the constant length for all cracks will only yield a lower bound for the expected crack distribution. Another conservatism of the crack distribution function is that the cladding of main coolant pipe is not considered. The following shape of the frequency distribution of the flaws was assumed:

$$\tilde{f}(x) = a.e^{-b.x}$$

$$0 \leq x \leq \text{Wallthickness of the pipe}$$

with x crack-depth [mm]

$\tilde{f}(x)$ absolute number of cracks with the depth x

a,b constants depending on the quoted assumptions

The loads (changes in pressure and temperature, vibrations) for the considered weld are listed in Table 1. They were taken from recordings and specifications. At first it is shown that the changes in pressure and temperature as listed in the specifications i.e. loadings due to operational conditions have almost no influence on the leakage probability of the pipe:
For instance, the pressure transients for ten years of operation increase the leakage probability only by a factor of two.
Therefore only the vibrations experienced during normal operation are considered in the following calculations. In this context the term "load" is defined as follows:

$$\text{load} = N \cdot (\Delta\sigma)^n \qquad (1)$$

with N number of the vibrations

$\Delta\sigma$ change in stress during one vibration [N/mm²]

n exponent in the Paris-law (equ. (2))

Starting with the initial crack distribution the crack growth is calculated using the wellknown Paris-law:

$$\frac{da}{dN} = C \cdot (\Delta K)^n \qquad (2)$$

with $\Delta K = \frac{M_m}{\sqrt{Q}} \sqrt{\pi a}\ \Delta\sigma$ in direction of depth

and $\Delta K = \frac{M_m}{\sqrt{Q}} \sqrt{\pi a}\ \sqrt{\frac{a}{c}}\Delta\sigma$ in direction of length

where $\frac{da}{dN}$ crack growth rate [mm/cycle]

a crack depth [mm]

c crack length [mm]

N frequency of load cycle

$\Delta\sigma$ change in stress of load cycle [N/mm²]

M_m,Q factors corresponding to the crack geometry

C,n material-constants

The constants M_m, Q, C, n were chosen according to ASME XI, Appendix A. In particular

$$C = 1{,}75 \cdot 10^{-14} \quad \text{for wet conditions}$$

$$n = 3{,}726$$

Direct integration of the Paris-law yields to the crack growth in the direction of the depth. The following expressions are obtained

$$a = \left[\frac{2-n}{a_o{}^2} + \frac{2-n}{2} \, C \cdot N \cdot \left(\frac{M_m}{\sqrt{Q}} \sqrt{\pi} \; \Delta\sigma \right)^n \right]^{\frac{2}{2-n}} \qquad (3)$$

On the other hand the crack growth in the direction of the length is calculated according to:

$$c = \left[c_o^{\frac{2+n}{2}} + \frac{2+n}{2} \, C \cdot N \cdot \left(\frac{M_m}{\sqrt{Q}} \sqrt{\pi} \; \Delta\sigma \cdot a_o \right)^n \right]^{\frac{2}{2+n}} \qquad (4)$$

a_o marks the initial crack depth and c_o the initial crack length.
Because of the fact that the constant C of the Paris-law is taken as an upper bound it is assumed as a distributed value. The distribution is taken between the following limits of C/10 and C preferring the higher values. The complete analysis is performed using Monte-Carlo-techniques in which the crack depth a and the material constant C are assumed random variables.

All other variables are considered constant. Keeping in mind all the assumptions made, the most important result of this study was that the vibrations experienced during normal operation are the most sensitive parameter for the leakage probability of the main coolant pipe. The results in detail are given in Fig. 3. Furthermore, it has been found that additional vibrations may be added to the operational vibrations in terms of "loads" as defined by equ.(1) for any given period of life. The terms realistic ans pessimistic used in Fig. 3 refer to the loading conditions as shown in Table 2. The results shown in Fig. 3 represent all possible operational situations which the pipe experiences. In this context it should be mentioned that the leakage probability of Fig. 3 were calculated without regard to ultra-sonic testing. The influence of the variation of the stress ratio and ultra-sonic testing at the leakage probability has been carried out in ref [12].

5. Concluding Remarks

The analysis carried out in this paper shows, that methods used in structural reliability may be successfully applied to problems of systems reliability. This analytical approach of determining the failure probability of systems components provides additional insight with respect to the importance of crack length, crack depth, type of crack distribution etc.. In other words, in addition to the absolute failure estimates, the analysis recognizes also the weak points, which are important to know for future production process, quality control and inspection procedures. In the future more emphasis should be put on this aspect rather in the estimation of absolute failure values from insufficient sample statistics.

Finally it is concluded that in the future the treatment of the problem of interaction between electronic, mechanical and structural reliability analysis requires also a great deal more interaction between the experts in these fields. An attempt in this direction is made in ref.[13].

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Table I: Load cycles for primary piping at several plant conditions

plant condition	load cycles per plant condition				frequency of the plant condition within 40 years life time
	p[bar]	t[°C]	rate of change [°C/h]	s mm	
start up/ shut down	1 time 30; 1 time 155	1 time 260	50		240
normal operation (75% life time)	0,5 at 10 Hz			0,12 mm at 8/25 Hz	
load ramp ± 15%/min	1 time 2	-			$3 \cdot 10^4$
load step ± 10%	2 time 4	2 time 4	850		10^5
scram	1 time 6	1 time 19	450		400
turbine trip, load rejection	1 time 10; 1 time 9	1 time 7, 1 time 3	1000		400
turbine trip without steam by-pass (30 min till shut down)	180 time 2	180 time 1,5	1100		80
	1 time 13		940		
	1 time 10	1 time 7	1100		
failure of one reactor coolant pump	1 time 13, 2 time 5	1 time 10 1 time 9	1400 290		80
loss of off-site power	1 time 4, 1 time 12, 4 time 3	1 time 11 1 time 16	2600 600		80
periodic pressure test	1 time 228		NDTTmax $+33^{\circ}$ $+\Delta$NDTT		20

Table II: Pessimistic and realistic loading conditions

vibrations	"load"	
	pessimistic	realistic
<u>normal operation:</u>	($\Delta\sigma = 4,3$ N/mm^2)	($\Delta\sigma = 1$ N/mm^2)
4 years/8 Hz	$1,7 \cdot 10^{11}$	$7,4 \cdot 10^{8}$
4 years/25 Hz	$5,4 \cdot 10^{11}$	$2,4 \cdot 10^{9}$
<u>start-up:</u>	($\Delta\sigma = 21,5$ N/mm^2)	($\Delta\sigma = 5$ N/mm^2)
4 years/ 8 Hz/15 min	$1,6 \cdot 10^{10}$	$7,0 \cdot 10^{7}$
4 years/ 8 Hz/30 min	$3,2 \cdot 10^{10}$	$1,4 \cdot 10^{8}$
4 years/25 Hz/30 min	$1,0 \cdot 10^{11}$	$4,4 \cdot 10^{8}$
4 years/25 Hz/60 min	$2,0 \cdot 10^{11}$	$8,8 \cdot 10^{8}$

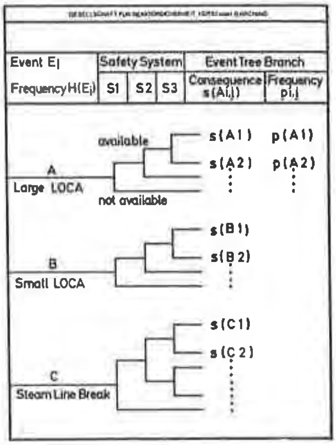

Fig. 1: Sample of event tree for three initiating events

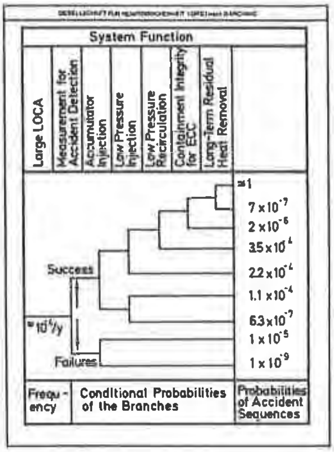

Fig. 2: Event tree for large LOCA

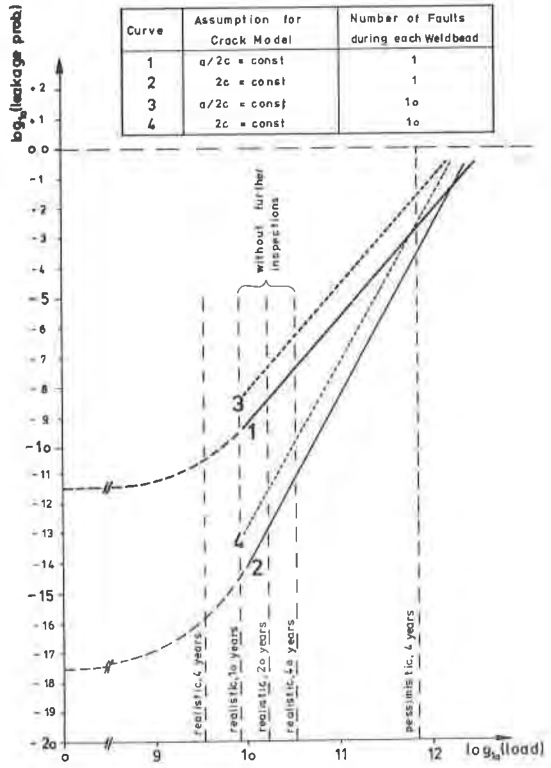

Fig. 3: Dependence between leakage probability and load