Seismic Failure Probabilities of PWR-Components

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Abstract

A simplified reliability analysis of PWR-components under seismic loads is presented. The analytical model includes the vibration analysis of the components and the investigation of their failure. The exceedance probabilities for significant limit states are calculated by use of the first-order second-moment reliability method.

The paper concentrates on the development of simple but nevertheless realistic failure criterions for the three categories: loss of stability, integrity and operability. Limit states are developped for the integrity of vessel shells and piping systems, the stability of supporting structures and the operability of mechanical components. The method is applied to the estimation of failure probabilities of some characteristic components in PWR-plants.

1. Introduction

As part of risk-studies of nuclear power plants, the failure probability (that is the release frequency of radioactive material) of the power plant, caused by an internal or external event, is calculated. One of the bases for the calculation of the failure probability of the plant is the knowledge of the failure probability of its components. In the presented paper a simplified analytical model is described for the evaluation of the failure probabilities of components in a PWR-plant under earthquake loads as initiating event. The model was developped appropriate to the German Risk Study of Nuclear Power Plants, Phase B [1].

From the total seismic calculation path (seismic hazard analysis; soil-structure-interaction; structure response; structure-component-interaction; component or subsystem response) only the last step, that is the vibration analysis of the components and the investigation of their failure, is discussed in this paper. The report concentrates on the development of simple but largely realistic failure criterions. The analytical model and limit states are based on commonly used calculation methods and code requirements, which are accessible by any practising engineer. After a general description of the analytical model used, some utilizable failure criterions are introduced for the most common components in a PWR, that are vessels, pipes and mechanical components like motors or pumps. Finally some numerical results are presented.

2. Analytical Method

2.1 General Procedure

Five steps are necessary to evaluate the seismic failure probability of PWR-components.

(1) vibration analysis of the component
(2) definition of limit states (mechanical model)
(3) derivation of statistical parameters (probabilistic model)
(4) calculation of exceedance probabilities for significant limit states
(5) calculation of the conditional failure probability of the component

The seismic load is taken as the only time dependent random variable which allows the use of common deterministic methods for the vibration analysis, step 1. The results of the vibration analysis are forces, stresses, deformations, strains etc., which are compared with the proper resistance capacity of the component. The different possible limit states are defined in the mechanical model, step 2, as failure criterions. Each failure criterion describes the relation of the random variables with any linear or nonlinear function. In the probabilistic model, step 3, the statistical parameters of the random variables (mean value, standard deviation, distribution function) are summarized, which afterwards are used in step 4 to calculate the exceedance probability for each of the limit states. In a final step, the combination of the different limit states by a system analysis must be observed. This analysis can generally be simplified by an idealization of the component as series system, parallel system, or a combination of both.

2.2 Mechanical Model

The failure of a component is classified into three main categories: loss of stability, integrity and operability. Loss of stability is caused by failure of supporting structures or anchors, loss of integrity (for pressure retaining components) by leakage or rupture, and loss of operability (of mechanical components like pumps, motors and valves) is defined by the violation of specified deformation or acceleration limits.

For stability and integrity a three-levelled failure criterion is used:

(1) first crossing of a stress or strain limit (elastic or brittle limit)
(2) local plastification with assumption of global elastic behaviour (plastic limit)
(3) ideal load bearing capacity after redistribution of loads (ultimate load limit)

Level 1 is appropriate for brittle material or if serviceability does not allow permanent deformations after an earthquake. For metallic material with sufficient plastic deformation capability, as it is generally used for nuclear reactor components, criterions on level 2 are used. On this level fictitious stress limits are introduced which allow comparison of elastically calculated stresses with a limit stress that accounts for plastic load bearing reserves. On level 3, the realistic nonlinear behaviour of the structure by time dependent cyclic load histories must be investigated. The limit state is defined by ultimate plastic strains or deformations. Failure criterions on this level demand a comprehensive amount of computational efforts.

The presented investigations are limited to failure criterions on level 1 and 2 for a preliminary, conservative estimation of the conditional failure probabilities.

2.3 Probabilistic Model

The controlling random load variable is the seismic excitation of the component. Because this variable is the only time dependent random variable it is unnecessary to describe its characteristics as a stochastic process. It is sufficient to model the probabilistic characteristics of the maximum of the base acceleration of a component as well as its response like inertia forces, stresses, and deformations. All other load variables, namely selfweight, internal pressure, and temperature, can be taken in general as deterministic values compared to the large variation of the earthquake loads.

The controlling random resistance variable is the strength of the material. The significant limit parameter may be the yield stress, the ultimate tensile stress or any fictitious stress limit, depending on the kind of failure and the environmental conditions like temperature. Other random resistance variables are stress indices, forces in prestressed bolts, friction between adjacent structural members, and geometrical dimensions of significant randomness like welded seams.

2.4 Solution Algorithm

The analytical problem that must be solved is the calculation of the probability that the load parameter S will exceed the resistance parameter R

$$p_f = P\ (S \geqq R) \tag{1}$$

S and R are random variables which may be any functions of one or more other random variables with arbitrary distribution functions and correlation between particular variables.

A level 2 method is used to solve this problem, best known as "first-order second-moment reliability analysis" (Shinozuka [2]). In this method the failure surface is approximated by a tangential hyperplane at the design point, that is the point on the failure surface closest to the origin after transformation into standard normal coordinates. The distance of the design point to the origin is called realiability index and serves as measure for the failure probability. The numerical calculations are done by the program system FORM (Fießler/Hawranek/Rackwitz [3]).

3. Failure Criterions for PWR-Components

3.1 Integrity of Vessel Shells

The failure criterion for the integrity of vessel shells is defined as plastic limit criterion (level 2) with reference to the ASME-code [4]. The primary membrane, bending, and shear stresses are calculated with the assumption of a linear elastic behaviour. After superposition of the stress components, the stress intensity S_v as load parameter is computed according to the shearing-stress hypothesis and is compared with a fictitious stress-limit as resistance parameter, which is 1.5 times as large as the limit stress R. The factor 1.5 is the plasticity stress-concentration factor. The limit state as it is used in eq. (1) then writes

$$S_v \geqq 1.5\ R \tag{2}$$

3.2 Integrity of Piping Systems

The integrity of pipes is guaranteed by application of the level D service limit of the ASME-code [4] for class 1 components

$$B_1 \cdot \frac{p \cdot d_a}{2 \cdot t} + B_2 \cdot \frac{d_a \cdot M}{2 \cdot I} \geqq 3 \cdot S_m \tag{3}$$

(d_a = outside diameter; t = wall thickness; I = moment of inertia; p = internal pressure; M = resultant moment of mechanical loads, namely self weight and earthquake; B_1, B_2 = primary stress indices; S_m = allowable design stress intensity)

Eq. (3) defines a failure criterion on level 2. This criterion is a good approximation for the real failure state of pipes with significant internal pressure, because the redistribution of loads after plastification of parts of the cross section is limited in these cases. A failure criterion on level 1 is necessary for bolted flanges if the integrity of the flange demands tightness after the end of an earthquake. Tightness of the flange is guaranteed, if the sealing remains in place and if no plastic deformations of the flange or bolts occur.

3.3 Stability of Supporting Structures

It is not possible to state general rules for the derivation of failure criteria for supporting structures because the variety of their type and design. Hints for the proper failure criterion may be taken from the appropriate codes for steel or reinforced concrete structures. Some limit conditions for often used types of supports are listed below.

The anchorage of the supports in the reinforced concrete building by embedded anchors or later set dowels needs particular attention. Above all, later set dowels are often the weakest link in the chain of supporting structures because the large scatter of its load bearing capacity. The limited plastic deformation capacity of concrete demands a brittle failure criterion on level 1. The anchorage fails, if the ultimate load capacity P_{ult} is exceeded by the existing load P in the mostly stressed dowel

$$\max P \geqq P_{ult} \tag{4}$$

A plastic limit state on level 2 is a useful, although conservative, estimation for the failure probability of welded or bolted steel frame systems as supporting structures. A simplified limit state as proposed in [5] is used for H-beams under uniaxial bending M_x around the main axis (x-axis) with normal force N and shear force V_y lateral to the x-axis

$$\frac{M_x}{M_{pl}} + 1.1 \frac{N}{N_{pl}} + 0.3 \frac{V_y}{V_{pl}} \geqq 1.1 \tag{5}$$

(M_{pl}, N_{pl}, V_{pl} = fully plastic limit forces of the cross-section)
A good approach for the general case of biaxial bending is the assumption that N and V_y are carried by the web of the H-beam while both bending moments as well as the shear force V_x are carried by the flanges. The limit state for one flange of rectangular cross-section is:

$$\frac{M_y}{2 \cdot M'_{pl}} + \left(\frac{M_x}{h \cdot N'_{pl}}\right)^2 + \frac{3}{4}\left(\frac{V_x}{2 \cdot V'_{pl}}\right)^2 \geqq 1 \tag{6}$$

(M'_{pl}, N'_{pl}, Q'_{pl} = fully plastic limit forces of one flange; h = distance of the flanges)

3.4 Operability of Mechanical Components

The use of analytical tools for the estimation of the loss of operability of mechanical components during operation is rather limited. Resistance parameters for the loss of operability in its strict meaning, that is the failure of shaft bearings, deadlock of motor shafts, leakage of gaskets etc., are obtained with more advantage by dynamic tests. In some cases, analytical statements on ultimate deformations are possible.

Limit states on level 1 are necessary, if the active serviceability of the component does not allow permanent deformations after an earthquake. If only global, permanent deformations affect the active serviceability, but local plastifications are allowed, limit states on level 2 are appropriate. If only passive serviceability (safe enclosure) must be guaranteed, the proof of integrity is authoritative. The proper failure criterions depend on the type of the component and are comparable to the criterions as derived in section 3.1 and 3.2.

4. Numerical Examples and Discussion of Results

The presented analytical model is applied to the estimation of the failure probabilities of some characteristic components in PWR-plants under an earthquake load comparable to a safe shutdown earthquake. The selected components are a cylindrical flat bottom tank, a branched piping system with elastic supports and snubbers, the supporting structure of vessels and a power unit. Some characteristic failure probabilities are displayed in table I. The types of failure were choosen in such a way to demonstrate the most characteristic peculiarities of the method without an exhaustive investigation of the final failure probabilities.

The flat bottom tank is fixed on the floor by bolts and has an additional upper horizontal support. This upper support is exclusively designed to withstand an earthquake and therefore fails with rather high probability. Failure of the upper support, however, does not mean failure of the tank itself because its anchorage at the bottom. To give an idea of the possible load bearing capacity, the probability of the loss of integrity of the vessel wall at the bottom edge for the supposition that the upper support does not fail is additionally noted in table I.

The investigated piping system is composed of several branches, separated by valves, with DN 100 to 300 mm. The pipes are partly under pressure, up to 16 N/mm^2, and partly without internal pressure. The probabilities of the loss of integrity for a branch of the pipe under pressure and for a branch without pressure are compared in table I. It is evident that the failure probability for the pressure pipe is less than for the depressured pipe because the relatively low influence of the earthquake on the total stresses in the wall of the pressure pipe.

The next component mentioned in table I is a couple of vessels supported by a girder grillage. The calculated failure probability is the exceedance probability of the plastic limit load in the maximum stressed cross-section of the girder grillage.

The power unit under investigation consists of a Diesel motor and power generator which are fixed on a joint steel frame. The steel frame is supported by several spring elements which are anchored in the reinforced concrete floor. Table I gives the failure probability of the anchorage of the maximum loaded spring element. It is assumed that the failure of the anchorage of one element causes a permanent warping of the steel frame that deteriorates the continuous operation of the unit.

The presented examples are only a very particular selection of PWR-components. Furthermore the used failure criterions are partly rather conservative. Nevertheless it is possible to gain some general statements about the seismic failure probabilities by comparison of the different components. It is obvious, for example, that the weakest links in the chain of possible failures are mostly the supports of components, prior to the loss of integrity or operability. Loss of integrity or operability is generally caused as secondary effect after the failure of the supporting structure. The main points of interest should be laid to supports which were especially designed to withstand earthquake loads, because these supports are normally designed with a low safety-factor. For components or parts of components, which were primarily designed for operational loads with earthquakes as additional loads, the conditional seismic failure probability, conditioned by the occurence of the earthquake will remain in the range of 10^{-2} to 10^{-4}.

References

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Table I: Conditional Seismic Failure Probabilities of Some Characteristic PWR-Components

Component	Type of failure	failure prob.
cylindrical	upper support	0.16
flat bottom tank	integrity of wall at bottom-edge	$5 \cdot 10^{-4}$
piping system	integrity of pressured pipe	$4 \cdot 10^{-4}$
	integrity of pressure-less pipe	$4 \cdot 10^{-3}$
vessel on beam grillage	plastic limit of main supporting beam	$3 \cdot 10^{-2}$
power unit	anchorage in reinforced concrete floor	$8 \cdot 10^{-3}$