Failure Probability of The HDR - Containment Under Shaker Loading

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ABSTRACT

A method to calculate failure probabilities of critical cross sections of containment structures is developed. Uncertainties of structural as well as of material parameters are taken into account. The HDR-containment under shaker loading conditions is utilized as sample structure. This provided the possibility to verify the mechanical i.e. structural model. The failure probabilities are calculated by utilizing the response surface method along with advanced simulation procedures.

INTRODUCTION

Since containments of NPP's - in case of an accident - represent the last barrier to prevent fission products to be released in the atmosphere, their reliability is of paramount interest within a risk evaluation of such plants. Since full scale model tests in large number are beyond feasibility, theoretical modeling is required to compute the estimates of failure rates under the various loading conditions expected to occur during the design life of such structures. For this purpose realistic, stochastic loading and - equally important - structural and materials models have to be developed. If collapse failure conditions are the focus of interest, the nonlinear range of the structural response - leading to failure - is to be investigated. For this stage of the analysis, full scale tests of the HDR-plant (Flade et al) under shaker loading can be utilized to verify the physical, i.e. mechanical modeling. Practical applications such as this generally require the analysis of nonlinear MDOF-Systems under stochastic loading. Moreover, the randomness of the structural properties also has to be taken into account. The calculation of the structural response, and consequently the reliability require the development of computational procedures. In this paper the goodness of the mechanical modeling of a containment structure is verified by utilizing full scale shaker tests. The model is then used for computing the failure probabilities of critical sections under various shaker loading conditions.
In general, stochastic mechanics is considered to be a tool for information processing. Not only representative (maximum and/or minimum) values but the entire spectrum of loads and material properties, i. e. their distribution are considered. This increased effort provides the possibility of quantifying reliability estimates.

STRUCTURAL MODEL

Shell type containment structures (Fig. 1) may be represented sufficiently well by beam models (Fig. 2a) where the flow of forces between internal and external structural parts (Fig. 2b) and the soil require particular attention. These

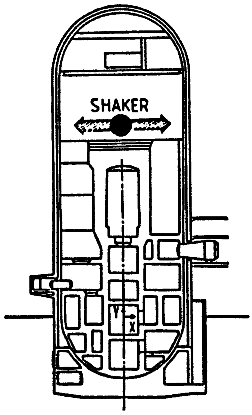

Fig. 1: Containment Structure
and Shaker

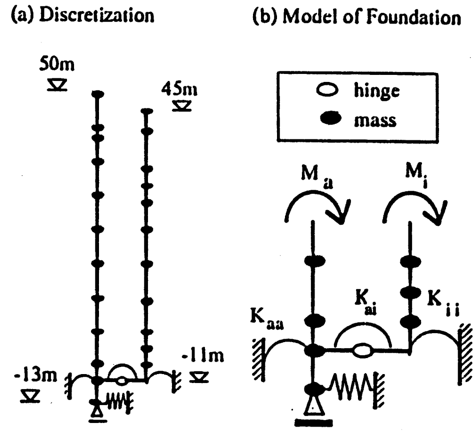

Fig. 2: Structural Beam Model
(Schuëller, Pradlwarter, 1987)

simplified models have to be considered as a compromise beetween accuracy and computational effort. The shaker-tests as described below confirm the adequacy of this type of modeling.

PROBABILISTIC MODELS OF INPUT PARAMETERS

Critical locations, where the failure probabilities are of primary interest are generally those under reinforced sections, where the failure condition is governed by the exceedence of the concrete tensile strenght. Hence the following parameters, i.e. their statistical properties deserve considerable attention, i.e. (1) The total stiffness of the soil ($K\phi_B$), (2) the damping (c), (3) a measure (F) of the total stiffness of the concrete and (4) the ultimate concrete tensile stress β_Z. Their probabilistic models and respective parameters (mean, variance, etc.) are based on statistical evidence and physical reasoning.

SOLUTION OF NONLINEAR EQUATION OF MOTION

The mass and inertia forces respectively of the horizontally rotating shaker are shown schematically in Fig.3

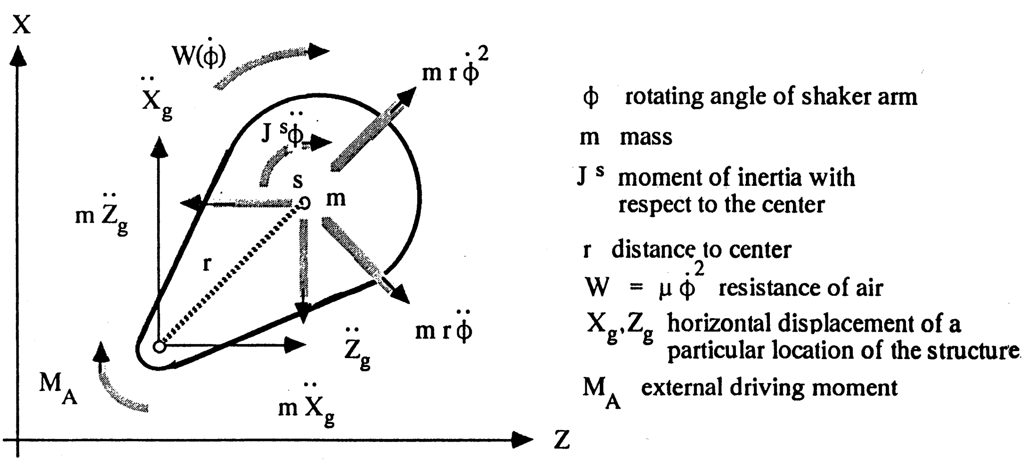

Fig. 3: Schematic Sketch of Shaker

Utilizing D'Alambert's notation, the equilibrium conditions with respect to the axis of rotation (Y) are:

$$(mr^2 + J^s)\ \ddot{\phi} = M_A - m\ddot{X}_g r\cos\phi + m\ddot{Z}_g r\sin\phi - W(\phi) \tag{1}$$

and in the X and Z directions respectively

$$F_x = -m\ddot{X}_g - mr\ddot{\phi}\cos\phi + mr\dot{\phi}^2\sin\phi \tag{2}$$

$$F_x = -m\ddot{Z}_g + mr\ddot{\phi}\sin\phi + mr\dot{\phi}^2\cos\phi \tag{3}$$

Eq. (1) governs the rotational velocity of the shaker while eq. (2) and (3) determine the shaker forces. From eq. (1) it is clear that the time history of the angular velocity depends on the structural response $\ddot{x}_g$ and $\ddot{z}_g$. Consequently it has to be integrated simultneously with the equations of motion of the structure. The equation of motion of the nonlinear structure reads:

$$M\ddot{X} + C\dot{X} + R(X) = F(t) \tag{4}$$

where X is the displacement vector, M the mass matrix, C the damping matrix, F(t) the time variant load vector and R(X) the structural response. F(t) contains the shaker forces as defined by eq (2) and (3) which are coupled with the equation of motion (1). Hence eq. (1) and (4) have to be integrated simultaneously. The nonlinearities of the structure are taken into account by modifying the right hand side of eq. (4); i.e. the load vector F(t). This implies a reformulation of eq. (4):

$$M\ddot{X} + C\dot{X} + KX = F(t) + KX - R(X) = F^*(t) \tag{5}$$

where K is the (constant) matrix of the initial stiffness and $F^*(t)$ the modified load vector. For a numerical procedure to solve the equations of motion it is referred to (Schuëller, Pradlwarter, 1987).

DETERMINATION OF THE RESPONSE SURFACE

In order to determine the failure probability of large (MDOF) structures under stochastic dynamic loading, various methods, such as simulation and equivalent linerization are available. (see Pradlwarter, Schuëller, 1988). However, if the structural properties are also considered to be random, the response surface method (RSM) appears to be most advantageous. By this procedure, the limit state function $g(\underline{x}) \leq 0$ is approximated by a polynomial $\bar{g}(\underline{x})$ which is a function of the various random input parameters. If, for example the difference between the concrete tensile strength β_z, i. e. x_4 and the occurring concrete tensile stress $h\ (x_1, x_2, x_3)$ is to be defined, the response surface

$$\bar{g}\ (\underline{x}) = \bar{g}(x_1, x_2, x_3 x_4) = x_4 - h\ (x_1, x_2, x_3) \tag{6}$$

where h(.) is $h\ (k_{\phi B}, c, F)$. This function is then determined for several points, preferably $\bar{x}_i \pm 1.5\sigma_i$, where $\bar{x}_i$ and σ_i are the mean and the standard deviation of the variables respectively. For any particular loading condition this requires - for a quadratic interpolation - $3^3 = 27$ parameter combinations and hence 27 nonlinear FE- analyses.

COMPUTATION OF FAILURE PROBABILITIES

Depending on the failure condition to be investigated, the respective response surface, i.e. limit state function has to be derived. The numerical evaluation of the failure probability is, most advantageously, accomplished by applying advanced simulation procedures, which are both accurate and efficient. In particular, importance sampling procedures using the design point (Schuëller, Stix, 1987; Bourgund, Bucher, 1986) is utilized in this study. This procedure centers the importance sampling, i.e. the weighting distribution on the design point and hence reduces the computational effort and the statistical error considerably.

LOADING CONDITIONS

The loading conditions are characterized by the initial frequency, mass, excentricity, moment of inertia as well as the drag coefficient of the shaker. The uncertainties of all these parameters are assumed to be negligibly small.

NUMERICAL EXAMPLE

The failure probabilities of the containment are now determined for two critical cross sections as indicated in Fig. 4. For both sections the failure criterion is defined by the exceedance of the concrete tensile stresses ($\beta_{F,Z}$ for the foundation and $\beta_{A,Z}$ for the outer shell). The statistical parameters as well as the probabilistic information of the input parameters are listed in Table 1. The analysis is carried out for two load cases. The respective input data are listed in Table 2. The results of the reliability analysis are listed in Table 3.

No.	Notation	Mean	Deviation	Coefficient of variation	Distribution
1	$K_{\phi B}$	$2.00 \cdot 10^{12}$ Nm/rad	$0.60 \cdot 10^{12}$	0.30	lognormal
2	C	4.5 %	2.5	0.55	lognormal
3	F	1.00	0.1 u.0.15	0.1 u.0.15	normal
4	$\beta_{F,Z}$	2.200 N/mm^2	0.50	0.227	normal
5	$\beta_{A,Z}$	1.223 N/mm^2	0.343	0.280	normal

Table 1: Statistical Information of Input Parameters

Loading Parameter of shaker loading T40.13				
starting frequency	1.6 Hz	=	10.05	rad/sec
mass	2 x 2278	=	45 560	kg
eccentric weight		=	59 821	kgm
moment of inertia with respect to the center	2 x 63189	=	126 378	kgm^2
factor of resistance of air		=	176	kgm^2
Loading Parameter of shaker loading T40.37				
starting frequency	2.1	=	13.20	rad/sec
mass	2 x 13021	=	26 042	kg
eccentric weight		=	27 673	kgm
moment of inertia with respect to the center	2 x 24983	=	49 966	kgm^2
factor of resistance of air		=	43.1	kgm^2

Tab. 2 Load Data of Shaker

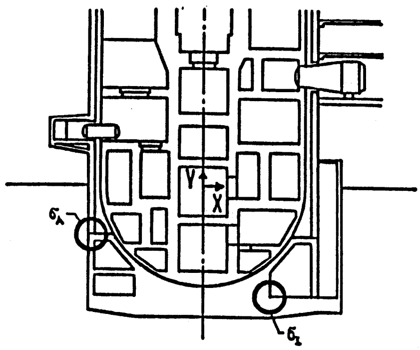

Fig. 4: Critical Cross Sections of Containment Structure

Loading/ Position	Variavle*	Design point	Probability of failure p_f
T40.37 Foundation	1 2 3 4	$1.68 \cdot 10^{12}$ Nm/rad 2.76 % 0.94 - 1.68	$5.9 \cdot 10^{-2}$
T40.37 outer shell	1 2 3 5	1.84 3.22 0.98 1.02	$1.6 \cdot 10^{-1}$
T40.13 Foundation	1 2 3 4	2.70 3.20 1.06 1.82	$5.4 \cdot 10^{-2}$
T40.13 outer shell	1 2 3 5	2.70 3.20 0.97 0.61	$2.2 \cdot 10^{-2}$

*) see Table 1

Table 3:Failure Probabilities of Cross-Sections(Coefficient of Variation of F = 0.1)

DISCUSSION OF RESULTS AND CONCLUSIONS

A procedure to determine the reliability of a containment structure under deterministic (shaker) loading has been developed, where the uncertainties of the structural as well as material parameters are taken into account. The intention of the shaker test loading war primarily to investigate the nonlinear range of the structural response. For the purpose of this analysis the application of the response surface method is shown to be most useful. The very high failure probabilities of critical cross-sections indicate that, under the selected loading conditions, failure is very likely.

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