THE STRUCTURAL FAILURE PROBABILITY ANALYSIS OF PIPE IMPACT ONTO A CONCRETE WALL

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1. Introduction

In modeling structural mechanics problems, structural reliability analysis is as important as the deterministic results. Structural mechanics modeling should involve state-of-the-art methods for structural analysis, such as finite element techniques. The theoretical background for the use of probabilistic methods in structural analysis has been developed for many years. But generally, applications were introduced only after advanced computer codes were developed.

The closest estimate to the exact solution for the probability of structural failure can be obtained by using the Monte Carlo simulation (MCS) method. In this method, the samples of input variables are generated based on their cumulative distribution functions (CDF) or their probability density functions (PDF). An output is then evaluated at each sample. MCS is flexible for all types of input distributions and all forms of model functions. Neglecting the algorithmic error caused by simulations, if a sufficient number of simulations, N, are used, MCS often results in solutions with a high accuracy. An important aspect of MCS compared to other numerical methods is that its accuracy does not depend on the dimension of the random model input variables. Unfortunately the cost of computations using Monte Carlo method can be very high. The applicability of this method is therefore offset by its computational expense. The CPU time increases rapidly for real 3D nonlinear dynamic problems. This increase is related to the necessity to execute a large number of finite element analyses (FEA) solutions with random parameter values. A complete finite element analysis that is performed for each of the vectors of random variables is costly in itself.

In order to reduce the total CPU time, several alternative methods have been proposed /1,2/: first order reliability method (FORM), second order reliability moment method (SORM), response surface (RS) method, tangent multi-plane surface (TMPS) method, interior multi plane surface (IMPS) method, Importance Sampling Algorithm (IS) and others. These methods are faster than the Monte Carlo method but have limitations. They are based on the assumptions that the state of the structure is defined in the outcome space of a vector of random variables. An important assumption for a structural failure probability is that the structure can be in one of two states, the safe state or the failed state. The boundary between those two states is known as the limit state surface.

2. Structural reliability techniques

For the deterministic solution, the vector of structural parameters is described quit exactly. This solution can be named as *F(P₀)*, where $P = P_{1,0}, P_{2,0}, \ldots, P_{n,0}$ is vector of parameters at initial solution. In the structural integrity analysis those parameters can be material properties, loads, geometrical factors, FE mesh size and gradients near irregularities. The graphical view of this solution on the F-P space is presented in the Fig. 1. The random function value $F(P_i)$ can be computed by the FORM equation:

$$F(P_i) = F(P_0) + \sum_{m=1}^{N} \frac{\partial F(P)}{\partial P_m} \Delta P_{m,i} \tag{1}$$

where $F(P_i)$, $F(P_0)$ - random value and initial solution; $\frac{\partial F(P)}{\partial P_m}$ - partial derivatives by parameters in region of initial solution; $\Delta P_{m,i}$ - random values of parameters alterations as showed in the Fig. 1. The probability function distributions for those parameters can be arbitrary selected by the user.

If the influence of the parameters, P, on the region of initial solution is strongly non-linear, then the random value of the function can be evaluated using the SORM equation:

$$F(P_i) = F(P_0) + \sum_{m=1}^{N} \sum_{n=1}^{N} \frac{\partial^2 F(P)}{\partial P_m \partial P_n} \Delta P_{m,i} \Delta P_{n,i} \tag{2}$$

In comparison to the Monte Carlo method, FORM and SORM save CPU time because they minimize the required number of FEM solutions. If the structural integrity problem contains N parameters (random variables) with their probability distribution functions, then the probability of result can be realized in (2N+1) FEM solutions.

The probability for the value of the functions to be in the interval (F_{min}, F_{max}) can be computed as follows:

$$\Pr ob(F_0) = \frac{\sum_{i=1}^{N} F(P_i)}{NP}, \tag{3}$$

where NP - number of different values of parameter vectors, $F(P_i) < F_{\max}$, $P_{i,\min} < P_i < P_{i,\max}$.

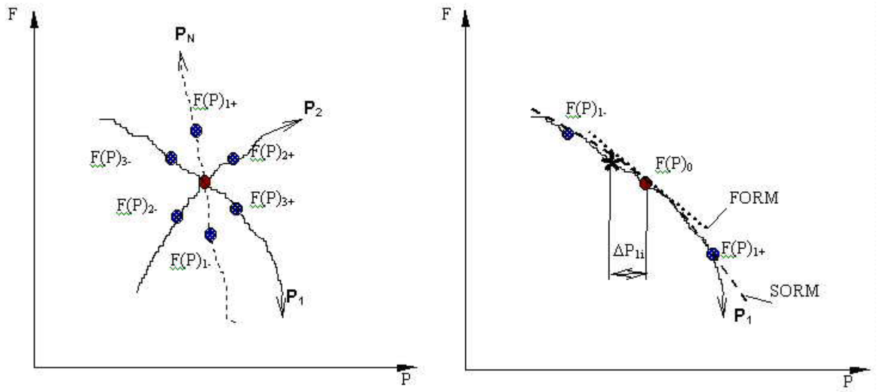


Fig. 1. Initial solution in the F-P space and random value of parameter alteration

Output uncertainty can be characterized by stress, displacement, velocity and other response parameters. It can be caused by uncertainty of input variables, model and software uncertainty. Random input variables as parameters, which are presented in the Equations (1)-(3), can come to a considerable list. Those parameters can be grouped as follows: initial conditions, material properties, loads and geometry/tolerance. Model uncertainty can be predetermined by physics, model and mesh uncertainties. Coding, algorithm and numerical errors can cause software uncertainty.

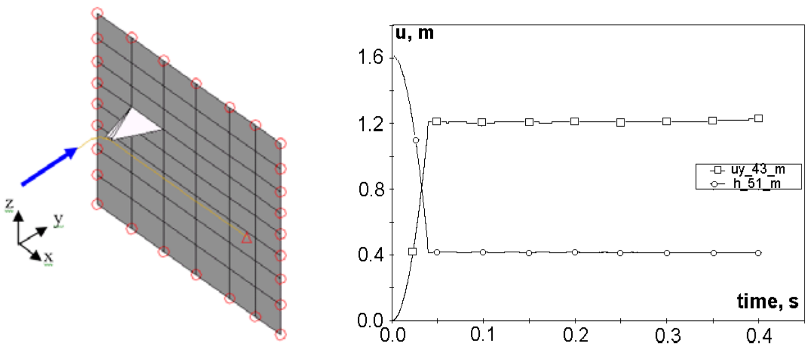
Numerous commercial codes for the evaluation of probabilistic structural failure are available in both Europe and the United States. A partial list consists of the following: PROFES /3/, DAKOTA /4/, RELIAB01 /5/, STRUREL /6/. In this paper, an original procedure for probabilistic estimations was developed which used the FORM and SORM methods.

3. Numerical results

The impact of a pipe onto a concrete wall is an important problem in the structural integrity assessment of nuclear power plants (NPPs). In this paper a simple problem was used to illustrate the use of the above procedure in the calculation of a probabilistic safety assessment. The problem assumes that a pipe, cantilevered at one end, experiences a guilotine break at the other end that creates transverse hydrodynamic forces, which cause the pipe to whip into a nearby concrete wall. The interaction between the wall and the pipe is taken into account by using contact elements. The FE model is shown in Fig. 2a. Quadrilateral reinforced concrete plate elements are used to model the wall; pipe elements are used to model the pipe; and point-to-line contact elements are used to model the contact mechanics. The boundary conditions for the wall do not allow translation but do allow rotations. Because the point-to-line contact element was used, the pipe was constrained to move in the x-y plane. At the guilotine end of the pipe, a hydrodynamic force is applied perpendicular to the pipe; this is the force that drives the pipe into the reinforced concrete wall. Note, for the first study the force is assumed constant and remains on througthout the simulation. The FE analyses were performed using the NEPTUNE /7,8,9/ structural analysis software. The deflection-time histories for the pipe and wall are shown in Fig. 2b and Fig. 3, respectively. The wall deflection starts to increase rapidly at 0.25 sec. Recall that in this simulation, the hydrodynamic force is continuously being applied to the pipe and this is causing the pipe and wall to vibrate. The vibrations cause the concrete to continuously crack and, thus, have its stiffness reduced. This results in the large deflections of the wall as shown in Fig. 3a. When linear elastic concrete material was assumed, then the deflections of the wall changed its character as shown in Fig. 3b. Without the ability to crack, the deflections are bounded even with the continually applied load.

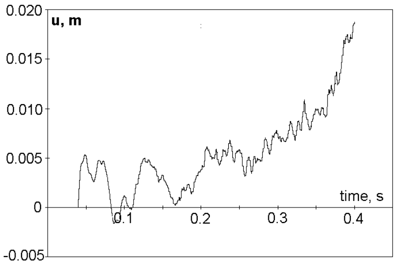
The next two problems were solved by modifying the load-time history. The first modification was to set the value of the hydrodynamic force to zero after 50 ms and the second was to use a damping ratio of 0.2 for the contact element.

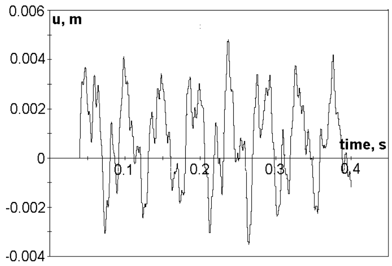
Probabilistic analyses using FORM were performed using six parameters, with the nominal magnitudes and standard deviations shown in the Table 1.



(a) (b)

Fig. 2. (a) FE model for a pipe impacting onto a concrete wall, and (b) the temporal history of the pipe deflection at node #43





(a) (b)

Fig. 3. Wall deflection at node #60: (a) - nonlinear material, (b) – linear material.

Table 1

Nominal magnitudes and standard deviations of the random variables (parameters)

ID	Parameter	Dimensions	Nominal	Assumed std. deviation
1	Hydrodynamic force	N	500000	50000
2	Wall thickness	m	0.50818	0.050818
3	Elasticity modules of concrete	Pa	2.70E+10	2.70E+09
4	Ultimate compression strength of concrete	Pa	1.72E+07	1.72E+06
5	Yield limit of rebars	Pa	3.92E+08	3.92E+07
6	Ultimate strain of rebars	-	0.5	0.05

The following output functions were chosen for the probabilistic structural analysis:

- maximum displacement of wall at node #60;
- maximum axial strains in rebar's of element #34, layer 1;
- maximum axial strains in rebar's of element #34, layer 2.

A parameters sensitivity analysis of maximum displacement of wall at node #60 near to nominal value F_0 are presented in Fig. 4.

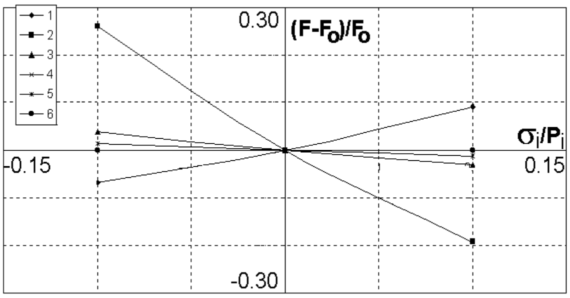


Fig. 4. Parameter sensitivity illustration of maximum wall displacement u_y at node #60

4. Conclusions

The purpose of this study was to perform a probabilistic safety assessment of a steel pipe impacting against a concrete wall. The probabilistic structural integrity evaluation was coupled with a deterministic FE program, NEPTUNE. This evaluation included deterministic modeling, definition of random variables, description of failure criterion or limit state function, running the probabilistic analysis and reviewing the final results.

5. Acknowledgement

The work of the U. S. authors was performed under the auspices of the U. S. Department of Energy, Office of International Nuclear Safety and Cooporation, under Contract W-31-109-Eng-38. The work of the first author was founded by IAEA as fellowship program at ANL.

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Summary

The paper presents an investigation of the structural failure probability analysis of pipe impact onto concrete wall. The FORM/SORM probabilistic methods are commented and used for the FEM probabilistic analysis. The sensitivity analysis of the wall displacement was evaluated.

Key words: probabilistic analysis, finite element method, FORM, SORM.