Transactions of the 13th International Conference on Structural Mechanics in Reactor Technology (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Analysis of base isolation and energy dissipation systems for NPP structures using fragility models

Vulpe, A.
Technical University of Iasi, Dept. of Structural Mechanics, Romania
Cărăusu, *A.*
Technical University of Iasi, Dept. of Mathematics, Romania

ABSTRACT: Some extensions of analytical models for base isolation and energy dissipation systems, involving fragility models, are presented. The equation of motion is extended with a term corresponding to ED effect, and the fragility of IEDS is evaluated using a bilinear regression line.

1 INTRODUCTION

Among various types of techniques and devices developed (during the last decade) for reducing the effect of strong earthquake excitations on NPP facilities, the base isolation systems have been rather widely accepted or even preferred (Kato, Watanabe & Kato 1991), (Tajirian & Abrahamson 1991), (Ishida et al. 1991). They are better suited for isolating heavy structures constrained to high safety level requirements (like the reactor vessel, for example). However, restrictions have to be observed on the relative displacements between the upper structure and foundation / ground (Kouizumi et al. 1991). Therefore, it has appeared as useful to combine base isolation devices with hysteretic energy dissipators / absorbers (Zhou 1991), (Sone & Yamamoto 1991). As regards the analytical models behind the aforementioned techniques and devices, it has to be remarked that the probabilistic and stochastic concepts and methods have been involved up to a rather limited extent.

In this paper we present extensions of some energy-based models for base isolation and energy dissipation systems (IEDS) of NPP structures / facilities, thus developing our research reported at the SMiRT 12 Conf. (Cărăuşu & Vulpe 1993). Starting from a model of F.Zhou (1991), we derive simpler analytical expressions for the acceleration attenuation ratio AR and for the maximum relative displacement between structure and ground (base mat) D_u. Other parameters as equivalent damping ratio and the restoring force are also reformulated. Next, A.Hadjian's (1993) BMER (balance mitigation of earthquake responses) model is extended in two ways. The expression of the restoring function also includes the damping effect on the vertical displacement of the supports by the hysteretic energy dissipation, what leads to an alternative equation of motion. Finally, fragility curves are derived for the proposed IEDS, using an equivalent linearization on the hysteretic multilinear curve. The fragility of IEDS is then evaluated using a multilinear regression line. Formulas for the estimation of regression parameters are also given by adapting our previuosly derived expression presented in (Carauşu & Vulpe 1993). They can be employed in connection with efficient simulation techniques like the LHS (Latin hypercube sampling).

2 BASE ISOLATION AND ENERGY DISSIPATION SYSTEMS

Let us consider a structure of mass M subjected to a ground displacement X_g with the structural response X_a. The basic differential equation of motion is (Zhou 1991):

$$(1) \qquad M\ddot{X}_a + C_e\dot{X}_a + KX_a = C_e\dot{X}_g + KX_g,$$

where C_e = the equivalent viscous damping, and K = the elastic stiffness of the IEDS, respectively. An analytical expression is given in (Zhou 1991) for the acceleration attenuation ratio $AR = \ddot{X}_a / \ddot{X}_g$. We propose a simpler expression for this parameter using the ratio $\eta = \omega / \omega_n$ where ω is the circular and ω_n is the natural circular frequency of the IEDS :

$$(2) \qquad AR = \frac{1}{\sqrt{\dfrac{1}{\eta} + \dfrac{\eta^3 - 2\eta}{1 + 4B^2}}},$$

in which B = the energy dissipation ratio. As regards the maximum relative displacement, its expression (Eq.(4) in (Zhou 1991)) in terms of AR, $\ddot{X}_g$, ω and ω_n can be replaced by the simpler one

$$(3) \qquad D_u = \frac{\operatorname{sgn} \ddot{X}_g}{\omega} \cdot \frac{\|(\ddot{X}_a, \ddot{X}_g)\|}{\sqrt{\omega^2 - 2\omega_n^2}}.$$

In Eq.(3), sgn is the well-known signum function and $\|\cdot\|$ is the Euclidean norm in the 2-space : $\|(u, v)\| = \sqrt{u^2 + v^2}$. The equivalent damping ratio $E_e = C_e / 2M\omega_n$ can be expressed in terms of AR and η by

$$(4) \qquad E_e = \frac{1}{2\eta}\sqrt{\frac{1 - AR^2(1 - \eta^2)^2}{AR^2 - 1}}.$$

Finally, the energy dissipation ratio B can be written as

$$(5) \qquad B = \frac{2(D_u - D_y)D_y}{D_u^2 \pi},$$

where D_y is the relative displacement at the yield point.
These parameters may be introduced in the equation of motion for a base isolated structure with a nonlinear damper, given by (Sone & Yamamoto 1991) for a SDOF model as $m\ddot{x} + kx + f(x, \dot{x}) = -m\ddot{y}$, where m, k are the mass of the isolated structure and the spring constant of the rubber bearing (respectively), while $f(x, \dot{x})$ is the damping force, x is the relative displacement response and y is the seismic input

ground motion. Taking into account Eq.(1) and replacing M by m, K by k (and so on), we get

(6) $\quad f(x, \dot{x}) = C_e \dot{x}$ and $m\ddot{y} + C_e \dot{y} + ky = 0$.

Another model we have taken into account is BMER (balance mitigation of earthquake response) due to A. Hadjian (1993), of which we recall the expression of the restoring force only :

(7) $$g_r(x, \dot{x}) = \frac{x^{b-1}[a^2 b^2 (b-1) x^{b-2} \dot{x}^2 + a b g]\, \dot{x}}{1 + a^2 b^2 x^{2b-2}},$$

where x is the relative horizontal displacement (as above) while a, b are parameters in the equation of the cross section of the bowls which the cylindric supports roll in :

(8) $\quad z = a x^b$.

The BMER is completed as to damp the vertical displacement of the supports by hysteretic energy dissipation due to a set of rubber bearings, as represented in Fig.1. The resulting equation of motion will be

(9) $\quad m\ddot{x} + kx + f(y, \dot{y}) + g_r(x, \dot{x}) = -m\ddot{y},$

and it can be integrated using a Runge-Kutta numerical integration method.

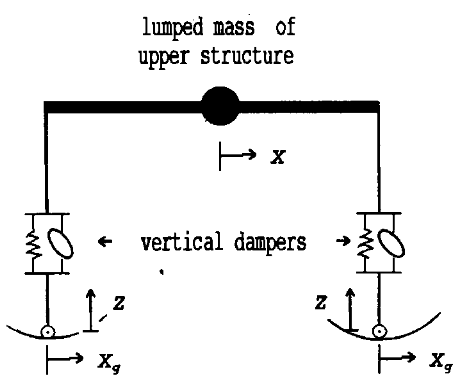

Fig.1 Base IEDS with vertical dampers and rollers-in-bowls ED supports

The restoring function $g_r(x, \dot{x})$ in Eq.(9) can also be expressed as a function of z, $\dot{z}$ using Eq.(8); thus, $\dot{z} = a b x^{b-1} \dot{x}$. Parameters a, b giving the shape of the cross-sectional curve of Eq.(8), that is, the generatrix of the cylindrical surface of the support bowls, have to be found so as to achieve a maximum ED effect. They will depend on mechanical and geometric properties of the upper structure and base isolation system. For instance, the vertical restoring force to be taken into account for one of the n supports of the base plate will be equal to

(10) $$-\frac{M\ddot{z}}{n} = a b x^{b-2}[(b-1)\dot{x}^2 + b\ddot{x}]\ .$$

Before deriving the horizontal restoring force in the case of (generalized) parabolic contact surfaces for the bowls, let us remark that expression (7) of the restoring function $g_r(x, \dot{x})$ is obtained not from Eq.(8) of (Hadjian 1993) but from

(11) $\quad (1 + a^2 b^2 x^{2b-2})\, \ddot{x} + a b g x^{b-1} \dot{x} + (b-1) a^2 b^2 x^{2b-3} \dot{x}^3 = 0$.

Let us now consider an upper structure of mass M equally distributed on the n

supports, giving (on each support) a mass $m = M/n$, and a vertical force $= mg\vec{k}$. If it is decomposed along the horizontal direction $\vec{i}$ and the normal direction $\vec{v}$ to the surface of Eq.(8) at a contact point P on it we get

$$(12) \qquad mg\vec{k} = \frac{mg}{\cos\theta}\,\vec{v} + (mg)_x\,\vec{i}$$

where $\vec{v} = \dfrac{-ax^b\vec{i} + \frac{x}{b}\vec{k}}{\sqrt{a^2x^{2b} + x^2/b^2}}$. After some computations we find

$$(13) \qquad (mg)_x = -\operatorname{sgn}\theta\,(mg\tan\theta) = (-\operatorname{sgn}\theta)\;abx^{b-1}\dot{x}.$$

The parameters and forces involved in the above equations are (in part) represented in Fig.2.

Let us denote by W_x the energy corresponding to the horizontal component of the restoring force $(mg)_x$. Then the energy equilibrium equation (extending Eq.(1) of Sone & Yamamoto (1991)) should also include the term W_x :

$$(14) \qquad W_e + W_h + W_p + W_x = E,$$

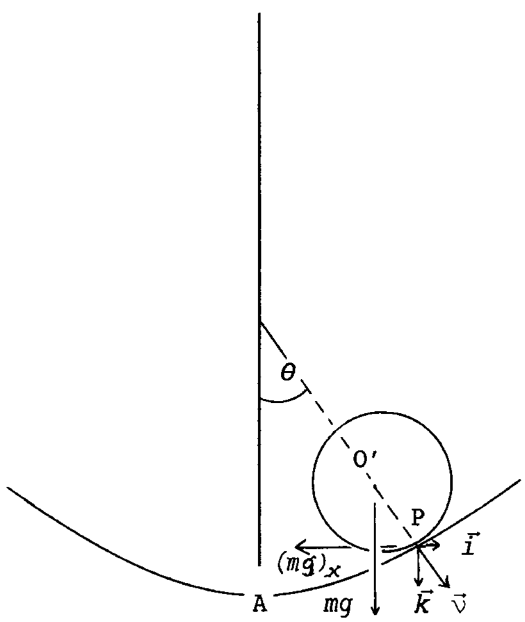

Fig.2 Forces at a contact point P on the rolling surface (Eq.(8))

where the forst three terms denote the elastic vibrating energy, the energy dissipated by the linear damping mechanism and the cumulative inelastic strain energy. E is the total energy input by a seismic ground motion. According to the assumptions included in our model (see Fig.1), W_h should also include the energy dissipating effect of the rubber bearings for damping the vertical motions implied by the oscillations of the roller supports on the bowl surfaces. Alternatively, Eq.(1) should be extended by an additional term corresponding to the horizontal restoring force of Eq.(13). In both alternatives, the resulting equation of motion is similar to Eq. (11) in (Hadjian 1993), with the additional term that appears corresponding to the vertical energy damper / to the horizontal restoring force.

The numerical integration method there applied (of Runge-Kutta type) could also be used for solving the resulting equations.

3 EVALUATING FRAGILITY OF IEDS SYSTEMS

The above models do not include any probabilistic approach. However, they offer a more realistic basis for evaluating the fragility, that is, the conditional probability of failure for the base isolation and energy dissipating systems.

The previously presented model can be further extended to nonlinear damping systems (similar but more general than the ones considered in (Koizumi et al. 1991)) that is of types $x^{\lambda}\dot{x}^{\lambda}$ with λ not necessarily $= 1,2$).

The fragility curves are derived for the structure with an isolation and energy dissipation system (IEDS), using the well-known equivalent linearization technique on the hysteretic multilinear curve and the multilinear regression method, as presented in an extended version of our paper (Cărăuşu & Vulpe 1993).

The failure probability of the IEDS is evaluated using HCLPF (high confidence low probability of failure) values, corresponding to the adopted fragility model under the "double lognormal format" :

$$
(15) \qquad \begin{cases} F_A(a) = \Phi\left[\dfrac{\ln(a/A_m)}{\sigma_R}\right], \\[2ex] f_C(c) = \dfrac{1}{\sqrt{2\pi}\sigma_U c}\exp\left[-\dfrac{1}{2}\left[\dfrac{\ln(c/C_m)}{\sigma_U}\right]^2\right], \end{cases}
$$

where the fragility parameters in Eq.(15) are well known (see (Hirata et al. 1991), (Hirata et al. (1993)).

The evaluation of the fragility parameters is performed in terms of a bilinear regression model, with the regression coefficients estimated on the basis of statistical evidence and what we have called 'tolerance intervals'. This regression line is derived on the basis of an equivalent linearization technique. The effective estimation of the regression coefficients and fragility parameters is performed by means of the LHS method (Latin hypercube sampling), known as an efficient simulation method.

5 CONCLUDING REMARKS

We have discussed some existing models and techniques for base isolation and energy dissipation devices in NPP structures and equipment, giving some extensions and stating proposals for a combination of well-known elastic (rubber) dampers and BMER system due to Hadjian (1993). Our study is rather theoretical, so far. It follows to introduce some numerical data and check the efficiency of our models. The fragility of isolation systems has received a rather limited attention [(Hirata 1989, 1991, 1993)]. It seems that our methods for evaluating fragility parameters for isolating and energy dissipating systems (extending the ones due to Hirata et al.) would be applicable.

REFERENCES

Cărăuşu, A. & A. Vulpe 1993. Fragility estimation for seismically isolated nuclear structures by HCLPF values and bi-linear regression. *Trans. SMiRT-12*, Vol. **M**, 237-242.

Hadjian, A.H. 1993. BMER - balance mitigation of earthquake responses - theory. *Trans. SMiRT-12*, Vol. **K2**, 327-332.

Hirata, K., Y. Kobayashi, H. Kameda, & H. Shiojiri 1989. Reliability analysis for seismically isolated FBR system. *Trans. SMiRT-10*, Vol. **M**, 115-120.

Hirata, K., S. Yabana, K. Ishida, H. Shiojiri & S. Yoshida 1991. Fragility estimation of isolated FBR structure. *Trans. SMiRT-11*, Vol. **M**, 235-240.

Hirata, K., A. Yamamoto & K. Ishida 1993. Evaluation of component fragility in isolated structure. *Trans. SMiRT-12*, Vol. **M**, 255-260.

Ishida, K., S. Yabana, G. Yoneda, J. Suhara & K. Yoshikawa 1993. Analytical Study on Ultimate Response Characteristics of Base Isolated Structures. *Trans. SMiRT-11*, Vol. **K2**, 309-314.

Kato, M., Watanabe, A. & A. Kato 1991. Study on the seismic base-isolated reactor building for demonstration FBR plant in Japan. *Trans. SMiRT-11*, Vol. **K2**, 97-102.

Koizumi, T., N. Tsujiuchi, F. Kishimoto, H. Iida & T. Fujita 1991. Base isolation technique for Tokamak type tusion teactor using adaptive control. *Trans. SMiRT-11*, Vol. **K2**, 49-54.

Sone, A. & S. Yamamoto 1991. Response analysis of base isolated structure with nonlinear damper. *Trans. SMiRT-11*, Vol. **K2**, 259-264.

Tajirian, F.F. & N.A. Abrahamson 1991. Response of seismic isolated structures during extreme events. *Trans. SMiRT 11*, Vol. **K2**, 247-252.

Zhou, F.L. 1991. Optimal design of base isolation and energy dissipation system for nuclear power plant structures. *Trans. SMiRT-11*, Vol. **K2**, 91-96.