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Publication date:
1995

Document Version
Publisher's PDF, also known as Version of record

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PAPER NO. 139

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MARCH 1995 ISSN 0902-7513 R9507

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Sensitivity of Reliability Estimates in Partially Damaged RC Structures subject to Earthquakes, using Reduced Hysteretic Models

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Abstract

The subject of the paper is the investigation of the sensitivity of structural reliability estimation by a reduced hysteretic model for a reinforced concrete frame under an earthquake excitation. Reliability is defined as the probability of excursion of the maximum softening damage indicator of a critical predefined level. The reliability estimation is performed based on a simplified model single-degree-of-freedom (SDOF) hysteretic oscillator with degrading stiffness (a modified Clough-Johnston hysteretic model) with three free parameters to be calibrated from a past earthquake. In lack of a large sample of shake table experiments the predictions of the model is compared with those obtained from a much more involved and time-consuming numerical model, which has previously been demonstrated to model structures of the considered type with sufficient accuracy. A sensitivity analysis of the parameters of the simplified model is performed, and the results show that two of the three parameters become increasingly elastic as the initial damage of the structure is increased. Hence, these parameters should be modelled as random variables. It is demonstrated in the paper that even relatively small coefficients of variations of these parameters may effect the probability of failure significantly in case of large initial damage levels.

Key Words: Earthquake excitation, RC-structures, damage prediction, structural reliability, sensitivity.

1 Introduction

Global damage indicators are response quantities characterizing the damage state of the structure after an earthquake excitation, and such can be used in decision-making of various draft proposals during the design phase, or in post-earthquake reliability and repair problems of damaged structures. In serving these purposes the global damage indicator should be observable for practical purposes, be a non-decreasing function of time unless the structure is repaired or strengthened, provide a unique failure criterion to separate the safe states from the unsafe ones, and, possess Markov property so that post-earthquake reliability estimates for a partly damaged structure can be estimated solely from the latest recorded value of the damage indicator, Nielsen and Çakmak [7].

The maximum softening damage indicator, introduced by DiPasquale and Çakmak [1] as a global damage indicator, measures the maximum relative reduction of the eigenfrequency of an equivalent linear SDOF oscillator with slowly varying stiffness properties, displaying the combined damaging effects of the maximum displacement ductility of the structure during extreme plastic deformations and the stiffness deterioration in the elastic regime, the latter effect being referred to as final softening. Köylüoğlu et al. [4] proposed a modified Clough-Johnston hysteretic oscillator as a simple model describing the behaviour of the first eigenmode. A novelty was the modelling of the elastic fraction of the restoring force as a decreasing function of the accumulated numerical plastic displacements on the hysteretic component displaying the transition from elastic to plastic behaviour as cracks and damage occur. The circular eigenfrequency, damping ratio and modal participation factor of the first mode of the undamaged structure were assumed to be known, measured before the arrival of the first earthquake from non-destructive vibration tests or by means of structural analysis. The other two parameters of the hysteretic model were identified and updated after each earthquake. Upon suitable calibration of the two hysteretic parameters, the model was observed to be capable of predicting the displacement response and the development of the maximum softening compared to the recorded response of shake table experiments on frame RC-structures, Çecen [2].

The model was later slightly modified by Nielsen et al. [8], introducing also a strength deterioration into the model at the expense of one extra hysteretic parameter to be updated. This study was concentrated on the prediction of the residual reliability of partially damaged RC-structures, the failure event beeing defined as the first-passage of a certain critical level of the maximum softening damage indicator. As a reference the failure prediction obtained from the SARCOF finite element program by Mørk, [6] was used. Among many facilities this program can model the transition from uncracked to cracked sections during the initial phase of the earthquake, and the program provides the development of softening via smoothing of the instantaneous, calculated eigenperiods. The simplified model relies heavily on the three hysteretic parameters. Hence, it is important to investigate the so-called modelling uncertainty, as measured by the socalled sensitivity of the relative change of the failure probability to the relative change in any of the free parameters. In the present study such a sensitivity analysis has been performed. Still, the SARCOF sample has been used for parameter calibration. The objection that the SARCOF program, being another model, may not represent reality, is taken as being irrelevant to the subject of study. Thus, the SARCOF program is used to produce some time series of the displacement and damage development, which may have been measured, and the simplified model is only calibrated during the past earthquake to reproduce approximately the same response time series in the future earthquake. In any case the SARCOF program is pretty good in predicting the response of RC-structures as indicated in Figure 1, showing the measured and predicted top-storey displacement relative to the shown ground surface of a 10-storey, 3-bay RC-model frame to the scale 1:10, Çecen [2].

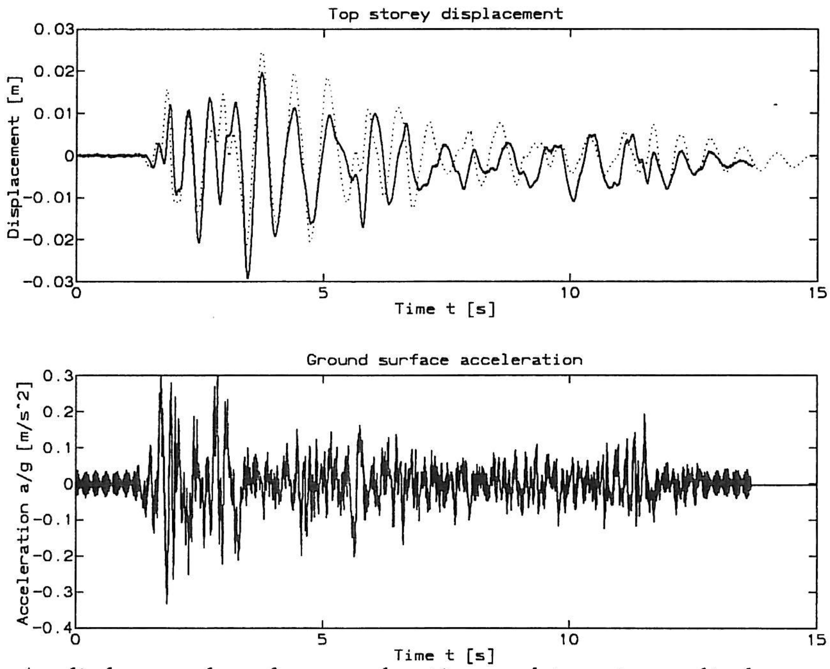

Figure 1: *Applied ground surface acceleration and top storey displacement response of 10-storey , 3-bay RC-model frame, Çecen [2]. [——]: measured response. [· · ·]: Response calculated by SARCOF.*

2 Hysteretic Model for SDOF Oscillator

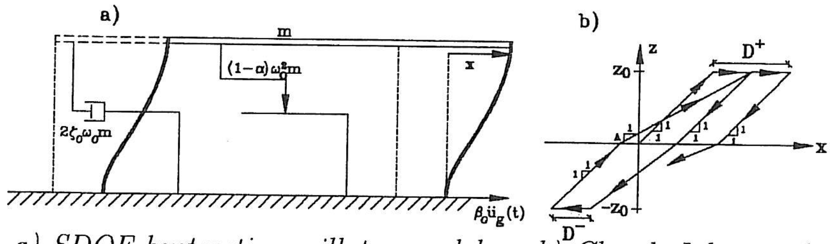

Figure 2: *a) SDOF hysteretic oscillator model b) Clough-Johnston hysteretic model.*

The equations of motion in the first mode are modelled by the following coupled differential equations, Köylüoğlu et al. [4]

$$\ddot{x}(t) + 2\zeta_0\omega_0\dot{x}(t) + \omega_0^2\Big[\alpha(t)x(t) + (1-\alpha(t))z(t)\Big] = \\ -\beta_0\ddot{u}_g(t) \quad , \quad t > t_0 \quad , \quad x(t_0) = \dot{x}(t_0) = 0 \tag{1}$$

$$\dot{z}(t) = \Big[H(z)\Big(A(t)H(\dot{x})(1 - H(z - z_0(t))) + H(-\dot{x})\Big) + \\ H(-z)\Big(A(t)H(-\dot{x})(1 - H(-z - z_0(t))) + H(\dot{x})\Big)\Big]\,\dot{x}(t) \quad , \quad z(t_0) = 0 \tag{2}$$

$$\dot{D}(t) = [H(\dot{x})H(z - z_0(t)) - H(-\dot{x})H(-z - z_0(t))]\,\dot{x}(t) \quad , \quad D(t_0) = d \tag{3}$$

$$\alpha(t) = \exp\left(-n_0 \cdot \frac{D(t)}{z_{0,0}}\right) \quad , \quad z_0(t) = z_{0,0}\exp\left(-n_1 \cdot \frac{D(t)}{z_{0,0}}\right) \tag{4}$$

$$A(t) = \frac{z_0(t)}{z_0(t) + D(t)} \quad , \quad H(x) = \begin{cases} 1 & , \quad x \geq 0 \\ 0 & , \quad x < 0 \end{cases} \tag{5}$$

The first modal coordinate $x(t)$ can be defined as the top storey displacement of the structure relative to the ground surface in a simple mode expansion if the mode shape is suitably normalized. The linear circular eigenfrequency, ω_0, the damping ratio, ζ_0, and the mode participation factor, β_0, of the first mode are assumed to be known before the arrival of the first earthquake. $\ddot{u}_g(t)$ indicates the horizontal earth surface acceleration signal and the earthquake starts at the time $t = t_0$. $\alpha(t)$ is the elastic fraction of the restoring force, which is assumed to decrease as a function of the accumulated plastic deformation $D(t)$. $z(t) \in [-z_0(t), z_0(t)]$ is the hysteretic component, which is modelled using the Clough-Johnston hysteretic model, and $z_0(t)$ signifies the instantaneous strength (yield level) of the oscillator, which is deteriorating from its initial value $z_{0,0}$ as the accumulated plastic deformations evolve. This deterioration was not included in the first formulation of the model by Köylüoğlu et al. [4] and seems to provide significant improvements at the expense of the extra parameter $z_{0,0}$. The stiffness degrading hysteretic constitutive law of the model can be represented as shown in Figure 2.b. The Clough-Johnston model deals with the stiffness degradation by changing the slope $A(t)$ of the elastic branches as the accumulated plastic deformations, $D^+(t)$ and $D^-(t)$ at positive and negative yielding, increase as shown in Figure 2.b. $D(t) = D^+(t) + D^-(t)$ are the total accumulated plastic deformations. For loading branches, the slope $A(t)$ is selected such that the elastic branch always aims at the previous unloading point with the other sign. At unloadings, the slope is 1. D_0 is the initial value of the total accumulated damage which is zero before the first earthquake hits and is assumed to be determined from previous earthquake and displacement response records for the succeeding earthquakes. $H(x)$ is the Heaviside unit step function.

The hysteretic parameters $z_{0,0}, n_0$ and n_1 are to be identified from the experienced excitation and the displacement response time series with a suitable optimization method. The Clough-Johnston hysteretic model was originally designed for reinforced concrete beams. The differential description of the model, applied herein, is due to Minai and Suzuki [5].

3 Damage Measures and Prediction of Damage and Reliability

The instantaneous softening, $\delta(t)$, of a structure is defined as, Çakmak et al. [1].

$$\delta(t) = 1 - \frac{T_0}{T(t)} \tag{6}$$

where T_0 is the first period of the equivalent linear structure and $T(t)$ is the first period of the equivalent linear structure with slowly varying stiffness characteristics during an earthquake excitation, which is estimated from the excitation and displacement response time series of the experienced earthquake. The maximum softening damage indicator, δ_M, is the maximum of $\delta(t)$ during the seismic excitation.

Consider the SDOF hysteretic model where $D(t)$ is related to an average equivalent slope of the hysteretic loops. This is chosen as the slope of the line through the extreme points, see Figure 2.b

$$\overline{m}(t) = \frac{2z_0(t)}{2z_0(t) + D(t)} \tag{7}$$

The circular eigenfrequency of the equivalent linear oscillator then becomes $\omega(t) = \omega_0\sqrt{\alpha(t) + (1-\alpha(t))\overline{m}(t)}$, resulting in the estimated instantaneous softening

$$\hat{\delta}(t) = 1 - \sqrt{\frac{2z_0(t)}{2z_0(t) + D(t)}\Big(1-\alpha(t)\Big) + \alpha(t)} \tag{8}$$

As seen from (8), $\hat{\delta}(t)$ is non-decreasing during a seismic event and fully correlated to $D(t)$. The proposed hysteretic model for the SDOF system is defined by six parameters, namely, ζ_0 , ω_0 , β_0 , $z_{0,0}$, n_0 and n_1. The constants ζ_0 , ω_0 , β_0 are measured on the undamaged structure (here obtained from the SARCOF program), whereas $z_{0,0}$, n_0 and n_1 are estimated from the following least square criterion

$$\min_{\hat{z}_{0,0},\hat{n}_0,\hat{n}_1} \Big(\sum_l w_{1,l}(\hat{\delta}_l - \delta_l)^2 + \sum_k w_{2,l}(\hat{x}_k - x_k)^2\Big) \tag{9}$$

where $\hat{\delta}_l = \hat{\delta}(l\Delta t)$ is the instantaneous softening at the l th time step obtained by the hysteretic model with the parameter $\hat{z}_{0,0}$, $\hat{n}_0$ and $\hat{n}_1$, and δ_l is the corresponding measured quantity (here from SARCOF realizations). Similarly, $\hat{x}_k$ and x_k are the estimated and measured displacement, respectively. $w_{1,l}$ and $w_{2,l}$ are positive weights, which are assigned such that displacement and instantaneous softening contributions in the error are approximately equal. Furthermore, large oscillations are weighted higher than small oscillations by excluding parts of the time series.

4 Reliability and Sensitivity Estimates

In an earlier study by Nielsen et al. [8] the quality of the residual reliability estimates of the simplified model was investigated based on the quality of the predicted conditional mean value $\mathrm{E}[\delta_2(t)|\delta_1]$ and the conditional variance $\mathrm{Var}[\delta_2(t)|\delta_1] = \mathrm{E}[\delta_2^2(t)|\delta_1] - (\mathrm{E}[\delta_2(t)|\delta_1])^2$. It was found that the hysteretic oscillator (1)-(5) sligthly underestimates the conditional mean value and overestimates the variance at low initial damage levels. These two quantities are normally the ones used in practice, but, in case of a sufficiently large sample, the probability of failure P_f can be estimated directly as the number of samples which exceeds the critical damage level δ_0. This means that the probability of failure P_f is defined as the number of samples exceeding δ_0 divided by the total number of samples.

However, these estimations are dependent on the parameters defining the SDOF hysteretic oscillator ($z_{0,0}$, n_0 and n_1) and since the determination of these is based on a more or less arbitrary least square criterion, as e.g. (9), some uncertainty is to be expected in the determination of these. It is therefore important to have a measure of the sensitivity of each of these three parameters in the model. Such a measure can be obtained by considering the proportionality factor between the relative change in P_f due to a relative change of some parameter p_i, i.e.

$$\frac{\Delta P_f}{P_f} = e_i \cdot \frac{\Delta p_i}{p_i} \tag{10}$$

$$e_i = \frac{\Delta P_f}{\Delta p_i} \frac{p_i}{P_f} \approx \frac{\Delta \ln P_f}{\Delta \ln p_i} \tag{11}$$

The coefficient, e_i, is termed the elasticity of the parameter p_i. If this is relatively high, it means that the failure probability is highly sensitive to the parameter p_i. Because of the uncertainty with which the parameter is specified, such parameters, should be considered as random variables.

Numerically, e_i is estimated from the difference quotients

$$e_i \approx \frac{\ln P_f(p_i + \Delta p_i) - \ln P_f(p_i)}{\ln(p_i + \Delta p_i) - \ln p_i} \tag{12}$$

The change in the parameters e_i is chosen so P_f is changing approximately 5 per cent, which is nessecary due to the small number of samples.

5 Numerical Examples

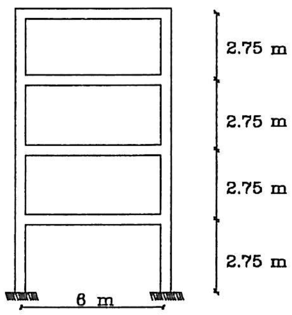

Figure 3: *4-storey, 1-bay reinforced concrete frame.*

The 4-storey, 1-bay reinforced concrete structure shown in Figure 3 is used to illustrate the performance of the method. The ground surface acceleration process is modelled as a non-stationary white noise (shot noise) filtered through a Kanai-Tajimi filter. The generation of the stationary white noise forming the input to the Kanai Tajimi filter is approximated by a broad-banded broken line process, se Penzien [9]. The damping ratio of the filter is 0.3, and the circular eigenfrequency is set to 8.8 sec^{-1}. The modulation function attains its maximum after 3 sec's and stays constant for 15 sec's and then decays exponentially. The intensity of the peak acceleration time series is chosen so that the peak acceleration is $0.5g$ in all the realizations in the 2nd earthquake. The equations of motion are solved using a 4th order

Runge-Kutta scheme for both the SARCOF model and the simple hysteretic oscillator. The time step is selected as $\Delta t = 0.008$ sec, where it has been checked that no drift occurs in the simulated signal due to numerical instability. The parameters have been selected so that for the uncracked structure one has $\omega_1 = \omega_0 = 8.25 \text{ sec}^{-1}$, $\omega_2 = 26.25 \text{ sec}^{-1}$, $\zeta_2 = \zeta_1 = \zeta_0 = 0.05$ and $\beta_1 = \beta_0 = 1.33$. The unconstrained minimization problem (9) is solved by trial-and error. More efficient optimization methods based on gradient calculations fail since the gradients are non-continuous in the present problem as a consequence of the non-analytic right-hand sides of the differential equations (2) and (3). Furthermore, there are several local minima in the optimization problem. The model is tested for eight different values of the initial damage in the range $\delta_1 \in [0, 0.4]$. The parameters for the hysteretic models are in these cases determined as shown in table 1.

δ_1	0.069	0.114	0.182	0.217	0.258	0.307	0.351	0.405
$z_{0,0}$ [mm]	41.0	48.0	51.0	55.0	80.0	101.0	154	184
n_0	1.50	1.45	1.35	1.20	1.20	1.20	0.90	0.75
n_1	0.00	0.15	0.23	0.29	0.60	0.98	1.52	1.64

Table 1: *The estimated parameters defining the hysteretic model.*

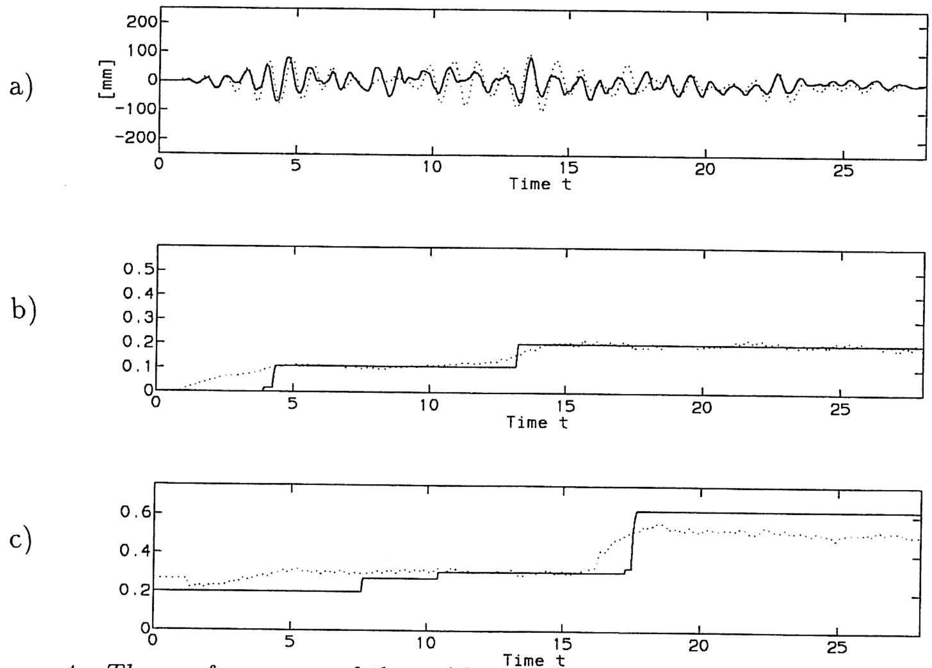

Figure 4: *The performance of the calibrated hysteretic model for an excitation realization in the 1st and 2nd earthquake. a) Top storey displacement response. b) Damage development in the 1st earthquake. c) Damage development in the 2nd earthquake.* [· · ·]: *Reference data.* [——]: *Hysteretic model.*

The performance of the calibrated hysteretic oscillator in the first earthquake is shown in Figure 4 for a sample with δ_1=0.217 (the 4th case of table 1). In Figure 4a and 4b it is seen that the model has been calibrated to fit very well to the reference data for both the damage level and the top storey displacements. Next, in Figure 4c the development of the maximum softening in the 2nd earthquake is seen as predicted by the calibrated hysteretic model in comparison to the reference data. As seen, the hysteretic model overestimates the maximum softening slightly in the last part of the earthquake.

The probability of failure, with the critical barrier of the maximum softening δ=0.5, conditioned on different damage levels in the 1st earthquake is shown in Figure 5. It is seen that the hysteretic model is very poor at estimating the probability of failure for very low initial damage levels ($\delta_1 < 0.15$). The reason is that at this damage state the damage is only due to cracking and therefore, the structure behaves practically linear. The hysteretic parameters of the model are therefore estimated very well and the extrapolation to heavy hysteretic behaviour becomes poor. It is also seen that the predictions of the model are getting poorer when the initial damage gets close to the critical damage level and the changes of the softening in the second earthquake are relatively small.

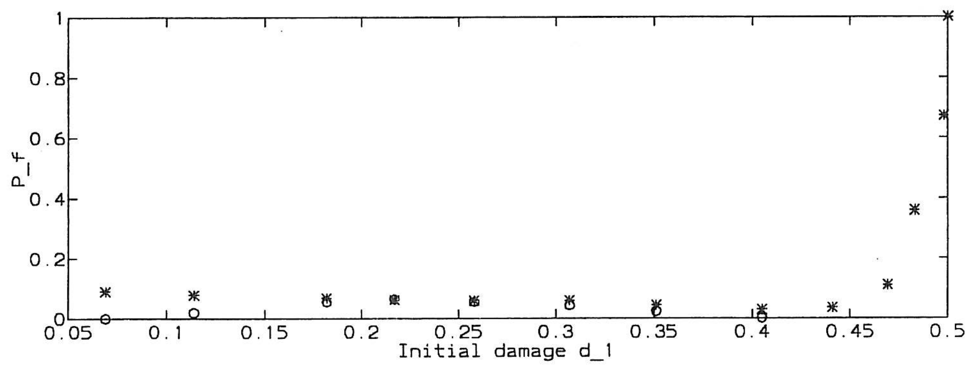

Figure 5: *The conditional probability of failure.* $*$: *Reference data obtained via SARCOF and* o: *Predictions by the hysteretic model.*

The statistical analysis is carried out by simulating $n = 1000$ independent realizations of the 2nd earthquake by the SARCOF model and the calibrated hysteretic oscillator, using the same ground accelerations in both models.

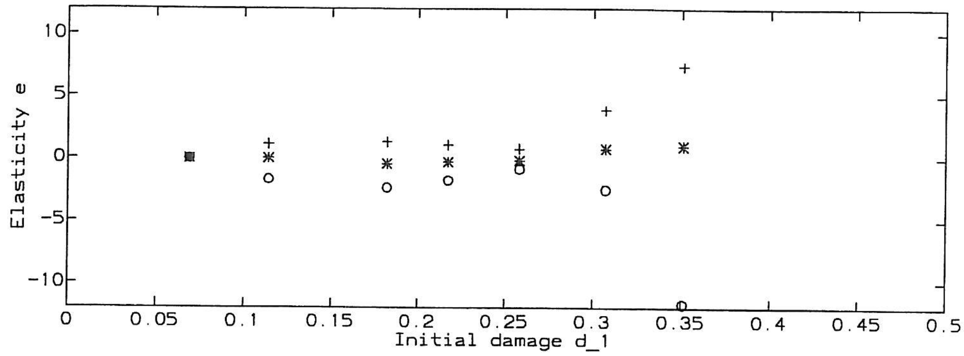

Figure 6: *The development in the elasticities as function of initial damage.+: $z_{0,0}$, $*$: n_0 and* [o]*: n_1.*

The development in the elasticity of the three free parameters as a function of the initial damage is shown in Figure 6. In the Figure the sensitivity is plotted as zero in the cases where the probability of failure is predicted to be zero due to the limited number $n = 1000$ of samples. It is seen that P_f is only moderately sensitive to the parameter n_0 througout the range of initial damage $[0, 0.35]$. The parameters $z_{0,0}$ and n_1 have moderate sensitivity to the failure probability for $\delta_1 \in [0, 0.22]$, followed by a relatively low sensitivity at $\delta_1 \approx 0.25$. For $\delta_1 \in [0.30, 0.50[$ the probability of failure is seen to be highly sensitive to these parameters. At the same time it is registered that for initial damage in the said interval the predictions of future damage become increasingly poor. So, the elasticity is in fact a good indicator of the capability of the simplified model. The model performs poorer in case of large sensitivity of one or more of the hysteretic parameters, because of the problem of calibrating these. From the sensitivity study it is then concluded that $z_{0,0}$ and n_1 should be modelled as stochastic variables, at least when δ_1 is above 0.3.

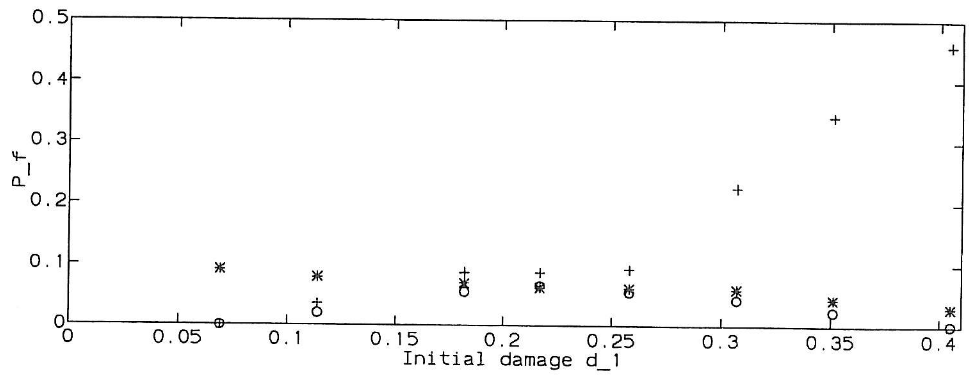

Figure 7: *The conditional probability of failure. $*$: Reference data obtained via SARCOF. o: Predictions by the hysteretic model. +: Predictions by the hysteretic model with log-normally distributed parameters $z_{0,0}$ and n_1.*

In Figure 7 the impact on the probability of failure at such an approach is shown assuming $z_{0,0}$ and n_1 to be independent log-normally distributed stochastic variables with the mean value as the estimated values of these parameters and a variation coefficient of 0.1, whereas n_0 is kept deterministic at its estimated value.

From Figure 7 it is seen that the probability of failure is increased dramatically at initial damage levels above 0.25, even for the relatively small variation coefficient of 0.1 of the uncertain parameters. From the sensitivity study this was also to be expected.

6 Conclusions

The performance of a reduced SDOF hysteretic oscillator model with three free parameters is investigated with emphasis on the sensitivity of these parameters on the probability of failure. The parameters are updated sequentially after each major earthquake. The model can be used for prediction of displacements as well as structural damage, but the study in this paper focuses on the sensitivity of the predictions of the probability of failure provided by the reduced model with respect to the realizations of statistically equivalent future earthquakes. Failure is defined when the maximum softening exceeds a critical level $\delta_1 = 0.5$. The reference sample set for comparison was generated by the SARCOF program. In the studied examples, the probability of failure is investigated for different initial damage levels in the range $[0, 0.4]$ for a 4-storey, 1-bay RC-frame. It is observed that at very low initial damage levels $\delta_1 < 0.15$, i.e. when only cracking occurs, the model is very poor at predicting the probability of failure. At higher initial damage levels the model is very good at predicting the probability of failure. At rather high initial damage the model gets poorer again in predicting the probability of failure. This is due to the fact that the structure is already very heavily damaged in the first earthquake and the predictions by the model get very sensitive to the estimated parameters in the model. However, the model seems to work very well in a certain range of the initial damage, which in the studied example must be designated as the relevant range of a past earthquake damage level of a structure which is not demolished.

7 Acknowledgement

The present research was partially supported by The Danish Technical Research Council within the project: Response and Reliability of Partially Damaged Reinforced Concrete Structures subject to Random Dynamic Loads.

References

[1] DiPasquale, E. and Çakmak, A. Ş. Detection of Seismic Structural Damage using Parameter-Based Global Damage Indices, *Probabilistic Engineering Mechanics*, Vol. 5, No. 2, pp. 60-65, 1990.

[2] Çecen, H., *Response of Ten Story, Reinforced Model Frames to Simulated Earthquakes,* Thesis presented to the University of Illinois, Urbana, Ill., in partial fulfilment of the requirements for the degree of Doctor of Philosophy, 1979.

[3] Hansen, H. I., Kirkegaard, P. H., and Nielsen, S. R. K., *Modelling of deteriorating RC Structures under Stochastic Dynamic Loading by Neural Networks* Structural Reliability, Paper no. 125, 1994.

[4] Köylüoğlu, H. U., Nielsen, S. R. K., Çakmak, A. Ş. and Kirkegaard, P. H. Prediction of Global and Localized Damage and Future Reliability for RC Structures Subject to Earthquakes, *Submitted to Earthquake Eng. and Struc. Dynamics*, 1994.

[5] Minai, R. and Suzuki, Y., Seismic Reliability Analysis of Building Structures, *Proc. ROC-Japan Joint Seminar on Multiple Hazards Mitigation*, National Taiwan University, Taiwan, ROC, March 1985, 193-207.

[6] Mørk, K. J., Stochastic Analysis of Reinforced Concrete Frames under Seismic Excitation, *Soil Dynamics and Earthquake Engineering*, Vol. 11, No. 3, 1992.

[7] Nielsen, S. R. K., Köylüoğlu, H. U. and Çakmak, A. Ş., *One and Two-Dimensional Maximum Softening Damage Indicators for Reinforced Concrete Structures under Seismic Excitation.* Structural Reliability Theory, Paper No. 92, University of Aalborg, 1992.

[8] Nielsen, S. R. K., Skjærbæk, P. S., Köylüoğlu, H. U. and Çakmak, A. Ş., *Prediction of Global Damage and Reliability based upon Sequential Identification and Updating of RC Structures subject to Earthquakes.* Structural Reliability Theory, Paper No. 138 (Submitted to 7th int. conf. on Soil Dynamics and Earthquake Engineering 24-26 May 1995, Chania, Crete, Greece), University of Aalborg, 1995.

[9] Penzien, J. and Ruiz, P., *Probabilistic study of behaviour of structures during Earthquakes* Report no. EERC 69-3, university of California, Berkley, Cal.

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