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An approximate method for seismic damage analysis of buildings

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ABSTRACT: A relatively simple method for the nonlinear seismic analysis of buildings oscillating predominantly in the first mode (the N2 method) has been extended in order to include the computation of seismic demand expressed in terms of dissipated hysteretic energy. Based on the results of the extended method, the structural behaviour can be estimated by using advanced damage models including cumulative damage. A 7-story RC frame building was used as a test example. Some partial results obtained using the N2 method were compared with the results obtained by the nonlinear dynamic analysis of a MDOF mathematical model. The comparison indicated reasonable accuracy of the approximate results, provided that the higher mode effects are not important.

1 INTRODUCTION

In earlier papers by the senior authors (Fajfar and Fischinger, 1987, 1988), a relatively simple method for the non-linear seismic analysis of buildings oscillating predominantly in a single mode was presented (the N2-method). Similar methods have been proposed by several other researchers (e.g. Saiidi and Sozen, 1981, Qi and Moehle, 1991). Following analysis according to those methods, seismic demand in terms of maximum displacements (and/or rotations) and displacement (and/or rotation) ductilities can be obtained, and compared with the corresponding capacity. It has been widely recognized, however, that structural damage due to earthquakes does not depend only on maximum displacements, and that the cumulative damage resulting from numerous inelastic cycles should also be taken into account. The importance of the balance between the seismic energy demand in a structure and its dissipation capacity has been emphasized. In order to estimate the structural behaviour by using more realistic and advanced damage models including cumulative damage, the N2 method has been extended in this paper (a similar attempt was made by Baik et al, 1988). A simple procedure for determining seismic demand in terms of dissipated hysteretic energy has been proposed. A seven-story RC frame has been used to demonstrate the applicability of the method. Two variants of the structure (the strong-columns and weak-beams concept, as well as the weak first-story concept, were used in the design) have been subjected to four ground motions of very different characteristics. The results of nonlinear dynamic analyses were compared with the results obtained by the proposed method.

2 DESCRIPTION OF THE METHOD

2.1 *The original method*

In the original N2 method, two different mathematical models and three steps of analysis are used. In the first step, stiffness, strength and supplied displacement ductility are determined by nonlinear static analysis of a multi-degree-of-freedom (MDOF) system under a monotonically increasing lateral load. Then, in the second step, an equivalent single-degree-of-freedom (SDOF) system is defined. The nonlinear characteristics of the equivalent system are based on the base shear - top displacement relationship, obtained by the nonlinear static analysis in the first step. In the third step of the N2 method, maximum displacements (and the corresponding ductility demand) are determined by carrying out nonlinear dynamic analysis of the equivalent SDOF system. Alternatively, inelastic response spectra can be used (e.g. the displacement spectra proposed by Fajfar et al, 1989, or Qi and Moehle, 1991). Such an approach can greatly simplify the analysis and make it suitable for use in everyday practice. The actual ductility demand in different structural elements is assumed to be approximately equal to the demand in the MDOF model at a static displacement corresponding to the maximum displacement of the equivalent SDOF model.

2.2 *Extension of the method*

In order to include the effect of cumulative damage, the following procedure has been implemented into the N2-method. In the third step, in addition to the maximum displacement, the input energy imparted to the SDOF system is determined. Input energy can be obtained either from nonlinear dynamic analysis, or from input energy spectra (Akiyama, 1985). Input energy is a relatively stable parameter and is reasonably independent of the structural system, as well as of the properly normalized input ground motion (Fajfar et al, 1989, 1992). The input energy based on a SDOF system provides a very good estimate of the input energy for multi-story buildings (Akiyama, 1985) - unless the influence of the higher modes is important (Zhu et al, 1992). The hysteretic energy demand (E_H) can be computed from the input energy as a function of the viscous damping (Fajfar et al, 1992). E_H can be approximately distributed to the various elements of the MDOF system proportionally to the energy dissipated under monotonic static loading up to the maximum displacement. Finally, damage indices are computed at the component level using an advanced damage model, which takes into account both damage due to large deformations as well as cumulative damage, e.g. the Park-Ang model (Park et al, 1984)

$$DM = \frac{u}{u_u} + \beta \frac{E_H}{F_y u_u} \qquad (1)$$

where DM is the damage index, u and u_u are the actual and ultimate displacement, respectively, E_H is the dissipated hysteretic energy, F_y is the yield strength, and β is a constant which depends on the structural characteristics. In the reported study, the Park-Ang model was modified and expressed in terms of rotations rather than displacements.

2.3 *Limitations*

The assumptions used in the development of the method suggest that the application of a method based on an equivalent SDOF system may be limited to building structures oscillating predominantly in a single (fundamental) mode. This expectation has been confirmed by several researchers, and by the results obtained in this study, too. Some proposals have been made to include the higher mode effects (e.g. Baik et al, 1988). Attempts by the authors of this paper to simulate the details of the structural response, when strongly influenced by vibrations in the higher modes (e.g. Model 1 subjected to Llolleo ground motion), by using the N2 method, have so far failed. If the dynamic behaviour of a structure is governed by the fundamental mode, however, the proposed method seems to be fairly stable. The results seem to be not very sensitive to small changes in the vertical distribution of the lateral loads used in the static analysis. An inverted triangular lateral load distribution (story force linearly proportional to the height above base and to the story mass) and the corresponding displacement shape (at the moment when the target top displacement is reached) yields results of adequate accuracy. It should be emphasized, however, that premature shear and other non-ductile failures should be avoided (e.g. by "capacity" design). Shear (especially base shear) demand, determined using the inverted triangular distribution of lateral loads, is usually underestimated.

3 NUMERICAL EXAMPLES

A 7-story RC frame building structure was chosen as a test example. The building completely corresponds to the RC frame-wall building tested in Tsukuba within the joint U.S. - Japan research project, with the exception of the structural wall which was omitted. Consequently, the structure consists of three identical three bay frames. The story height is 3.00 m, except for the first story, where it is 3.75 m. The total mass of the building is 1200 tons. The frames were designed according to the strong column - weak beam concept (Model 1). More data on the structure are given elsewhere (e.g. Kaminosono et al, 1984). A model corresponding to the weak story concept (Model 2) has also been studied. The concrete cross-sections of the structural elements are the same in both cases. In all columns longitudinal reinforcement of 8 ϕ 22 mm is provided, with exception of the first story of the Model 2 (4 ϕ 16). All beams in Model 2 are forced to behave elastically. It should be noted that the columns of Model 2 have a strength discontinuity but no stiffness discontinuity in the first story. Both models have the same initial natural periods.

All analyses were performed by the IDARC-L program. This program is based on the IDARC program (Park et al, 1987)) which has, however, been subjected to major modifications. The validity of several assumptions made in the N2 method has been tested by comparing the results of this method and of more accurate nonlinear dynamic analysis of MDOF systems. Four different input accelerograms were chosen in order to include ground motions of different characteristics (especially frequency content and duration).

The basic data of the accelerograms are given in Table 1 (a_g and v_g are the peak ground acceleration and velocity of the original ground motion, respectively, t_D is the duration of strong ground motion according to Trifunac and Brady, 1975. Bar was recorded during the 1979 Montenegro, YU, earthquake). All accelerograms were scaled (using a trial and error procedure) in order to obtain a target top maximum displacement of Model 1 of about 24 cm

Table 1. Input motions

Accelerogram	a_g [cm/s^2]	v_g [cm/s]	t_D [s]	scaling factor
El Centro S00E	342	33.5	24.0	1.50
Bar EW	353	52.0	15.2	0.72
Llolleo N10E	640	41.1	34.7	1.30
SCT N90W	168	60.5	29.1	0.50

Table 2. Top displacements, total hysteretic energies and total damage indices.

Input motion	Model, Method	u [cm]	E_H [kNm]	DM Dyn.	DM Stat.
1.50 El Cen.	1 MDOF	24.4	698	0.15	0.21
	1 SDOF	21.7	531		
	2 MDOF	13.7	857	0.74	0.76
	2 SDOF	14.3	805		
0.72 Bar	1 MDOF	24.3	475	0.16	0.19
	1 SDOF	24.1	421		
	2 MDOF	17.2	659	0.75	0.78
	2 SDOF	19.1	632		
1.30 Llolleo	1 MDOF	24.0	1996	0.20	0.33
	1 SDOF	21.0	786		
	2 MDOF	20.6	1925	1.15	1.39
	2 SDOF	21.9	1661		
0.50 SCT	1 MDOF	24.3	807	0.21	0.22
	1 SDOF	16.9	609		
	2 MDOF	2.8	42	0.05	0.04
	2 SDOF	2.6	33		

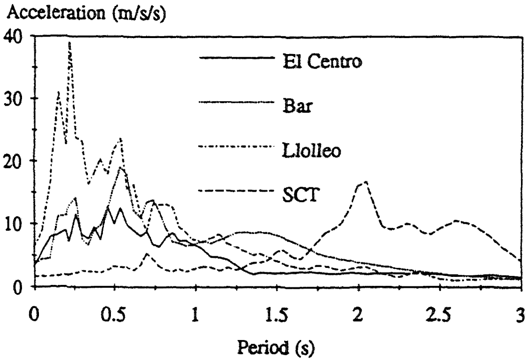

Figure 1. Elastic response spectra, 2 % damping.

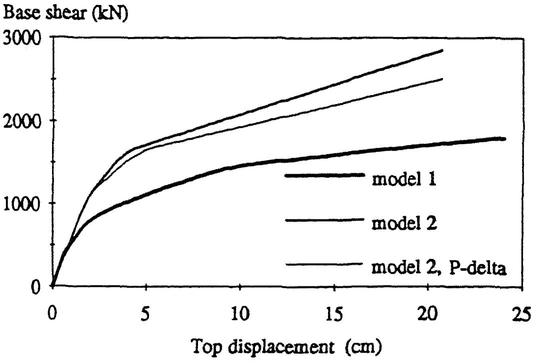

Figure 2. Base shear - top displacement relationship.

(1.1 % of the height of the structure). Two per cent mass-proportional damping, which exaggerates the higher mode effects, was chosen. The initial fundamental natural period of the structure, based on uncracked cross-sections, is equal to 0.74 sec. Considering the elastic response spectra of the input motions, shown in Fig. 1, the strongest higher mode effects can be expected in the case of the Llolleo input motion, and the weakest in the case of the SCT record.

The most important results of the comparative analyses are shown in Table 2 and in Figs. 2 to 5. It should be noted that the analyses are intended to judge the accuracy of the individual steps in the N2 method. For this reason the target values in the static MDOF analysis (top displacements and total histeretic energies) are taken from the dynamic analyses, rather than from the analysis of equivalent SDOF systems or even from general purpose inelastic spectra.

In Fig. 2 is presented the base shear (Q) - top displacement (u) relationship obtained in the static analysis (with an inverted triangular distribution of the lateral load) for both models. The greater lateral strength of the structure with a weak first story (about 23 % of the weight comparing to about 13 % of the weight in the case of Model 1) can be attributed to the strong beams. In the case of Model 2, the influence of second order theory was checked. It was not possible to observe any dramatic changes in the results. Consequently, first order theory has been used in the computations which followed.

Based on the static Q - u relationship two equivalent SDOF systems were determined.

The top displacement time-histories of the MDOF and SDOF systems are shown in Fig. 3. Good agreement can be observed. The higher mode effects, which can be clearly seen especially in the case of Model 1 when subjected to the Llolleo ground motion, cannot be reproduced by the SDOF model. In the case of the SCT ground motion, the fundamental natural period is lower than the predominant period of the ground motion, and the response is highly influenced by the details of the model. The response of Model 2 to SCT ground motion is practically elastic and is not taken into consideration in the discussions which follow.

Some conclusions regarding the total dissipated hysteretic energy E_H can be made based on the results presented in Table 2. E_H increases with the duration of strong ground motion. It is much influenced by the

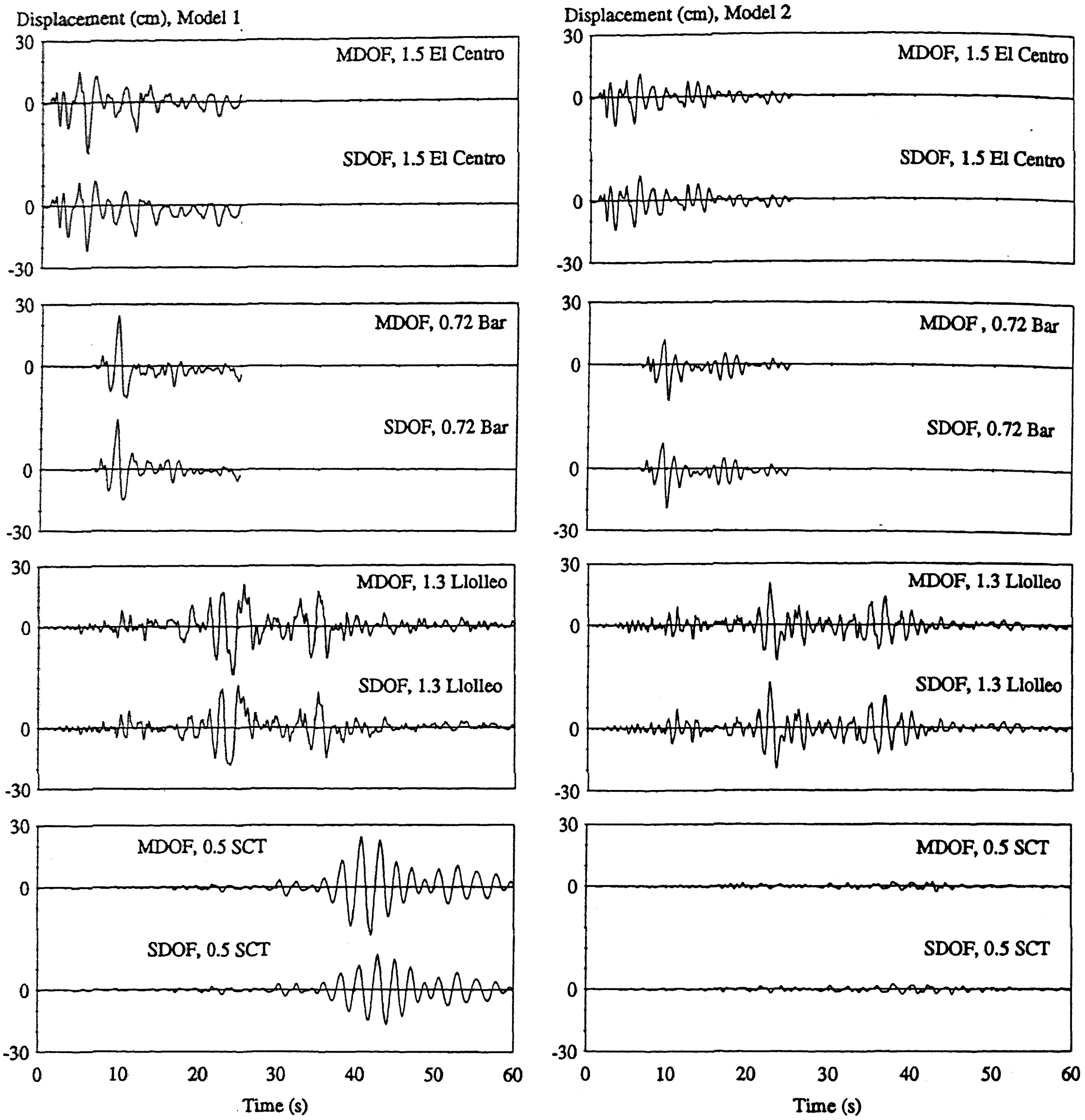

Figure 3. Top displacement time-histories.

change in the strength of the structural elements. The SDOF system provides a fair estimate of E_H, except in the case of Model 1 when subjected to the Llolleo ground motion, where the SDOF estimate is much too low due to large higher mode effects.

In Figs. 4 and 5 the distribution of various response parameters along the height of the building is shown. The maximum values obtained in the dynamic time-history analysis have been compared with the results obtained under a monotonically increasing lateral load with inverted triangular distribution. The target top displacements and the total dissipated histeretic energies in the static analysis are assumed to be the same as the corresponding maximum values determined in the dynamic analyses.

As far as displacements and story drifts are concerned (Fig. 4), very good agreement between the static and dynamic results can be observed in the case of Model 1 when subjected to the SCT and Bar ground motions, where the influence of vibrations in higher modes is negligible. In the case of the Llolleo and El Centro ground motions, the difference between the dynamic and static results is important. The dynamic story drifts in the upper stories are larger than those predicted by static analysis. The opposite is true in the lower stories. In the case of Model 2 the inelastic

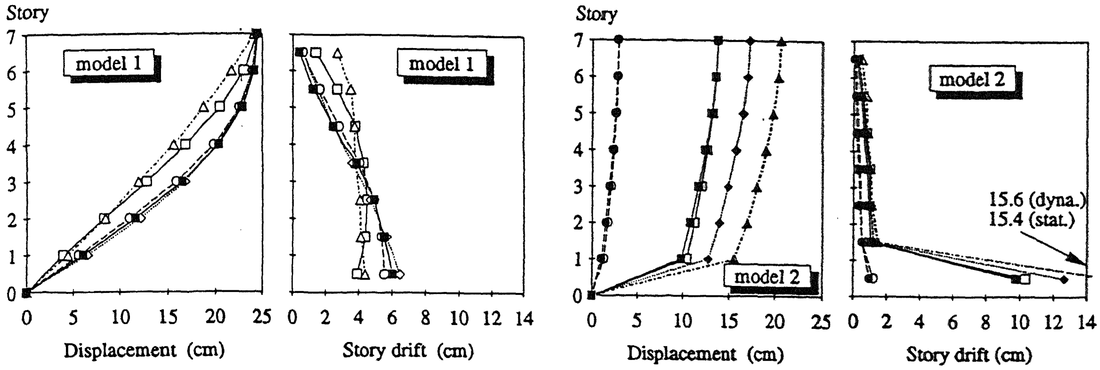

Figure 4. Displacements and story drifts.

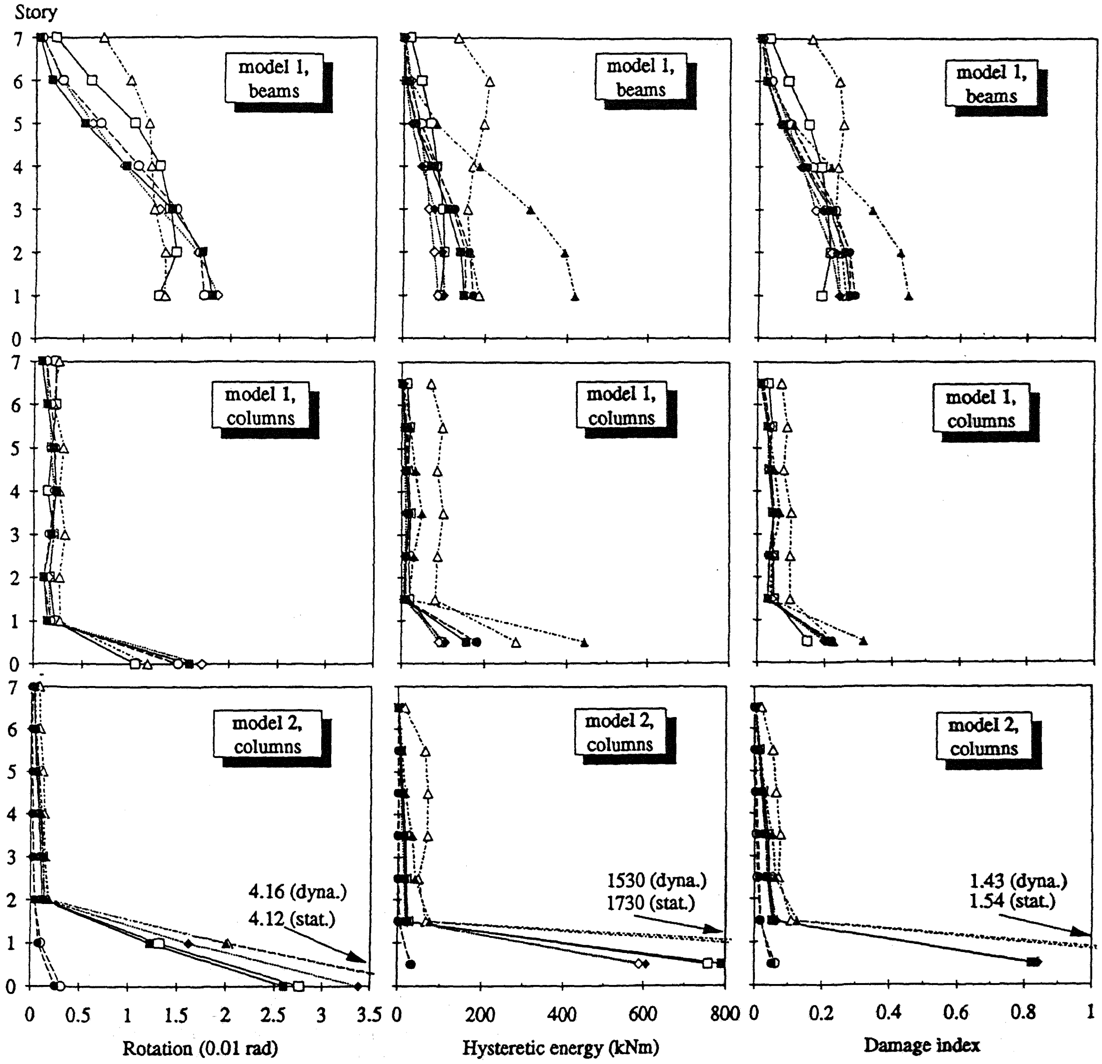

Figure 5. Rotations, hysteretic energies and damage indices.

behaviour is governed by the weak first story. Excellent agreement between the static and dynamic results can be observed for all ground motions.

Similar conclusions can be drawn from Fig. 5, where the rotations (average values of maximum joint rotations in each story), dissipated hysteretic energies E_H (the sum of maximum E_H for the elements in each story) and the story level damage indices DM are shown. The damage indices were determined according to the procedure developed by Park et al (1987), using the Park-Ang model (Eq. 1) expressed in terms of rotations ($\beta = 0.15$ was chosen). A DM larger than 1 represents collapse. The results in Fig. 5 show that large energy and damage concentrations in the weak first story of Model 2 can be accurately predicted by static analysis.

The damage indices for the whole structure, shown in Table 2, indicate acceptable behaviour of Model 1 and the potential collapse of Model 2, especially in the case of a long duration ground motion like Llolleo.

CONCLUSIONS

Based on the limited amount of data obtained in the reported study, as well as on the results published by other researchers, the following general conclusions can be drawn.

A simplified method for nonlinear seismic analysis, like the N2 method, yields results of reasonable accuracy provided that the structure oscillates predominantly in the first mode. An approximation to the distribution of maximum deformations, as well as the dissipated hysteretic energy throughout the structure (which may be very important in the case of an input motion of long duration) can be obtained. The method detects the weak points of a structure (e.g. the weak first story in Model 2) and may contribute to a more rational design of building structures.

If the first natural period of the structure is much larger than the predominant period of the ground motion, the higher mode effects may be important. In such a case the input energy and dissipated hysteretic energy of a MDOF system are generally larger than the corresponding quantities in the equivalent SDOF system. Furthermore, all quantities which govern damage will be underestimated in the upper part of the structure, if the N2 method is used. An improvement of the results could be obtained by using a modified vertical distribution of the lateral load. General rules for such a distribution, however, have not yet been defined.

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