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Input energy based seismic design code

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ABSTRACT: Shear buildings up to four stories high, subjected to different earthquake loadings, have been analyzed and evaluated. A Newmark linear acceleration direct integration method has been employed. Deformations, forces and energy in the elasto-plastic ranges have been computed. The results show that as a basis for a seismic design code, the energy approach is relatively more consistent than the base shear approach.

1. INTRODUCTION

Base shear coefficient used in most seismic codes as suggested by Choi (1988), IMPW (1983), and Naeim (1989) depends on factors such as importance, site condition, desired response and the building predominant period. For multistory buildings the shear distribution along the stories is defined as a function of the mass and height of each building story.

This paper proposes a design approach with improved accuracy requiring little sophistication. It has been shown by Akiyama (1985 and 1988) that the energy based design is proven to be simple and yet more consistent. Subsequent studies by Noor (1989) and Surahman (1990 and 1991) confirmed this claim.

Table 1. Generated earthquake records.

Name	Year	Direction	Duration [sec.]	Maximum acceleration [gal]
Denpasar	1979	EW	36	175
Denpasar	1979	NS	36	117
El Centro	1940	NS	40	349
Hachinohe	1968	EW	35	166
Hachinohe	1968	NS	35	200
Taft	1952	N21E	17	175
Mexico City	1964	NS	40	25
Parkfield	1966	N39W	14	488

The scope of this paper is limited to shear buildings up to four stories high. An elastic perfectly plastic hysteresis model has been employed. Two different stiffness distributions (uniform and linear, i.e., k, 2k, 3k, ... from top to bottom) and mass distributions (uniform and half mass at the top) for the models have been assumed.

The accelerograms are generated to resemble known records as shown on Table 1. These generated earthquake loadings do not exactly match the actual records as given by Okamoto (1973) and Wiegel (1970), however, result in similar structural responses. This approach is taken with a notion that future earthquakes will not duplicate past records but the same site conditions will carry similar characteristics. The structures are evaluated at a 5% damping ratio.

2. PROPOSED DESIGN FORMAT

The input energy of a building due to earthquake can be expressed in the form of the equivalent velocity V_E:

$$V_E = \sqrt{(2E/M)} \qquad (1)$$

where E is the input energy and M is the total mass of the building. This ensures that the energy per unit mass is unique for a certain earthquake. Since the maximum ground acceleration varies from one earthquake to another it is then more convenient to derive the equivalent velocity for a standardized value of maximum ground acceleration. For different values of maximum ground accelerations, proportioning is applied. To reduce the effects of nonlinearities, the standard maximum ground acceleration should be taken from the statistics (briefly discussed by Newmark (1971) and Rosenblueth (1980)) as the expected maximum ground acceleration for a certain return period.

The standard equivalent velocity for a given site condition can be represented by a single curve as a function of the building period whereas the seismic zone factor is replaced by the proportioning procedure. The importance factor does not affect the time history analysis, moreover, it is also applicable to other loading conditions, therefore it should be part of an LRFD format.

Site and soil conditions can change the shape of the equivalent velocity curve. Unless the peak values differ significantly, this too can be conservatively simplified into a bilinear curve.

The curve is derived for a damping ratio of 5%. For other values of damping ratio the following empirical formula is used :

$$V/V_E = 1.418/(1 + 3h + 1.2\sqrt{h}) \qquad (2)$$

where h is the damping ratio and V is the respective equivalent velocity. To allow for elasto-plastic responses, the following formula is used:

$$E = F\,\delta(0.5 + n) \qquad (3)$$

where F and δ are the yield strength and deformation respectively, and n is the total cumulative ductility ratio. The relationship between n and the maximum ductility ratio μ depends on the amount of yield excursions but can be estimated by:

$$0.25n \le \mu \le n \qquad (4)$$

Equations (1) to (4) can readily be used for single story buildings. For multistory buildings it is proposed to use derived energy distribution curves of most common cases. One of such energy distribution curves is shown in the results given below.

3. DISCUSSIONS OF THE RESULTS

To underscore the limitations, the discussions and the resulting conclusions are valid only for the cases within the scope of this paper. However, some portions of the discussions are based on the results given by Noor (1989) and Surahman (1990 and 1991).

Table 2. Normalized maximum base shear coefficient for different building heights.

Earthquake	1 story	2 stories	3 stories	4 stories
El Centro NS	2.49	2.79	3.18	4.05
Denpasar EW	4.66	6.15	6.75	8.41
Denpasar NS	4.51	5.64	5.97	6.40

Table 2 shows that the maximum base shear, normalized with respect to the maximum ground acceleration (instead of the gravity), increases as the building height increases. These values are taken from models with uniform mass and stiffness distributions. The increase in the base shear is not as much in other models. Still, this implies that base shear derived from single degree of freedom models may result in unconservative design if applied to multistory buildings. A research is still being carried out to verify these results.

Figure 1 shows that the equivalent velocities (for one to four story models with uniform mass and stiffness distributions) do not depend on the building height or number of stories. It is also valid for other models and earthquake loadings. This shows that the energy concept can accurately be applied to multistory buildings at least up to four stories high.

Figures 2, 3 and 4 are taken from the results of four story models with uniform mass and stiffness distributions subjected to El Centro earthquake loading. Figure 2 shows the shear coefficient ratios of the upper stories to that of the base. The values significantly change when the mass and stiffness distributions change. According to the above referred seismic codes, assuming identical story heights, the values for the second, third and fourth stories would have been 1.2, 1.4, and 1.6 respectively. The discrepancies are expected since the structural responses depend on story mass and stiffness rather than height. Moreover, the recorded maximum shear forces along the stories do not necessarily occur at the same time.

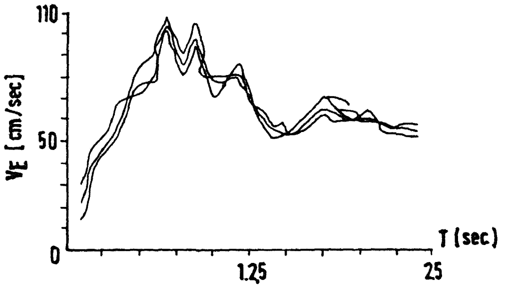

Figure 1. Equivalent velocities of El Centro earthquake for different building heights.

Figure 3 shows the energy absorbed by each story normalized to make the total energy equal to unity. It can be observed that the first story absorbs the largest amount of energy. This is even more distinct *when the mass of the fourth story is only half as* much. However, the energy is almost evenly distributed. The energy distribution also shifts to the story where plastification occurs most. Considering the inconsistency shown in Table 2 and the erratic curves shown in Figure 2 it is worthwile to consider the energy concept as a new approach for seismic

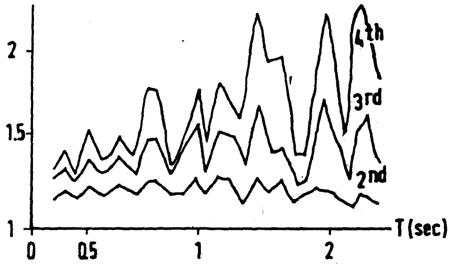

Figure 2. Upper story shear coefficient ratios.

the energy concept as a new approach for seismic design.

Tables 3 and 4 show shear and energy distributions obtained from two story elastic models with uniform mass distribution, and first natural periods up to 2.40 and 2.70 seconds for the models with uniform and linear stiffness distributions respectively.

Table 3. Second story shear coefficient ratio ranges for constant and linear stiffness distributions.

T [seconds]:	0.0-1.0	1.0-2.0	over 2.0
Mexico	1.04-1.22	1.15-1.25	1.24-1.29
	1.08-1.39	1.20-1.46	1.27-1.56
Parkfield	1.10-1.34	1.34-1.79	1.50-1.78
	1.11-1.53	1.53-1.84	1.47-1.84
Taft	1.15-1.44	1.27-1.55	1.21-1.36
	1.25-1.64	1.37-1.69	1.40-1.64
Denpasar	1.14-1.51	1.45-2.09	1.21-1.41
(EW)	1.24-1.94	1.10-2.15	1.07-1.47
Denpasar	1.15-1.46	1.46-2.02	1.30-1.48
(NS)	1.25-1.85	1.23-2.21	1.16-1.55
Hachinohe	1.12-1.30	1.22-1.39	1.21-1.30
(EW)	1.23-1.47	1.23-1.55	1.32-1.55
Hachinohe	1.14-1.24	1.10-1.32	1.19-1.32
(NS)	1.10-1.48	1.25-1.53	1.27-1.56

The results show significant deviations from the value of 1.33 obtained from the seismic codes. It is important to keep in mind that based on energy approach an over designed second story may result in more damage to the first story. The variations for constant stiffness models are relatively smaller in the energy distributions as shown on Table 4. For linear stiffness models the variations are still too high, however, adjustments in the design can easily be made by making use of Equation (3), explained below, and the graphs of Figure 1.

Table 4. First story energy percentage ranges for constant and linear stiffness distributions.

T [seconds]:	0.0-1.0	1.0-2.0	over 2.0
Mexico	73-77	72-75	71-72
	50-64	49-58	45-55
Parkfield	69-77	56-69	56-64
	46-61	37-46	37-48
Taft	68-73	66-73	68-73
	43-56	41-52	43-50
Denpasar	64-75	48-64	66-70
(EW)	35-56	30-62	47-62
Denpasar	37-57	58-64	64-71
(NS)	37-55	29-57	45-61
Hachinohe	70-76	67-73	70-73
(EW)	48-56	46-53	47-51
Hachinohe	72-75	70-77	70-74
(NS)	48-62	45-59	49-55

The accuracy of Equation (2) has been proven to be satisfactory by the above mentioned studies. The standardized value of 5% is taken since this value of damping ratio is often used in design practice. Deviations from 5% are expected to be small thus reducing inaccuracies.

Equation (3) provides an analytical basis for reducing the design shear capacity when taking plastification into account. It can also be used for designing against two consecutive (or more) earthquakes. The outstanding question in this matter is the relationship between μ (often used in design) and n (representing cumulative damage). Equation (4) provides a relationship between the two variables. The ratio n/μ is large for a large number of yield excursions, becomes unity for a single yield excursion, and undefined in the elastic range. Figure 4 shows that the ratio tends to decrease as the building period increases. A research to determine this relationship and its practical use in the design is also being carried out.

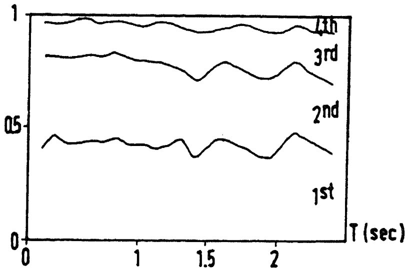

Figure 3. Energy distribution.

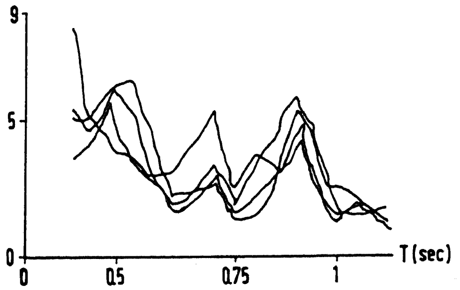

Figure 4. Ratio of total to maximum ductility.

In the analysis the elastic undamped building period has been used. This way, apart of keeping the procedure as practical as possible the effects of plastification can easily be compared.

4. CONCLUSIONS

From the above analyses and discussions the following conclusions are derived :

1. The same curve of equivalent velocity is ap-

plicable to buildings regardless of the number of building stories. This may not be true for the base shear coefficient. More research is needed to implement the latter statement.

2. The seismic zone and return period can be directly incorporated into the design curve by proportioning provided that there is no significant differences in the soil behavior.
3. The importance factor should be applied only in an LRFD format.
4. Damping and plastification effects are included in the energy input design format by using relatively simple equations.
5. Curves for energy distribution and ratio between total and maximum ductility ratios can be generated as function of mass, stiffness and yield strength of each story.

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