A STUDY ON THE ENERGY METHOD FOR SEISMIC DESIGN OF STRUCTURES

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SYNOPSIS

The relationship between strong ground motion and input energy has been examined for structures of SDF system as well as shearing type MDF system. The influences of some structural parameters on energy response of the structures has been discussed. A suggestion of using parameter RYE to express energy spectrum is presented. For MDF system, if the yielding levels of different storeys have the same RYE value, the storey-distribution of hysteretic energy will be comparatively uniform. Otherwise, the concentration of hysteretic energy will occur in the weakened storey. The results in this paper are qualitative.

INTRODUCTION

The earthquake action on a structure is a time-history procedure, in which the earthquake energy transfers into the structure and, at the same time, the structure dissipates and reflects the energy. Therefore, it would be more realistic and rational to use the energy method which considers the energy consumption capacity of a structure, for seismic design. However, the seismic design method based on energy concept has not been studied thoroughly, therefore, it has not been used in engineering practice so far. It is still a rather difficult problem which must be studied with great efforts.

The topics of study in this respect are as follows:

(1) The relationship between ground motion and the energy input to the structures;
(2) The relationship between hysteretic energy and total input energy;
(3) The distribution of hysteretic energy in various parts of a structure;
(4) The relationship between hysteretic energy and ultimate bearing capacity of structures;
(5) The criteria and method for earthquake resistant design based on energy concept.

The authors attempt to examine the first three above mentioned topics, mainly the SDF system as well as the shearing type MDF system.

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CALCULATION OF ENERGY RESPONSE

1. The energy balance equation

The energy balance equation at any time can be expresed as

$$E_k + E_v + E_p + E_y = E_t$$

The terms in the equation represent kinetic energy E_k, energy dissipated due to viscous damaping E_v, elastic potential energy E_p, hysteretic energy E_y and the total input energy E_t, respectively.

2. Input excitation (ground motion)

In the calculation of energies, the following accelerograms are used: El-Centro NS 1940; Taft N69W 1952; Parkfield N65W 1956; Vernon NE 1933; Olimpia SW 1949; Los Angeles SW 1971.

3. Yield level of structure

It is concerned in two cases:

(1) Yield strength ratio (YSR)

$$YSR = \frac{\text{Horizontal Acceleration to Produce Yielding}}{\text{Maximum Peak Ground Acceleration}}$$

(2) The ratio of yield level to maximum elastic response level (RYE)

$$RYE = \frac{\text{Yield Level of System}}{\text{Maximum Elastic Response Level}}$$

4. Hysteretic properties of structure

3 restoring force models are used,i.e. elasto-plastic, bi-linear and tri-linear models.

5. Viscous damping

The critical damping is taken as 5 %.

FACTORS AFFECTING ENERGY RESPONSE

1. The normalization of acceleration records

The earthquake records have been normalized using maximum peak ground acceleration, maximum peak ground velocity and spectrum intensity (SI), respectively,and tried to calculate the energy response. The results indicate that the differences among energy responses of different input motions will be the least when the normalization is carried out with a common peak acceleration. Thus, we adopted this normalization in the later energy calculation, and 200 gal. is taken as the common normalized maximum acceleration.

2. The duration of strong motion

The accumulated total input energy of a structure increases consistently with time because the dissipated energy due to viscous damping exists throughout the whole duration. However, the hysteretic energy only arises from strong ground motion. The time by which the hysteretic energy reaches its maximum value relates to the nature of the input accelerogram. For the El-Centro and Parkfield earthquakes, the hysteretic energy is very close to the maximum value at t = 16sec. and t = 5-6sec., respectively (see Fig.1). The distribution of the time as the hysteretic energy reaches its maximum value is shown in Fig.2, which is calculated from the structures having different YSR and RYE values and periods.

3. Hysteretic model

Taking 3 different hysteretic models subjected to the same excitation (El-Centro earthquake), energy response of a structure with YSR = 0.3 has been calculated. The results indicat the following facts:

On total input energy, the influence of different hysteretic models is very little. For kinetic energy, potential energy and dissipated energy due to damping, the largest response occurs when the tri-linear model is used and the samallest response occurs when the elasto-plastic model is used, but vice versa for hysteretic energy.

4. The use of YSR and RYE

The influences of these two parameters on energy response are compared and the results will be discussed later. The main feature is that the variation of energy responses calculated from YSR value shows more dependence on the input excitation while the variation of energy responses calculated from RYE value appears some regularities which are independent of the input excitation.

ENERGY RESPONSE PROPERTIES OF SDF SYSTEM

The energy responses of two groups of SDF structures have been studied. The masses of which are all equal to 1 ton and the periods are 0.1, 0.2, 0.3, 0.5, 0.8, 1.0, 1.2, 1.5, 1.8, 2.0, 2.2, 2.5 and 3.0 sec.,respectively. The yielding levels are defined as YSR for one group and RYE for another group. For each group, the relationship between structural period and, respectively, the the maximum velocity responses, total input energies, maximum hysteretic energies and the ratios between the latter two values are presented. The following properties can be seen from the results.

1. The variationa of maximum velocity response with structural period (velocity spectrum) of the two groups of SDF structures are shown in Figs.3a and 3b. The spectrum values are the average velocity response values of 6 earthquakes.

(1) The two velocity spectra are very similar to the elastic velocity spectrum.

(2) Following the reduction of YSR and RYE values, the velocity spectra decrease gradually and regularly, and the variation of the values becomes more and more flat.

2. The variations of total input energy with period (input energy spectrum) of the 2 groups of structures are shown in Figs.4a and 4b. The spectra are the average total energy response values of 6 earthquakes.

(1) The 2 groups of input energy spectra vary in a rather similar regularity to the corresponding velocity spectrum.

(2) Following the reduction of YSR and RYE values, the total input energy spectra decrease gradually and regularly, and the variation of the values gets more and more flat too.

(3) The spectra of input energy calculated from RYE decrease slightly

with the increase of structural period.

3. The variation of hysteretic energy with period (spectra of hysteretic energy) of the 2 groups of structures are shown in Figs.5a and 5b. The spectra are the average values of hysteretic energy calculated from 6 input accelerograms.

(1) The hysteretic energy calculated from RYE values and the total input energy calculated from RYE values have a similar shape of spectrum.
(2) The spectra of hysteretic energy calculated from YSR values vary unregularly, especially when $YSR \geqslant 0.5$, that reduce rapidly with the increase of structural period. Thus, they are inconsistant with the total input energy spectrum.

4. The variations of ratios of hysteretic energy and total input energy with structural period are calculated from RYE values (3 typical acceleration records are used) and shown in Figs.6a, 6b and 6c. It is indicated that the variations are very regular.

5. Converted index of plastic deformation

We defined $\frac{E_\rho}{E_y} = D_\rho$ as the converted plastic deformation and $\frac{D_\rho}{P_d} = I_\varepsilon$ as the converted index of plastic deformation (P_d is real plastic deformation of structure during earthqauke). The variation of I_ε with period are shown in Fig.7. the index characterized the comparative correlation between the influences of hysteretic energy and deformation. For some type of earthquake (see Fig.7a, Parkfield earthquake), the indexes are relatively small, which indecates that the damage due to energy dissipation is somewhat less significant; for the other type of earthquake (see Fig.7b, El-Centro earthquake and 7c, Taft Earthquake), the indexes are relatively large, which indecates that the damage due to energy dissipation is somewhat more significant, and for this type of earthquake, the indexes in the part of short periods are larger than that in the part of long periods. This index seems to be a reference datum to establish the energy-deformation criteria of seismic safety of structures.

From the foregoing analyses to the energy response of SDF structures, the following can be derived:

(1) The total input energy to a SDF structure can be related to the ground motion by means of velocity spectrum or total input energy spectrum directly.
(2) The hysteretic energy of a SDF structure can be related to the total input energy by means of yielding level expressed by RYE value.
(3) The yielding level of a structure is an important structural parameter which defines the hysteretic energy, and it can be characterized much better with RYE than with YSR.

ENERGY RESPONSE PROPERTIES OF MDF SYSTEM

Taking systems with 3 masses as typical MDF systems, we studied the effects of different structural parameters on energy response of MDF systems.

1. The structures in table 1 show the variation in storey-distribution of yielding strength (A and B lines), storey-distribution of stiffness (B and C

lines), masses (C and D lines) and RYE value (E,F and G lines), respectively. The energy response of different structures are shown in table 2. From the results of first four structures it can be seen that the values of total input energy and the ratios between hysteretic energy and the total input energy are more or less the same for the structures having the same periods and the same YSR, the storey-distribution of stiffness and masses have only a little effect on the storey-distribution of hysteretic energy, but the variation of storey yielding strength has considerable influences on it. From the results of other three structures it can be seen that the total energy decreases with the reduction of RYE value. The ratio between hysteretic energy and total energy vary slightly.

2. Figs.8-11 show the variation of total energy and hysteretic energy with fundamental period for the structures having uniform RYE value (0.1, 0.2 and 0.3, respectively) and the comparison with SDF systems. These results indicate that the variation of energies with fundamental period for 3 degree of freedom structures are similar to the energy spectra of SDF systems, and that it seems to be hopeful to determine the total input energy to MDF systems by means of the energy spectrum of SDF systems.

3. Figs.12 - 13 show the comparison of energies for the structures having weakened RYE values (see curves E_1, E_2) and for the structures having uniform RYE value (see curve E). When 30 % of the RYE is weakened in a centain storey the amount of total input energy and hysteretic energy do not vary substantialy.

4. The energy response of 5 and 8 degree of freedom structures has been calculated. Fig.14 shows the comparison between storey hysteretic energy and storey deformation of structures having uniform and weakened RYE values, respectively. It is shown that the storey-distribution of hysteretic energy and the distribution of storey deformation are analogous and have identical tendency. When the RYE values are uniform, both the hysteretic energy and the deformation will be distributed comparatively uniformly.But, if the RYE values are weakened in one storey, they will considerably concentrate in the weakened storey.

CONCLUSIONS

1. For a SDF system, the total input energy and the hysteretic energy can be related to the strong ground motion by means of velocity spectrum or, more directly, energy spectrum.
2. for a MDF system, it appears to be possible to determine the total input energy and the hysteretic energy by means of the corresponding energy spectrum of SDF systems.
3. The RYE value is a better parameter for establishing energy spectrum. For a MDF system, if the yielding level in every storey has the same RYE value, the storey-distribution of hysteretic energy will be comparatively uniform. the storey where the RYE value is weakened will be the one where the hysteretic energy and the deformation are concentrated. Thus, it is the weak link for earthquake resistance.
4. The converted index of plastic deformation may be a reference datum to establish the energy-deformation criteria of seismic safety of structures.
5. Only qualitative conclusions have been discussed in this paper. The quantitative expressions have to be studied further.

ACKNOWLADGEMENT

The authors are thankful to Mr.Zhou Xiyan, Mr.Liu Xihui, Mr.Dai Guoying and Mr.Wei Chengji for their great help.

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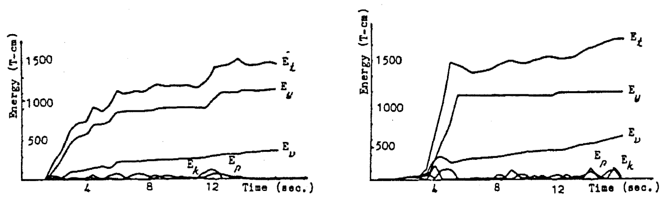


a. El-Centro Earthquake

b. Parkfield Earthquake

Fig.1 Time History of Energy Response

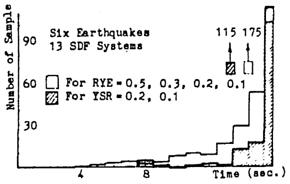
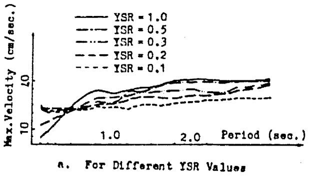
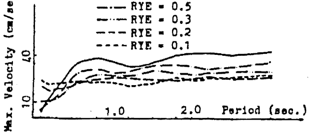


Fig.2 Distribution of Time of Reaching Max. Hyst. Energy

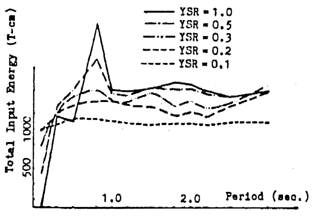


a. For Different YSR Values

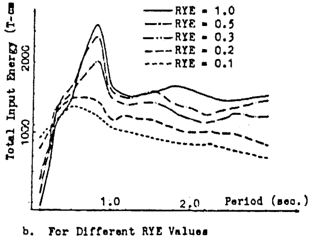


b. For Different RYE Values

Fig.3 Max. Velocity v. Period(SDF)

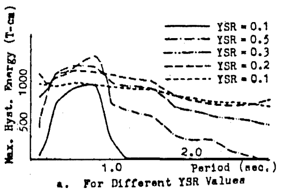


a. For Different YSR Values

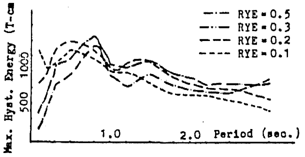


b. For Different RYE Values

Fig.4 Total Input Energy v. Period (SDF)

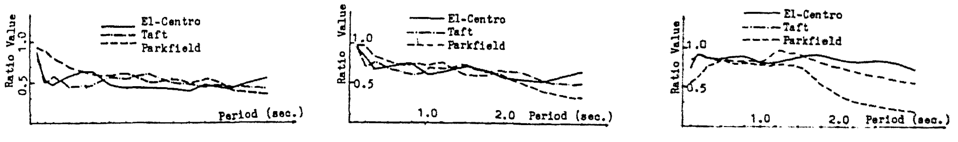


a. For Different YSR Values



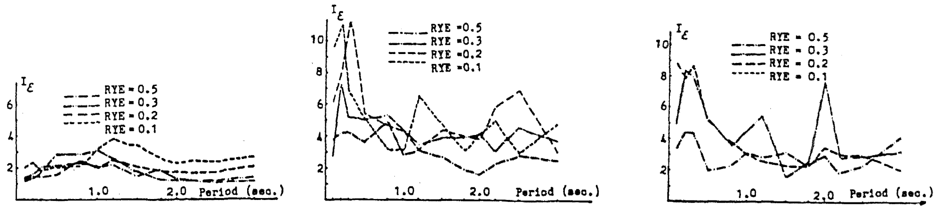
b. For Different RYE Values

Fig.5 Max. Hyst. Energy v. Period (SDF)



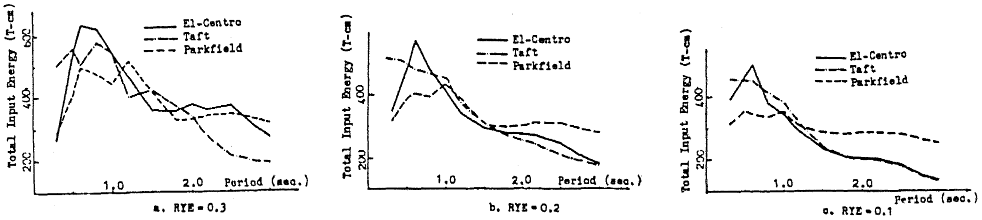
a. RYE = 0.5 b. RYE = 0.3 c. RYE = 0.1

Fig.6 Ratio of E_y to E_ℓ v. Preiod (SDF)



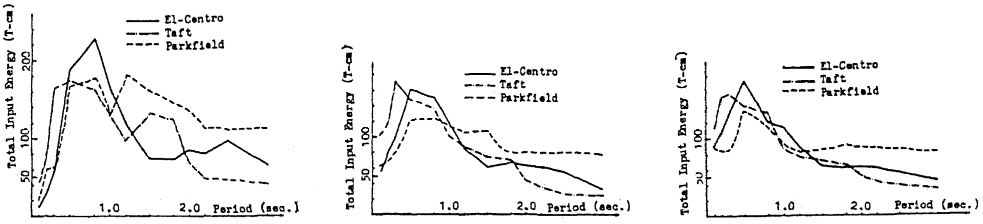
a. For Parkerfield Earthquake b. For El-Centro Earthquake c. For Taft Earthquake

Fig.7 Converted Hyst. Deformation Index



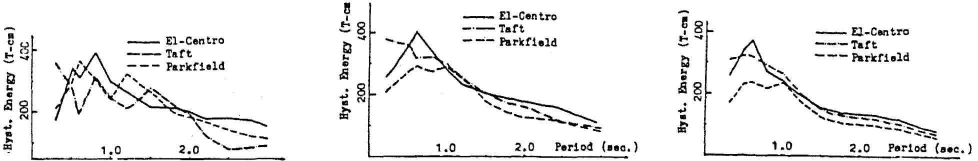
a. RYE = 0.3 b. RYE = 0.2 c. RYE = 0.1

Fig.8 Total Input Energy v. Fund. Period (MDF)



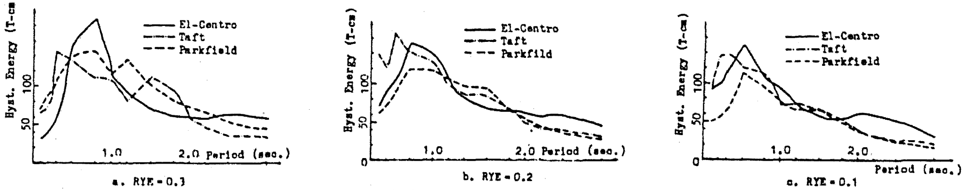
a. RYE = 0.3 b. RYE = 0.2 c. RYE = 0.1

Fig.9 Total Input Energy v. Period (SDF)



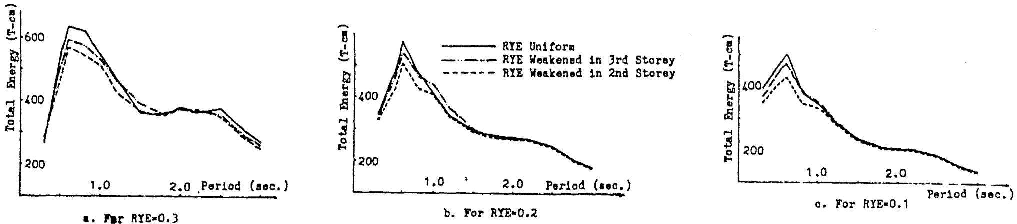
a. REY = 0.3 b. RYE = 0.2 c. RYE = 0.1

Fig.10 Hyst. Energy v. Fund, Period (MDF)



a. RYE = 0.3 b. RYE = 0.2 c. RYE = 0.1

Fig.11 Hyst. Energy v. Period (SDF)

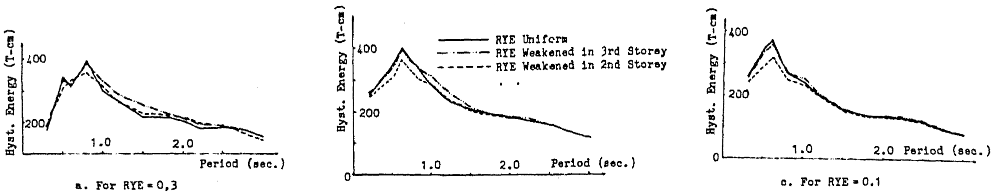


a. For RYE=0.3

b. For RYE=0.2

c. For RYE=0.1

Fig.12 Total Energy V. Fund. Period For Uniform and Weakened RYE

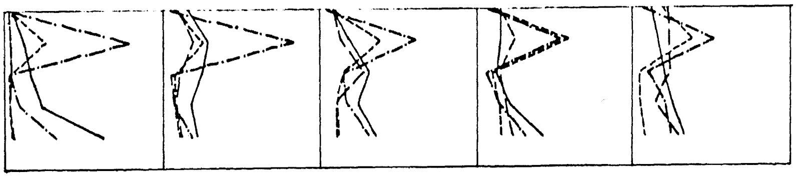


a. For RYE = 0,3

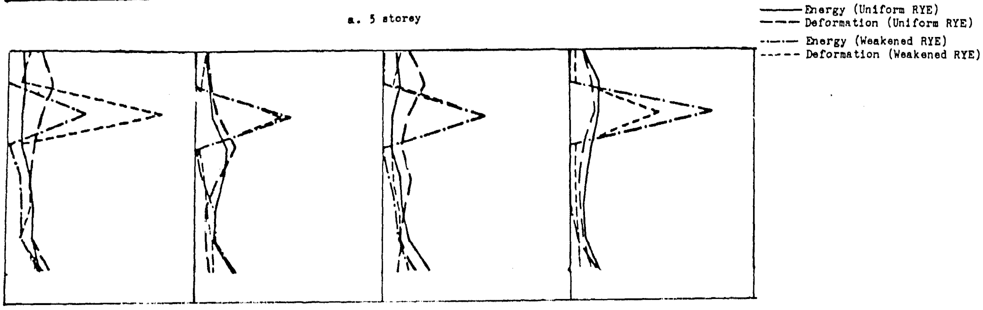
b. For RYE = 0.2

c. For RYE = 0.1

Fig.13 Hyst. Energy v. Fund.Period for Uniform and Weakened RYE Values



a. 5 storey



b. 8 storey

Fig.14 Storey Hyst. Energy & Deformation

Table 1 Parameters of 3-Storey Structures

Parameters / Structures	Storey Masses (T·sec /cm) 1st	2nd	3rd	Storey Yielding Strength (T) 1st	2nd	3rd	Ratios of Storey Stiffness 1st : 2nd : 3rd	YSR	RYE
A	0.1	0.1	0.1	20	20	20	1 : 1 : 1	0.2	
B	0.1	0.1	0.1	30	20	10	1 : 1 : 1	0.3	
C	0.1	0.1	0.1	30	20	10	1 : 0.8 : 0.6	0.3	
D	0.1	0.08	0.06	30	20	10	1 : 0.8 : 0.6	0.3	
E	0.1	0.1	0.1				1 : 0.7 : 0.4		0.3
F	0.1	0.1	0.1				1 : 0.7 : 0.4		0.2
G	0.1	0.1	0.1				1 : 0.7 : 0.4		0.1

Table 2 Results for 3-Storey Structures

Structures	Fund. Period sec	YSR	RYE	Total Energy T·cm	Hyst. Energy / Total Energy %	Distribution of Hyst. Energy % 1st : 2nd : 3rd
A	1.4	0.2		959	41	93.0 : 6.0 : 1.0
	0.6	0.2		1347	65	85.0 : 14.6 : 0.4
B	1.4	0.3		1083	42	21.0 : 22.0 : 57.0
	0.6	0.3		1507	68	34.0 : 39.0 : 27.0
C	0.6	0.3		1464	68	28.0 : 35.0 : 37.0
D	0.6	0.3		1345	64	40.8 : 38.5 : 20.7
E	1.2		0.3	466	56	34.5 : 31.1 : 34.4
F	1.2		0.2	342	68	52.6 : 21.2 : 26.2
G	1.2		0.1	291	69	63.3 : 19.6 : 17.2