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EARTHQUAKE RESISTANT DESIGN BASED ON THE ENERGY CONCEPT

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SUMMARY

The most fundamental problem in carrying out earthquake resistant design is to grasp the nature of seismic input on buildings. The author has demonstrated that the energy input should be considered as the principal loading effect on buildings (Ref.1,2). On the basis of energy concept, an unified criterion for earthquake resistant design can be derived. This criterion is expressed in a simplest form and can meet any sort of buildings. This paper aims at interpreting the criterion and exploring possibilities of advantageous design methods by way of shear-type of multi-story of buildings.

DESIGN METHODOLOGY BASED ON THE ENERGY CONCEPT

Total Energy Input The total energy input made by an earthquake depends mainly on the total mass, M and the fundamental natural period of structure, T, and is scarcely affected by the strength and the type of restoring force characteristics (Ref.3). Thus, the energy concept initiated by Housner must be the most sound basis for developing the earthquake resistant design for buildings (Ref.4).

The total energy input becomes more stable as the nonlinearity of structures develops. Generally, structure can develop considerable amount of plastic deformations until their ultimate strength state is reached. Therefore, when the ultimate resistance of the structure is discussed, the total energy input can be represented by one which corresponds to one-mass elastic system with high damping capacity. In this paper the energy spectrum is defined to be the $V_E - T$ relationship, where V_E is a pseudo-velocity converted from the total energy input to the one-mass system with 10% of damping constant, E through Wq(1).

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

As is shown in Fig.1, the energy spectrum can be simply expressed by two line segments which envelop the energy spectrum. One is parallel to the T-axis and V_0 is given by the ordinate of this line segment. Another line passes through the point of origin and envelops the shorter period range of the V_E-T curve. T_{G0} is the period which corresponds to the intersection of two line segments. To meet the fact that the energy input of structures with shorter natural period is increased by a substantial increase of period of vibration due to their plastification, T_{G0} should be shortened to T_{G0}/β (= T_G in Fig.1). Then, the energy spectrum for the ultimate strength design is depicted by solid lines in the figure. For ordinary buildings, β should be taken to be 1.2.

Damage Concentration The equilibrium of energy in a structure under an earthquake is described as

$$W_e + W_p + W_h = E \qquad (2)$$

where W_e :elastic vibrational energy, W_h : energy absorption due to miscellaneous damping, W_p :cumulative inelastic strain energy.

W_p consists of cumulative inelastic strain energy in every story, W_{pi}. Thus,

$$W_p = \sum_i W_{pi} \qquad (3)$$

where N;number of story.

W_p and W_{pi} can be regarded as structural damage. Each story of a shear type multi-story structures is considered to be composed of a stiff element and a flexible element. The flexible element has a small stiffness and remain elastic, whereas the stiff element has a large stiffness and behaves inelastically. The relation between the shear resistance and the story displacement is depicted in Fig.2, where the elastic-perfectly plastic restoring force characteristics of the stiff element is assumed. Assuming that the spring constant of the stiff element, k_s is sufficiently larger than that of the flexible element, k_f , the contribution of energy absorption of the flexible element can be neglected. Then, the damage of the first story of a building is written as

$$W_{p1} = \frac{Mg^2T^2}{4\pi^2} \times \frac{2\alpha_1^2\ \bar{\eta}_1}{\kappa_1} \qquad (4)$$

where α_1 :yield shear force coefficient of the first story ($=Q_{Y1}/Mg$), Q_{Y1} :yield shear force of the first story, $\bar{\eta}_1$: averaged cumulative inelastic deformation ratio of the first story (=cumulative inelastic deformation/ two times of yield displacement, δ_Y(see Fig.2(a)), $\kappa_1 = k_1/(4\pi^2 M/T^2)$, g :acceleration of gravity.

The total damage of a structure, W_p can be formally related to W_{p1} as

$$W_p = a_1\ W_{p1} \qquad (5)$$

In the shear-type muti-story structures, it has been made clear that a_1 is expressed by the following formula.

$$a_1 = 1 + \sum_{j\neq 1} s_j\,(\ p_j/p_1\ )^{-n} \qquad (6)$$

where $p_j = \dfrac{\alpha_j}{\alpha_1\bar{\alpha}_j}$, $s_j = (\sum_{i=j}^{N} m_i/M)^2\bar{\alpha}_j^2\,(k_1/k_j)$

$\bar{\alpha}_j$:optimum yield shear force coefficient distribution,
α_i/α_1:actual yield shear force coefficient distribution
m_i:mass of ith floor, k_i :spring constant of ith story.

p_j means a deviation of the actual yield shear force distribution from the optimum yield shear force distribution under which the damage of every story, $\bar{\eta}_i$ is equalized, and is termed the damage concentration factor. n is termed the damage concentration index. When n becomes sufficiently large, a_1 becomes unity. It means that a sheer damage concentration takes place in the first story. When n is nullified, a most preferable damage distribution is realized. Practically, the value of n ranges between 2.0 and 12.0. Weak-column type of structures are very susceptible of damage concentration, and the n-value for them should be 12.0. In weak-beam structures, the damage concentration is considerably mitigated due to the elastic action of columns, and the n-value can be reduced to 6.0. In Fig. 3(c), a generallized form of weak-beam type structure is shown. The presence of a vertically extending elastic column is essential to this type of structure. The elastic column by itself is not required to withstand any seismic forces. While ordinary frames pin-connected to the elastic column absorbs inelastically seimic energy, the elastic column plays a role of damage distributor. By applying this type of structure, the n-value can be reduced to 2.0.
The damage concentration is also governed by the value of p_j. To simply estimate the damage concentration in the first story, an unified value may be applied as p_j as follows.

$$p_1 = 1.0 \qquad p_{j\neq 1} = p_d \qquad (7)$$

Eq(7) signifies that the strength gap is assumed between the first story and the other stories. It is impossible to make the yield shear force distribution of an actual multi-story building agree completely with the optimum distribution. The reasons are easily found in the scatter in mechanical properties of materials and the rearrangement of geometrical shapes of structural members for the purpose of simplification in fabricating process. Taking account of such a situation, The following value is proposed as a minimum strength gap to be taken into accout in the design procedure.

$$p_d = 1.185 - 0.0014N \qquad p_d \geq 1.1 \tag{8}$$

Design Formulation The elastic vibrational energy is expressed as follows.

$$W_e = \frac{Mg^2T^2}{4\pi^2} \times \frac{\alpha_1^2}{2} \tag{9}$$

Taking account of damping, Eq(1) is reduced to

$$W_p + W_e = E \times \frac{1}{(1 + 3h + 1.2\sqrt{h})^2} \tag{10}$$

where h = damping constant.

Substituting Eqs(9) and(5) into Eq(10) and using Eq(4), the following formula is obtained.

$$\alpha_1 = \frac{\alpha_e}{\sqrt{1 + 4\frac{a_1\bar{\eta}_1}{\kappa_1}}} \qquad \alpha_e = \frac{2\pi V_E}{Tg}\frac{1}{1 + 3h + 1.2\sqrt{h}} \tag{11}$$

Eq(11) is rewritten as

$$\alpha_1(T) = D_s(\bar{\eta})\,\alpha_e(T) \tag{12}$$

where $\alpha_e(T)$:required minnimum yield shear force coefficient for the elastic system with the fundamental natural period, T,
$\alpha_1(T)$:required minimum yield force coefficient of the first story for the inelastic system with T,
$D_s(\bar{\eta}_1)$:reduction factor for the yield shear force coefficient, which depends on $\bar{\eta}_1$.

Numerical Examples The distribution of masses is assumed to be uniform. The yield deformation of every story is also assumed constant. Then, the stiffness distribution, k_i/k_1 becomes equal to the strength distribution, Q_{Yi}/Q_{Y1}. The optimum yield shear force coefficient distribution, $\bar{\alpha}_i$ is given by the following formula.

$$\bar{\alpha}_i = f\left(\frac{i-1}{N}\right) \tag{13}$$

for $x > 0.2$, $f(x) = 1 + 1.5927x - 11.8519x^2 + 42.583x^3 - 59.48x^4 + 30.16x^5$

for $x \leq 0.2$ $f(x) = 1 + 0.5x$

Using the above-mentioned parameters, a_1 in Eq(5) and κ_1 are calculated and approximated by the following relations.

$$a_1 = 1 + 0.64(N-1)\ p_d^{-n} \tag{14}$$

$$\kappa_1 = 0.48 + 0.52N \tag{15}$$

Then, the D_s-value is written as

$$D_s = \frac{1}{\sqrt{1 + \frac{4\{1 + 0.64(N-1)p_d^{-n}\}\bar{\eta}_1}{0.48 + 0.52N}}} \tag{16}$$

The D_s-value for the one-story structure can be written as

$$D_{s1} = \frac{1}{\sqrt{1 + 4\eta_1}} \tag{17}$$

Applying Eqs(16) and (17), the ratio of D_s to D_{s1} is obtained for two values of $\bar{\eta}_1$ as shown in Fig.4. For comparison's sake, an increased value of p_d (=1.1 p_{d0}, p_{d0}:the value of Eq(8)) is applied under n=12.0 and the result is shown by broken lines. It is clearly shown that the required strength in multi-story structures becomes largely influenced by the damage concentration as the number of story, N and the inelasric deformation capacity, $\bar{\eta}_1$ increase.

POSSIBILITIES IN EARTHQUAKE RESISTANT DESIGN

The goal of earthquake resistant design can be summarized as follows.

1) to minimize α_1
2) to minimize the maximum story displacement , δ_{max}
3) to minimize the residual story displacement, δ_{pr}(see Fig.2(a))

To attain the first item, the following two measures are practicable.

1) to increase the deformation capacity, $\bar{\eta}_1$
2) to reduce the damage concentration index, n

The former is realized by applying mild steels to the stiff element. When the structural members are carefully selected so as to avoid structural instability such as local buckling and lateral buckling, it is not impossible to attain the value of $\bar{\eta}_1$ greater than 100. The later is realized by applying the weak-beam type structure or more general damage dispersing systems as shown in Fig.3(c). High-strength steels can be most effectively used as a vertical damage distributor.

To discuss the maximum story displacement, the inelastic deformation ratio, $\bar{\mu}$ is introduced as follows.

$$\bar{\mu} = (\bar{\delta}_{max} - \delta_Y) / \delta_Y \qquad (18)$$

where $\bar{\delta}_{max}$:avarage value of the maximum story displacement in the positive and negative directions.

The residual story displacement, δ_{pr} is equal to the difference between the cumulative inelastic deformations of positive and negative directions as seen in Fig.2(a). To reduce δ_{pr} and $\bar{\mu}$, the most effective measure is the application of "the fexible-stiff mixed structure". Only slight participation of the flexible element enables to nullify δ_{pr} and to reduce $\bar{\mu}$ remarkably as is seen in the following empirical relations (Ref.5).

$$\text{for} \quad k_f / k_s = 0, \ \bar{\mu} = \frac{\bar{\eta}}{2} , \quad \text{for} \quad k_f / k_s > 0.03, \ \bar{\mu} = \frac{\bar{\eta}}{4} \ \text{to} \ \bar{\mu} = \frac{\bar{\eta}}{6} \qquad (19)$$

The stiff elements are the source of energy absorption, whereas flexible elements restrain effectively development of excessive deformations and one-sided deformations. Again, high-strength steels can be very suitable materials to form the flexible element.

CONCLUSION

The total energy input made by an earthquake depends mainly on the total mass and the fundamental natural period of structure, and the damage concentration is very likely to occur in multi-story structures. To meet such a situation, it is concluded that the flexible-stiff mixed structure is the most preferable structural form and this form can be realized by the combined use of ordinary structural steels and high-strength steels (Ref.6). While the ordinary steels absorb energy inelastically, the high-strength steels prevent damage concentration and excessive deformations.

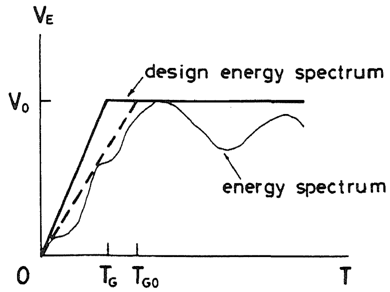

Fig.1 ENERGY SPECTRUM

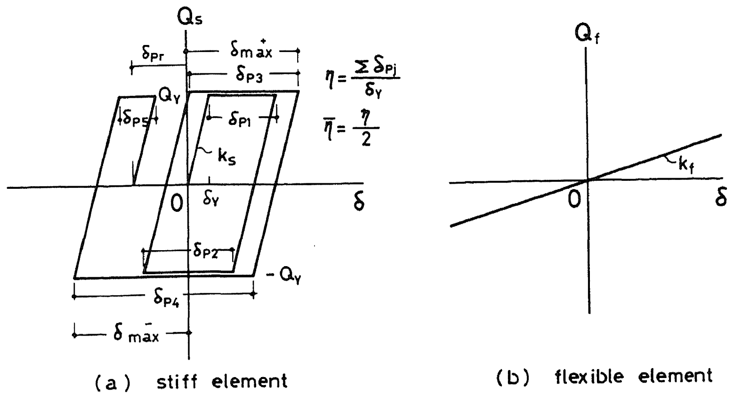

Fig.2 EARTHQUAKE-RESISTANT ELEMENTS IN EACH STORY OF A BUILDING

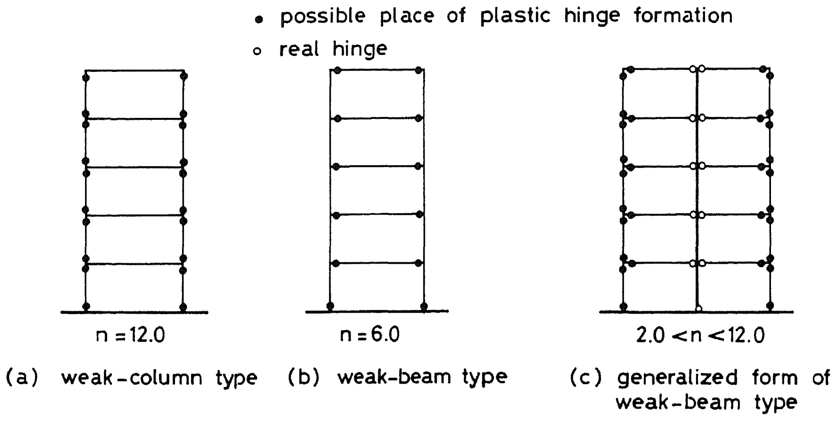

Fig.3 CLASSIFICATION OF STRUCTURES IN TERMS OF DAMAGE CONCENTRATION

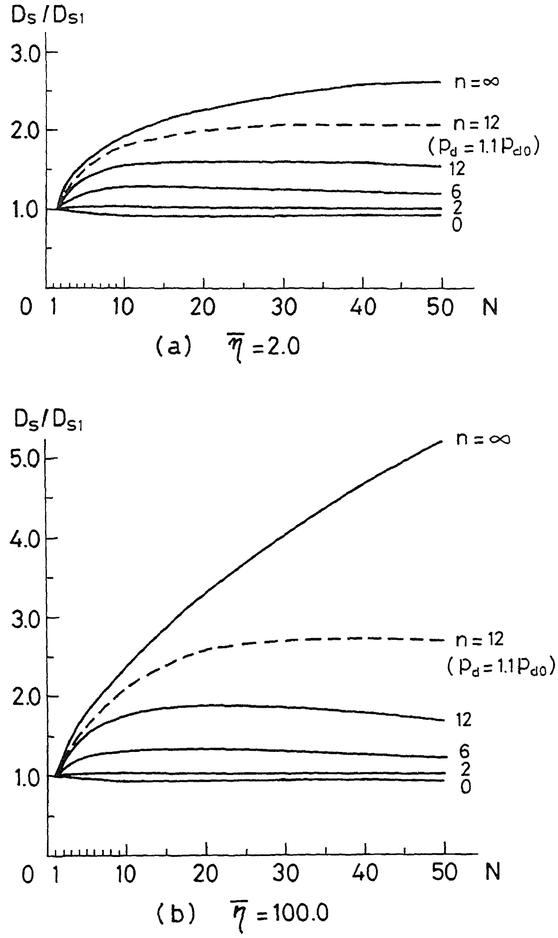

Fig.4 GENERAL SKETCH OF D_s/D_{s1} — N RELATIONSHIP

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