AN ENERGY DISSIPATION FACTOR AS STRUCTURAL DESIGN CRITERION FOR STRONG EARTHQUAKE MOTION

by

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SYNOPSIS

An energy dissipation factor defined as ratio between the energy stored in the structure at ultimate stage and that at yield point, is proposed. Practical application of the factor is given for coupled shear walls, assuming an upper triangular load pattern to simulate the dynamic effect of earthquake motion. This factor may be compared with ratio of energies expressed by the ratio between the squares of the spectral velocities for a given critical damping factor of a strong earthquake and a moderate one on which the code is based.

INTRODUCTION

Previous earthquakes have demonstrated that energy dissipation is a key factor in explaining the behaviour of structures during strong motion earthquakes. Reflecting this experience it has been suggested that aseismic design should consist of two steps: (1) elastic design according to codes which generally simulate moderate earthquakes, and (2) limit design for strong earthquakes. The first step is already accomplished by using well established principles in the theory of structural dynamics. For the second step design procedures based on energy considerations have been proposed, but they seem to be to sophisticated for design practice. The need for simplicity in practical design requires that the second step should take the form of pseudo static method as well. Many codes avoid the second step, by requiring a ductility factor and by introducing a penalty for structures not meeting these requirements. These requirements have only a qualitative basis without any quantitative criteria to predict the strength of the earthquakes for which the structure will resist at limit. In modern structures the nonstructural elements have a very low ability to dissipate energy and may be neglected. For such structures a more rational criterion to qualify quantitatively the ability of a structure to resist at limit a given earthquake may be formulated on energy basis. The proposed energy dissipation factor is defined to be the ratio between the elastic energy stored plus energy dissipated by plastic deformations when the structure reaches its limit stage, and the elastic energy at yield point stored in the structure. This factor may be then compared with the ratio of energies expressed by the ratio between the squares of the spectral velocities for a given critical damping factor of a strong motion earthquake and a moderate one on which the code is based.

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The paper presents the practical application of the energy dissipation factor in designing coupled shear walls (see Fig. 1a). The ability of these structures to dissipate energy by plastic deformation is a direct function of the rotational ductility factor at the coupling beam supports. Given charts may be used directly to establish the energy dissipation factor for coupled shear walls and associated with it, the rotational ductility factor of coupling beams. The charts were calculated for an upper triangle lateral load pattern which is very often used to simulate the dynamic effect of earthquake motion.

For analysis of the coupled shear wall the laminar approach was applied. In this technique the coupling beams formed by vertically arranged uniform openings in a wall are replaced by infinetisimal elastic laminas of equivalent stiffness (see Fig. 1b). The ultimate stages will depend on the slenderness of the wall. For low structures plastic hinges at coupling beam supports may develop over nearly the whole height of the wall, before one of the ultimate stage criteria are reached i.e. rotational ductility factor at coupling beam ends, deflection or drift. In slender structures the plastic hinges may develop only in the middle part of the height while in the upper and lower parts the behavior is elastic. Assuming as unknown functions the axial forces in the walls and denoting with Q_s, Q_m and Q_i = the axial force function in respectively upper, middle and lower zones, the solution of the problem is involved with solution of two second order differential equations for the upper and lower zones and an algebraic equation for the middle zone. From solution of the equations with the corresponding boundary conditions results [1,2]:

$$Q_s = \gamma W H^3\left\{A_s \operatorname{sh} \beta\xi + B_s \operatorname{ch} \beta\xi - [\xi^3/3 - \xi^2 + 2(\xi-1)/\beta^2]/\beta^2\right\} \qquad (1)$$

$$Q_m = Q_s(\xi_1) + q_u H(\xi-\xi_1) \qquad (2)$$

$$Q_i = \gamma W H^3\left\{A_i \operatorname{sh} \beta\xi + B_i \operatorname{ch} \beta\xi - [\xi^3/3 - \xi^2 + 2(\xi-1)/\beta^2]/\beta^2\right\} \qquad (3)$$

where A_s, B_s, A_i, B_i = coefficients to be determined from boundary conditions; q_u = ultimate laminar shear which may be expressed as function of the yield rotation φ_y of the coupling beam at support, $q_u = 12\, E\, I^* \varphi_y/(h\, c^2)$, and

$$\beta = H\sqrt{12\, I^*[\ell^2/(I_1 + I_2) + 1/(A_1 + A_2)]/(h\, c^3)} \qquad (4)$$

$$\gamma = 12\,\ell\, I^*/[h\, c^3(I_1 + I_2)] \qquad (5)$$

The plastic rotation angle at the supports of the laminas along the middle zone where plastic hinges have developed is given by (see Fig. 2):

$$\varphi_p = \varphi\ell/c - (\delta_1 + \delta_2)/c - \varphi_y \qquad (6)$$

and accordingly, the rotational ductility of the critical coupling beam end will be

$$\mu = (\varphi_{p\,max} + \varphi_y)/\varphi_y \qquad (7)$$

The graphs in Fig. 3 show the value of μ as function of β for various values of $\varepsilon = q_u/q_{e\,max}$, where $q_{e\,max}$ = maximum elastic shear in the lamina(at yield). Recent researches [3,4] have shown that standard reinforcing of coupling beams may supply a rotational ductility factor of 4 and with special diagonal reinforcing it may reach the value of 12.

The plastic energy dissipation factor is defined to be the following ratio

$$d_p = E_u/E_y \tag{8}$$

where E_y = elastic strain energy in the structures at yield point in the critical coupling beam and E_u = total energy (elastic and plastic) at ultimate stage. The values of d_p as function β and for various values of ε and $\lambda = \gamma H^2 l/\beta^2$ are shown in Fig. 4 . The ability of a structure to supply the necessary dissipated energy for a strong earthquake will be established by comparing d_p with the ratio of energies induced in the structure by a strong and moderate earthquake on which the design code is based. This ratio may be expressed as the ratio between the squares of the spectral velocities of respective earthquakes for a given critical damping factor.

Numerical Example. A box shaped symmetrical shear core of 18 story containing identical openings in opposite walls is considered[4]. The energy dissipation factor was evaluated for six different assumptions taking into account the reduction in stiffness due to cracking of the beams and shear walls. Case A: Beams and walls crack free. Case B: All beams cracked (70% reduction in stiffness), walls crack free. Case C: All beams cracked, shear wall 1 in tension cracked (30% reduction in axial stiffness, 50% in flexural stiffness), shear wall 2 in compression free of crack. Case D: All beams cracked, shear wall 1 in compression free of crack, shear wall 2 in tension cracked. Case E: All beams cracked, shear wall 1 in tension cracked, shear wall 2 in compression cracked (reduction of 25% in flexural stiffness only). Case F: Identical with case E changing between them wall 1 and 2. The ratio between the squares of spectral velocity of El Centro 18 May 1940 earthquake and an average spectral velocity[5] is approximated to $2.7^2 = 7.29$. Assuming a maximum rotational ductility factor of 12 for the coupling beam end, the following energy dissipation factors and overall ductility factors are obtained: Case A: d_p=3.5, μ_o= 2.1. Case B: d_p=7.0, μ_o=3.4. Case C: d_p= 8.0, μ_o=3.4. Case D: d_p=6.1, μ_o= 3.1 . Case E: d_p=5.2, μ_o=2.9. Case F: d_p=3.9, μ_o=2.7 . It is to be mentioned that the decrease in stiffness of the coupling beam and shear walls has a positive effect on energy absorption capability which is more evident on the energy dissipation factor than on the overall ductility factor.

1. Gluck J., "Elasto-Plastic Analysis of Lateral Loaded Coupled Shear Walls", (submitted for publication).
2. Gluck J., "An Overall Ductility Factor for Coupled Shear Walls" (submitted for publication).
3. Pauly, T., "Coupling Beams of Reinforced Concrete Shear Walls", Journal of the Structural Div., ASCE Vol. 97, No.ST3, Proc.Paper 7984, pp.843-862
4. Pauly, T., "Elasto-Plastic Analysis of Coupled Shear Walls", ACI Journal, Proceedings V. 67 No. 11, Nov. 1970, pp. 915-922.
5. Housner G.W., "Behaviour of Structures during Earthquakes", Journal of the Engineering Mechanics Div., ASCE, Vol. 85, No. EM4, Proc. Paper 2220, October 1959, pp. 109-129.

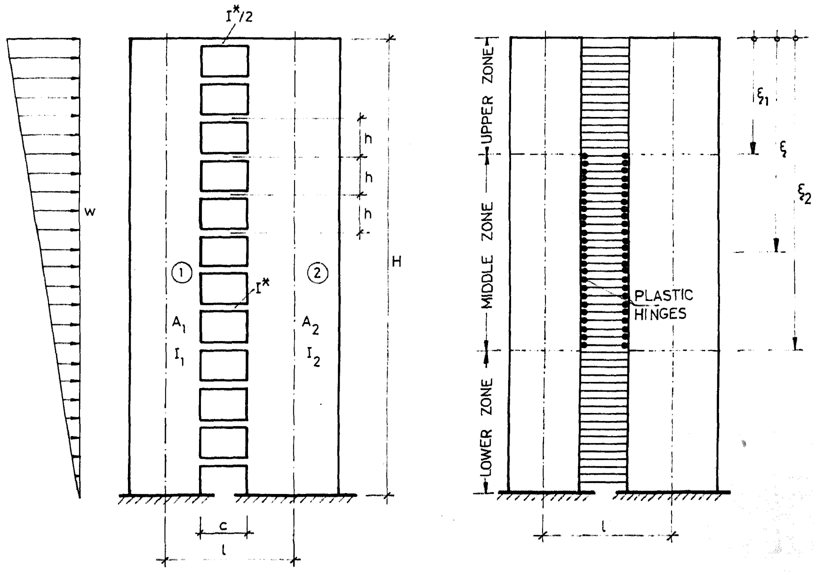


Fig.1

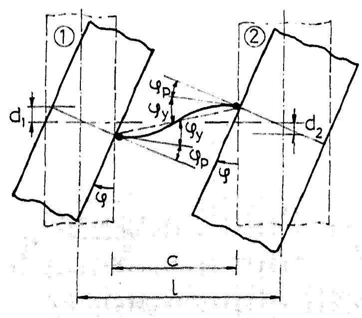


Fig 2

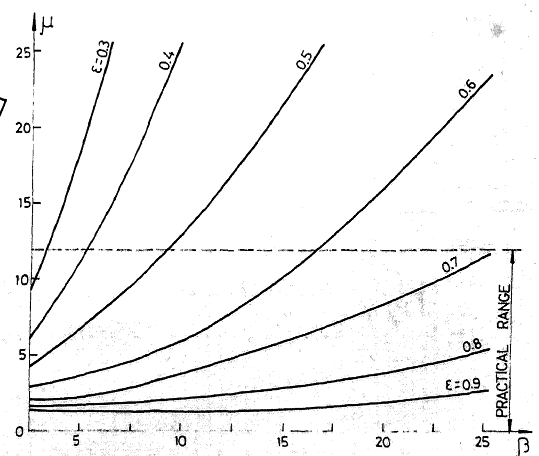
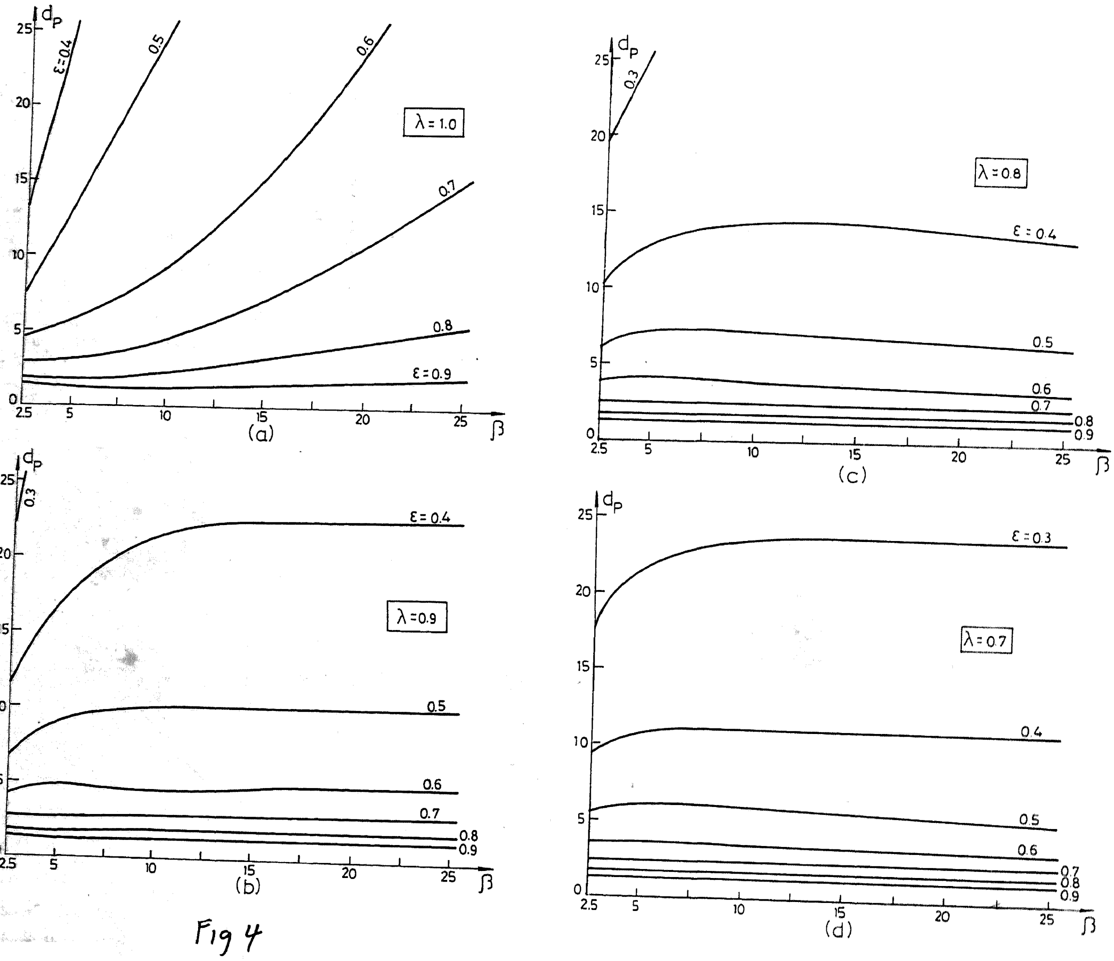


Fig 3



dP
ε=0.4
0.5
0.6
λ=1.0
0.7
0.8
ε=0.9
β
(a)
dP
0.3
λ=0.8
ε=0.4
0.5
0.6
0.7
0.8
0.9
β
(c)
dP
0.3
ε=0.4
λ=0.9
0.5
0.6
0.7
0.8
0.9
β
(b)
dP
ε=0.3
λ=0.7
0.4
0.5
0.6
0.7
0.8
0.9
β
(d)

Fig 4

Fig 4