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USE OF ENERGY AS A DESIGN CRITERION IN EARTHQUAKE-RESISTANT DESIGN

by

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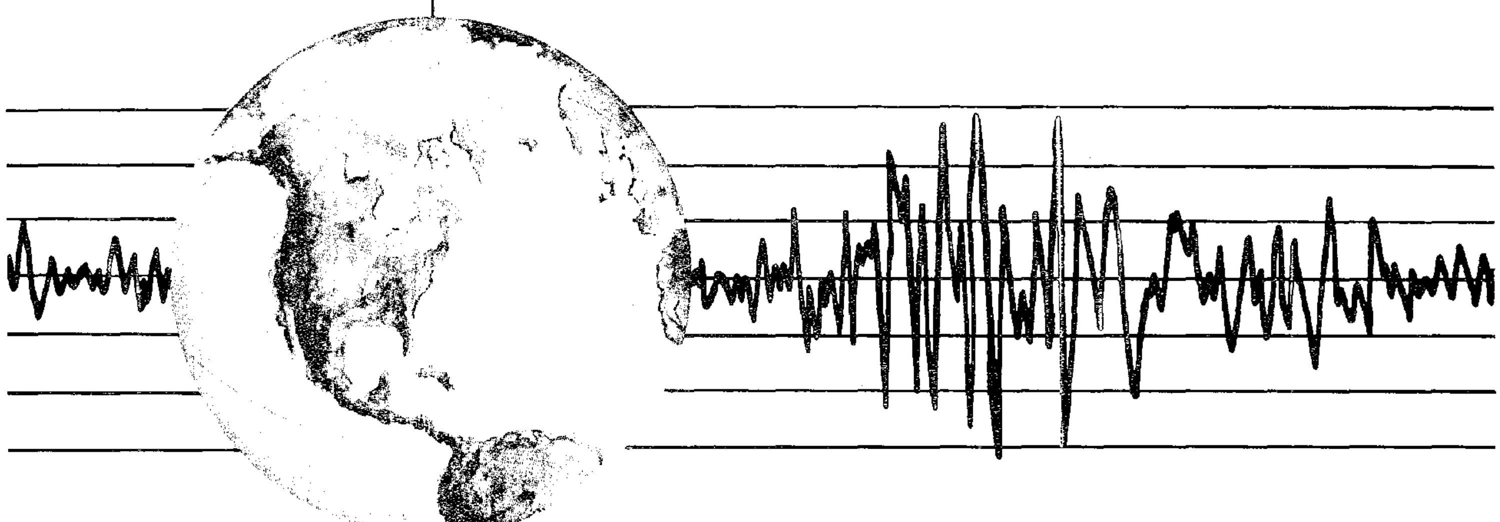
Report to the National Science Foundation



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The reliability of using input energy spectra derived for a single-degree-of-freedom system to predict the input energy to multi-story buildings is illustrated by correlating the analytical prediction with the experimental results of a six-story steel frame. Finally, the uniqueness of the energy dissipation capacity of a structural member is evaluated. Test results for three types of structural members--steel beams, reinforced concrete shear walls, and composite beams--are examined, with the conclusion that the energy dissipation capacity is not unique but is highly dependent on the loading and deformation paths.

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I. INTRODUCTION

1.1. Statement of the Problem

Traditionally, displacement ductility has been used as a criterion to establish inelastic design response spectra (IDRS) for earthquake-resistant design of buildings.[16, 21] The minimum required *strength* (or capacity for lateral force) of a building is then based on the selected IDRS. As an alternative to this traditional design approach, an energy-based method was proposed by Housner.[10] Although Anderson and Bertero[3] estimated the energy input in steel structures designed considering inelastic behavior in 1969, it is only recently that this approach has gained extensive attention.[2, 5, 8, 12-15, 18, 22] This design method is based on the premise that the *energy demand* during an earthquake (or an ensemble of earthquakes) can be predicted and that the *energy supply* of a structural element (or a structural system) can be established. A satisfactory design implies that the energy supply should be larger than the energy demand.

1.2. Objectives

The first objective of this report is to analyze the physical meaning of two energy equations that are derived and used in the literature. The second objective is to use these two definitions to construct inelastic input energy spectra for a single-degree-of-freedom (SDOF) system, and then to compare the spectra, as well as to evaluate the reliability of using SDOF energy spectra to predict the input energy to multi-story buildings. The third objective is to assess the reliability of predicting the energy dissipation capacity of a given structural member or structural system, and to investigate how different loading and deformation paths can affect the energy dissipation capacities of structural members.

1.3. Scope

Evaluation of the energy equations is limited to an elastic-perfectly plastic SDOF system. Five earthquake ground motions (see Table 1.1 and Fig. 1.1) including some recently recorded destructive earthquakes are used in this study. The reliability of using SDOF input energy spectra for determining the input energy to a multi-story building is assessed by studying the correlation of SDOF results with those obtained from shaking table experiments conducted on a six-story steel frame. The energy supplies, in particular energy dissipation capacities, of three types of structural members — steel, reinforced concrete and composite members — subjected to cyclic loading, are discussed.

II. PREDICTION OF INPUT ENERGY DEMANDS

2.1. Derivation of Energy Equations for a SDOF System

Given a viscous damped SDOF system subjected to a horizontal earthquake ground motion (Fig. 2.1a), the equation of motion can be written as

$$m\ddot{v}_t + c\dot{v} + f_s = 0 \tag{2.1}$$

where m = mass

c = viscous damping coefficient

f_s = restoring force

$v_t = v + v_g$ = absolute (or total) displacement of the mass

v = relative displacement of the mass with respect to the ground

v_g = earthquake ground displacement.

Note that f_s may be expressed as kv for a linear elastic system (k = stiffness.) By letting $\ddot{v}_t = \ddot{v} + \ddot{v}_g$, Eq. 2.1 may be rewritten as

$$m\ddot{v} + c\dot{v} + f_s = -m\ddot{v}_g \ . \tag{2.2}$$

Therefore the structural system in Fig. 2.1a can be conveniently treated as the equivalent system in Fig. 2.1b with a fixed base and subjected to an effective horizontal dynamic force of magnitude $-m\ddot{v}_g$. Although both systems give the same relative displacement, this ''convenience'' does cause some confusion in the definition of input energy and kinetic energy. Depending upon whether Eq. 2.1 or 2.2 is used to derive the energy equation, different definitions of input and kinetic energies may result.

2.1.1. Method 1 — Derivation of "Absolute" Energy Equation

Integrate Eq. 2.1 with respect to v from the time that the ground motion excitation starts:

$$\int m\ddot{v}_t dv \; + \; \int c\dot{v} dv \; + \; \int f_s dv \; = \; 0 \; . \tag{2.3}$$

Replacing v by $(v_t - v_g)$ in the first term in Eq. 2.3, then

$$\int m\ddot{v}_t dv \; = \; \int m\ddot{v}_t (dv_t - dv_g) \; = \; \int m\frac{d\dot{v}_t}{dt} dv_t - \int m\ddot{v}_t dv_g \; = \; \frac{m(\dot{v}_t)^2}{2} - \int m\ddot{v}_t dv_g \; . \tag{2.4}$$

Substituting Eq. 2.4 into Eq. 2.3 yields

$$\frac{m(\dot{v}_t)^2}{2} \; + \; \int c\dot{v} dv \; + \; \int f_s dv \; = \; \int m\ddot{v}_t dv_g \; . \tag{2.5}$$

The first term of the above equation is the "absolute" kinetic energy E_k

$$E_k \; = \; \frac{m(\dot{v}_t)^2}{2} \tag{2.6}$$

because ***absolute*** velocity ($\dot{v}_t$) is used to calculate the kinetic energy. The second term in Eq. 2.5 is the damping energy (E_ξ), which is always non-negative because

$$E_\xi \; = \; \int c\dot{v} dv \; = \; \int c\dot{v}^2 dt \; . \tag{2.7}$$

The third term in Eq. 2.5 is the absorbed energy (E_a), which is composed of recoverable elastic strain energy (E_s) and irrecoverable hysteretic energy (E_h) :

$$E_a \; = \; \int f_s dv \; = \; E_s \; + \; E_h \tag{2.8}$$

where $E_s = \dfrac{(f_s)^2}{2k}$.

The right-hand side term in Eq. 2.5 is, by definition, the input energy (E_i):

$$E_i \; = \; \int m\ddot{v}_t \, dv_g \; . \tag{2.9}$$

In this study E_i is defined as the "absolute" input energy. This definition is physically meaningful in that the term $m\ddot{v}_t$ represents the inertia force applied to the structure. This force, which from Eq. 2.1 is equal to restoring force plus damping force, is the same as the total force applied to the structure foundation. Therefore E_i represents the work done by the total base shear at the foundation on the foundation displacement. The absolute energy equation (Eq. 2.5) then can be written as follows:

$$E_i = E_k + E_\xi + E_a = E_k + E_\xi + E_s + E_h \ . \tag{2.10}$$

2.1.2. Method 2 — Derivation of "Relative" Energy Equation

Integrate Eq. 2.2 with respect to v:

$$\int m\ddot{v}dv + \int c\dot{v}dv + \int f_s dv = -\int m\ddot{v}_g dv \ . \tag{2.11}$$

Notice that the second term ($=E_\xi$) and the third term ($=E_a$) on the left side of the equation remain unchanged. The first term in Eq. 2.11 can be rewritten as

$$\int m\ddot{v}dv = \int m\frac{d\dot{v}}{dt}dv = \int md\dot{v}(\dot{v}) = \frac{m(\dot{v})^2}{2}$$

which is the "relative" kinetic energy (E'_k) calculated from relative velocity:

$$E'_k = \frac{m(\dot{v})^2}{2} \ . \tag{2.12}$$

The right-hand side term of Eq. 2.11 is conventionally defined as the "input energy" (E'_i):

$$E'_i = -\int m\ddot{v}_g dv \ . \tag{2.13}$$

In this study E'_i is defined as the "relative" input energy. This definition of input energy physically represents the work done by the static equivalent lateral force ($-m\ddot{v}_g$) on the equivalent fixed-base system; that is, it neglects the effect of the rigid body translation of the structure. The relative energy equation is then expressed as

$$E'_i = E'_k + E_\xi + E_a = E'_k + E_\xi + E_s + E_h \ . \tag{2.14}$$

2.2. Comparison of Energy Time Histories

Input energy as defined by either Eq. 2.9 or 2.13 is a function of time. Figure 2.2 shows the energy time histories for a short period (T = 0.2 sec) and a long period (T = 10.0 sec) elastic-perfectly plastic SDOF structure subjected to the 1971 Pacoima Dam earthquake ground motion.

Damping energy (E_ξ), strain energy (E_s), and hysteretic energy (E_h) terms are uniquely defined, irrespective of what method is used, but the input energy and kinetic energy are different, depending upon which method is used. High fluctuations in the E_i time history are apparent for the short period structure, and the same phenomenon for E_i' is apparent for the long period structure. Note also the significant difference in the magnitudes of E_i and E_i' for the long period structure. When the period of the structure is significantly larger than the predominant excitation period of the ground motion, the structure's center-of-mass essentially remains stationary. Therefore the absolute input energy for the relatively long period structure should be low, as is reflected in the E_i time history.

To construct input energy spectra, the time at which the input energy is evaluated should be specified. Most previous researchers evaluated the input energy at either (i) the end of the earthquake ground motion, or at (ii) the end of the earthquake ground motion plus a time equal to one half of the period of free vibration of the structure,[22] or at (iii) the end of the earthquake ground motion plus a time at which the velocity of the structure changes sign.[12] If the relative energy equation is used, the time at which the input energy is evaluated by the methods just described, is suitable for short period structures (see Fig. 2.2); for long period structures these methods may significantly underestimate the maximum input energy that may occur early in the ground motion (see Fig. 2.2b.) For this reason the maximum input energy measured during the ground motion is used to construct the input energy spectra in this study. It should be noted that if E_i and E_i' are evaluated at the end of the ground motion, which corresponds to the time at which $\dot{v}_g = 0$, the rigid body kinetic energy is zero and hence the values of E_i and E_i' are identical.

To solve the problem of the nonzero initial condition of each ground motion, the method of prefixing a two second acceleration pulse, proposed by Pecknold and Riddle,[17] was adopted in these analyses.

2.3. Estimation of the Difference between Input Energies from Different Definitions

The definition of input energy given by Eq. 2.9 has been used by Berg and Thomaides,[5] Goel and Berg,[8] Mahin and Lin, [14] Uang and Bertero,[20] among others. Equation 2.13 has been used by most other researchers. The difference between the input energies of Methods 1 and 2 is derived below.

$$E_i = \int (m\ddot{v}_t)dv_g = \int (m\ddot{v}_t)(dv_t - dv) = \int (m\ddot{v}_t)dv_t - \int m(\ddot{v} + \ddot{v}_g)dv$$

$$= \frac{m}{2}(\dot{v}_t)^2 - \frac{m}{2}(\dot{v})^2 + E_i' = \frac{m}{2}(\dot{v}_g)^2 + m\dot{v}\dot{v}_g + E_i'$$

that is,

$$E_i - E_i' = \frac{m}{2}(\dot{v}_g)^2 + m\dot{v}\dot{v}_g \ . \tag{2.15a}$$

It can be proved easily that the difference between the kinetic energies due to the different definitions is:

$$E_k - E_k' = \frac{m}{2}(\dot{v}_g)^2 + m\dot{v}\dot{v}_g \ . \tag{2.15b}$$

Because the last term in the above equation contains the term $\dot{v}$, the error cannot be estimated easily. However, the values of E_i and E_i' for very long and very short period structures can be calculated as follows.

For a structure with very long period ($T \to \infty$), the input energy tends to converge to a constant value, depending upon which definition of input energy is used. For a structure with infinitely long period,

$$v = -v_g$$

$$v_t = v + v_g = 0 \qquad ; \qquad \ddot{v}_t = 0 \ .$$

Therefore,

Method 1: $$\frac{E_i}{m} = \int \ddot{v}_t \, dv_g = \int (0) \, dv_g = 0 \tag{2.16a}$$

Method 2: $$\frac{E_i'}{m} = -\int \ddot{v}_g \, dv = -\int \ddot{v}_g \, (-dv_g) = \int \ddot{v}_g \, dv_g = \frac{(\dot{v}_g)^2}{2} \tag{2.16b}$$

i.e., the difference between the input energies E_i and E_i' for a structure with $T=\infty$ is equal to $m(\dot{v}_g)^2/2$. If the input energy E_i' is evaluated at the end of duration, its value will be very small because $\dot{v}_g$ tends to be vanishingly small. If E_i' is evaluated as the maximum throughout the duration, then E_i'/m will then converge to $\dot{v}^2_{g(max)}/2$ for long period structures.

For a structure with very short period ($T \to 0$), the input energy will also converge to a constant value, depending upon the definition used. For a structure with zero period, i.e., a rigid structure,

$$\ddot{v}_t = \ddot{v}_g$$

$$v_t = v_g , \qquad \text{or} \quad v = 0 .$$

Therefore,

Method 1: $$\frac{E_i}{m} = \int \ddot{v}_t \, dv_g = \int \ddot{v}_g dv_g = \frac{(\dot{v}_g)^2}{2} \tag{2.17a}$$

Method 2: $$\frac{E_i'}{m} = -\int \ddot{v}_g \, dv = -\int \ddot{v}_g \, (0) = 0 \tag{2.17b}$$

i.e., the difference between the input energy spectra for a structure with zero period is equal to $m\dot{v}^2_{g\,(max)}/2$.

On the basis of the above derivation, it appears that from the energy point of view the peak ground velocity plays an important role as a damage index. It would be misleading, however, to use E_i as a damage index for very long period structures because the value of E_i is very small. Such structures are so flexible that nonstructural component damage in real buildings may be excessive. The use of E_i' in this case may give a more reasonable index for damage. Similarly, the use of E_i for a very short period structure serves as a better damage index than the use of E_i'. Relative input energy may give misleading information for a rigid structure because Eq. 2.17b implies that no energy is input to a rigid structure.

2.4. Comparison of Input Energy Spectra

The input energy spectra for five earthquake records (see Table 1.1) are generated for a constant displacement ductility of five. The input energy is converted to an equivalent velocity by the following relationship:

$$V_i = \sqrt{\frac{2E_i}{m}} \quad ; \quad V_i' = \sqrt{\frac{2E_i'}{m}} \ . \tag{2.18}$$

The input energy equivalent velocity spectra are shown in Fig. 2.3; the solid line represents the input energy calculated by Method 1 and the dashed line by Method 2. Note again that the input energy (E_i or E_i') plotted is the maximum input energy; this energy may occur before the ground motion ends.

Figure 2.3 shows that V_i and V_i' are very close in the intermediate period ranges: to be more specific, the input energies calculated by Methods 1 or 2 are very close in the vicinity of the predominant excitation periods of the earthquake ground motions. The difference between V_i and V_i' increases for longer and shorter period structures. The level of maximum ground velocity $\dot{v}_{g\,(max)}$ is also shown in Fig. 2.3 for each earthquake record. The trend that V_i converges to $\dot{v}_{g\,(max)}$ as the period of the structure tends to zero and that V_i' converges to $\dot{v}_{g\,(max)}$ as the period of the structure tends to infinity (as stated in Eqs. 2.16b and 2.17a) is clearly shown in Fig. 2.3. The tendency for V_i' in the short period range and for V_i in the long period range to decrease to zero can also be observed (see Eqs. 2.16a and 2.17b.)

2.5. Influence of Displacement Ductility Ratios on Input Energy Spectra

It has been concluded that E_i' (or V_i' in the form of equivalent velocity) spectral values evaluated at the end of the duration of the ground motion are relatively insensitive to the displacement ductility level.[22] The variation of input energy equivalent velocity spectra for displacement ductility ratios of 2, 5, and 8 are shown in Fig. 2.4. It can be observed that the input energy (E_i) spectra are generally insensitive to the level of ductility ratio. The only exceptions to this observation are the spectra of the 1985 Mexico City Earthquake. For this highly harmonic, long duration earthquake record the input energy is significantly affected by the ductility level (especially from $\mu = 2$ to $\mu = 5$) in the period range to the left side of the predominant excitation period.

The peak of the spectrum, which corresponds to the predominant period of the ground motion, tends to shift slightly towards a smaller period value as the displacement ductility ratio is increased. Therefore, as the value of the displacement ductility ratio increases, the values of V_i in the period range immediately to the left of the peak increase and the values in the period range to the right of the peak decrease.

2.6. Verification of Housner's Assumption

For a linear elastic system the maximum input energy that is *stored* in a SDOF system is

$$E_D = \frac{1}{2}\,k\,(S_d)^2 = \frac{1}{2}\,m\,(S_{pv})^2 \tag{2.19}$$

where S_d is the linear elastic spectral displacement and S_{pv} is the linear elastic pseudo-velocity, both being a function of period and damping ratio. It should be noted that E_D is the maximum elastic energy that is stored in the structure; the damping energy is not included. Housner[10] assumed that E_D (or S_{pv} in the form of equivalent velocity) can be used as the energy demand for an inelastic system in his proposed limit design method. If S_{pv} spectra with 5% damping are compared with the V_i spectra with 5% damping and a ductility ratio of 5, it is seen from Fig. 2.5 that S_{pv} may significantly underestimate V_i.

2.7. Approximate Inelastic Input Energy Spectra

Inelastic behavior has the effect of (i) increasing the effective natural period, and (ii) increasing the effective damping ratio of a structure. On the basis of a study of a class of hysteretic structures subjected to a total of 12 earthquake ground motions, Iwan[11] found that an inelastic response spectrum can be approximated by an elastic spectrum corresponding to an equivalent viscous damping (ξ_e) and an equivalent natural period (T_e):

$$\xi_e = \xi + 0.0587\,(\mu-1)^{0.371} \tag{2.20a}$$

$$\frac{T_e}{T} = 1 + 0.121\,(\mu-1)^{0.939} \tag{2.20b}$$

where ξ is the nominal viscous damping ratio, T is the natural period in the elastic range, and μ is the ductility ratio.

For a given ductility ratio, the elastic input energy equivalent velocity spectra, constructed by using an equivalent damping ratio of ξ_e (Eq. 2.20a) and then performing a period shift using Eq. 2.20b, are compared with the inelastic spectra shown in Fig. 2.4. Figure 2.6 shows such a comparison for $\mu = 5$. It can be observed that although inelastic input energy equivalent velocity spectra appear to be predicted very well by elastic spectra constructed using Iwan's procedure, there are some significant differences. For example, for a period of about 2 seconds Iwan's elastic V_i spectral value for the Mexico City earthquake is twice the inelastic V_i spectral value; and therefore the elastic E_i value will be 4 times the value of the inelastic E_i. It is believed that this can be attributed to the highly harmonic nature of the Mexico City ground motion and that this type of motion was not taken into account in Iwan's derivation of Eq. 2.20.

In his study of the relationship of ξ_e and T_e for both harmonic and typical earthquake excitations, Hadjian[9] has shown that the equivalent damping ratios due to harmonic excitation are about five times those due to earthquake excitation, and the period changes due to harmonic excitation are about twice those due to earthquake excitation. It is believed that Eq. 2.20 significantly underestimates the values of ξ_e and T_e for the 1985 Mexico City earthquake. An increase in the value of ξ_e will lower the magnitude of Iwan's elastic input energy spectra, making them more comparable to the actual inelastic input energy spectra. Deriving appropriate values of ξ_e and T_e for the 1985 Mexico City earthquake is outside the scope of this study.

2.8. Input Energy Equivalent Velocity Amplification Factor and Strong Motion Duration Relationship

It is well-known that elastic spectral values like elastic pseudo-acceleration cannot reflect the effect of strong motion duration. This shortcoming carries through to any inelastic design spectra derived from them. Since input energy reflects the effect of the duration directly through integration, it is worthwhile to investigate the relationship between the maximum equivalent velocity of input energy and the strong motion duration. Two quantities — amplification factor and the strong motion duration used in this study — are described first.

The amplification factor (Ψ) of an input energy equivalent velocity spectrum for a given ductility ratio (μ) and a viscous damping ratio (ξ) is defined by the following:

$$\Psi(\mu, \xi) = \frac{V_i^{\max}(\mu, \xi)}{\dot{v}_{g\,(max)}} \tag{2.21}$$

where $V_i^{\max}(\mu,\xi)$ is the maximum value of V_i evaluated throughout the whole period range. In general $V_i^{\max}(\mu,\xi)$ occurs in the immediate vicinity of the predominant period of the earthquake ground motion.

One commonly used definition of strong motion duration is that due to Trifunac and Brady:[19]

$$t_D = t_{0.95} - t_{0.05} \tag{2.22}$$

where $t_{0.05}$ and $t_{0.95}$ define the times at which 5 percent and 95 percent, respectively, of the value of the Arias intensity (I_A) is achieved. Arias intensity is defined as follows:[4]

$$I_A = \frac{\pi}{2g} \int_0^{t_d} \ddot{v}_g^2(t)dt \tag{2.23}$$

where t_d is the total duration of the earthquake record. The calculated values of t_D for each earthquake record are listed in Table 1.1. A plot of Ψ (μ=5,ξ=5%) versus t_D for the five earthquake motions is shown in Fig. 2.7. It is observed that Ψ and t_D are linearly dependent; by letting the intercept of the line of best fit, shown in Fig. 2.7, be 1.0, the following equation is obtained by the method of least-squares:

$$\Psi\ (\mu{=}5,\ \xi = 5\%) = 1.0 + 0.12 t_D \tag{2.24}$$

Therefore, if the strong motion duration at a given site is known, it is possible to predict the maximum energy input to a structure with a specified ductility ratio (5 for the case used in developing Eq. 2.24.) The period of the structure at which this maximum input energy occurs is close to the predominant excitation period of the expected earthquakes at the site under consideration.

For example, if it is expected from previous earthquake records at a certain site that the maximum ground velocity is 30 in/sec and that the strong motion duration t_D is 20 sec, the maximum input energy per unit mass for a structure having a damping ratio of 5 percent and a ductility ratio of 5 can be estimated by the following procedure:

$$\Psi = 1.0 + 0.12 t_D = 1.0 + 0.12(20) = 3.4$$

$$V_i^{\max} = \Psi\, \dot{v}_{g\,(max)} = 3.4(30) = 102 \text{ in/sec}$$

$$\frac{E_i^{\max}}{m} = \frac{1}{2}(V_i^{\max})^2 = \frac{1}{2}(102)^2 = 5{,}202 \text{ in}^2/\text{sec}^2 = 36 \text{ ft}^2/\text{sec}^2$$

2.9. Input Energy to Multi-Story Buildings

The "absolute" energy equation for an N-story building has been derived as follows:[20]

$$\frac{1}{2}\dot{\mathbf{v}}_t^{\,T}\mathbf{m}\,\dot{\mathbf{v}}_t + \int \dot{\mathbf{v}}^T \mathbf{c}\, d\mathbf{v} + \int \mathbf{f}_s^T\, d\mathbf{v} = \int (\sum_{i=1}^{N} m_i \ddot{v}_{ti})\, dv_g \tag{2.25}$$

where $\mathbf{m}$, $\mathbf{c}$, and $\mathbf{v}$ are the diagonal mass matrix, viscous damping matrix, and relative displacement vector, respectively; m_i is the lumped mass associated with the i-th floor, $\ddot{v}_{ti}$ is the total acceleration at the i-th floor. The kinetic energy and input energy are calculated as follows:

$$E_k = \frac{1}{2}\dot{\mathbf{v}}_t^{\,T}\mathbf{m}\,\dot{\mathbf{v}}_t = \frac{1}{2}\sum_{i=1}^{N} m_i (\dot{v}_{ti})^2 \tag{2.26a}$$

$$E_i = \int (\sum_{i=1}^{N} m_i \ddot{v}_{ti})\, dv_g \tag{2.26b}$$

where E_k is the summation of the kinetic energy at each floor level, calculated using an absolute velocity ($\dot{v}_{ti}$) at the i-th floor, and E_i is the summation of the work due to an inertia force ($m_i \ddot{v}_{ti}$) at each floor for ground displacement.

Akiyama[2] has shown that the relative input energy E_i' based on a SDOF system can provide a very good estimate of the input energy for multi-story buildings. Although no parametric study is attempted here to verify the same conclusion for the absolute input energy E_i, shaking table test results for a six-story concentrically braced steel structure will be used to support this conclusion.

Figure 2.8 shows the 0.3-scale test model during the shaking table test; the 1978 Miyagi-Ken-Oki (MO) earthquake was used as the input ground motion. The test structure is classified by the UBC[1] as a dual system with two exterior ductile moment-resisting frames and one interior concentrically K-braced frame in the excitation direction. The magnitude of the earthquake record was scaled to different levels to represent different limit states of the structure responses. Details of the test results are reported in Reference 20. During the collapse level test (MO-65 Test, which had a measured peak base horizontal acceleration of 0.65g), the model experienced severe brace buckling in the bottom five stories, and the braces in the fifth story even ruptured. Figure 2.9 shows the envelope of base shear versus critical inter-story drift index obtained from different limit state tests. As a result of brace buckling and rupture, the envelope exhibits strength deterioration. Figure 2.10 shows the energy time histories of the MO-65 Test. Note that the ''viscous damped energy'' curve was calculated indirectly by the following expression:

$$E_\xi = E_i - E_k - E_s - E_h \ . \tag{2.27}$$

In order to compare the experimental input energy of this frame with an elastic-perfectly plastic SDOF system, an estimate of the displacement ductility ratio for this frame from the test envelope in Fig. 2.9 is needed. If this nonlinear envelope is approximated by two linear segments, with the yield level calculated from simple plastic analysis,[20] the corresponding ductility ratio is 2.6. The calculated input energy spectrum of a SDOF system with a ductility ratio of 2.6 and a viscous damping ratio of 2%, which was the measured first mode equivalent viscous damping ratio, is shown in Fig. 2.11. The quantities presented in Fig. 2.11 have been scaled to the prototype level by similitude laws. The correlation between the experimentally measured V_i for the multi-story structure and the calculated V_i for a SDOF system is excellent. It is concluded from this case study that the input energy spectra for a SDOF system can be used to predict the input energy demand for this type of multi-story building structure reliably.

III. ESTIMATION OF STRUCTURAL MEMBER ENERGY SUPPLY

3.1. Introductory Remarks

In the energy-based seismic design methods proposed by previous researchers, [2,10] it is commonly assumed that the energy dissipation capacity (or supply) of each member can be predicted reliably; this capacity is assumed to be identical under cyclic loading to that provided under monotonic loading. Some test results are considered with the purpose of examining this assumption. Test results of a series of steel beams under the same type of deformation pattern but with varying amplitudes are examined first in order to study the effect of amplitude on the energy dissipation capacity of a structural member. To study the effect of deformation path on the energy dissipation capacity, test results for two identical shear walls and two identical composite beams are examined.

3.2. Steel Beam Testing

A series of cantilever steel beams have been tested under strain reversal for different amplitudes.[6] The number of cycles required for the beam to fail versus strain amplitude is shown in Fig. 3.1. By ignoring strain hardening and Bauschinger effects a typical moment-curvature curve under cyclic loading can be idealized as shown in Fig. 3.2: these two factors tend to compensate each other from the standpoint of energy dissipation. The dissipated energy per unit length, e_d, is the area enclosed by the hysteresis loop:

$$e_d = \int M_p d\phi_p \simeq 2M_p \, (2\phi_p) \; = \; 4M_p \, \phi_p \approx 4M_p\bar{\phi} \tag{3.1}$$

where M_p is the plastic moment, ϕ_p is the plastic curvature, and $\bar{\phi}$ is the controlling (constant) curvature, which from Fig. 3.1 is the sum of ϕ_p and the yielding curvature ϕ_y. Plastic curvature ϕ_p is approximated by $\bar{\phi}$ in Eq. 3.1; this is a reasonable assumption when the controlling curvature is much larger than the yielding curvature. By letting

$$\bar{\phi} \; = \; \frac{\bar{\varepsilon}}{d/2} \tag{3.2}$$

where $\bar{\varepsilon}$ is the controlling strain at beam flange, and d is the beam depth, the total energy dissipated in n cycles (n = number of cycles required to rupture the beam), is

$$e_d = 4\,M_p\,n\,\bar{\varepsilon}\left(\frac{2}{d}\right) = \frac{8M_p}{d}(n\,\bar{\varepsilon}) \; . \tag{3.3}$$

Figure 3.1 also shows the $n\bar{\varepsilon}$ versus $\bar{\varepsilon}$ curve. By assuming constant plastic hinge length L_p for all the specimens tested, the total energy dissipation capacity $e_d L_p$ will be significantly smaller for beams subjected to larger amplitude cyclic deformations.

By extrapolating the energy dissipation capacity from the $n\bar{\varepsilon}$ curve for n =1, which corresponds to the case of monotonic loading, it is concluded that the energy dissipation capacity is much lower than that provided under cyclic loading, especially when the ductility ratio is low. If energy were to be used as a criterion for design, the energy dissipation capacity of structural elements derived from monotonic loading tests would be too conservative.

3.3. Shear Wall Testing

Figure 3.3 shows the hysteretic behavior of two identical reinforced concrete shear wall structures tested under monotonic and cyclic loading.[7] Although Wall 3 has a larger ductility ratio, the total energy dissipation capacity of Wall 3 is only 60% of that of Wall 1. This demonstrates that the energy dissipation capacity of a structural element is highly dependent on the loading path, the deformation path or both.

3.4. Composite Beam Testing

Figure 3.4 shows the load-deformation curves of two 0.3-scale composite beams tested under different deformation paths.[20] The first beam (CG1) experienced large displacement ductility in the first half cycle, followed by reversed loading in the opposite direction that caused severe flange local buckling. The energy dissipated is 27 kip-in. The second beam (CG3) was subjected to two complete cycles of loading reversals with displacement ductility smaller than that imposed on CG1. Another five complete cycles with displacement ductility similar to that imposed on CG1 were then applied. The energy dissipated in this beam is 128 kip-in, 4.7 times larger than that dissipated by CG1.

Strictly speaking, the comparison made above for these two composite beams is questionable. There is no reason why CG1 cannot dissipate more energy although it suffers flange local buckling when loaded into the reverse direction. Although the test of CG1 was terminated when strength deterioration was observed, it is believed that if a similar deformation path to that of CG3 but with higher displacement amplitudes were applied to CG1, the energy dissipation capacity would be smaller.

3.5. Concluding Remarks

These experimental results demonstrate that energy dissipation capacity is not constant and depends on loading path or deformation path or both. From analysis of available test results it appears that for properly designed and detailed structures, the energy dissipation capacity under monotonic loading is a lower limit on the energy dissipation capacity under cyclic loading or inelastic deformation or both. However the use of this lower limit could be too conservative for earthquake-resistant design, particularly if the ductility ratio is limited to low values with respect to the ductility ratio reached under monotonic loading. Thus, efforts should be devoted to determining experimentally the energy dissipation capacity of main structural elements as a function of the maximum deformation ductility that can be tolerated, and the relationship between energy dissipation capacity and loading and deformation paths.

IV. CONCLUSIONS

From the results obtained in the studies that have been summarized in this report, the following observations can be made.

(1) The use of an ''absolute'' energy equation rather than a ''relative'' energy equation has the advantage that the physical energy input is reflected.

(2) The profiles of the energy time histories calculated by the absolute energy equation differ significantly from those calculated by the conventional relative energy equation (see Fig. 2.2.)

(3) The absolute and the relative input energies for a constant displacement ductility are very close in the period range of practical interest, namely 0.3 to 5.0 sec (from Fig. 2.3.) The difference between these two input energies increases as the structure period differs more and more from the previous range. As the period decreases, the absolute input energy approaches $m\dot{v}^2_{g\,(max)}/2$, where $\dot{v}_{g\,(max)}$ is the maximum ground velocity, and the relative input energy approaches zero. The situation is reversed for long period structures.

(4) For certain types of earthquake ground motion, the absolute input energy spectra are sensitive to the variation of ductility ratio.

(5) Except for the highly harmonic earthquakes (1985 Mexico City earthquake for example), the absolute input energy spectra for a constant ductility ratio can be predicted reliably by the elastic input energy spectra using Iwan's procedure which takes into consideration the effect of increasing damping ratio and natural period.

(6) The maximum energy input to a structure whose fundamental period is close to the predominant excitation period of an expected earthquake can be predicted reliably with the expected maximum ground velocity and the amplification factor Ψ (one such expression for ductility ratio 5 and damping ratio 5 percent is presented in Eq. 2.24.) The amplification factor Ψ is approximately linearly related to the strong motion duration t_D defined in Eq. 2.22.

(7) For medium rise steel dual systems it is possible to estimate with sufficient accuracy the input energy to a multi-story building from the SDOF absolute input energy spectra using the fundamental period of the multi-story structure.

(8) The energy dissipation capacity of a structural member is not unique and depends on the loading or deformation paths or both. The energy dissipation capacity of a member under monotonic loading can only provide a lower bound estimate and may significantly underestimate its energy dissipation capacity, especially when the ductility ratio is limited to values that are low compared with the ductility ratio reached under monotonic loading.

(9) There is an urgent need to determine the energy dissipation capacity of the main types of structural elements and structural systems as a function of the maximum deformation ductility that can be tolerated and of the dynamic characteristics of the actual ground motions.

REFERENCES

1. *Uniform Building Code*, International Conference of Building Officials, Whittier, California, 1985.

2. Akiyama, H., *Earthquake Resistant Limit-State Design for Buildings*, University of Tokyo Press, 1985.

3. Anderson, J. C. and Bertero, V. V., "Seismic Behavior of Multistory Frames by Different Philosophies," *Report No. UCB/EERC-69/11*, Earthquake Engineering Research Center, University of California, Berkeley, California, October, 1969.

4. Arias, A., "A Measure of Earthquake Intensity," in *Seismic Design for Nuclear Power Plants*, ed. R.J. Hansen, pp. 438-469, Massachusetts Institute of Technology Press, Cambridge, Mass., 1970.

5. Berg, G. V. and Thomaides, S. S., "Energy Consumption by Structures in Strong-Motion Earthquakes," *Proceedings of the Second World Conference on Earthquake Engineering*, pp. 681-696, Tokyo, Japan, 1960.

6. Bertero, V. V. and Popov, E. P., "Effect of Large Alternating Strains on Steel Beams," *Proceedings*, vol. 91, no. ST1, pp. 1-12, ASCE, February, 1965.

7. Bertero, V. V., Popov, E. P., Wang, T. Y., and Vallenas, J. M., "Seismic Design Implications of Hysteretic Behavior of Reinforced Concrete Structural Walls," *Proceedings of the Sixth World Conference on Earthquake Engineering*, pp. 10-19, New Delhi, India, January, 1977.

8. Goel, S. C. and Berg, G. V., "Inelastic Earthquake Response of Tall Steel Frames," *Journal of the Structural Division*, vol. 94, no. ST8, pp. 1907-1834, ASCE, August, 1968.

9. Hadjian, A. H., "A Re-evaluation of Equivalent Linear Models for Simple Yielding Systems," *Earthquake Engineering and Structural Dynamics*, vol. 10, pp. 759-767, 1982.

10. Housner, G. W., "Limit Design of Structures to Resist Earthquake," *Proceedings of the First World Conference on Earthquake Engineering*, pp. 5-1 to 5-13, Berkeley, California,

1956.

11. Iwan, W. D., ''Estimating Inelastic Response Spectra from Elastic Spectra,'' *Earthquake Engineering and Structural Dynamics*, vol. 8, pp. 375-388, 1980.

12. Jennings, P. C., ''Earthquake Response of a Yielding Structure,'' *Journal of the Engineering Mechanics Division*, vol. 90, no. EM4, pp. 41-68, ASCE, August, 1965.

13. Kato, B. and Akiyama, H., ''Seismic Design of Steel Buildings,'' *Journal of the Structural Division*, vol. 108, no. ST8, pp. 1709-1721, ASCE, August, 1982.

14. Mahin, S. A. and Lin, J., ''Construction of Inelastic Response Spectrum for Single Degree of Freedom System,'' *Report No. UCB/EERC-83/17*, Earthquake Engineering Research Center, University of California, Berkeley, March, 1983.

15. McKevitt, W. E., Anderson, D. L., Nathan, N. D., and Cherry, S., ''Towards a Simple Energy Method for Seismic Design of Structures,'' *Proceedings of the Second U. S. National Conference on Earthquake Engineering* , pp. 383-392, EERI, 1979.

16. Newmark, N. M. and Hall, W. J., ''Procedures and Criteria for Earthquake Resistant Design,'' *Building Science Series No. 46*, pp. 209-236, Building Practices for Disaster Mitigation, National Bureau of Standards, February, 1973.

17. Pecknold, D. A. and Riddle, R., ''Effect of Initial Base Motion on Response Spectra,'' *Journal of the Engineering Mechanics Division*, vol. 104, no. EM2, pp. 485-491, ASCE, April, 1978.

18. Tembulkar, J. M. and Nau, J. M., ''Inelastic Modeling and Seismic Energy Dissipation,'' *Journal of the Structural Engineering*, vol. 113, no. 6, pp. 1373-1377, ASCE, June, 1987.

19. Trifunac, M. D. and Brady, A. G., ''A Study on the Duration of Strong Earthquake Ground Motion,'' *Bulletin of the Seismological Society of America*, vol. 65 , no. 3, pp. 581-626, June, 1975.

20. Uang, C.-M and Bertero, V. V., ''Earthquake Simulation Tests and Associated Studies of a 0.3-Scale Model of a 6-Story Concentrically Braced Steel Structure,'' *Report No. UCB/EERC-86/10*, Earthquake Engineering Research Center, University of California, Berkeley, California, December 1986.

21. Veletsos, A. S., Newmark, N. M., and Chelapati, C. V., ''Deformation Spectra for Elastic and Elastoplastic Systems Subjected to Ground Shock and Earthquake Motions,'' *Proceedings of the Third World Conference on Earthquake Engineering*, pp. II-663 to II-678, Wellington, New Zealand, 1965.

22. Zahrah, T. F. and Hall, W. J., ''Seismic Energy Absorption in Simple Structures,'' *Structural Research Series No. 501*, University of Illinois, Urbana, Illinois, July, 1982.

APPENDIX - NOTATION

c	viscous damping coefficient
$\mathbf{c}$	viscous damping matrix
d	beam depth
e_d	hysteretic dissipated energy of a steel beam
E_a	absorbed energy, $(= E_s + E_h)$
E_D	maximum elastic energy stored in a SDOF system
E_h	hysteretic dissipated energy
E_i	absolute input energy
E'_i	relative input energy
E_k	absolute kinetic energy
E'_k	relative kinetic energy
E_s	recoverable elastic strain energy
E_ξ	damping energy
f_s	restoring force
$\mathbf{f}_s$	restoring force vector
I_A	Arias intensity
m	lumped floor mass
$\mathbf{m}$	mass matrix of an N-story building structure
M_p	plastic moment
S_{pv}	linear elastic pseudo-velocity
S_d	linear elastic spectral displacement
t_d	total duration of an earthquake record
t_D	strong motion duration of an earthquake record
T_e	equivalent period
T	small-amplitude (or elastic) period
v	relative structural displacement
$\mathbf{v}$	relative structural displacement vector

$\dot{v}$	relative structural velocity
$\ddot{v}$	relative structural acceleration
v_t	absolute structural displacement
$\dot{v}_t$	absolute structural velocity
$\ddot{v}_t$	absolute structural acceleration
v_g	earthquake ground displacement
$\dot{v}_g$	earthquake ground velocity
$\dot{v}_{g\,(max)}$	maximum earthquake ground velocity
$\ddot{v}_g$	earthquake ground acceleration
V_i	absolute input energy equivalent velocity, $(= \sqrt{(2E_i)/m})$
V_i'	relative input energy equivalent velocity, $(= \sqrt{(2E_i')/m})$
ξ	nominal viscous damping ratio
ξ_e	equivalent viscous damping
ϕ	curvature
ϕ_p	plastic curvature
ϕ_y	yield curvature
$\bar{\varepsilon}$	controlling flange strain
Ψ	amplification factor of V_i above $\dot{v}_{g\,(max)}$

No.	Earthquake	Record	Comp.	Focal Depth (km)	M_s	MMI	Geology	Epicentral Distance (km)	$t_{\mathcal{D}}$ (sec)
1	Imperial Valley May 18, 1940	El Centro	N00E	16.0	6.3	VII-VIII	30m stiff clay volcanic rock	9.3	244
2	Mexico City September 19, 1985	SCT	N90E	4.2-5.0	8.1	IX	Soft lacustrine clay	360	38.8
3	San Salvador October 10, 1986	CIG	N90E	8.0	5.4	VIII-IX	Fluviatile pumice	9.0	4.3
4	San Fernando February 9, 1971	Pacoima Dam	S16E	13.0 to surface	6.6	IX-X	Highly jointed diorite gneiss	9.1	6.7
5	Kern County July 21, 1952	Taft	N21E	16.0	7.7	VII	Alluvium	43	30.5

Table 1.1 Earthquake Record Data

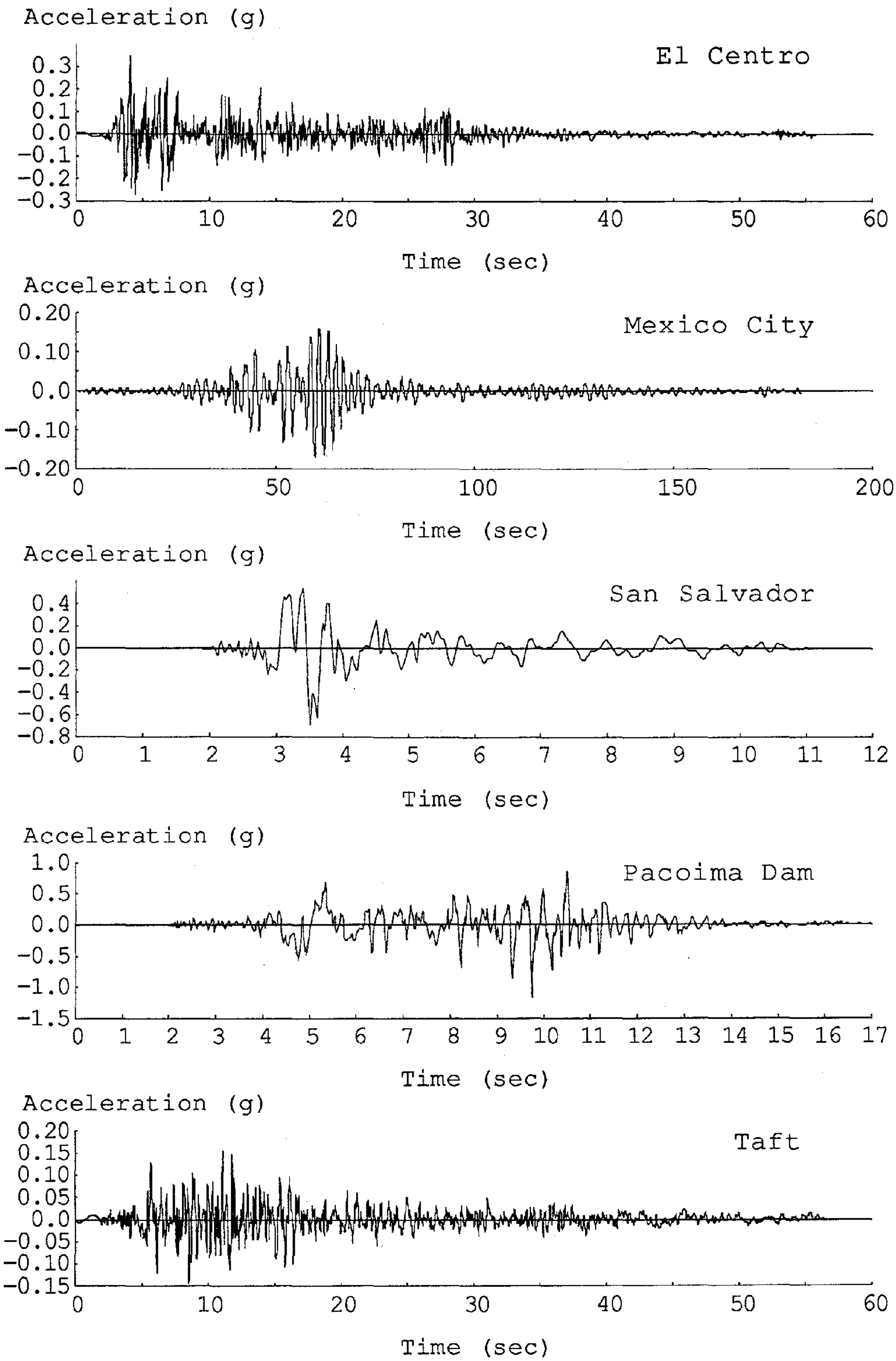
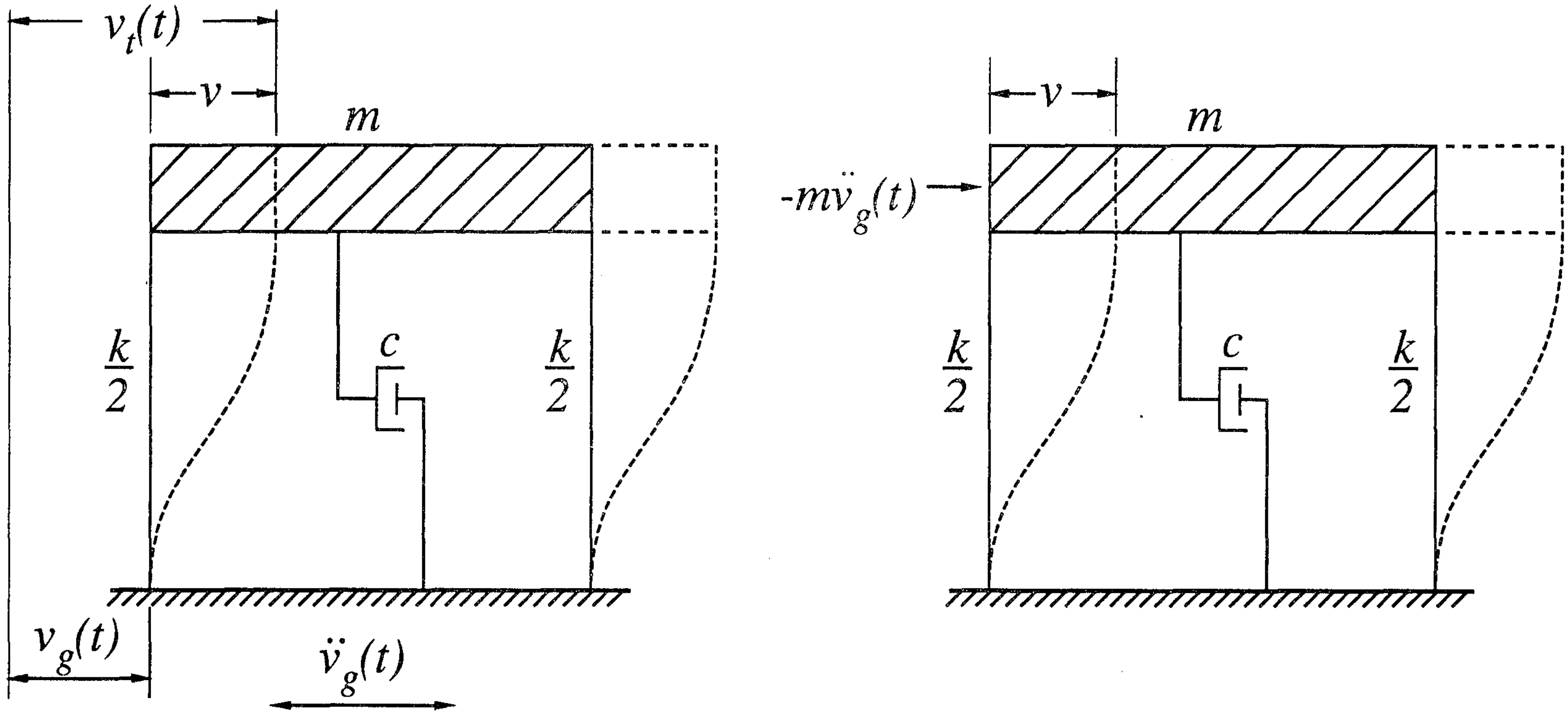


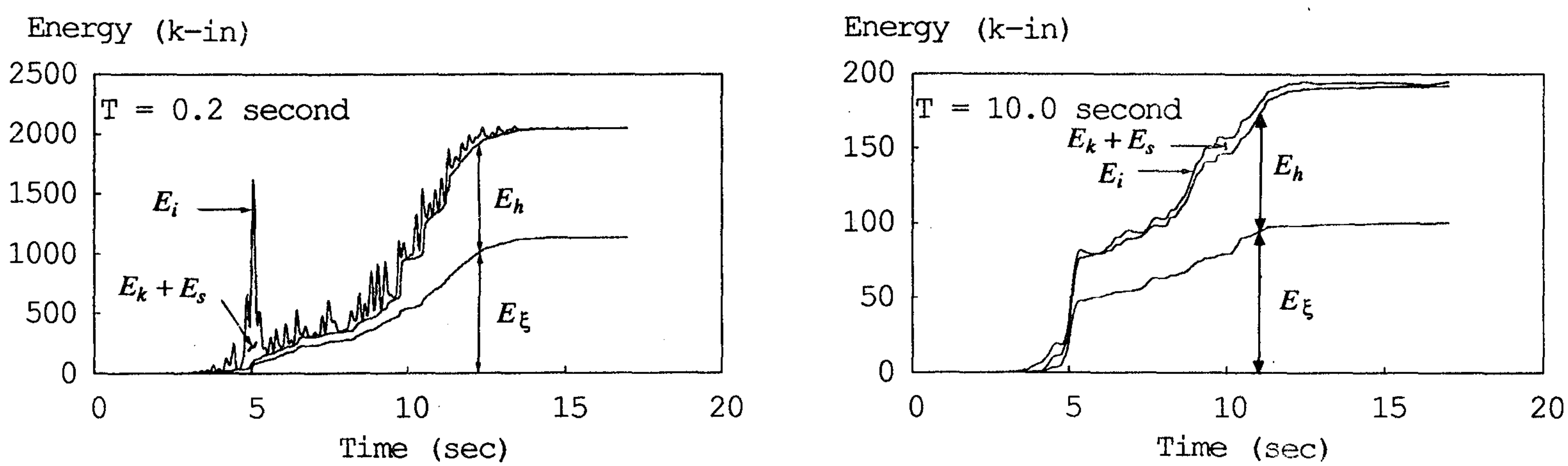
Fig. 1.1 Earthquake Ground Motion Acceleration Time Histories



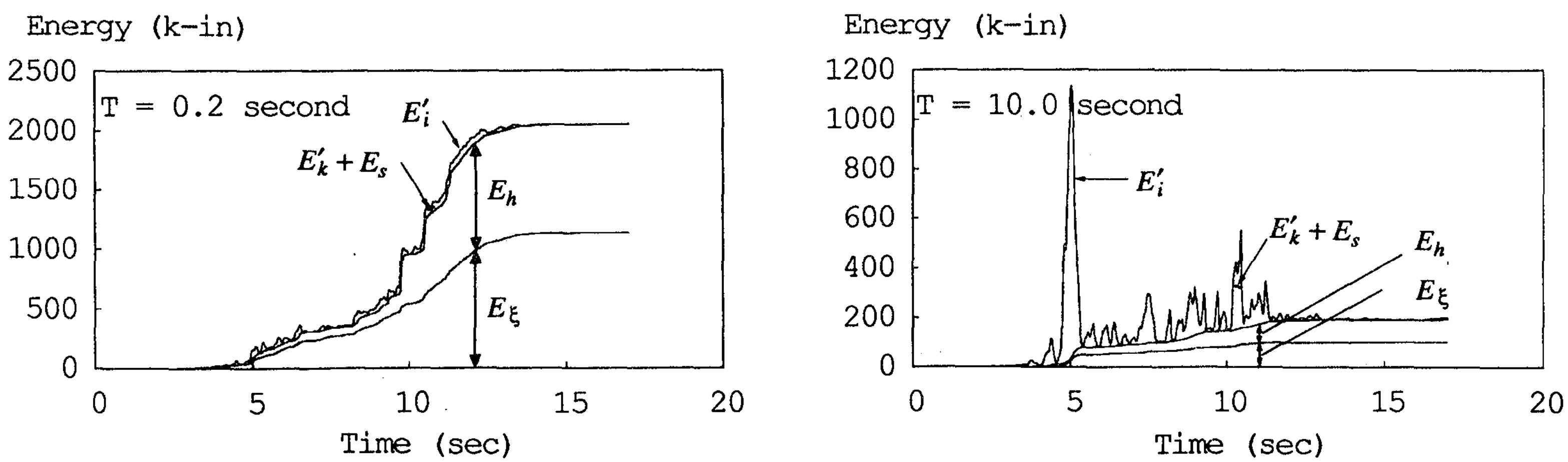
(a) Moving Base System

(b) Equivalent Fixed-Base System

Fig. 2.1 Mathematical Model of a SDOF System Subjected to an Earthquake Ground Motion



(a) Energy Terms Defined by Method 1



(b) Energy Terms Defined by Method 2

Fig. 2.2 Energy Time Histories for an Elastic-Perfectly Plastic System subjected to the 1971 San Fernando Earthquake — Pacoima Dam Record (Ductility Ratio 3, 5% Damping)

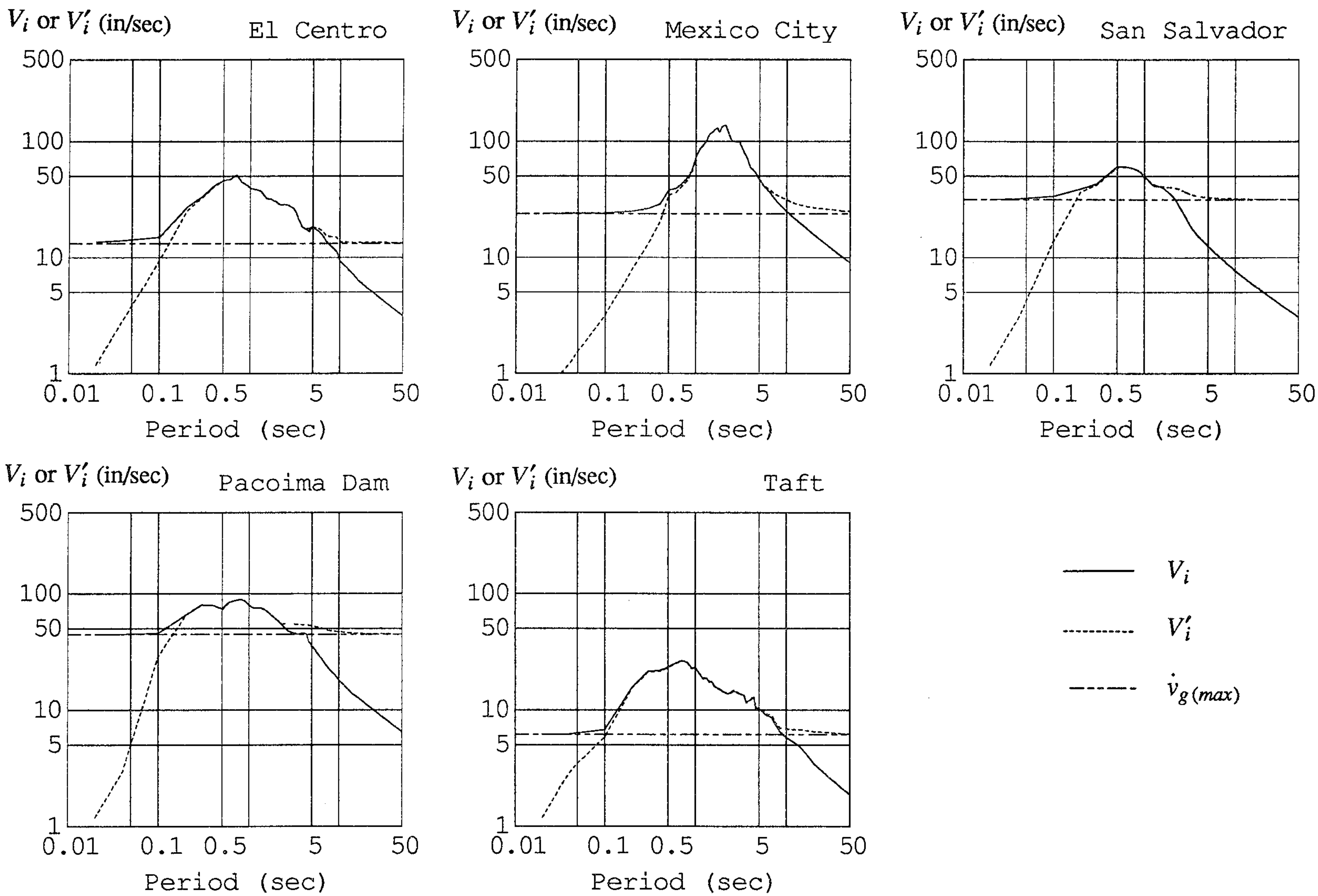


Fig. 2.3 **Comparison of Input Energy Equivalent Velocity Spectra for Ductility Ratio 5 (5% Damping)**

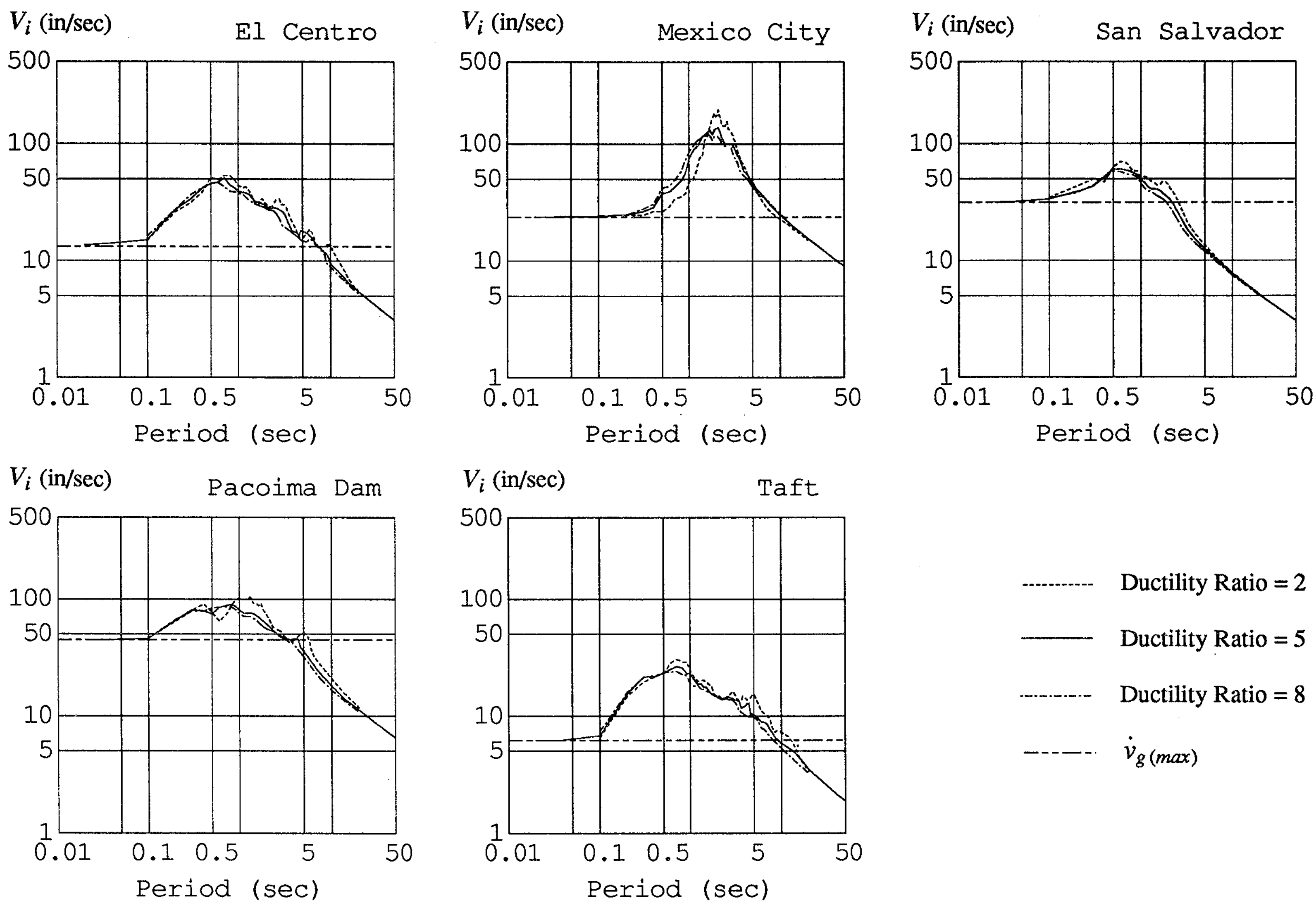


Fig. 2.4 **Comparison of Absolute Input Energy Equivalent Velocity Spectra for Ductility Ratios 2, 5, and 8 (5% Damping)**

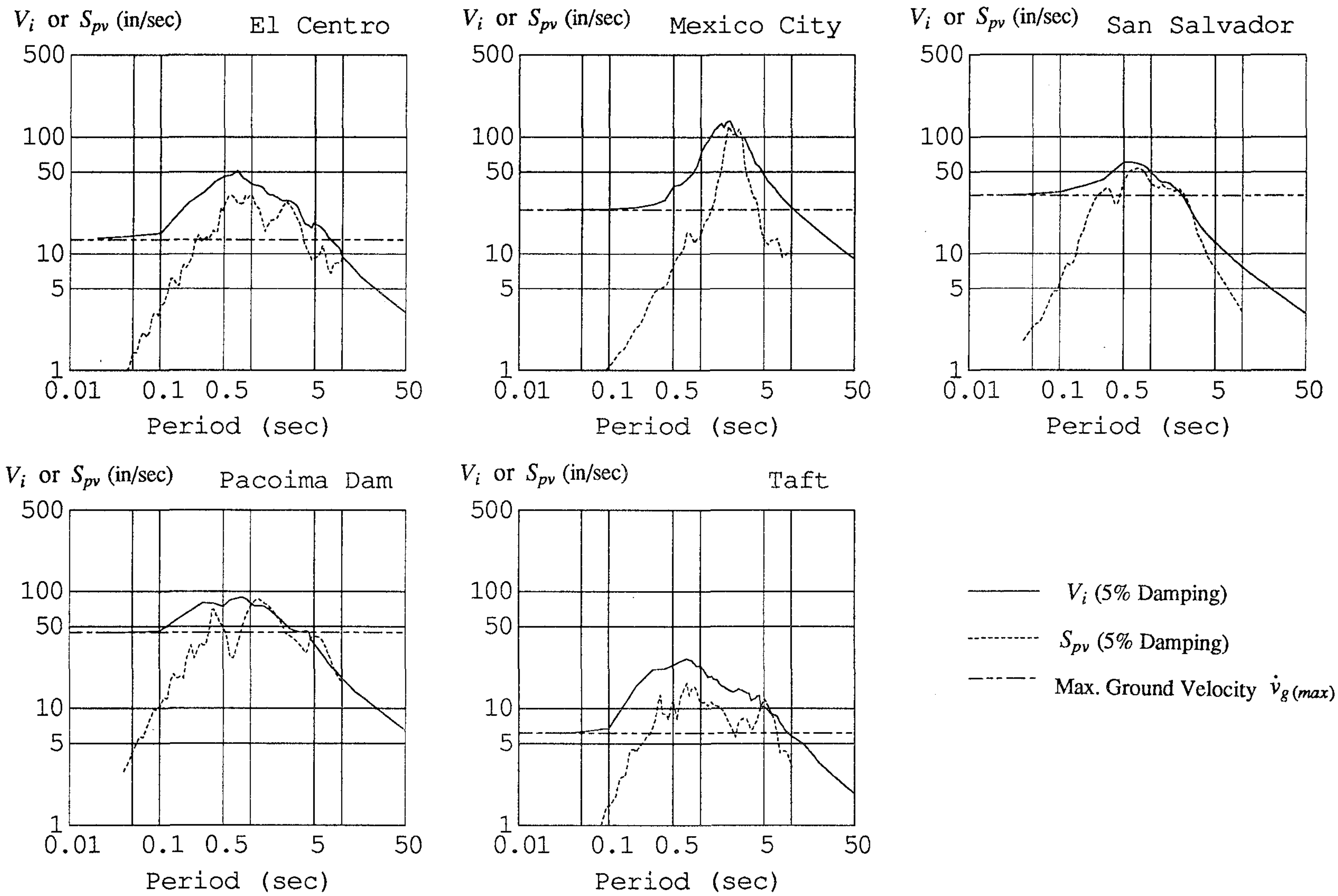


Fig. 2.5 **Comparison of Absolute Input Energy Equivalent Velocity Spectra and Linear Elastic Pseudo-velocity Response Spectra for Ductility Ratio 5 (5% Damping)**

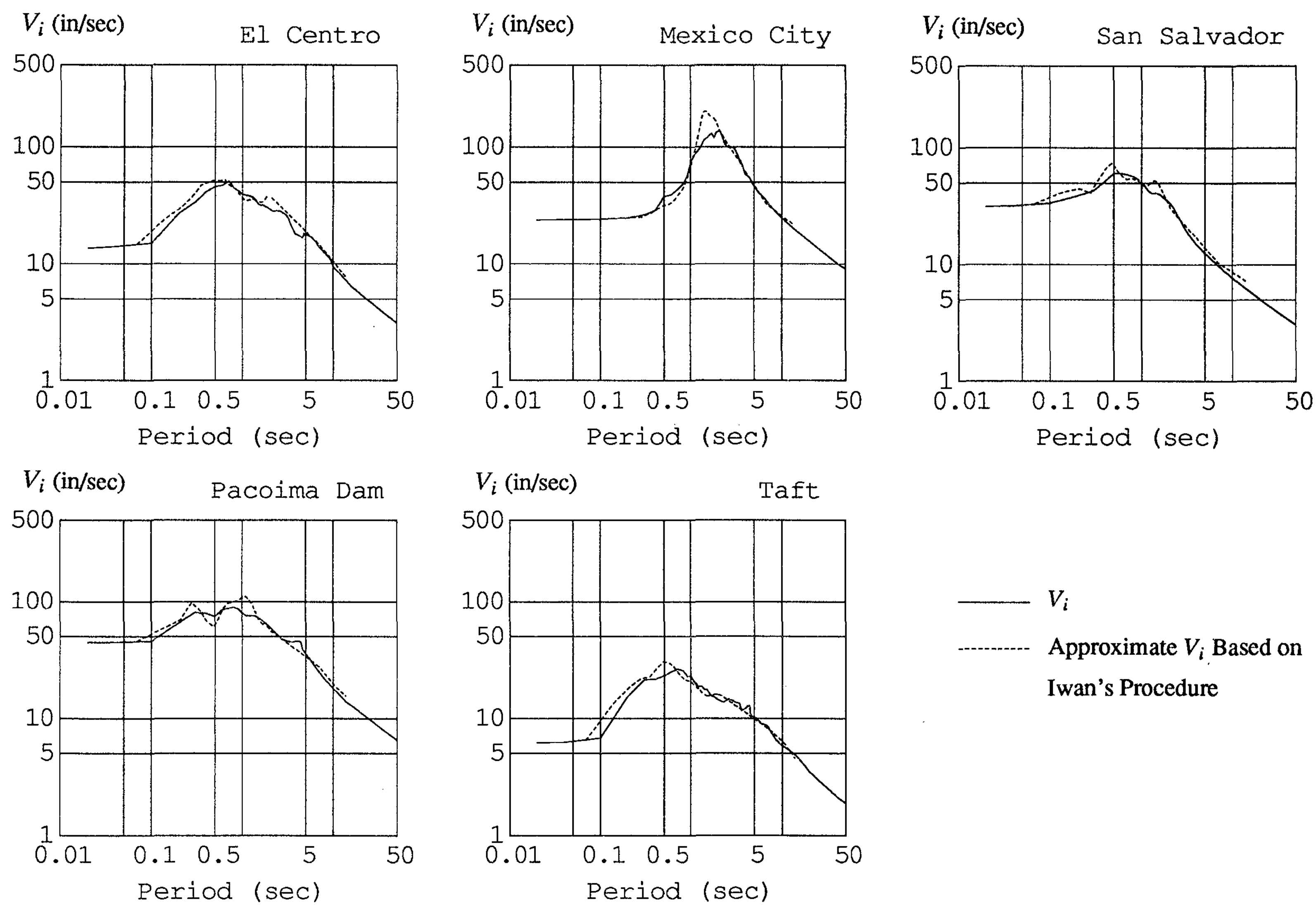


Fig. 2.6 **Comparison of Absolute Input Energy and Iwan's Elastic Input Energy Equivalent Velocity Response Spectra for Ductility Ratio 5 (5% Damping)**

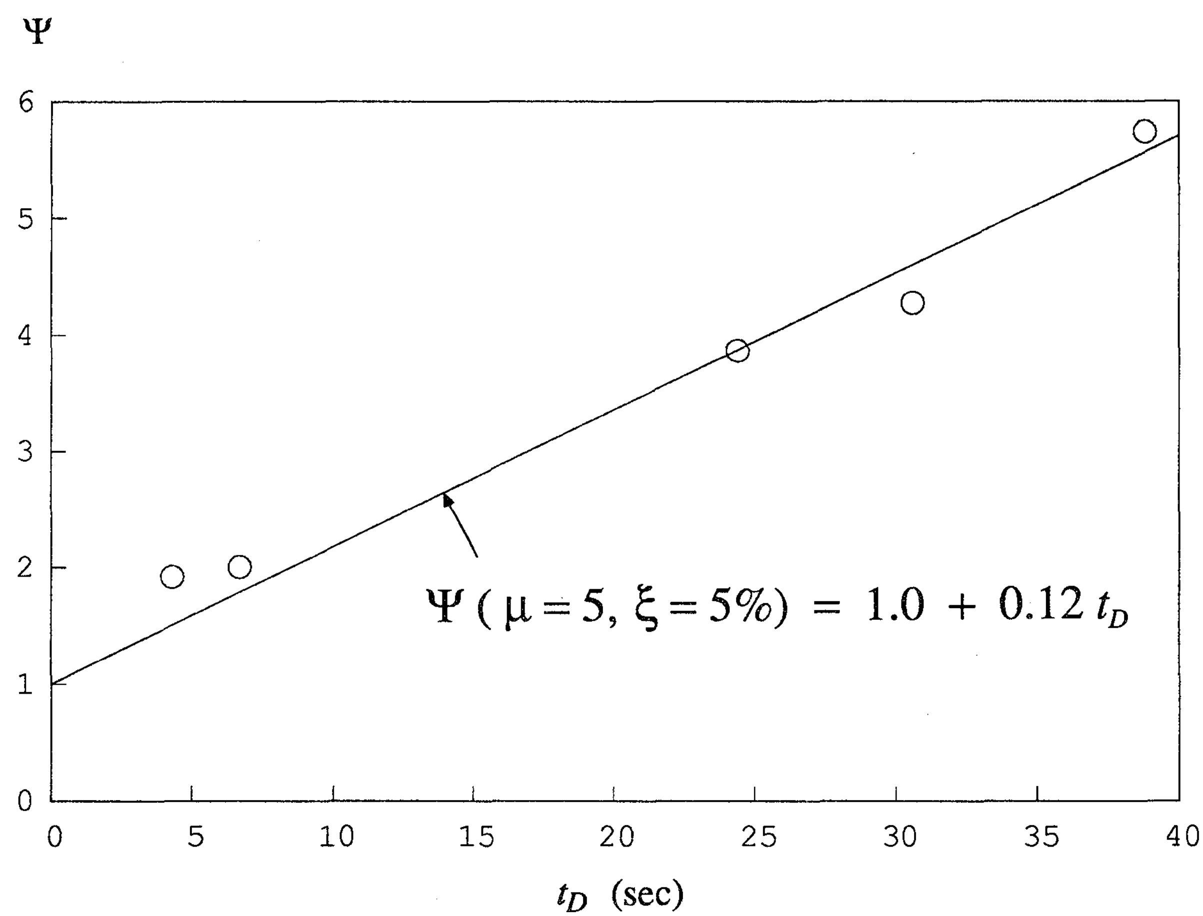


Fig. 2.7 **Input Energy Equivalent Velocity Amplification Factor and Strong Motion Duration Relationship**

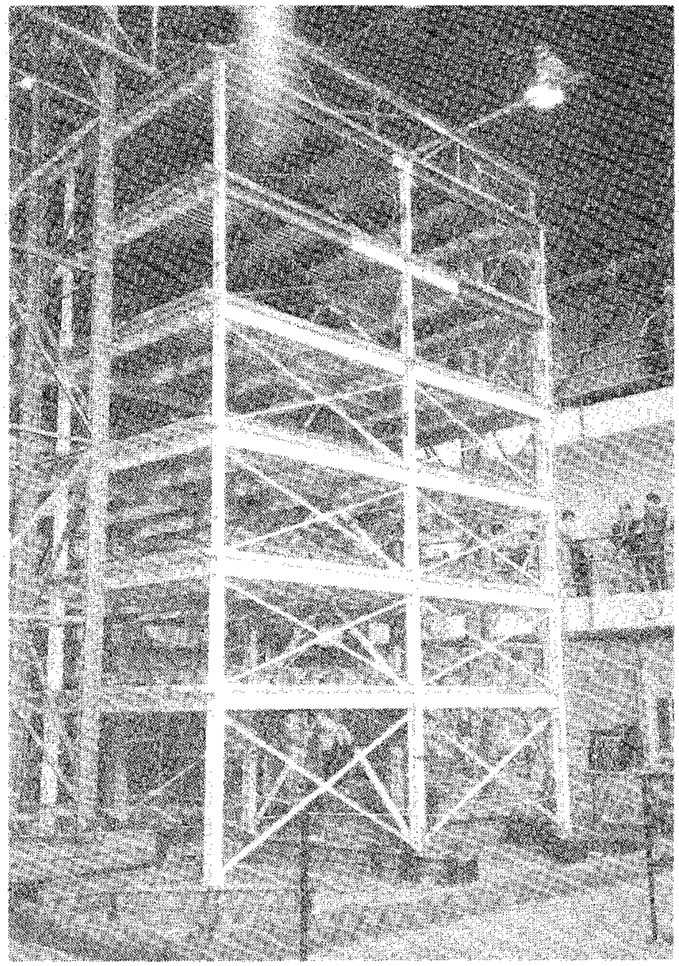


Fig. 2.8 Overall View of 0.3-Scale Model with Reference Frame[20]

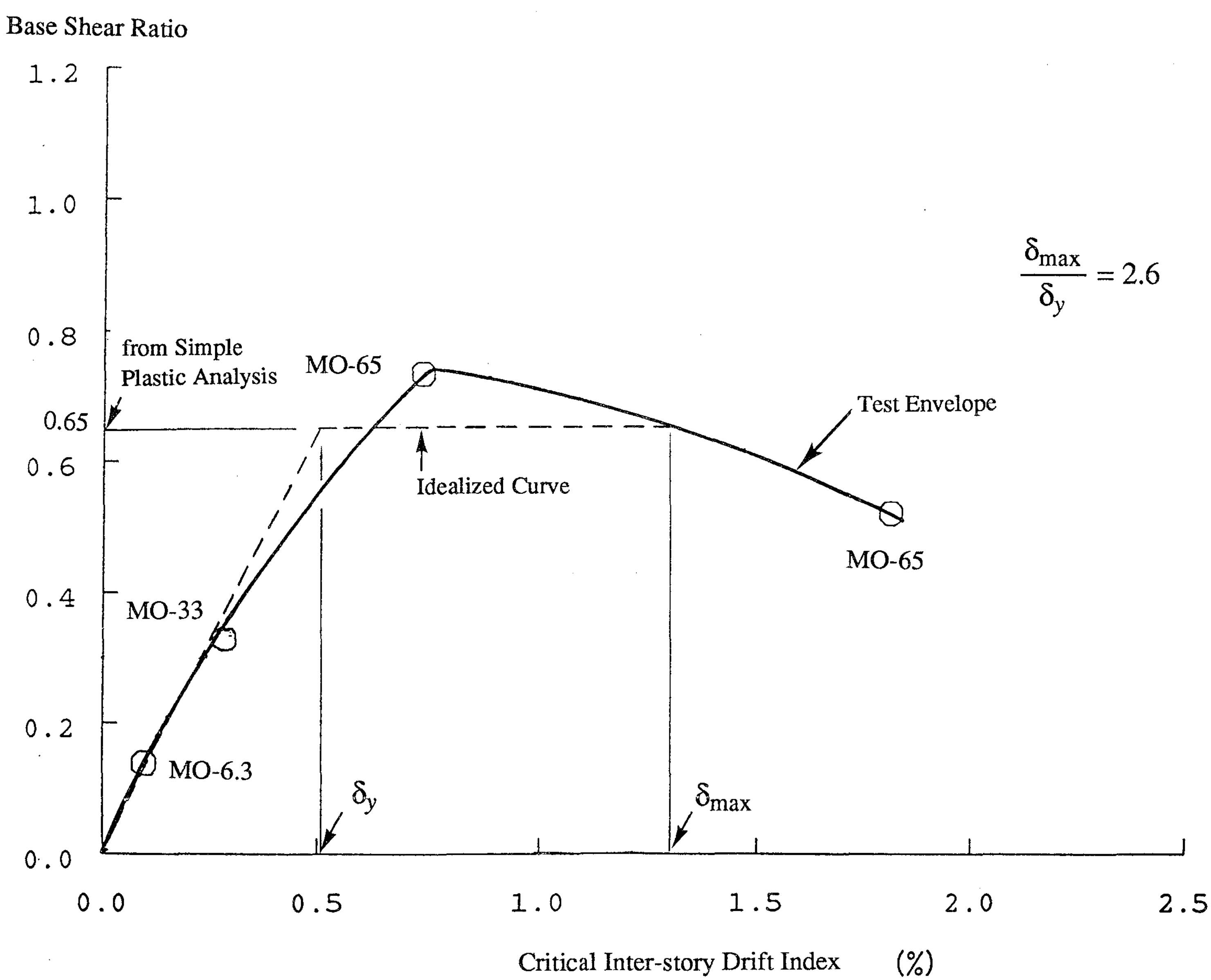


Fig. 2.9 **Envelope of Critical Inter-story Drift Index versus Base Shear Ratio**[20]

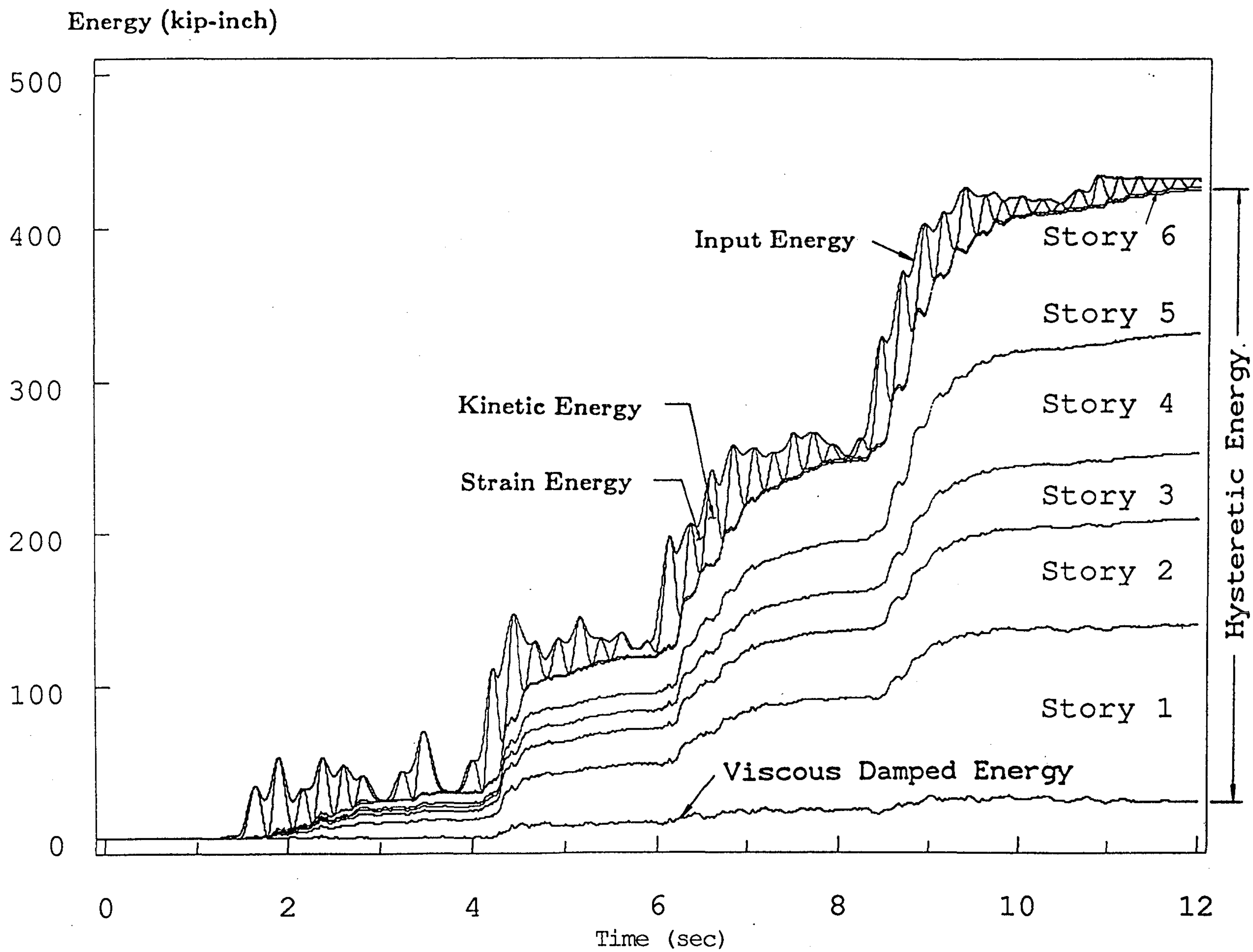


Fig. 2.10 Model Collapse Level Test (MO-65 Test) Energy Time Histories[20]

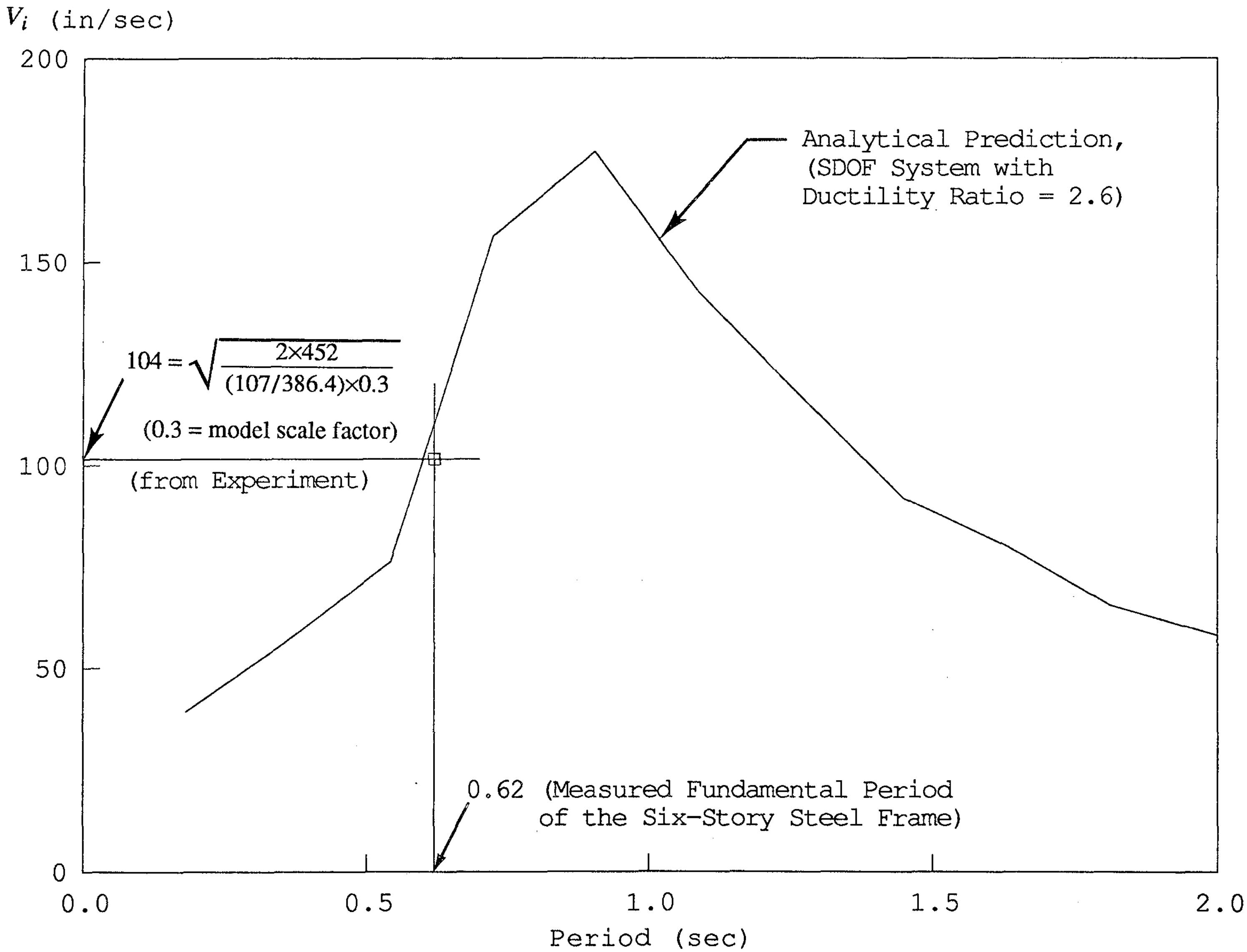


Fig. 2.11 Comparison of Analytical and Experimental Input Energy Equivalent Velocities

(Measured Ground Motion during MO-65 Test, 2% Damping Ratio)

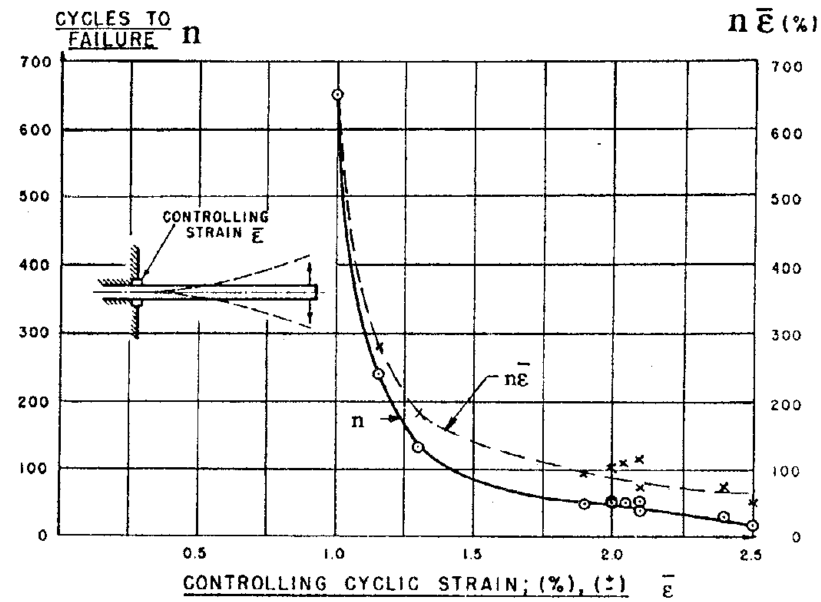


Fig. 3.1 Number of Cycles Required to Attain Fracture as a Function of the Controlling Strain[6]

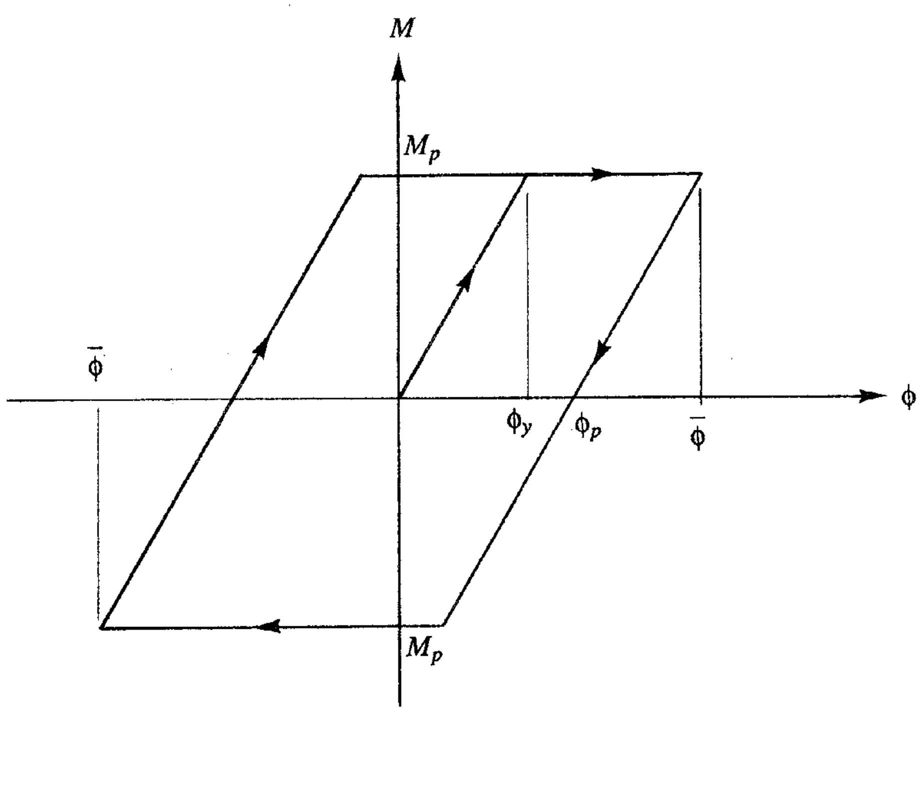


Fig. 3.2 Idealized Steel Beam Moment-Curvature Relationship

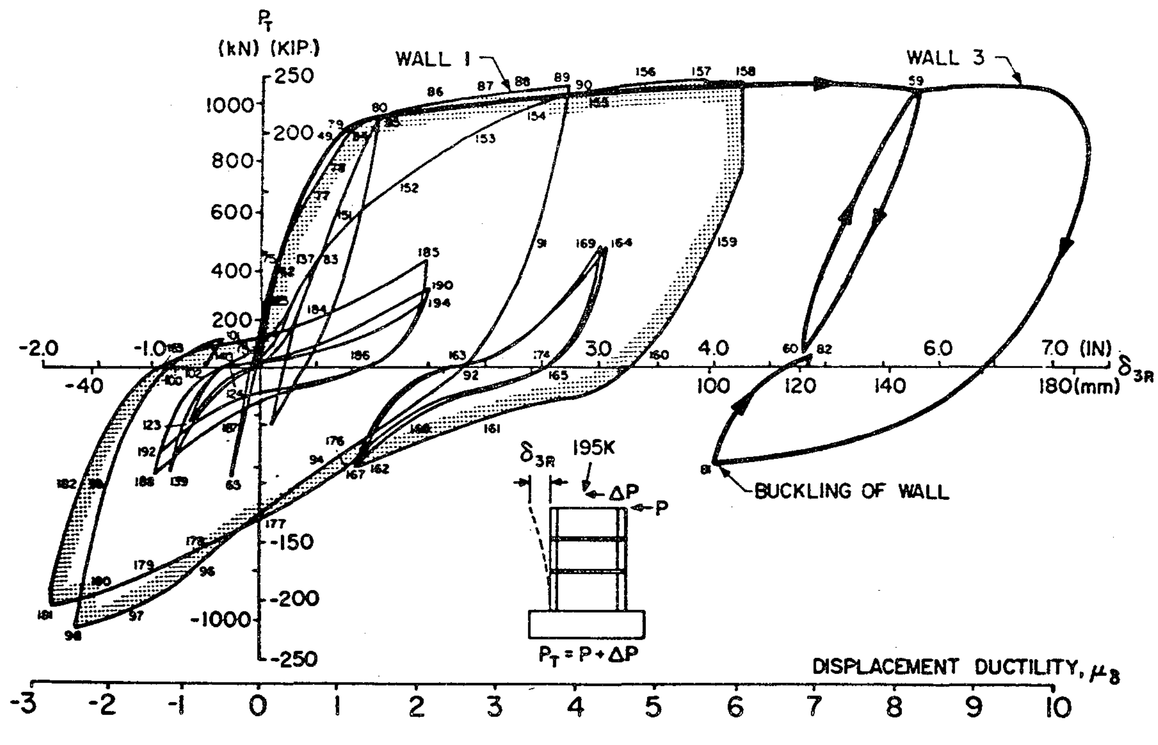
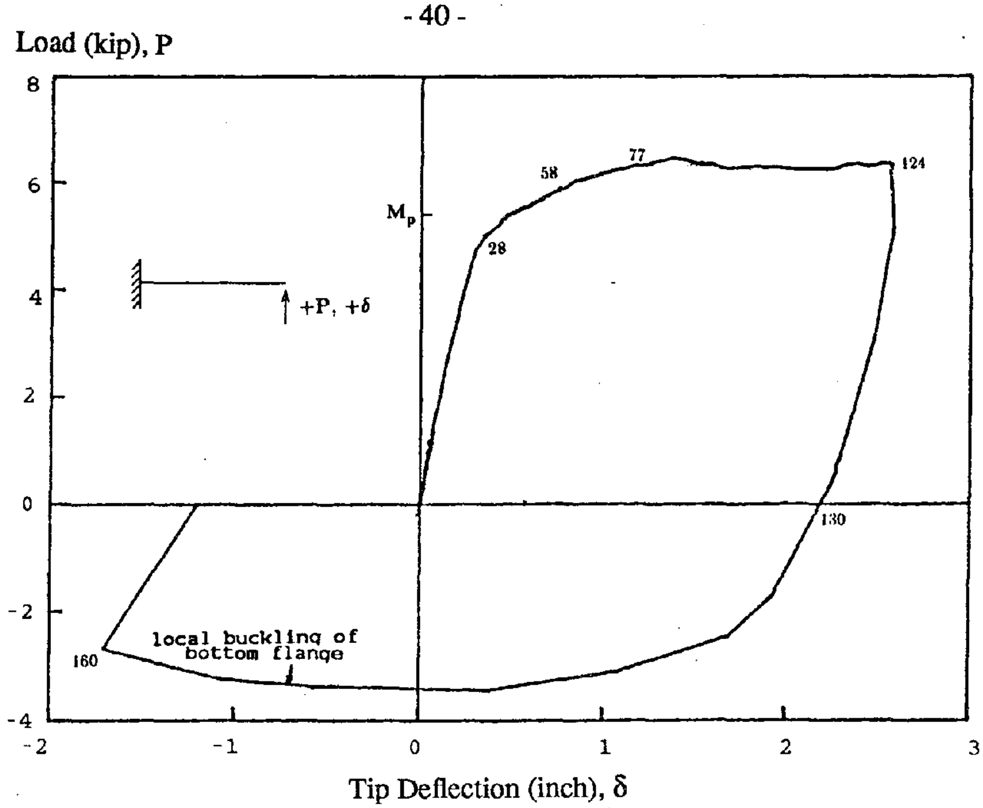
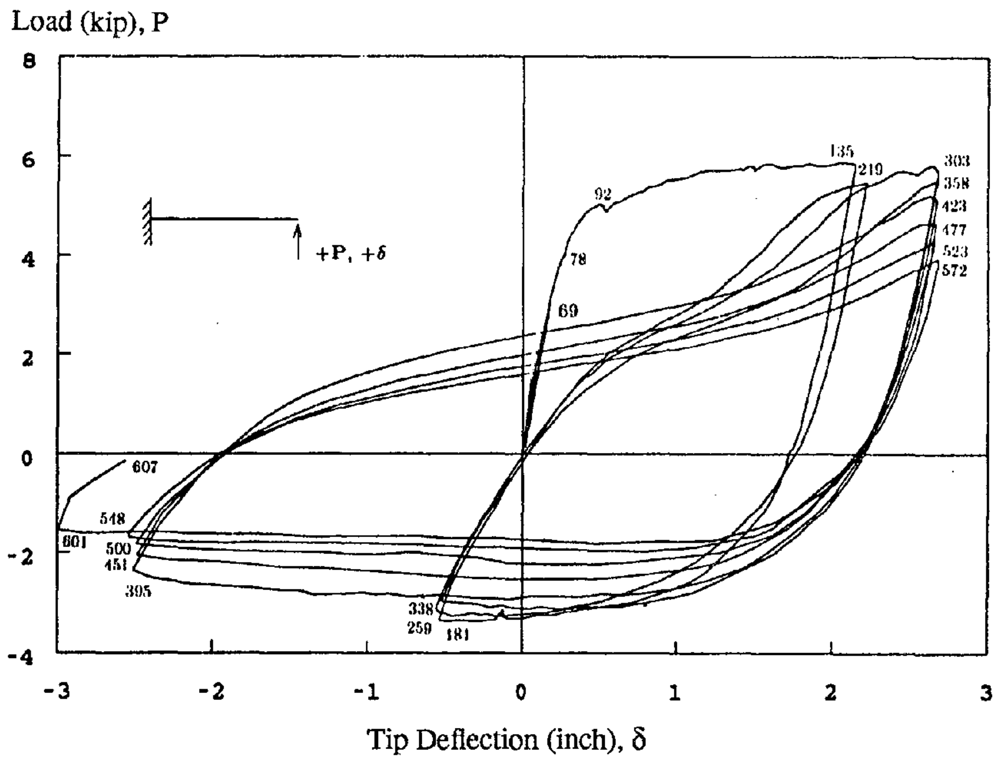


Fig. 3.3 Comparison of Energy Dissipation Capacities of Two Shear Walls[7]

(Wall 1: Cyclic Loading; Wall 3: Monotonic Loading)



(a) Load versus Deflection Curve of CG1



(b) Load versus Deflection Curve of CG3

Fig. 3.4 **Comparison of Energy Dissipation Capacities of Two Composite Girders**[20]

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UCB/EERC-80/20 "The Design of Steel Energy-Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety (Vol 1C): Numerical Method for Dynamic Substructure Analysis," by Dickens, J.M. and Wilson, E.L., June 1980.

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UCB/EERC-80/32 "The Design of Steel Energy-Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety (Vol 3): Testing of Commercial Steels in Low-Cycle Torsional Fatique," by Spanner, P., Parker, E.R., Jongewaard, E. and Dory, M., 1980.

UCB/EERC-80/33 "The Design of Steel Energy-Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety (Vol 4): Shaking Table Tests of Piping Systems with Energy-Absorbing Restrainers," by Stiemer, S.F. and Godden, W.G., September 1980, (PB82 201 880)A05.

UCB/EERC-80/34 "The Design of Steel Energy-Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety (Vol 5): Summary Report," by Spencer, P., 1980.

UCB/EERC-80/35 "Experimental Testing of an Energy-Absorbing Base Isolation System," by Kelly, J.M., Skinner, M.S. and Beucke, K.E., October 1980, (PB81 154 072)A04.

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