Seismic Design of Buildings with Viscous Damper

Dr. Yin-Nan Huang

Associate Professor of NTU, Courtesy Researcher of NCREE and Associate Director at the Center for Teaching and Learning Development of NTU

Experiences

- Assistant Professor, Nanyang Technological University, Singapore
- Board Member, Open Education Consortium

Dr. Huang currently works in the Department of Civil Engineering at National Taiwan University (NTU) as an associate professor. He also serves as an associate director in the Center of Teaching and Learning Development (CTLD) in NTU, in charge of orientation and professional development of new faculties in NTU.

Dr. Huang's research interests include the design of passive structural control systems, and seismic performance assessment of buildings and nuclear power plants. Other than his faculty position in NTU, he also serves as an associate researcher in National Center for Research on Earthquake Engineering in Taiwan. He has published 20+ academic journal papers and 60+ conference papers in the field of earthquake engineering. He received Outstanding Young Scholar Award from the Foundation for the Advancement of Outstanding Scholarship in 2011 through 2016 and the NTU excellent teaching award in 2013 and 2014.

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Yin-Nan Huang[1] and Jenn-Shin Hwang[2]

1、Introduction

In addition to the loads due to the effects of gravity, earthquake loading must be considered when designing structures located in seismically active areas. The philosophy in the conventional seismic design is that a structure is designed to resist the lateral loads corresponding to wind and small earthquakes by its elastic action only, and the structure is permitted to damage but not collapse while it is subjected to a lateral load associated with moderate or severe seismic events. As a consequence, plastic hinges in structures must be developed in order to dissipate the seismic energy when the structure is under strong shakings. The design methods based on this philosophy are acceptable to account for the needs for both economic consideration and life safety. However, the development of the plastic hinges relies on the large deformation and high ductility of a structure. The more ductility a structure sustains, the more damage it suffers. Besides, some important structures such as hospitals and fire stations have to remain their functions after a major earthquake, the aforementioned design philosophy (life-safety based) may not be appropriate. These structures should be strong enough to prevent from large displacement and acceleration so that they can maintain their functions when excited by a severe ground motion.

Structural passive control systems have been developed with a design philosophy different than that of the traditional seismic design method. These control systems primarily include seismic isolation systems and energy dissipation systems. A variety of energy dissipation systems have been developed in the past two decades, such as friction dampers, metallic dampers, visco-elastic dampers and viscous dampers. A structure installed with these dampers does not rely on plastic hinging to dissipate the seismic energy. On the contrary, the dissipation of energy is concentrated on some added dampers so that the damage of the main structure is reduced and the functions of the structure can then be possibly preserved.

This article will focus on the seismic design of structure with supplemental "viscous dampers". The effect of the supplemental viscous dampers to a structure in resisting seismic force can be clearly illustrated from energy consideration. The event of a structure responding to an earthquake ground motion is described using an energy concept in the follows. The absolute energy equation (Uang and Bertero, 1988) is given by:

$$E_I = E_k + E_s + E_h + E_d \tag{1}$$

where E_I is the earthquake input energy, E_k is the kinetic energy, E_s is the recoverable elastic strain energy, E_h is the irrecoverable hysteretic energy, and E_d is the energy dissipated by the inherent structural damping capability and/or the supplemental viscous dampers. The right hand side is basically the energy capacity or supply of the structure and

[1] Associate Professor, Department of Civil Engineering, National Taiwan University, Taipei, Taiwan
[2] Professor, Department of Construction Engineering, National Taiwan University of Science and Technology. Also, Division Head, National Center for Research on Earthquake Engineering of Taiwan.

the left hand side is the energy demand by the earthquake ground motion on the structure. For a structure to survive the earthquake, the energy supply must be larger than the energy demand. In conventional seismic design, the energy supply relies mostly on the hysteretic energy term, E_h, which results from the inelastic deformations of the structure. For a structure with viscous dampers, the energy dissipation capacity of the system will increase due to the addition of E_d, and the system will normally be designed to allow for an early engagement of the viscous dampers in dissipating the input energy prior to the inelastic deformation of the primary structure. In other words, the primary frame will be better protected, and the performance of the structure subjected to a ground motion can be improved.

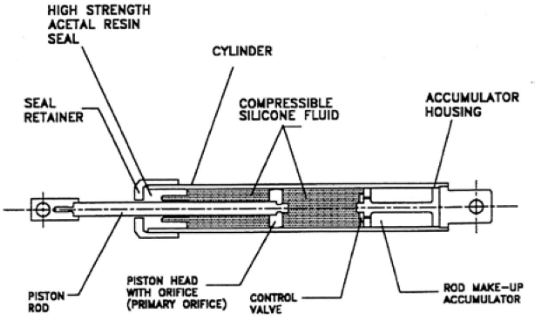
In September 1996, the Federal Emergency Management Agency of the United States published the ballot version of the NEHRP Guidelines and Commentary for the Seismic Rehabilitation of Buildings, which is known as FEMA 273 and 274 (Federal Emergency Management Agency of the United States, 1997). The guidelines have more documentation on the seismic design with energy dissipation devices than any other design codes published earlier. In this article, the mechanical properties of fluid viscous dampers are introduced. Besides, the derivation of the effective damping ratio of a structure implemented with linear and nonlinear dampers are summarized. They revised load combination factors, CF_1 and CF_2 (Ramirez et al., 2000) recommended by FEMA 273 are also presented. These factors are used to calculate the force of a viscously damped structure at the instant of the maximum acceleration. Finally, a design example of an elastic structure with linear viscous dampers is illustrated.

2、Mechanical properties of fluid viscous dampers

Since pure viscous behavior may be brought by forcing viscous fluid through orifices (Soong and Constantinou, 1994), fluid viscous dampers have been extensively applied to the seismic protective design of important structures (Whittaker and Constantinou, 2000). The devices were developed for various applications to the military and heavy industry. More recently, they have played an important role in seismic structural control after the cold war. Viscous dampers have been used as energy absorbers not only in seismic isolation system to prevent the system from a large deformation but also in energy dissipation system throughout the whole building to reduce its response subjected to wind forces or seismic loadings.

Figure 2-1 contains two typical longitudinal cross sections of fluid viscous dampers. They both consist of a stainless steel piston with an orifice head and are filled with viscous liquid, such as silicon oil. One of them has an accumulator while the other has a run-through rod instead. The difference of the pressure between each side of the piston head results in the damping force, and the damping constant of the damper can be determined by adjusting the configuration of the orifice of the piston head. When it comes to a pure viscous behavior, the damper force and the velocity should remain in phase. However, for a damper setup shown in Figure 2-1(a), the volume for storing the fluid will change while the piston begin to move. Thus a restoring force, which is in phase with displacement rather than velocity, will be developed. Configuration of an accumulator or a run-through rod is used to solve the problem. However, for high frequency motions, the accumulator valve may operate inaccurately, and the restoring force will occur.

(a)



(b)

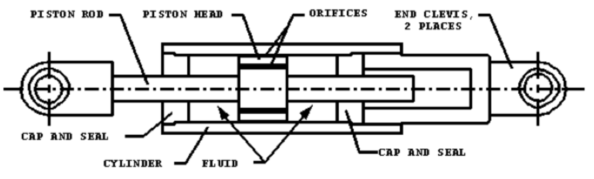


Figure 2-1 Longitudinal Cross Section of A Fluid Damper (a) Damper with An Accumulator (b) Damper with A Run-Through Rod (Seleemah and Constantinou, 1997)

The ideal force output of a viscous damper can be expressed as

$$F_D = C|\dot{u}|^{\alpha} \operatorname{sgn}(\dot{u}) \tag{2}$$

where F_D is the damper force, C is the damping constant, $\dot{u}$ is the relative velocity between the two ends of the damper, and α is the exponent between 0 and 1. The damper with $\alpha = 1$ is called a linear viscous damper in which the damper force is proportional to the relative velocity. The dampers with α larger than 1 have not been seen often in practical applications. The damper with α smaller than 1 is called a nonlinear viscous damper which is effective in minimizing high velocity shocks. Figure 2-2 shows the force-velocity relationships of the three different types of viscous dampers. This Figure demonstrates the efficiency of nonlinear dampers in minimizing high velocity shocks. For a small relative velocity, the damper with a α value less than 1 can give a larger damping force than the other two types of dampers.

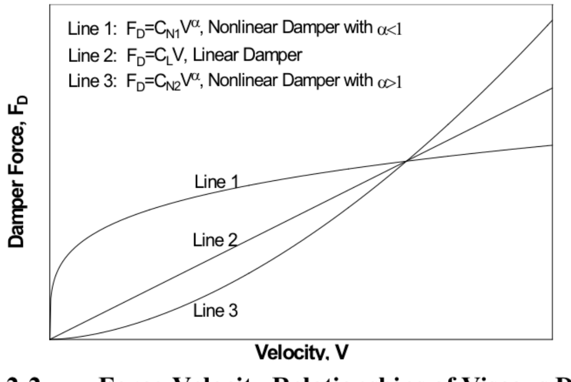


Figure 2-2 Force-Velocity Relationships of Viscous Dampers

Figure 2-3(a) shows the hysteresis loop of a pure linear viscous behavior. The loop is a perfect ellipse under this circumstance. The absence of storage stiffness makes the natural frequency of a structure incorporated with the damper remain the same. This advantage will simplify the design procedure for a structure with supplemental viscous devices. However, if the damper develops restoring force, the loop will be changed from Figure 2-3(a) to Figure 2-3(b). In other words, it turns from a viscous behavior to a viscoelastic behavior.

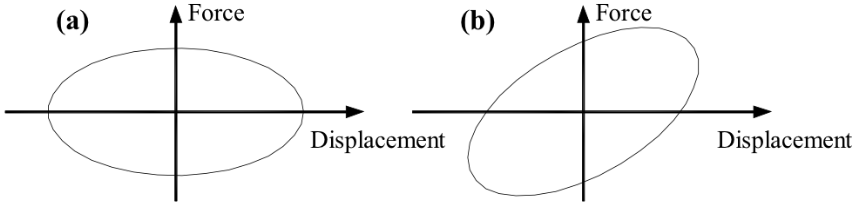


Figure 2-3 Hysteresis Loops of Dampers with Pure Viscous and Viscoelastic Behavior

3、The effective damping ratio of structures with linear viscous dampers

Considering a single degree of freedom system equipped with a linear viscous damper under an imposed sinusoidal displacement time history

$$u = u_0 \sin \omega t \tag{3}$$

where u is the displacement of the system and the damper; u_0 is amplitude of the displacement; and the ω is the excitation frequency. The measured force response is

$$P = P_0 \sin(\omega t + \delta) \tag{4}$$

where P is the force response of the system; P_0 is amplitude of the force; and the δ is the phase angle. The energy dissipated by the damper, W_D, is

$$W_D = \oint F_D du \tag{5}$$

where F_D is the damper force which equals to $C\dot{u}$; C is the damping coefficient of the damper; and $\dot{u}$ is the velocity of the system and the damper. Therefore,

$$\begin{aligned} W_D &= \oint C\dot{u}du = \int_0^{2\pi/\omega} C\dot{u}^2\,dt \\ &= C u_0^2 \omega^2 \int_0^{2\pi} \cos^2 \omega t \;\, d(\omega t) \\ &= \pi C u_0^2 \omega \end{aligned} \tag{6}$$

Recognizing that the damping ratio contributed by the damper can be expressed as $\xi_d = C / C_{cr}$, it is obtained

$$\begin{aligned} W_D &= \pi C u_0^2 \omega = \pi \xi_d C_{cr} u_0^2 \omega = 2\pi \xi_d \sqrt{Km} u_0^2 \omega \\ &= 2\pi \xi_d K u_0^2 \frac{\omega}{\omega_0} = 2\pi \xi_d W_s \frac{\omega}{\omega_0} \end{aligned} \tag{7}$$

where C_{cr}, K, m, ω_0 and W_s are respectively the critical damping coefficient, stiffness, mass, nature frequency and elastic strain energy of the system. The damping ratio attributed to the damper can then be expressed as

$$\xi_d = \frac{W_D}{2\pi W_s}\frac{\omega_0}{\omega} \quad (8)$$

W_D and W_s are illustrated in Figure 3-1. Under earthquake excitations, ω is essentially equal to ω_0, and Eq. (8) is reduced to

$$\xi_d = \frac{W_D}{2\pi W_s} \quad (9)$$

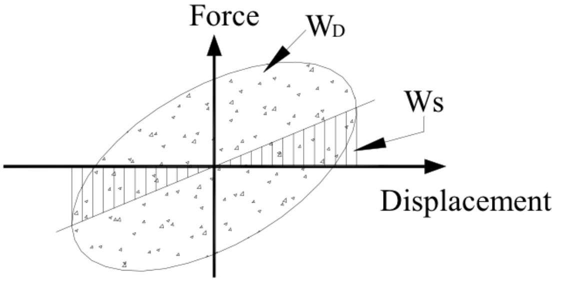


Figure 3-1 Definition of Energy Dissipated W_D in A Cycle of Harmonic Motion and Maximum Strain Energy W_s of A SDOF System with Viscous Damping Devices

Considering a MDOF system shown in Figure 3-2, the total effective damping ratio of the system, ξ_{eff}, is defined as

$$\xi_{eff} = \xi_0 + \xi_d \quad (10)$$

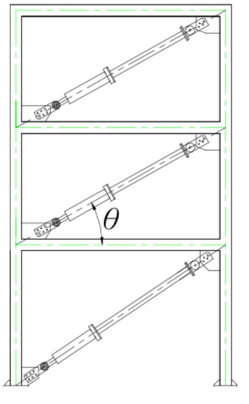


Figure 3-2 A MDOF Model of A Structure with Viscous Dampers

where ξ_0 is the inherent damping ratio of the MDOF system without dampers, and ξ_d is the viscous damping ratio attributed to added dampers. Extended from the concept of a SDOF system, the equation shown below is used by FEMA273 to represent ξ_d

$$\xi_d = \frac{\sum W_j}{2\pi W_K} \tag{11}$$

where $\sum W_j$ is the sum of the energy dissipated by the j-th damper of the system in one cycle; and W_K is the elastic strain energy of the frame. W_K is equal to $\sum F_i \Delta_i$ where F_i is the story shear and Δ_i is the story drift of the i-th floor. Now, the energy dissipated by the viscous dampers can be expressed as

$$\sum_j W_j = \sum_j \pi C_j u_j^2 \omega_0 = \frac{2\pi^2}{T} \sum_j C_j u_j^2 \tag{12}$$

where u_j is the relative axial displacement of damper j between the two ends.

Experimental evidence has shown that if the damping ratio of a structure is increased the higher mode responses of the structure will be suppressed. As a consequence, only the first mode of a MDOF system is usually considered in the simplified procedure of practical applications. Using the modal strain energy method, the energy dissipated by the dampers and the elastic strain energy provided by the primary frame can be rewritten as

$$\sum_j W_j = \frac{2\pi^2}{T} \sum_j C_j \phi_{rj}^2 \cos^2\theta_j \tag{13}$$

and

$$\begin{aligned} W_K &= \Phi_1^T [K] \Phi_1 = \Phi_1^T \omega^2 [m] \Phi_1 \\ &= \sum_i \omega^2 m_i \phi_i^2 = \frac{4\pi^2}{T^2} \sum_i m_i \phi_i^2 \end{aligned} \tag{14}$$

where $[K]$, $[m]$, Φ_1 are respectively the stiffness matrix, the lumped mass matrix and the first mode shape of the system; ϕ_{rj} is the relative horizontal displacement of damper j corresponding to the first mode shape; ϕ_i is the first mode displacement at floor i; m_i is the mass of floor i; and θ_j is the inclined angle of damper j. Substituting Eqs. (11), (13) and (14) into Eq. (10), the effective damping ratio of a structure with linear viscous dampers given by

$$\xi_{eff} = \xi_0 + \frac{\frac{2\pi^2}{T} \sum_j C_j \phi_{rj}^2 \cos^2\theta_j}{2\pi \frac{4\pi^2}{T^2} \sum_i m_i \phi_i^2} = \xi_0 + \frac{T \sum_j C_j \phi_{rj}^2 \cos^2\theta_j}{4\pi \sum_i m_i \phi_i^2} \tag{15}$$

Corresponding to a desired added damping ratio, there is no substantial procedure suggested by design codes for distributing C values over the whole building. When designing the dampers, it may be convenient to distribute the C values equally in each floor. However, many experimental results have shown that the efficiency of dampers on the upper stories is smaller than that in the lower stories (Pekcan et al., 1999). Hence an efficient distribution of the C values of the dampers may be to size the horizontal damper forces in proportion to the story shear forces of the primary frame.

4、The effective damping ratio of structures with nonlinear viscous dampers

Considering a SDOF system with a nonlinear viscous damper under sinusoidal motions, the velocity of the system is given by

$$\dot{u} = \omega u_0 \sin \omega t \tag{16}$$

Recognizing $F_D = C\dot{u}^{\alpha}$ and substituting Eqs. (2) and (16) into Eq. (5), the energy dissipated by the nonlinear damper in a cycle of sinusoidal motion can be acquired.

$$\begin{aligned} W_D &= \oint F_D du = \int_0^{2\pi/\omega} F_D \dot{u} dt \\ &= \int_0^{2\pi/\omega} \left| C\dot{u}^{1+\alpha} \right| dt \\ &= C(\omega u_0)^{1+\alpha} \int_0^{2\pi/\omega} \left| \sin^{1+\alpha} \omega t \right| dt \end{aligned} \tag{17}$$

Let $\omega t = 2\theta$ and $dt = \dfrac{2}{\omega} d\theta$, Eq. (17) is rewritten as

$$\begin{aligned} W_D &= C(\omega u_0)^{1+\alpha} \frac{2}{\omega} \int_0^{\pi} \left| \sin^{1+\alpha} 2\theta \right| d\theta \\ &= 2^{2+\alpha} C\omega^{\alpha} u_0^{\ 1+\alpha} \int_0^{\pi/2} 2\sin^{1+\alpha}\theta \cos^{1+\alpha}\theta d\theta \\ &= 2^{2+\alpha} C\omega^{\alpha} u_0^{\ 1+\alpha} \frac{\Gamma^2(1+\alpha/2)}{\Gamma(2+\alpha)} \end{aligned} \tag{18}$$

where Γ is the gamma function.

Following a similar procedure to that of the SDOF with linear viscous dampers, equivalent damping ratio of the SDOF system contributed by nonlinear dampers can be obtained

$$\xi_d = \frac{\lambda C\omega^{\alpha-2} u_0^{\ \alpha-1}}{2\pi m} \tag{19}$$

in which

$$\lambda = 2^{2+\alpha} \frac{\Gamma^2(1+\alpha/2)}{\Gamma(2+\alpha)} \tag{20}$$

For the convenience of practical applications, the values of λ are tabulated in FEMA 273 based on Eq. (20). It is worthy of noting that the damping ratio determined by Eq. (19) is dependent of the displacement amplitude u_0.

For a MDOF system with nonlinear dampers shown in Figure 3-2, Eq. (10) and (11) are used to represent the effective damping ratio of the whole system, and the damping ratio attributed to the added nonlinear viscous dampers is derived in the follows. Considering the first mode only, the elastic strain energy is

$$W_K = \omega^2 \sum_i m_i u_i^2 \tag{21}$$

Assuming that all dampers of the whole building have the same α and substituting Eqs. (19), (20) and (21) into Eq. (11), the damping ratio contributed by the dampers is obtained as

$$\xi_d = \frac{\sum_j \lambda C_j u_{rj}^{1+\alpha} \cos^{1+\alpha} \theta_j}{2\pi\omega^{2-\alpha} \sum_i m_i u_i^2} \tag{22}$$

where u_{rj} is the relative displacement between the ends of damper j in the horizontal direction. Since only the first mode is considered, the displacement response may be expressed as

$$u_i = A\phi_i \tag{23}$$

where ϕ_i is the first modal displacement of the i-th degree-of-freedom and A is the amplitude. Finally, substituting Eq. (22) and (23) into Eq. (10), the effective damping ratio of the structure with nonlinear dampers is obtained

$$\xi_{eff} = \xi_0 + \frac{\sum_j \lambda C_j \phi_{rj}^{1+\alpha} \cos^{1+\alpha} \theta_j}{2\pi A^{1-\alpha} \omega^{2-\alpha} \sum_i m_i \phi_i^2} \tag{24}$$

5、The loading combination factors, CF_1 and CF_2, of FEMA 273

Since the force of viscous dampers and the displacement response of the frame are out of phase, it is difficult to determine the internal force of each member of the frame through the static procedure. Therefore, when the rehabilitation of buildings is executed with velocity-dependent devices, FEMA 273 suggests engineers to check the actions for components of the buildings in the following three stages of deformation, and the maximum action should be used for design.

1. **Stage of maximum drift:** which is represented by point A of Figure 5-1.
2. **Stage of maximum velocity and zero drift:** which is represented by point B of Figure 5-1.
3. **Stage of maximum floor acceleration:** which is represented by point C of Figure 5-1.

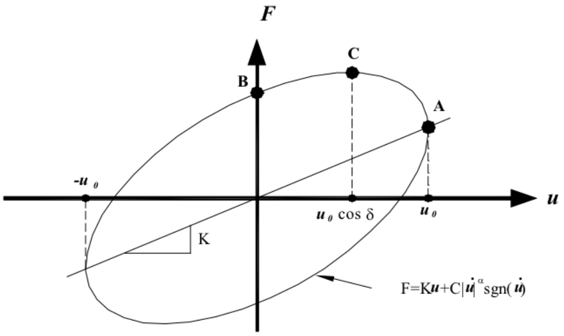


Figure 5-1 Force-Displacement Relationship of A Structure with Viscous Dampers

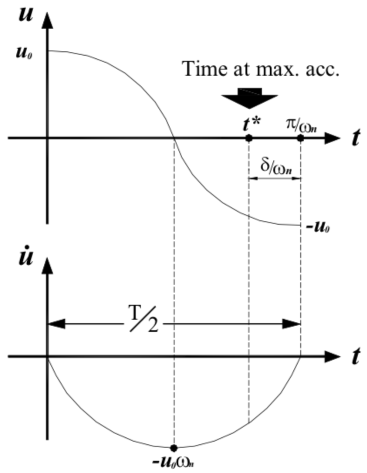


Figure 5-2 Harmonic Motion of A Structure with Viscous Dampers

Furthermore, FEMA 273 recommends a procedure to calculate the member force at the instant of the maximum acceleration. The procedure indicates that *design actions in components should be determined as the sum of "actions determined at the stage of maximum drift" times* CF_1 *and "actions determined at the stage of maximum velocity" times* CF_2, where

$$CF_1 = \cos\left[\tan^{-1}\left(2\xi_{eff}\right)\right] \tag{25}$$

$$CF_2 = \sin\left[\tan^{-1}\left(2\xi_{eff}\right)\right] \tag{26}$$

in which ξ_{eff} is given by Eq. (10). However, the two load combination factors are inappropriate for structures with nonlinear viscous dampers. The revised formulas have been proposed by Ramirez et al. (2000) and are implemented in NEHRP 2000. The follows are the derivation of the revised load factors.

For a linear elastic structure with a nonlinear viscous damper under a harmonic vibration at its natural frequency, ω_n, the displacement and velocity may be expressed as

$$u = u_0 \cos \omega_n t \tag{27}$$

$$\dot{u} = -\omega_n u_0 \sin \omega_n t \tag{28}$$

The force response should be

$$F = Ku + C|\dot{u}|^{\alpha}\,\mathrm{sgn}(\dot{u}) \tag{29}$$

where K is the stiffness of the system and is equal to $m\omega_n^2$. Figure 5-1 shows this force-displacement relationship. Substituting Eqs. (19), (20), (27) and (28) into Eq. (29), it yields

$$\frac{F}{m\omega_n^2 u_0} = \cos\omega_n t - \frac{2\pi}{\lambda}\xi_d \sin^{\alpha}\omega_n t \tag{30}$$

where λ is given by Eq. (20) and ξ_d is given by Eq. (19). It should be noted that Eq. (30) is obtained based on the assumption that the velocity is negative. In other words, the considered cycle of motion shown in Figure 5-2 is within the interval $0 \le \omega_n t \le \pi$. The maximum acceleration will occur when the force response reaches its maximum value, $F_{\max}$. The time when the maximum acceleration occurs can be determined simply by taking the first derivative of the right hand side of Eq. (30) with respect to t and setting the derivative to zero.

$$\frac{\sin^{2-\alpha}\omega_n t^*}{\cos\omega_n t^*} = -\frac{2\pi\alpha\xi_d}{\lambda} \tag{31}$$

where t^* is the time when the maximum acceleration and $F_{\max}$ occur. Since there exists a phase lag δ (shown in Figure 5-1 and 5-2) between the occurring instances of the maximum acceleration and the maximum displacement, it is obtained

$$\omega_n t^* = \pi - \delta \tag{32}$$

Eq. (30) and (31) can then be respectively rewritten as

$$F_{\max} = m\omega_n^2 u_0 \cos\delta + C\omega_n^{\alpha} u_0^{\alpha} \sin^{\alpha}\delta \tag{33}$$

$$\frac{\sin^{2-\alpha}\delta}{\cos\delta} = \frac{2\pi\alpha\xi_d}{\lambda} \tag{34}$$

It should be noted that, in Eq. (33), $m\omega_n^2 u_0$ is the force response at the stage of maximum drift and $C\omega_n^{\alpha} u_0^{\alpha}$ is the force response at the stage of maximum velocity. Therefore, the load combination factors should be

$$CF_1 = \cos\delta \tag{35}$$

and

$$CF_2 = \sin^{\alpha}\delta \tag{36}$$

δ can be solved using Eq. (34); however, it can't be solved exactly unless α equals to 1. An approximate solution is then adopted by assuming the phase lag, δ, is small. The phase angle can then be calculated using

$$\delta = \left(\frac{2\pi\alpha\xi_d}{\lambda} \right)^{\frac{1}{2-\alpha}} \tag{37}$$

It should be noted that when δ becomes larger, Eq. (37) will introduce more errors. For the case of linear dampers ($\alpha = 1$), Eq. (34) can be solved exactly

$$\delta = \tan^{-1}(2\xi_d) \tag{40}$$

which is adopted by FEMA 273 for linear dampers.

6、A design example of a structure (under elastic condition) with linear viscous dampers

This section presents a design example of a structure with linear viscous dampers. The primary (gravity) frame of the structure is assumed to remain elastic when subjected to a design earthquake. The damping constant of the dampers will be determined by using the formula of effective damping ratio. The earthquake responses of the building in three stages proposed in FEMA 273 will also be calculated to illustrate the FEMA procedure.

Description of the structure and the damping system

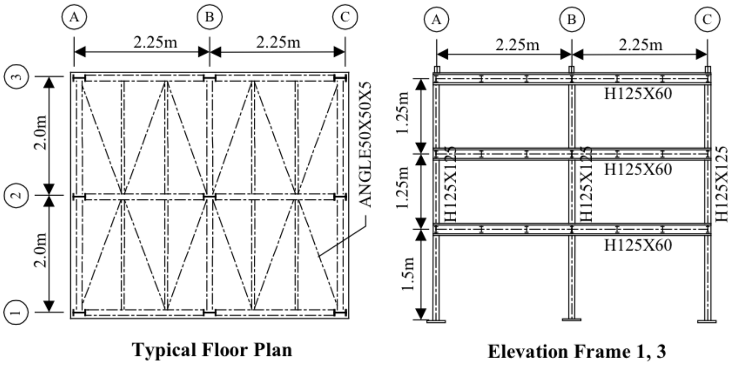


Figure 6-1 Typical Plan and Elevation of the Designed Structure

A three-story steel structure as shown in Figure 6-1 is a scale-down model. The linear viscous dampers will be installed with a diagonal brace configuration in frames 1 and 3. Each floor will contain two linear dampers. The inherent damping ratio of the structure is assumed to be 2%, and the effective damping ratio resulting from all added dampers is expected to reach 18%. That is to say, the total effective damping ratio of the whole system is designated at 20% of critical. Table 6-1 lists some necessary parameters of the structure for designing the viscous damping system.

Design of linear viscous damping system

Assume that all the dampers have the same value of damping constant, which can be determined from Eq. (15). (Note that it may be more practical to assume the damping constant of the damper such that the damper force to be proportional to the story shear force along the height of the structure.)

Table 6-1 Geometric and Modal Properties of the Designed Structure

Floor no.	Mass (kg)	$\cos\theta$ *	First mode Period (sec)	First mode mode shape
3	8155	0.87		1
2	9378	0.87	0.33	0.805
1	9378	0.83		0.494

- *Modal drift between floors*

$$\{\phi_r\}_1 = \begin{Bmatrix} 1-0.805 \\ 0.805-0.494 \\ 0.494 \end{Bmatrix} = \begin{Bmatrix} 0.195 \\ 0.311 \\ 0.494 \end{Bmatrix}$$

- *Effective damping ratio contributed by dampers*

$$\xi_d = 0.18 = \frac{2\times 0.33\times C\left(0.87^2\times 0.195^2 + 0.87^2\times 0.311^2 + 0.83^2\times 0.494^2\right)}{4\pi\left(8155\times 1^2 + 9378\times 0.805^2 + 9378\times 0.494^2\right)}$$

Therefore, the damping constant of each damper can be determined to be

$$C = 210 \quad (kN - s/m)$$

Calculation of response in design basis earthquake--first mode response

Design coefficients of design basis earthquake

As mentioned earlier, the gravity frame will stay in elastic condition when subjected to a design basis earthquake (DBE). According to the seismic design specifications of building structures in Taiwan, the spectral acceleration of DBE for this structure could be calculated with the following coefficients:

Seismic zone factor, $Z = 0.33$
Importance factor, $I = 1.0$
Elastic design spectral acceleration normalized to a PGA of 1.0g for a 5% damping ratio, $C_{sa} = 2.5$

Since the damping ratio has been raised to 20%, the damping modification factor, C_D, can be obtained by using the following formula:

$$C_D = \frac{1.5}{40\times\xi_{eff}+1} + 0.5 = \frac{1.5}{40\times 0.2+1} + 0.5 = 0.67$$

Therefore, the design spectral acceleration of DBE for the first mode of the system will be

$$S_{a1} = ZIC_{sa}C_D = 0.33\times 1\times 2.5\times 0.67 = 0.553 \quad (g)$$

Response at stage of maximum displacement

- *The modal participation factor of the first mode,* PF_1

* θ is the inclined angle of damper

$$PF_1=\frac{\sum_i m_i\phi_{im}}{\sum_i m_i\phi_{im}^2}=\frac{8155\times1+9318\times0.805+9378\times0.494}{8155\times1^2+9318\times0.805^2+9378\times0.494^2}=1.23$$

- *Floor acceleration,* A_{i1}

$$A_{i1}=PF_1\phi_{i1}S_{a1}$$

$$A_{i1}=1.23\cdot\begin{Bmatrix}1\\0.805\\0.494\end{Bmatrix}\cdot0.553=\begin{Bmatrix}0.68\\0.548\\0.336\end{Bmatrix}\quad(g)$$

- *Design lateral force,* F_{i1}

$$F_{i1}=m_iA_{i1}$$

$$F_{i1}=\begin{Bmatrix}8.155\cdot9.81\cdot0.68\\9.378\cdot9.81\cdot0.548\\9.378\cdot9.81\cdot0.336\end{Bmatrix}=\begin{Bmatrix}54.4\\50.4\\30.9\end{Bmatrix}\quad(kN)$$

- *Design story shear force,* V_{i1}

$$V_{i1}=\begin{Bmatrix}54.4\\54.4+50.4\\54.4+50.4+30.9\end{Bmatrix}=\begin{Bmatrix}54.4\\104.8\\135.7\end{Bmatrix}\quad(kN)$$

Response at stage of maximum velocity

- *Floor displacement,* Δ_{i1}

$$\Delta_{i1}=\left(\frac{T}{2\pi}\right)^2A_{i1}$$

$$\Delta_{i1}=\left(\frac{0.33}{2\pi}\right)^2\cdot9810\cdot\begin{Bmatrix}0.68\\0.548\\0.336\end{Bmatrix}=\begin{Bmatrix}18.4\\14.8\\9.1\end{Bmatrix}\quad(mm)$$

- *Floor drift between floors,* Δ_{ri1}

$$\Delta_{ri1}=\begin{Bmatrix}18.4-14.8\\14.8-9.1\\9.1\end{Bmatrix}=\begin{Bmatrix}3.6\\5.7\\9.1\end{Bmatrix}\quad(mm)$$

- *Velocity between ends of dampers,* ∇_{di1}

$$\nabla_{di1}=\left(\frac{2\pi}{T}\right)\Delta_{ri1}\cos\theta_i$$

$$\nabla_{di1}=\left(\frac{2\pi}{0.33}\right)\begin{Bmatrix}3.6\cdot0.87\\5.7\cdot0.87\\9.1\cdot0.83\end{Bmatrix}=\begin{Bmatrix}59.6\\94.4\\143.8\end{Bmatrix}\quad(mm/s)$$

- *Damper force,* F_{di1}

$F_{di1}=nC_i\nabla_{di1}$, where n is the total number of dampers in floor i

$$F_{di1} = 2 \times (210) \begin{Bmatrix} 59.6/1000 \\ 94.4/1000 \\ 143.8/1000 \end{Bmatrix} = \begin{Bmatrix} 25 \\ 39.7 \\ 60.4 \end{Bmatrix} \ (kN)$$

- *Horizontal component of damper forces,* V_{di1}

$$V_{di1} = \begin{Bmatrix} 25 \cdot 0.87 \\ 39.7 \cdot 0.87 \\ 60.4 \cdot 0.83 \end{Bmatrix} = \begin{Bmatrix} 21.8 \\ 34.5 \\ 50.1 \end{Bmatrix} \ (kN)$$

Figure 6-2 shows the design forces of these two stages.

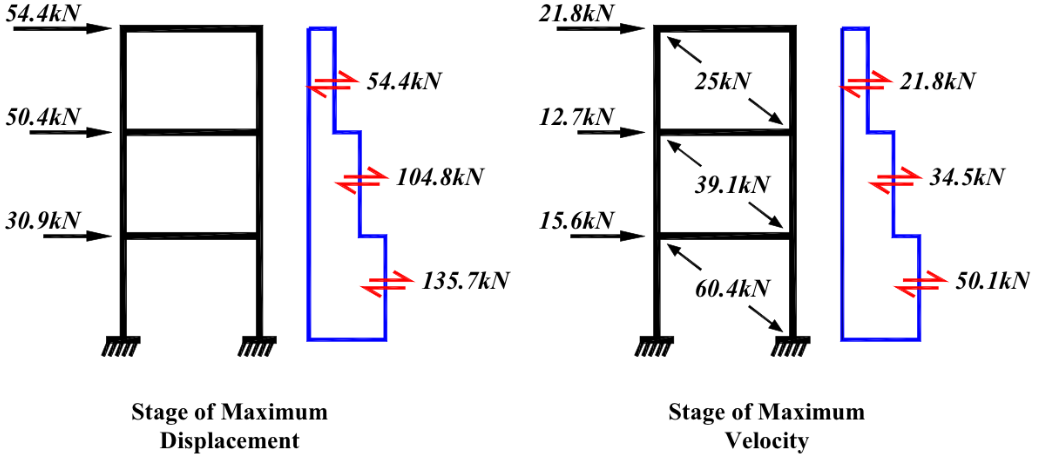


Figure 6-2 Seismic Design Forces at Stages of Maximum Displacement and Velocity

Response at stage of maximum acceleration

- *Coefficient* CF_1

  $CF_1 = \cos(\tan^{-1}(2\xi_a)) = \cos(\tan^{-1}(2 \cdot 0.2)) = 0.93$

- *Coefficient* CF_2

  $CF_2 = \sin(\tan^{-1}(2\xi_a)) = \sin(\tan^{-1}(2 \cdot 0.2)) = 0.37$

- *Maximum floor acceleration,* $A_{\max,i1}$

  For linear dampers, the relationship shown below can be derived from Eq. (33) by letting $\alpha = 1$.

$$A_{\max,i1} = (CF_1 + 2 \cdot \xi_{eff} CF_2) A_{i1} \tag{41}$$

  Thus,

$$A_{\max,i1} = (0.93 + 2 \cdot 0.2 \cdot 0.37) \begin{Bmatrix} 0.68 \\ 0.548 \\ 0.336 \end{Bmatrix} = \begin{Bmatrix} 0.73 \\ 0.59 \\ 0.36 \end{Bmatrix} \ (g)$$

- *Maximum story shear,* $V_{\max,i1}$

  $V_{\max,i1} = CF_1 \cdot V_{i1} |_{Max.\ Disp.} + CF_2 \cdot V_{di1} |_{Max.\ Vel.}$

$$V_{\max,i1} = 0.93\begin{Bmatrix} 54.4 \\ 104.8 \\ 135.7 \end{Bmatrix} + 0.37\begin{Bmatrix} 21.8 \\ 34.5 \\ 50.1 \end{Bmatrix} = \begin{Bmatrix} 58.7 \\ 110.2 \\ 144.7 \end{Bmatrix} \quad (kN)$$

Higher mode responses may be calculated through the same procedure. Design forces thus could be obtained by combining results of all modes with SRSS or CQC rules.

7、Reference

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Values of Parameter λ		
Exponent α	**Parameter** λ (Numerical)	**Parameter** λ (FEMA)
0.1	3.88	3.9
0.15	3.83	3.8
0.2	3.77	3.8
0.25	3.72	3.7
0.3	3.67	3.7
0.35	3.63	3.6
0.4	3.58	3.6
0.45	3.54	3.5
0.5	3.50	3.5
0.55	3.46	3.5
0.6	3.42	3.4
0.65	3.38	3.4
0.7	3.34	3.3
0.75	3.30	3.3
0.8	3.27	3.3
0.85	3.24	3.2
0.9	3.20	3.2
0.95	3.17	3.2
1	3.14	3.1

Taiwan Seismic Design Code for Passive Control Systems

Dr. Shiang-Jung Wang

Associate Professor of NTUST, Courtesy Researcher of NCREE, and Joint Appointment Associate Professor of NCKU

Experiences

- Research Fellow, NCREE
- Secretary General, Director, Chairman, CTSEE
- Chairman, Board Member, CSSE

Email:
sjwang@mail.ntust.edu.tw
sjwang@ncree.narl.org.tw

Dr. Shiang-Jung Wang is currently as an associate professor of the National Taiwan University of Science and Technology (NTUST), a courtesy researcher of the National Center for Research on Earthquake Engineering (NCREE), and a Joint Appointment Associate Professor of the National Cheng Kung University (NCKU) in Taiwan. He has been the secretary general, director, chairman, and board member of the Chinese Taiwan Society for Earthquake Engineering (CTSEE) and the chairman and board member of the Chinese Society of Structural Engineering (CSSE), since 2014.

Dr. Wang's researches are related to structural control technology and large-scale testing for structures and equipment. He has published over 30 peer reviewed journal papers and more than 80 conference papers, in which most are international journals and conferences. He has also published many technical reports, books, and patents. His outstanding research accomplishments have been implemented into many domestic seismic design codes.

Taiwan Seismic Design Code for Passive Control Systems

Shiang-Jung Wang

Associate Professor, NTUST, Taiwan

Joint Appointment Associate Professor, NCKU, Taiwan

Courtesy Researcher, NCREE, NARL, Taiwan

The International Joint Workshop
Structural Design of High-Rise Buildings with Passive Control Devices
Aula Barat, ITB Campus, 20-21 August 2018

Outline

An overview of Taiwan's current seismic design code for buildings with passive control systems (2011)

- **Ch9: Design for seismically isolated buildings**
- **Ch10: Seismic design for buildings with energy dissipation systems**

Development of Taiwan Seismic Design Code for Buildings with Passive Control Systems

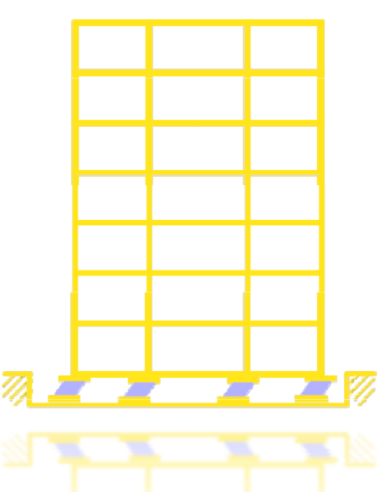
- ✓ Design guideline for seismically isolated buildings (1997)
- ✓ First official seismic isolation design code for buildings (2002)
- ✓ Seismic design code for buildings (2005)

Feedback from practical engineering experience
and reviews from academic communities

- ✓ Seismic design code for buildings (2011)
    - Ch9 - with seismic isolation systems
    - Ch10 - with passive energy dissipation devices

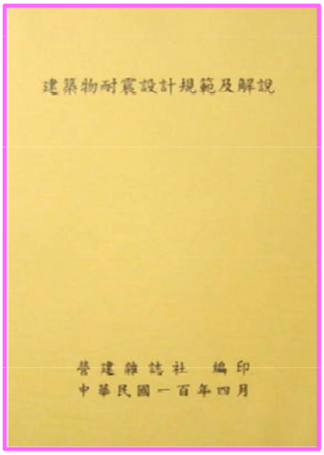
A more reasonable and practicable goal

Seismically Isolated Buildings



Taiwan's Relevant Seismic Isolation Design Codes

Ministry of the Interior

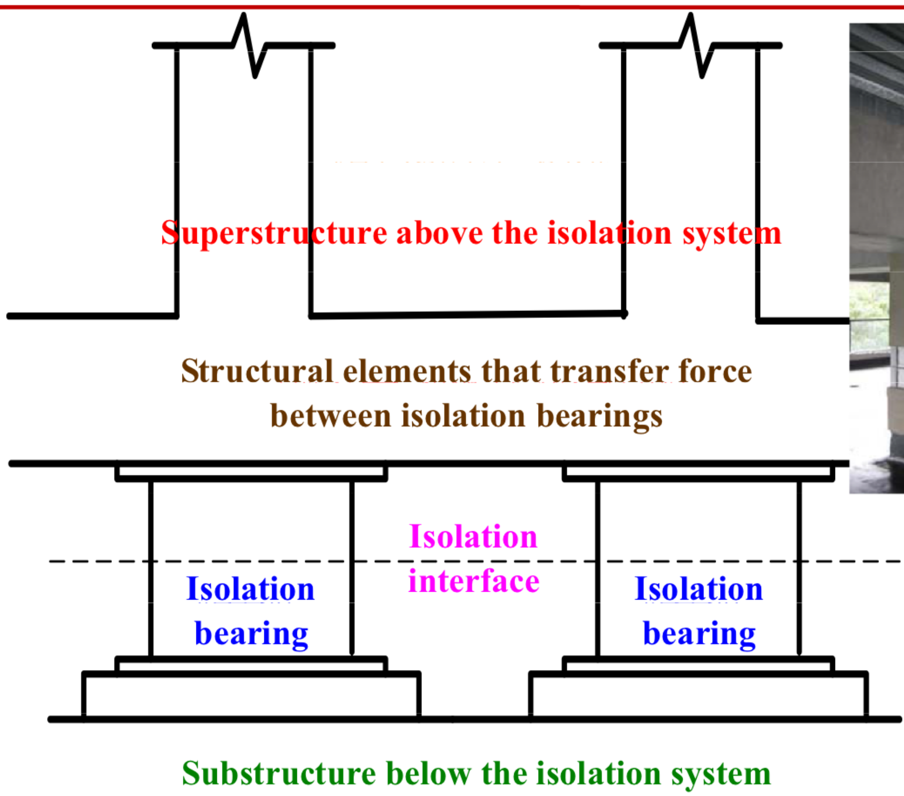


Ministry of Transportation and Communications

Ministry of Economic Affairs

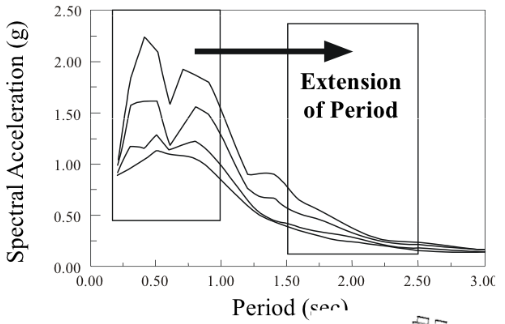
Ministry of Health and Welfare

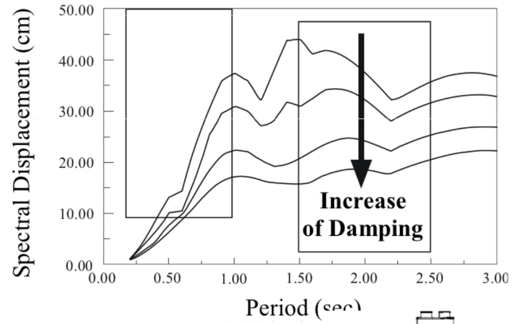
Isolation System Terminology

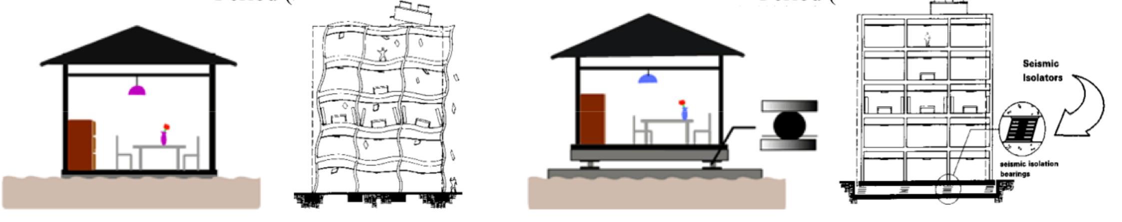


Design Principles (1)

- Reduction of acceleration transmitted to superstructure by extension of natural period
- Reduction of displacement across isolation system by increase of damping effect

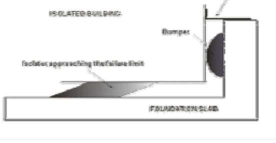






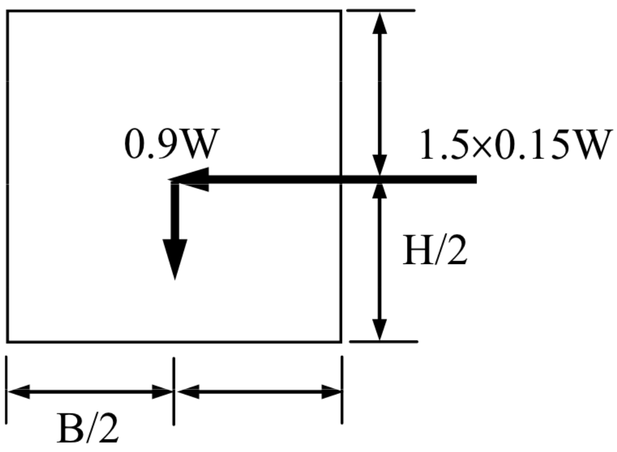
Design Principles (2)

- Stable under vertical load
- Horizontally flexible enough to elongate natural period
- Damping to suppress isolation displacement
- Restoring force (recentering) capability
- Restraint systems or sufficient lateral stiffness to resist wind load
- Environmental conditions
- Fire resistance rating
- Access for inspection and replacement
- Fail-safe systems



Design Principles (3)

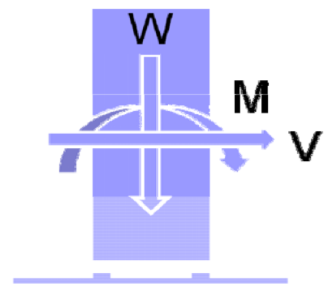
- **Stability of isolation system**



$$0.9W \times \frac{B}{2} = 1.5 \times 0.15W \times \frac{H}{2}$$

$$\Rightarrow 0.45B = 0.1125H$$

$$\Rightarrow \frac{H}{B} = 4$$



Design Principles (4)

- **Different design requirements and methods corresponding to different structural performances**

DBE: design shaking caused by earthquakes (475-year-return-period)
MCE: maximum considered shaking caused by earthquake (2500-year-return-period)

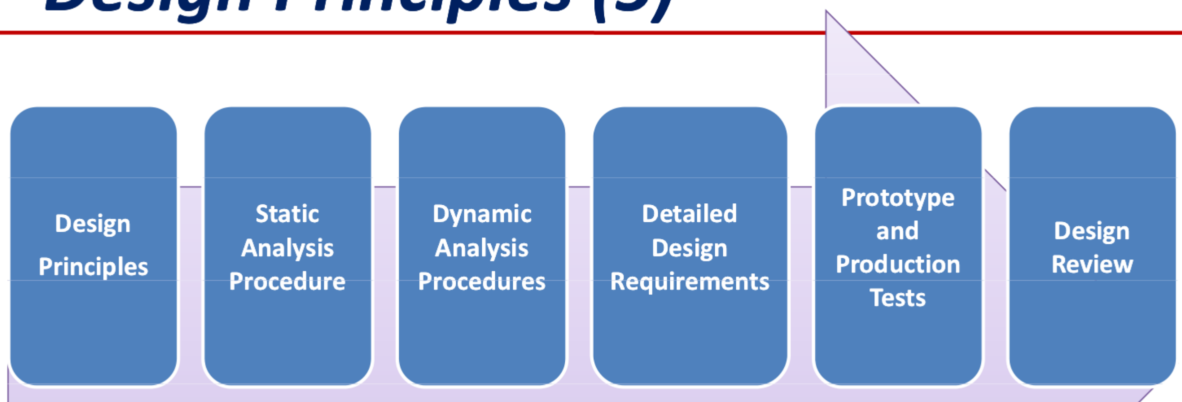
Regular in configuration → Static analysis → Structural elements remain elastic under DBE; Partial ductile design (e.g. intermediate MRF)

Irregular in configuration → Dynamic analysis → Structural elements remain elastic under DBE; Ductile design (e.g. MRF)

Dynamic analysis → Structural elements remain elastic under MCE; Ductile design is not required

DBE: design check
MCE: stability check

Design Principles (5)



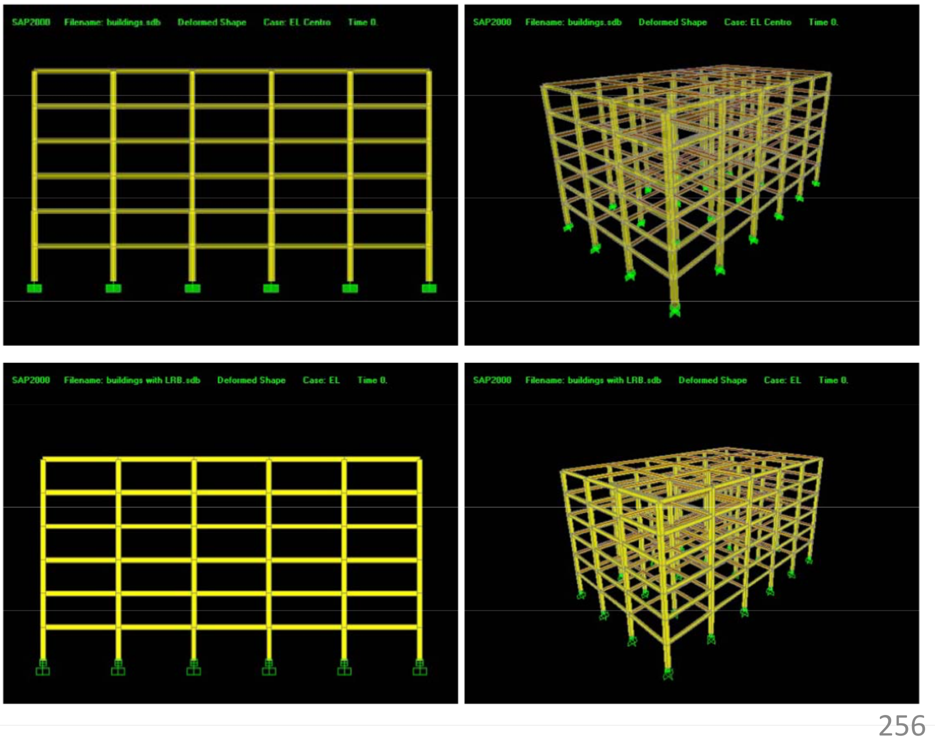
	Isolation System	Superstructure	Non-structural Components
DBE Level	Functional without Damage	Elastic Behavior	Functional without Damage
MCE Level	Functional and Stable	Ductile Behavior	Functional without Severe Damage

Unisolated and Isolated Structures

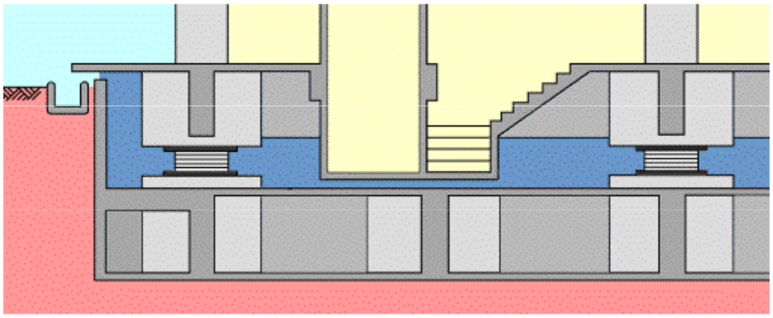
PGA = 350gal

Conventional MRF Structure

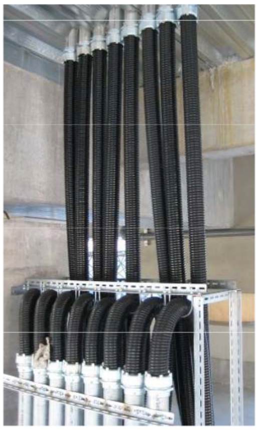
Seismically Isolated Structure



Design of Expansion Joints (1)



Design of Expansion Joints (2)



Design of Expansion Joints (3)

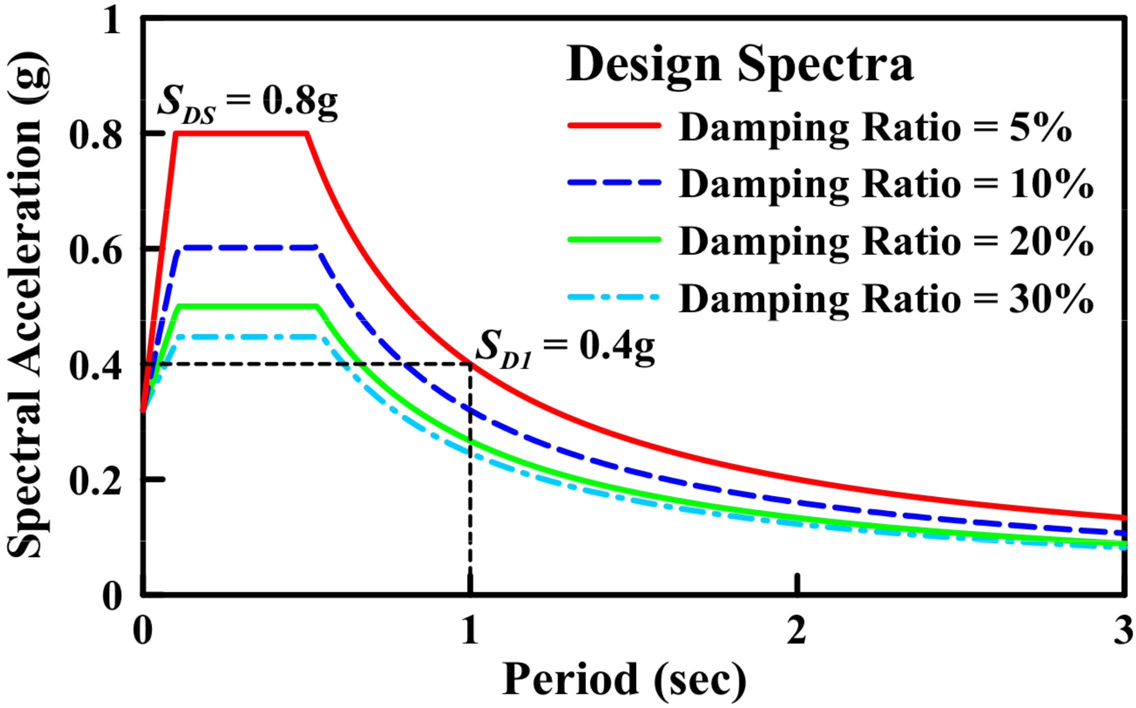
Analysis Procedures

- **Static**
  - Equivalent lateral force procedure
- **Dynamic**
  - Response spectrum procedure
  - Nonlinear response history procedure

Static Analysis Procedure

- **Equivalent lateral force procedure**
  - Regular configuration
  - Effective isolation period not greater than 2.5sec
  - Located on Class I or II site, not near Class I active fault
  - Capable of producing restoring force
  - Mechanical properties are independent of loading rates

Seismic Design Spectra



Damping Coefficients

Effective modal damping ratio ξ (%)	B_s	B_1
≤2	0.80	0.80
5	1.00	1.00
10	1.33	1.25
20	1.60	1.50
30	1.79	1.63
40	1.87	1.70
≥50	1.93	1.75

Design & Maximum Displacements

- **Minimum lateral displacement in each main horizontal direction (DBE level)**

$$D_D = \left[\frac{g}{4\pi^2}\right] S_{aD} T_{eD}^2 / B$$

$$\xi_{eD} = \frac{1}{2\pi}\left[\frac{A_{TD}}{K_{eD} D_D^2}\right]$$

$$T_{eD} = 2\pi\sqrt{\frac{W}{K_{eD}\, g}}$$

Design 5% damped elastic spectral acceleration parameter at T_{eD}

- **Maximum displacement in most critical direction (MCE level)**

$$D_M = \left[\frac{g}{4\pi^2}\right] S_{aM} T_{eM}^2 / B$$

$$\xi_{eM} = \frac{1}{2\pi}\left[\frac{A_{TM}}{K_{eM} D_M^2}\right]$$

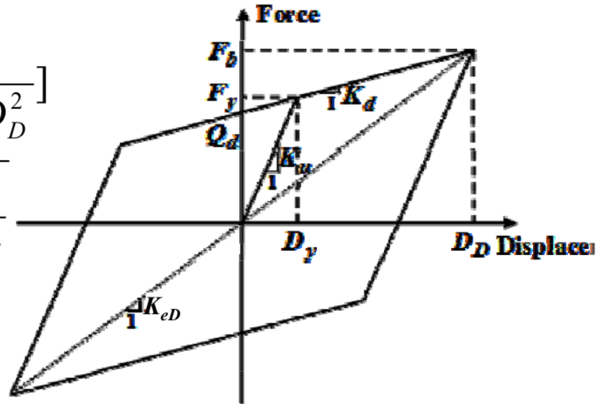
$$T_{eM} = 2\pi\sqrt{\frac{W}{K_{eM}\, g}}$$

Maximum considered 5% damped elastic spectral acceleration parameter at T_{eM}

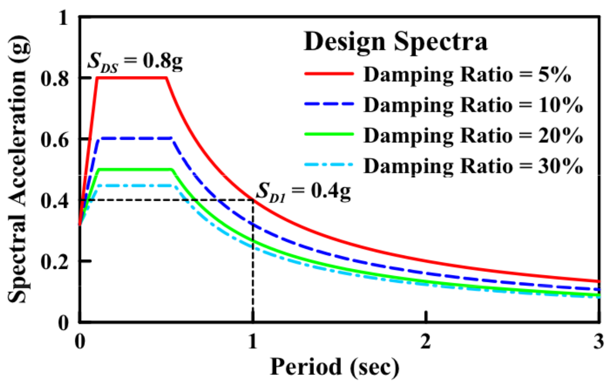
Displacement Design Concept

$$\xi_{eD} = \frac{1}{2\pi}\left[\frac{A_{TD}}{K_{eD}D_D^2}\right]$$

$$T_{eD} = 2\pi\sqrt{\frac{W}{K_{eD}g}}$$



$$D_D = \left[\frac{g}{4\pi^2}\right]S_{aD}T_{eD}^2 / B$$



Iteration until achieving convergent

Total Displacements (1)

- Including additional displacement due to inherent and accidental torsion
- Considering spatial distribution of lateral stiffness of isolation system
- Considering most disadvantageous location of eccentric mass
  - Total design displacement (DBE level)

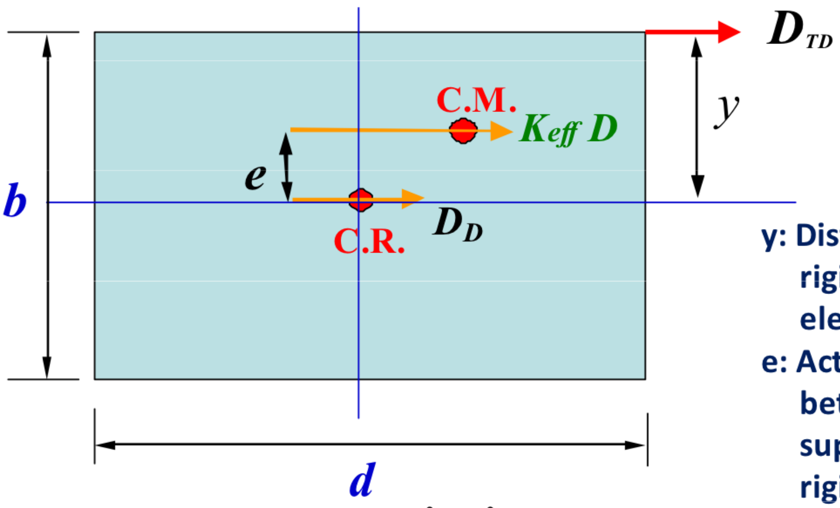
$$D_{TD} = D_D\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

  - Total maximum displacement (MCE level)

$$D_{TM} = D_M\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

Total Displacements (2)

- Additional displacement due to inherent and accidental torsion



Torsional Stiffness $K_T = K_{eff}(b^2+d^2)/12$

Rotational Angle $= K_{eff}D_D e / K_T = 12 D_D e / (b^2+d^2)$

Displacement $= 12 D_D ye / (b^2+d^2)$

Total Design Displacement $= D_D[1+12ye/(b^2+d^2)]$

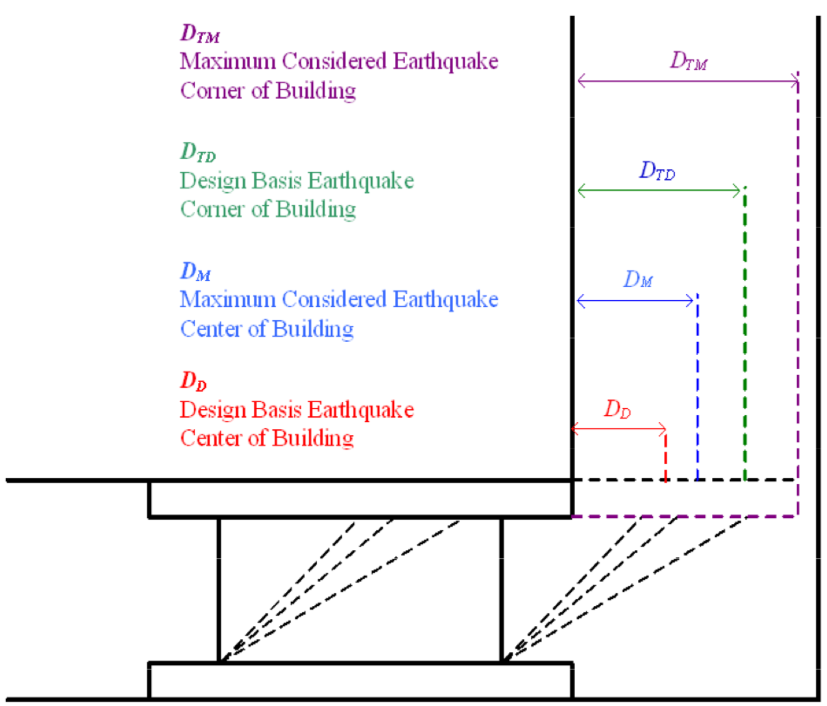
y: Distance between center of rigidity of isolation system and element of interest measured

e: Actual horizontal eccentricity between center of mass of superstructure and center of rigidity of isolation system, plus accidental eccentricity

b: Shortest plan dimension of superstructure

d: Longest plan dimension of superstructure

Isolation Displacement Terminology



Limitation：

$D_{TM} < 1.5\,D_{TD}$

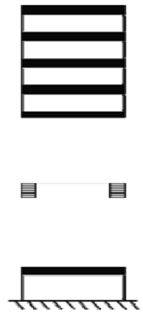
$D_{TD} \geqq 1.1\,D_D$

$D_{TM} \geqq 1.1\,D_M$

$D_{TD} <$ Displacement corresponding to shear strain of 200%

Minimum Total Lateral Forces

- All structural elements above isolation system → $V_s = \frac{K_{eD} D_D}{\alpha_y}$
- All structural elements below isolation system → $V_b = \frac{K_{eD} D_D}{0.8\alpha_y}$



$\frac{K_{eD} D_D}{\alpha_y}$: Elastic base shear without consideration of ductile behavior

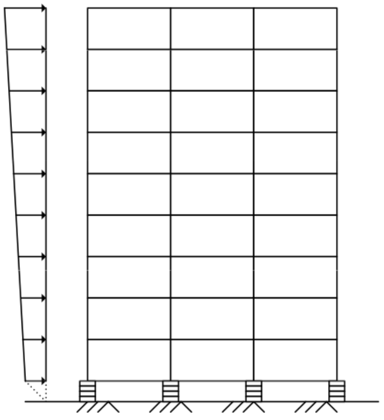
$0.8\alpha_y$: Amplification factor

V_s is greater than

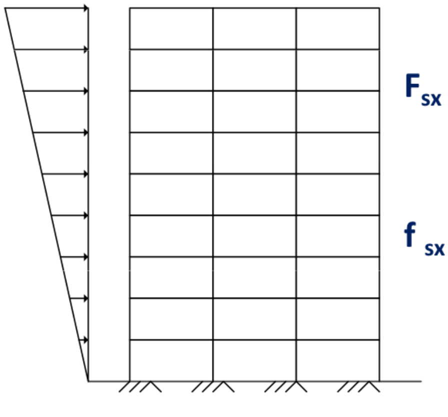
- Total lateral force corresponding to factored design wind load
- Total lateral force required to fully activate isolation system multiplied by 1.5

Vertical Distribution of Lateral Forces

- V_s is distributed over height of structure → $$F_{sx} = V_s \frac{W_x u_x}{\sum_{i=0}^{n} W_i u_i}$$
- u_x and u_i are correspondingly displacements at level x and i subjected to vertical distribution of f_{sx} → $$f_{sx} = K_{eD} D_D \frac{W_x}{\sum_{i=0}^{n} W_i}$$



Seismically Isolated Building

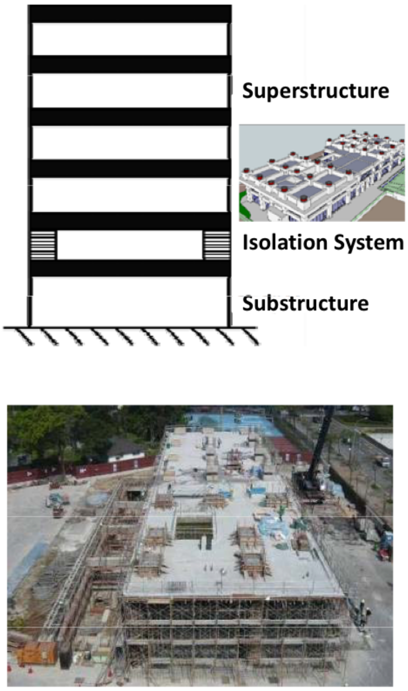


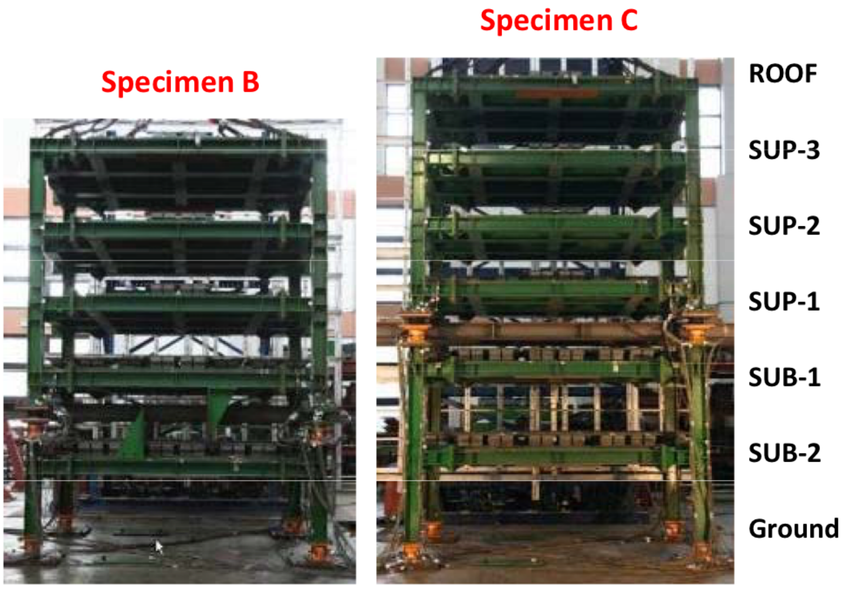
Conventional Nonisolated Building

F_{sx}: Lateral force at level x corresponding to first mode

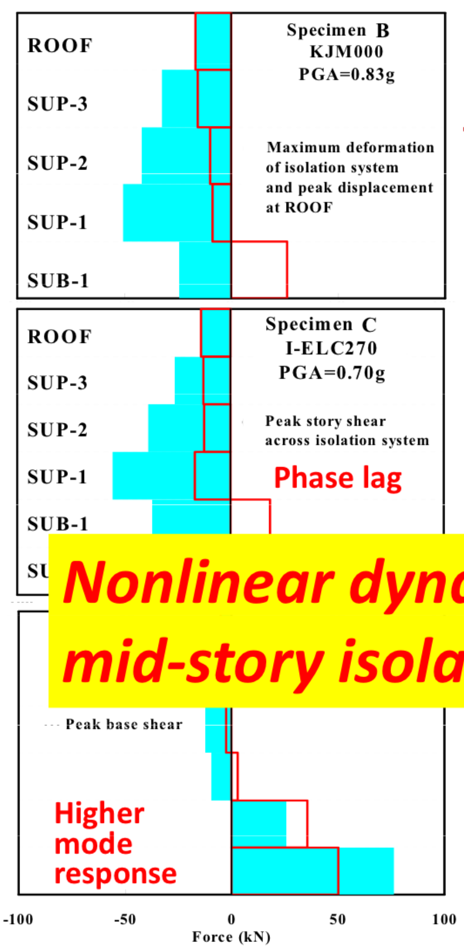
f_{sx}: Lateral force at level x based on assumption that superstructure exhibits a rigid body motion

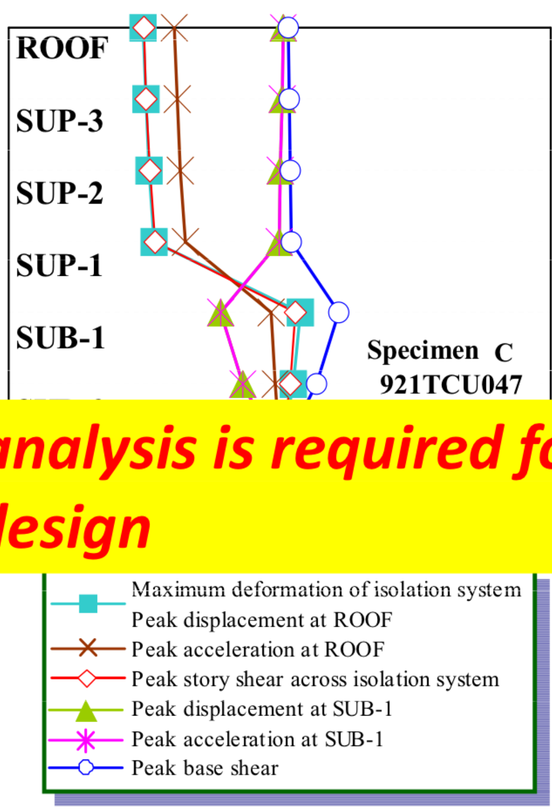
Analytical and Experimental Study on Mid-Story Isolation Design





Vertical Distributions of Inertia Force, Story Shear Force and Displacement Responses

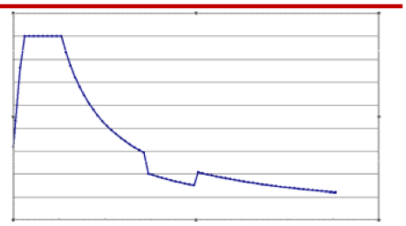




Nonlinear dynamic analysis is required for mid-story isolation design

Dynamic Analysis Procedure

- **Response spectrum procedure**



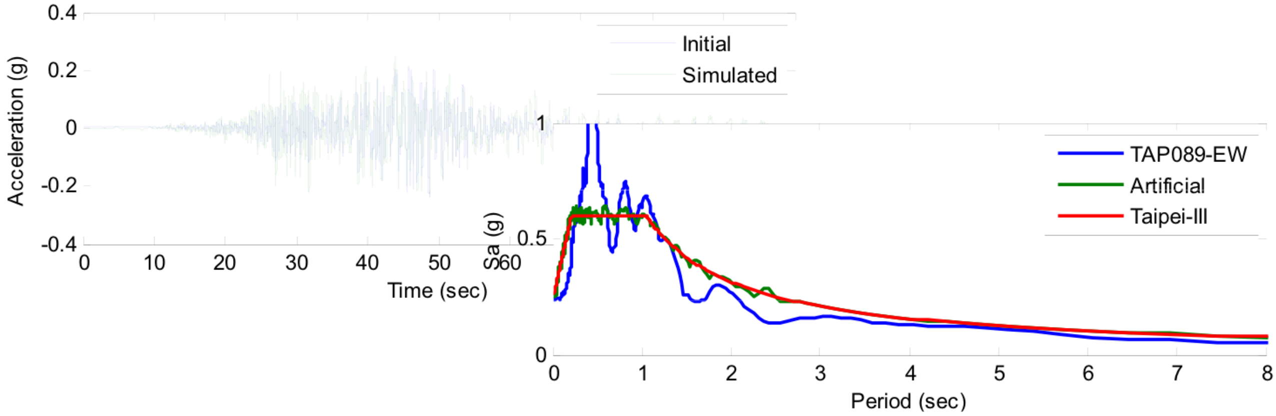
  – DBE level
  – Design acceleration response spectra considering damping coefficients corresponding to modal damping ratios
- **Nonlinear response history procedure**
  – DBE & MCE levels
  – Simulated ground motions compatible with 5% damped design acceleration response spectrum without considering lower limit of $0.4S_{DS}$ at long period

Response Spectrum Procedure

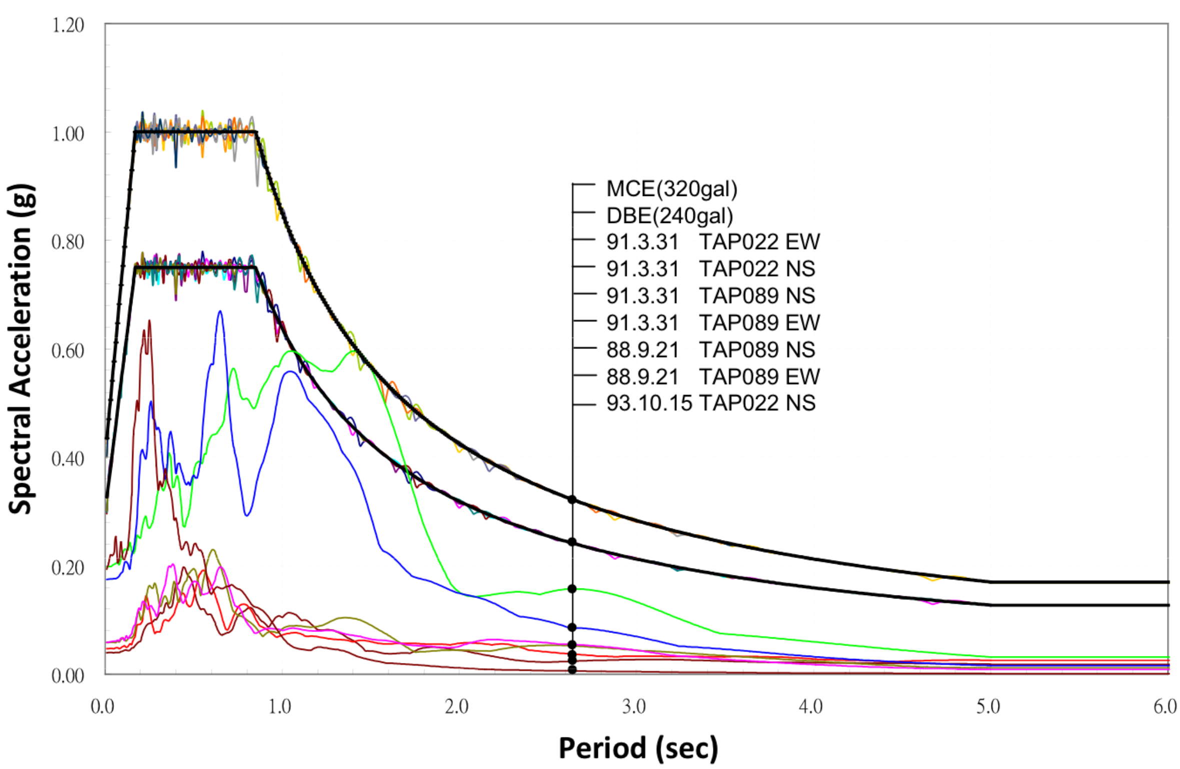
- Using fundamental modal damping ratio not greater than equivalent damping ratio of isolation system or 30% of critical, whichever is less
- Including a sufficient number of modes to obtain a combined modal mass participation ratio of at least 90% of the actual mass
- CQC method rather than SRSS method is used if closeness of modal frequencies is revealed
- Including simultaneous excitations by 100% of the ground motion in critical direction and 30% of ground motion in perpendicular, horizontal direction

Response History Procedure

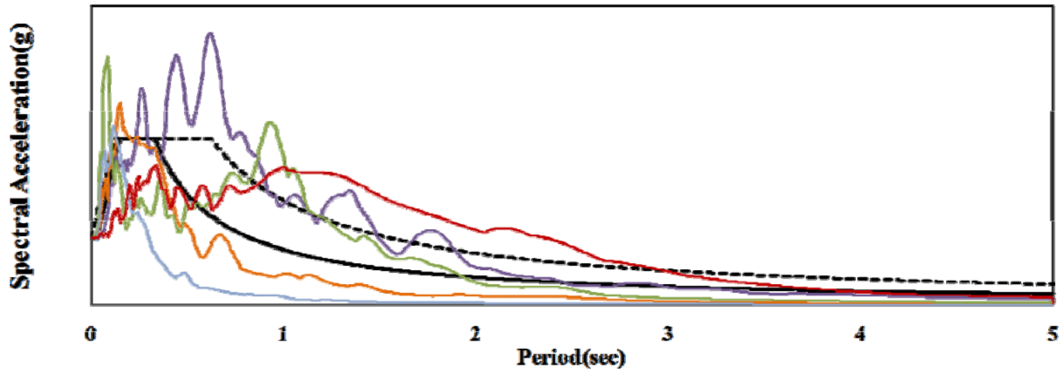
- Not fewer than three simulated ground motions
- Selected from recorded events near site consistent with DBE and MCE
- If at least seven simulated ground motions, average value is used for design
- If fewer than seven simulated ground motions, maximum value is used for design

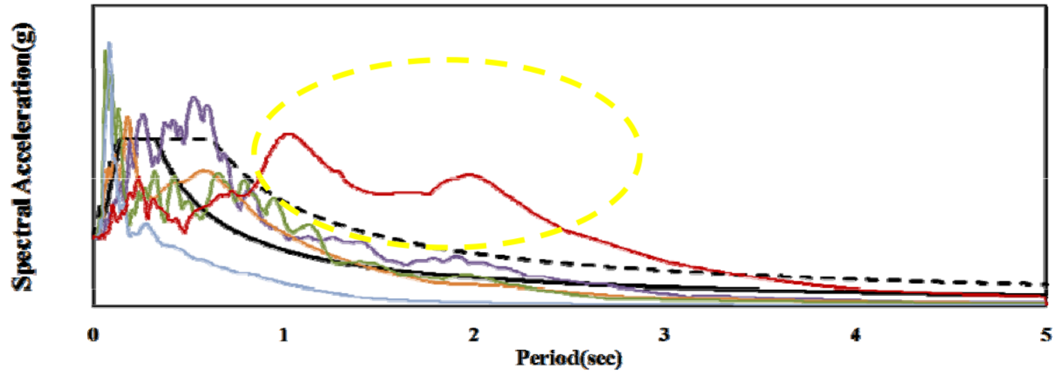


Seven Simulated Ground Motions



Enlarged Acceleration at Long Period





Minimum Total Forces & Displacements

	Static	Dynamic	
	Equivalent lateral force	Response spectrum	Nonlinear response history
Minimum total lateral force V_b (Isolation system, substructure)	$\frac{K_{eD}D_D}{0.8\alpha_y}$	$90\%\frac{K_{eD}D_D}{\alpha_y}$	$90\%\frac{K_{eD}D_D}{\alpha_y}$
Minimum total lateral force V_s (Regular superstructure)	$\frac{K_{eD}D_D}{\alpha_y}$	$80\%\frac{K_{eD}D_D}{\alpha_y}$	$60\%\frac{K_{eD}D_D}{\alpha_y}$
Minimum total lateral force V_s (Irregular superstructure)	$\frac{K_{eD}D_D}{\alpha_y}$	$\frac{K_{eD}D_D}{\alpha_y}$	$80\%\frac{K_{eD}D_D}{\alpha_y}$
Total design displacement D_{TD}	$D_D\left[1+y\frac{12e}{b^2+d^2}\right]$	$90\%D_D\left[1+y\frac{12e}{b^2+d^2}\right]$	$90\%D_D\left[1+y\frac{12e}{b^2+d^2}\right]$
Total maximum displacement D_{TM}	$D_M\left[1+y\frac{12e}{b^2+d^2}\right]$	$80\%D_M\left[1+y\frac{12e}{b^2+d^2}\right]$	$80\%D_M\left[1+y\frac{12e}{b^2+d^2}\right]$

$$D'_D = \frac{D_D}{\sqrt{1+(T/T_{eD})^2}} \qquad D'_M = \frac{D_M}{\sqrt{1+(T/T_{eM})^2}}$$

T: Elastic period of superstructure with fixed base

Drift Limit & Building Separations

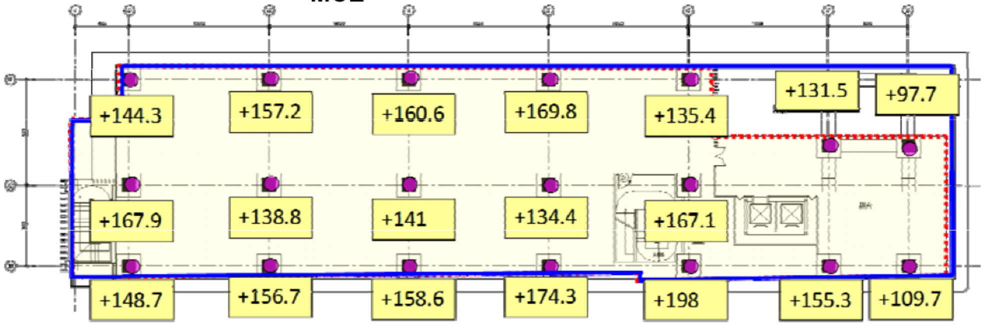
	Static	Dynamic	
	Equivalent lateral force	Response spectrum	Nonlinear response history
Minimum separation between seismically isolated structure and adjacent buildings	$0.6(D_{TD}+D_r)$	$0.6(D_{TD}+D_r)$	$0.6(D_{TD}+D_r)$
Minimum separation between seismically isolated structure and surrounding retaining walls or other fixed obstructions	D_{TM}	D_{TM}	D_{TM}
Maximum story drift of superstructure under DBE	$0.005/\alpha_y$	$0.005/\alpha_y$	$0.005/\alpha_y$

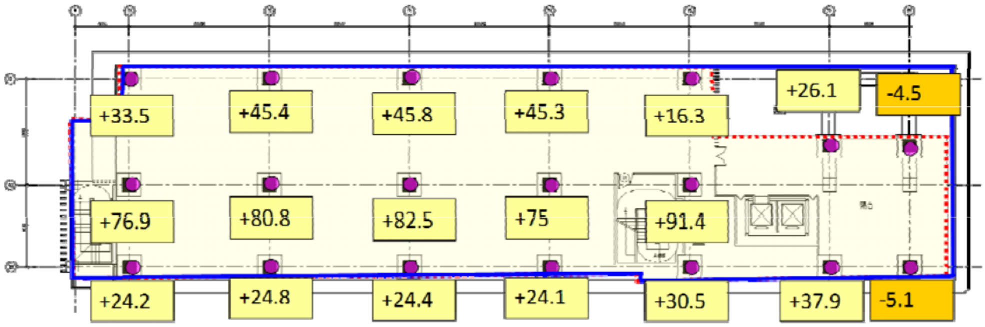
D_r: Deformation of seismically isolated structure relative to isolation layer

All structural elements of superstructure remain linearly elastic under DBE

Axial Stress (Permanent and Instant)

Permanent Compression : DL+0.5LL
Instant Compression : DL+0.5LL+EQ_{MCE}
Instant Tension : DL-EQ_{MCE}



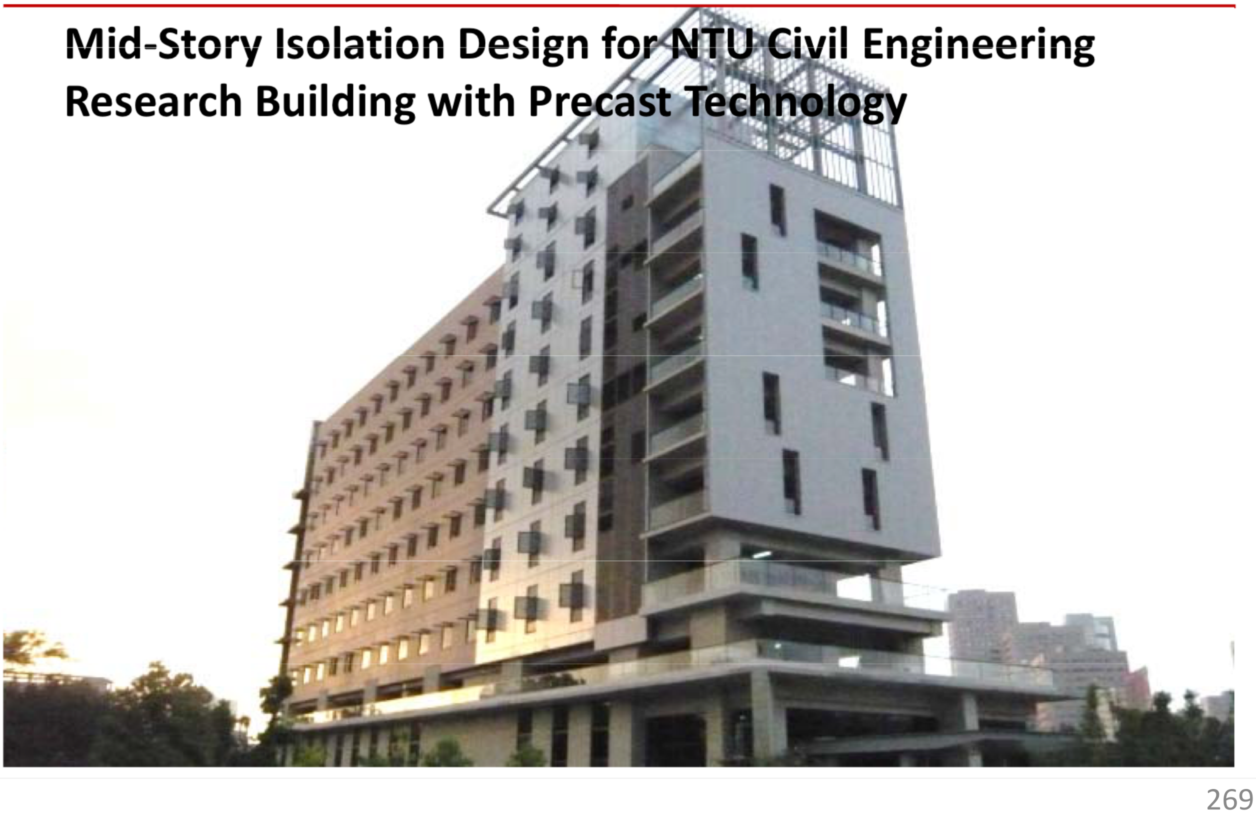


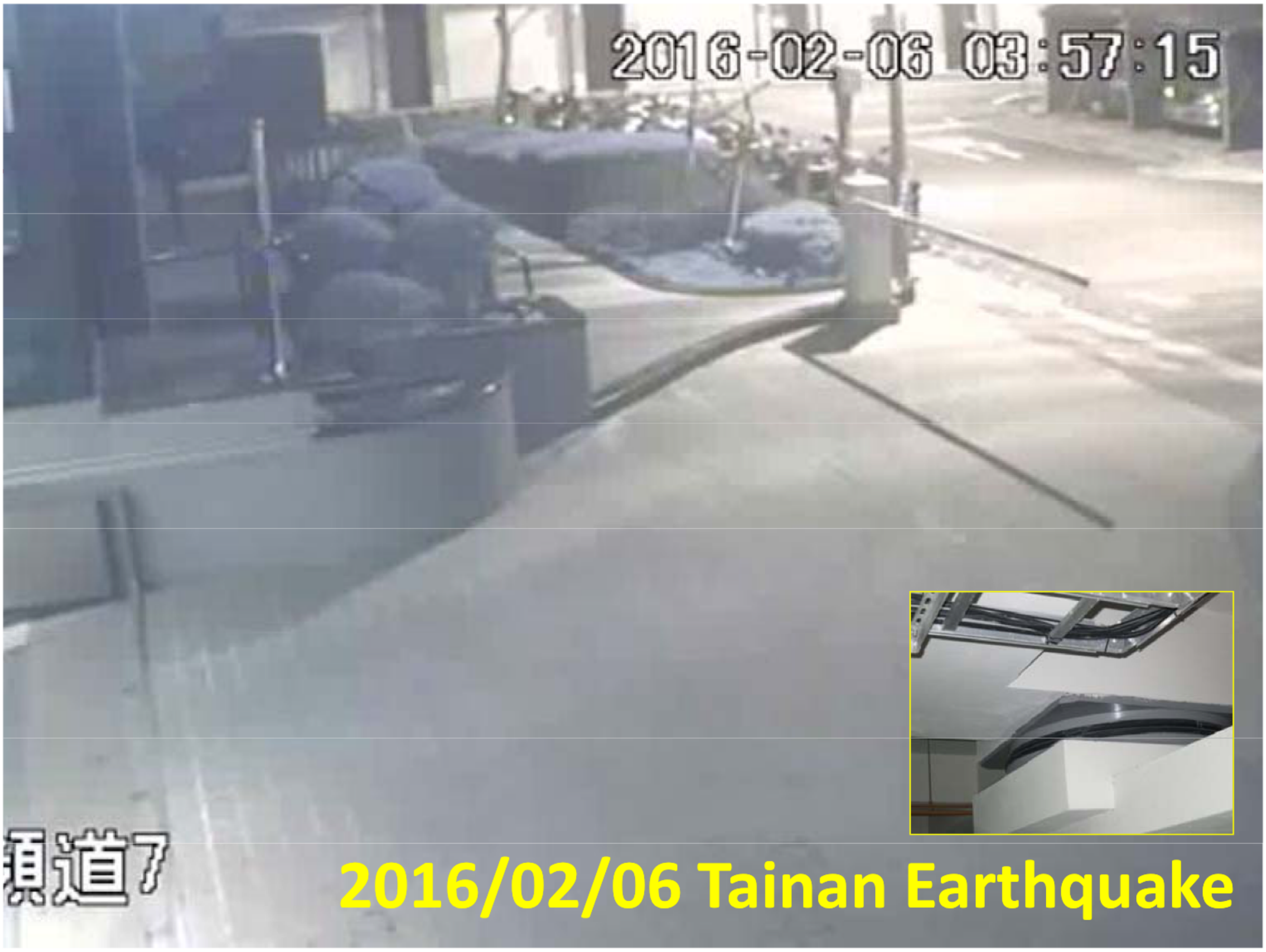
Base Isolation Design Example

Structural Design and Maintenances of Hualien Tzu Chi Seismically Isolated Hospital

Mid-story Isolation Design Example

Mid-Story Isolation Design for NTU Civil Engineering Research Building with Precast Technology



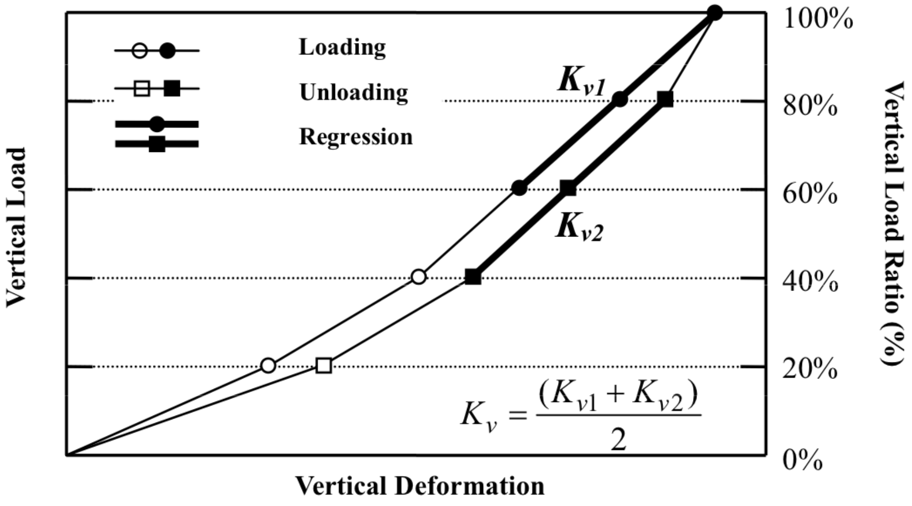


Prototype Tests

- Two full-size specimens for each predominant type and size of isolation bearings
- Test specimens are not used for construction
- Test specimens should include individual isolation bearings and additional wind restraint systems
- In addition to test protocol of vertical load vs. lateral displacement, test protocol of vertical stress vs. lateral strain can also be used if
  - Elastomeric bearings
  - Q_D+1/2Q_L+Q_E is not greater than vertical load corresponding to stress of 200kgf/cm^2
  - D_{TM} is not greater than lateral displacement corresponding to 250% of total rubber layer thickness

Compression Test

- Apply vertical compression load (stress) from zero to $Q_D+1/2Q_L+Q_E$ (200kgf/cm^2) and then release the load (stress)
  - Test specimens should remain stable without any obvious damage
  - Vertical stiffness determined by test results is not less than 80% of design value



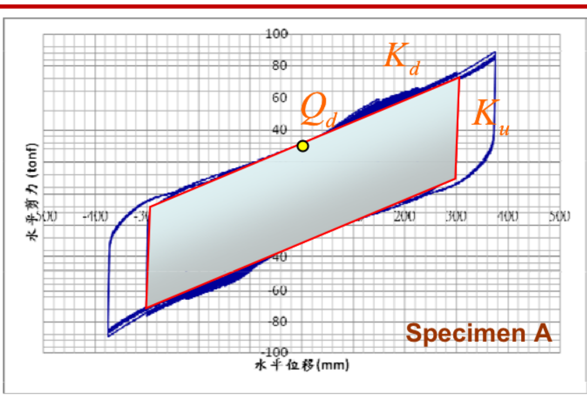
Normal Condition Test

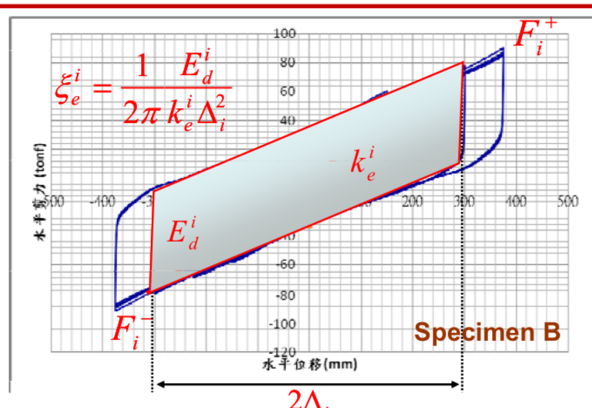
- Perform twenty fully reversed cycles of loading at lateral force corresponding to wind design force under vertical compression load (stress) of Q_D+Q_L (150kgf/cm^2)
  - Test specimens considering contribution of additional wind restraint systems should not exhibit plastic or sliding behavior under wind design force

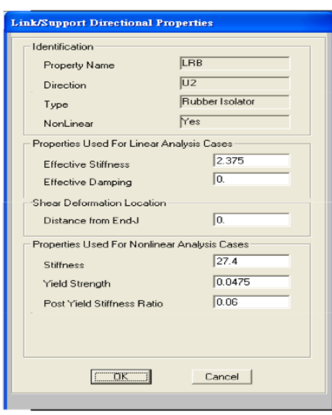
Different Deformation Test (1)

- Perform three fully reversed cycles of loading at 0.25D_D (50%), 0.5D_D (100%), 0.75D_D (150%), 1.0D_D (200%), 1.25D_D (250%) and 1.0D_D (200% of the total rubber layer thickness), under vertical compression load (stress) of Q_D (100kgf/cm^2)
  - Force-deflection plots should have positive increment force carrying capacity (tangent stiffness is a positive value)
  - Difference between effective stiffness at each of three cycles and average effective stiffness of three cycles is not greater than 10%
  - Subjected to last three fully reversed cycles of loading, difference between average effective stiffness of three cycles and design effective stiffness is not greater than 15%, and average energy dissipation capability (or average equivalent damping ratio) of three cycles is not less than 85% of design energy dissipation capability (design equivalent damping ratio)
  - Difference between average effective stiffnesses in two common specimens is not greater than 10%

Different Deformation Test (2)





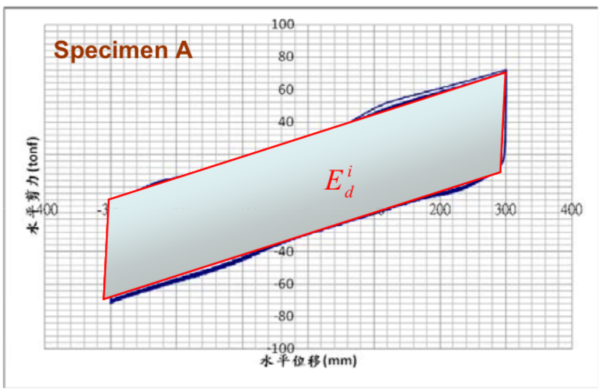


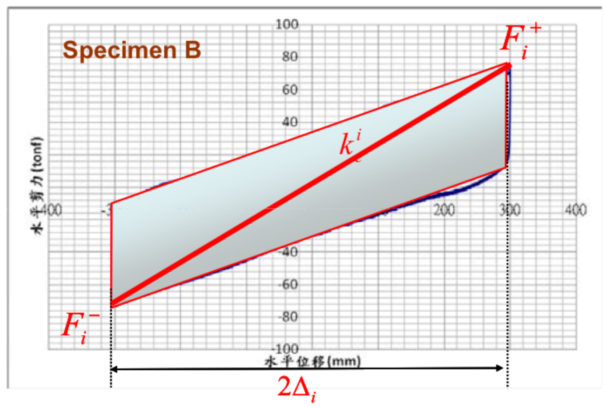
$$K_u = \frac{K_d}{\alpha_b}$$

$$F_y = \frac{Q_d}{1-\alpha_b}$$

Design Performance Test

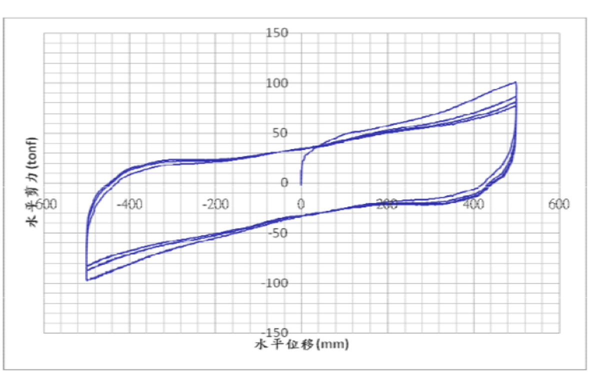
- Perform ten fully reversed cycles of loading at D_D (200% of the total rubber layer thickness) under vertical compression load (stress) of Q_D (100kgf/cm^2)
  - There is no greater than 20% change in initial effective stiffness over ten cycles, and there is no greater than 30% decrease in initial energy dissipation capability (or initial effective damping) over ten cycles

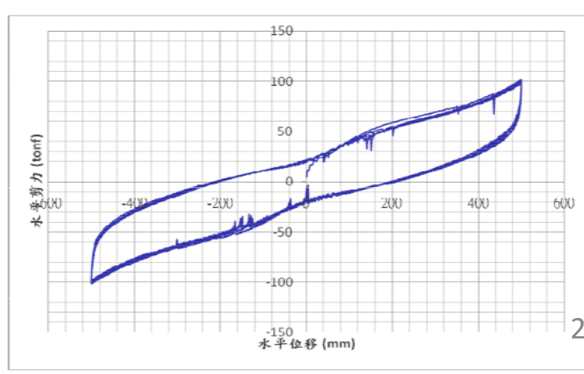




Stability Test

- Perform three fully reversed cycles of loading at D_{TM} (250% of the total rubber layer thickness) respectively under two vertical compression loads (stresses) of Q_D+1/2Q_L+Q_E (200kgf/cm^2) and Q_D-Q_E (20kgf/cm^2)
  - Test specimens should remain stable without any obvious damage

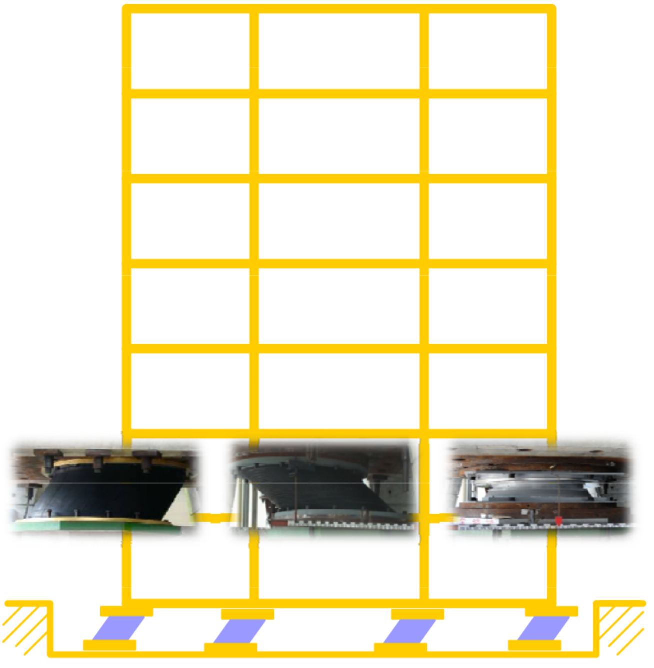


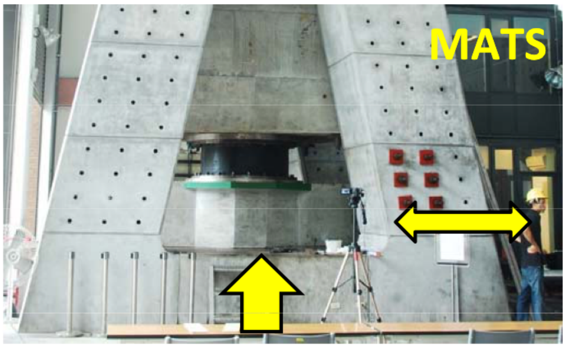


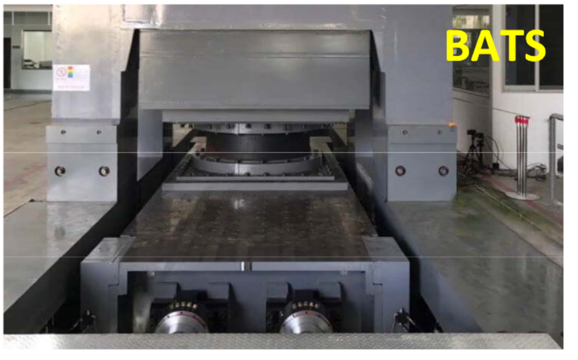
Production Tests

- **Compression Test**
  - Each test specimen should sustain vertical compression load of $1.5(Q_D+Q_L)$ at least five minutes
  - Any signs of deficient bond between rubber layers and steel shims and crack on cover rubber are not permitted for elastomeric bearings
  - Any signs of spalling of coating, scrape of stainless steel plate, permanent deformation and leakage of coating are disqualified for sliding bearings
- **Combined Vertical Load and Lateral Force Test**
  - Three fully reversed cycles of loading at D_D and vertical compression load of Q_D are jointly applied
  - Difference between average effective stiffness of three cycles and design effective stiffness is not greater than 15%
  - Average energy dissipation capability (average equivalent damping ratio) of three cycles is not less than 85% of design energy dissipation capability (design equivalent damping ratio)

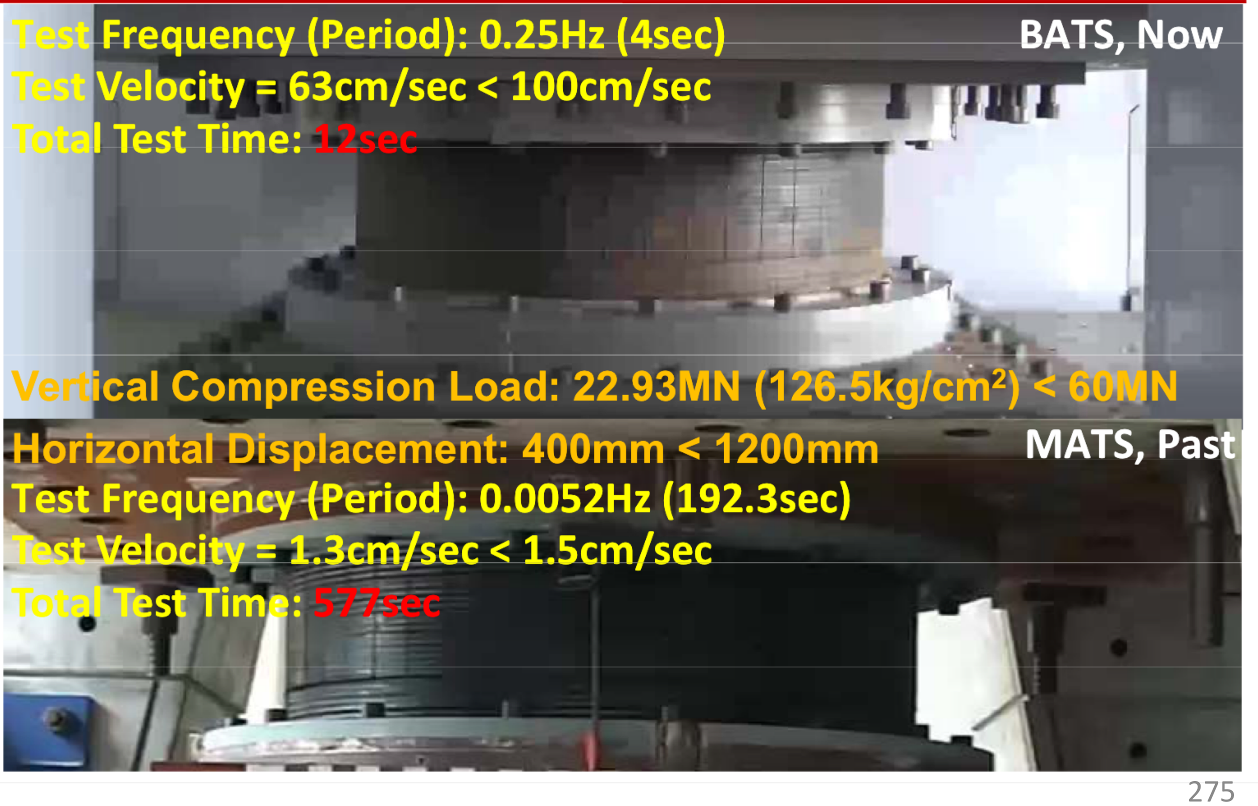
Facilities for Testing Bearings at NCREE



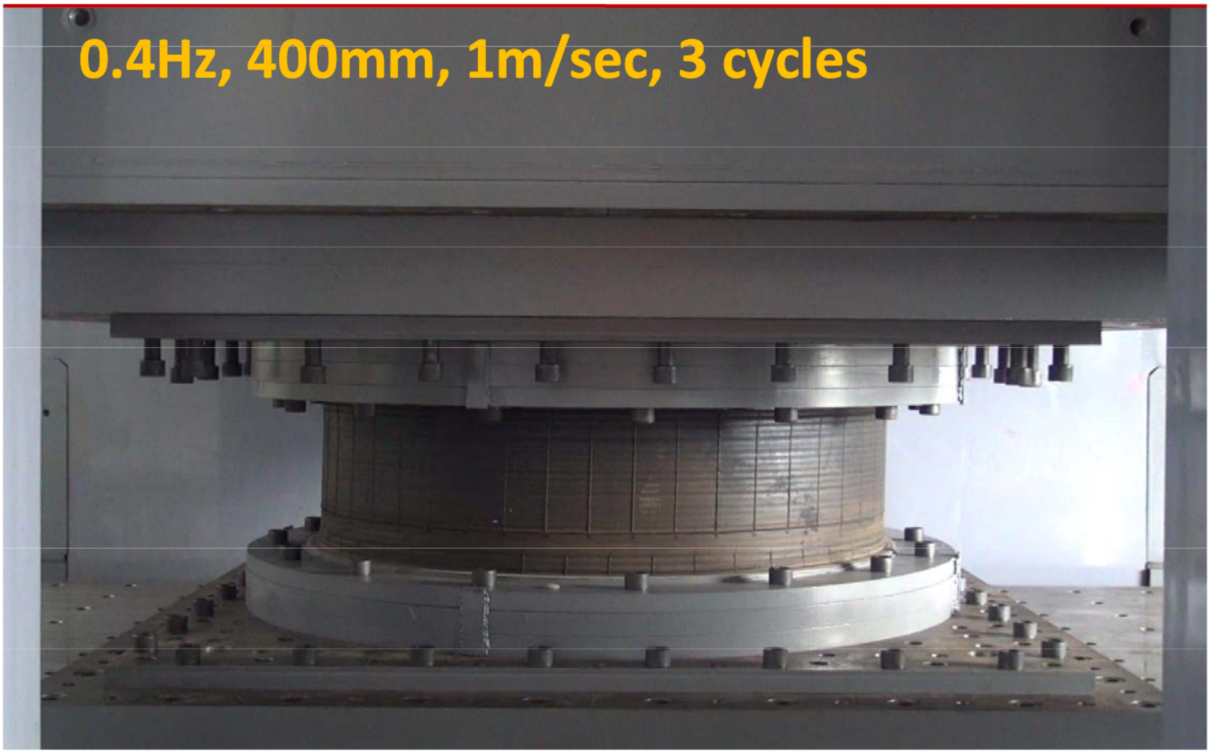




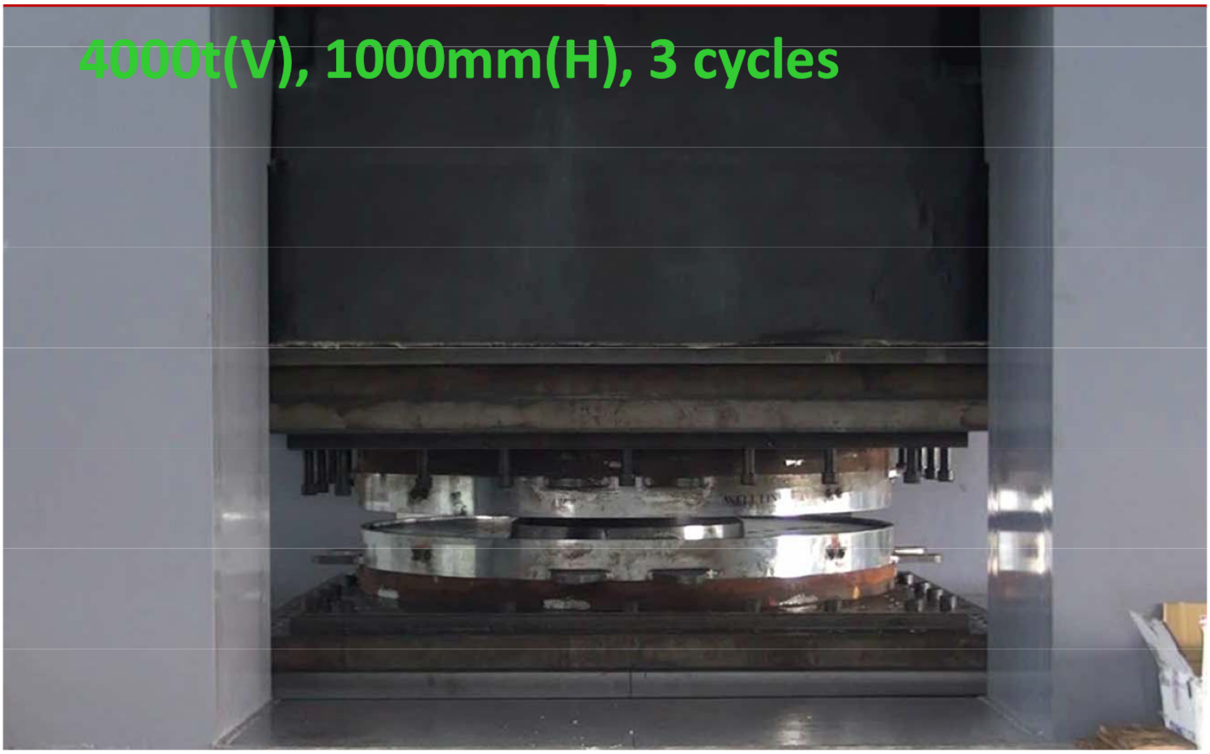
BATS vs. MTAS



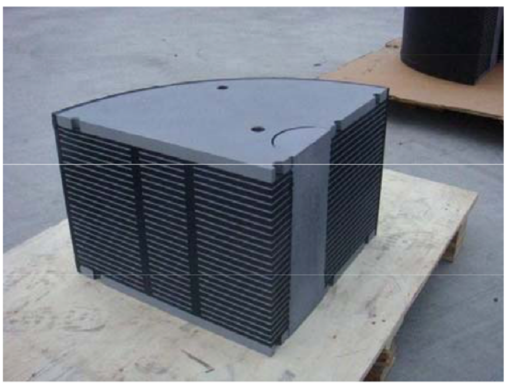
Dynamic Prototype Tests - LRB



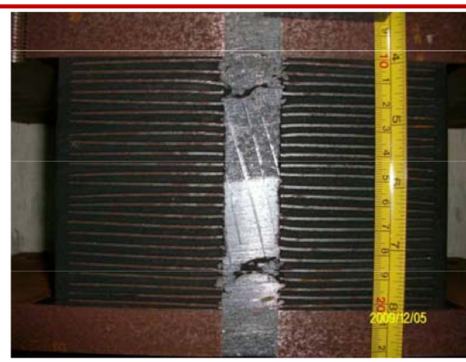
Dynamic Prototype Tests - FPB

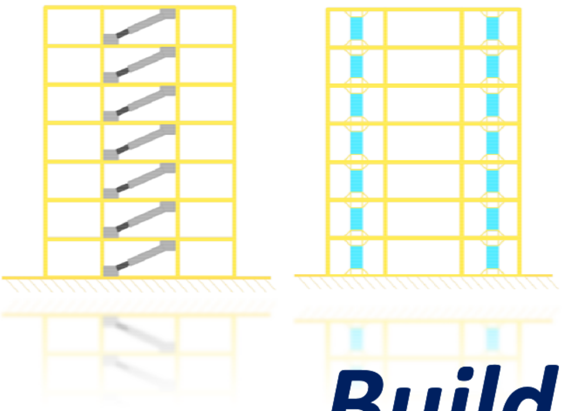


LRB after Prototype Tests (1)



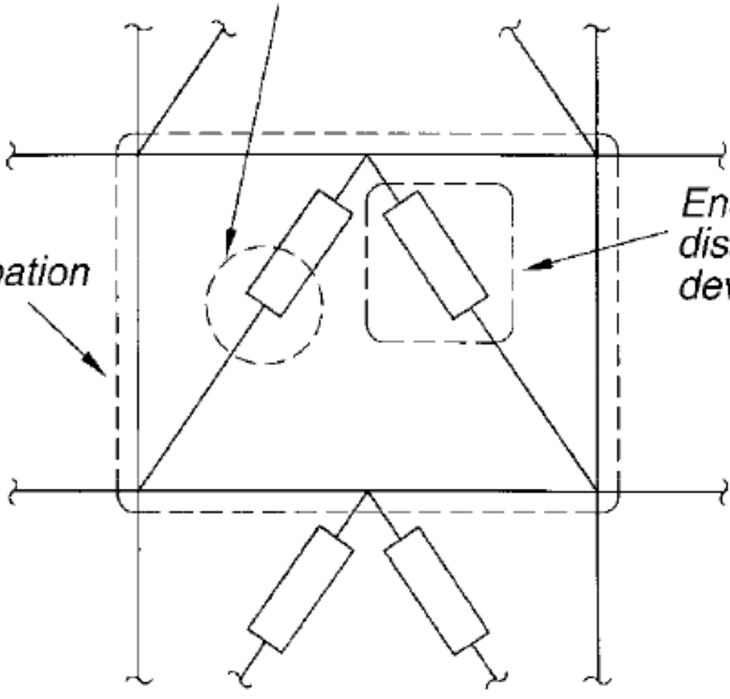
LRB after Prototype Tests (2)





Buildings with Energy Dissipation Systems

Energy Dissipation Nomenclature



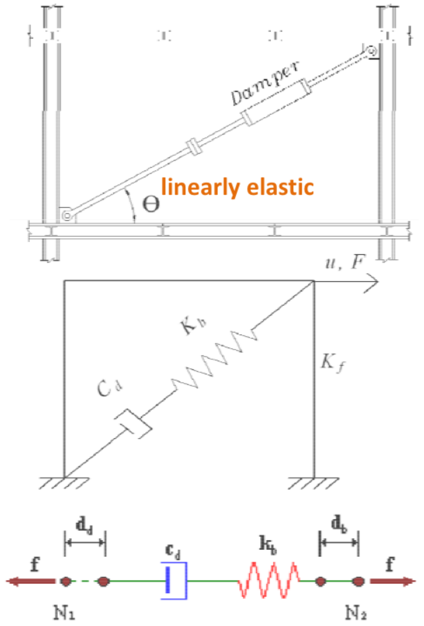
Design Principles (1)

- To reserve design flexibility in practice, requirements specified in newly design provisions are more concise
- Analyses of mathematical models should account for dependence of energy dissipation devices on excitation frequency, ambient and operating temperature, velocity, sustained loads and bilateral loads
- Energy dissipation devices should be designed with consideration given to other environmental conditions
- Models of energy dissipation system should include stiffnesses of structural components that are part of load path, if flexibility of these components is significant enough to affect performance of energy dissipation system
- Components and connections transferring forces between energy dissipation devices should be designed to remain linearly elastic

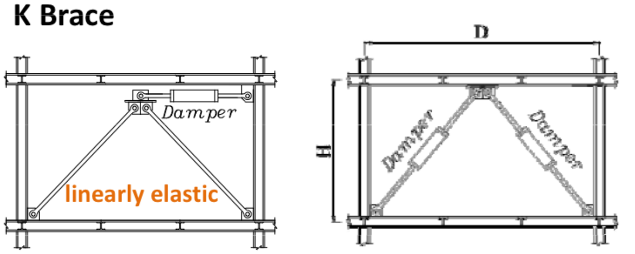
Design Principles (2)

- Installation Schemes

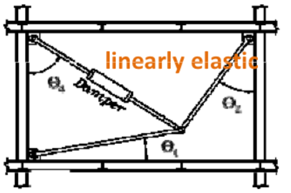
Diagonal Brace



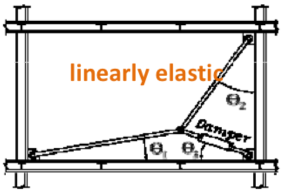
K Brace



Upper Toggle Brace

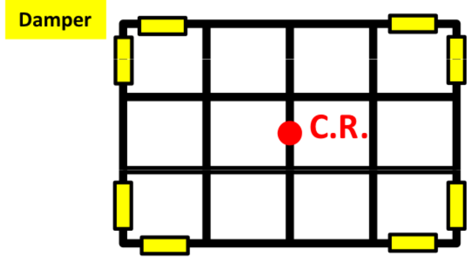


Lower Toggle Brace



Design Principles (3)

- **Two classifications: displacement-dependent and velocity-dependent devices**
  - If four or more energy dissipation devices are provided in given story of building in one principal direction of building, with minimum of two devices located on each side of center of stiffness of story, displacement-dependent devices (velocity-dependent devices) should be capable of sustaining displacement (force) equal to calculated displacement (force corresponding to calculated velocity) under MCE, i.e. D_{MCE} and $F_{V, MCE}$



D_{MCE} $F_{V, MCE}$ Otherwise → $1.5D_{MCE}$ $F_{1.5V, MCE}$

Two Design Objectives

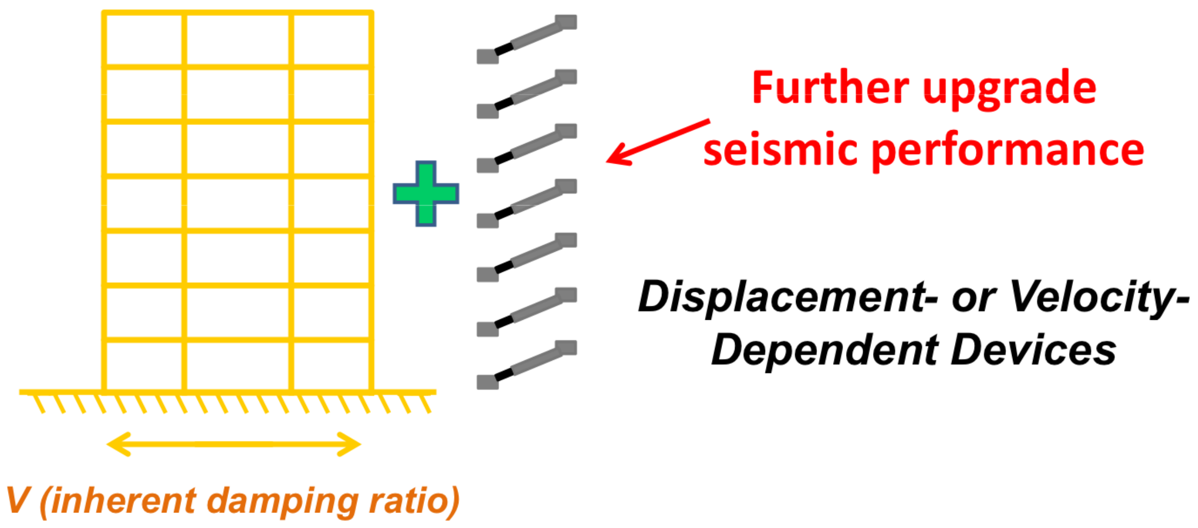
- Supplemental damping or stiffness effect to upgrade seismic performance of building that already conforms to minimum seismic requirements
  - Additional damping ratio contributed by energy dissipation devices is not considered to reduce minimum total lateral force of building with energy dissipation devices (B=1, minimum reduction= 15%)
- Added damping or stiffness effect to reduce minimum total lateral force of building that originally does not conform to minimum seismic requirements
  - Damping ratio contributed by energy dissipation devices is considered to reduce minimum total lateral force of building with energy dissipation devices (B>1)
    - Frequent earthquake level

      Structural elements remain elastic and no significant damage in nonstructural components
    - DBE level

      Ductility of structure is observable, but not greater than allowable capacity R_a
    - MCE level

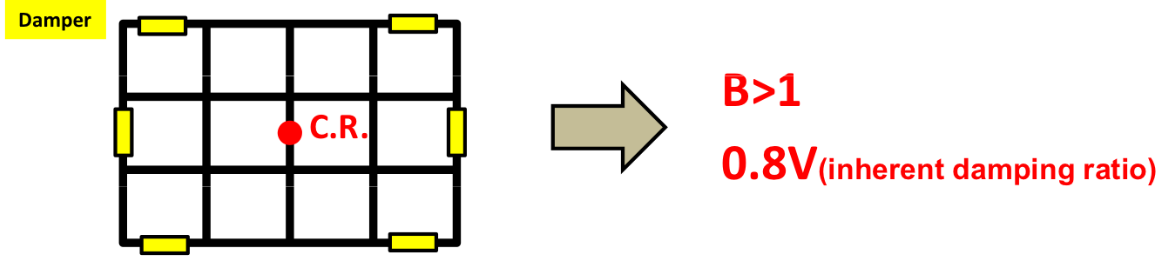
      Ductility of structure is observable, but not greater than allowable capacity R

Supplemental Damping Design



Design Considerations (1)

- **Minimum Total Lateral Force**
  – If two or more energy dissipation devices are provided in principal direction of given story of building, with minimum of one device located on each side of center of stiffness of story, equivalent damping ratio contributed by energy dissipation devices can be considered to reduce minimum total lateral force of building with energy dissipation devices (B>1 , maximum reduction= 20%)



Design Considerations (2)

- **Minimum Total Lateral Force**
  - If displacement-dependent devices are incorporated into building, energy dissipation devices and other structural elements of building should remain elastic under frequent earthquake level
  - Ductile behavior and equivalent damping ratio of displacement-dependent devices cannot be considered simultaneously to calculate minimum total lateral force of building with displacement-dependent devices

Either R (Ductility Capacity) or B (Damping Effect)

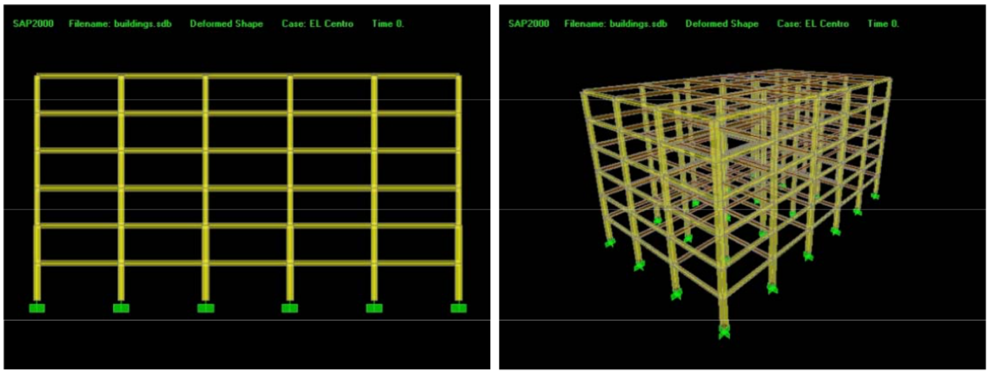
Design Considerations (3)

- **Drift Limit**
  - Maximum story drift of building with energy dissipation devices under frequent earthquake level should not exceed 0.005
  - Calculation of maximum story drift should include translation and torsion responses

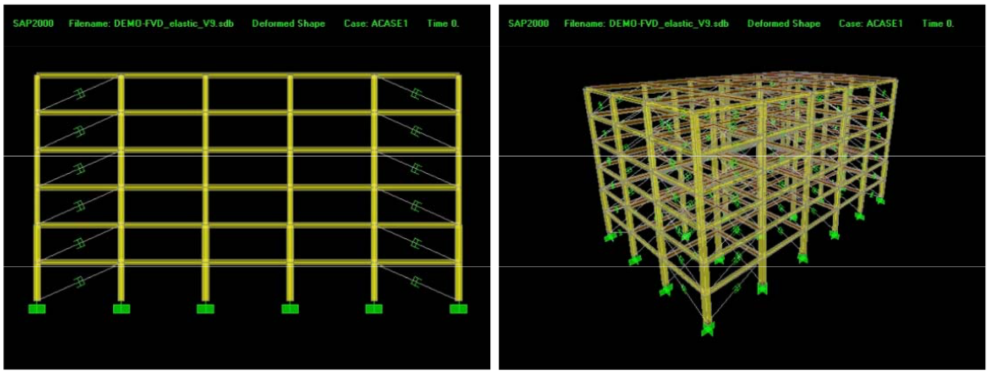
Structures with and without Additional Damping Devices

PGA = 350gal

Conventional MRF Structure

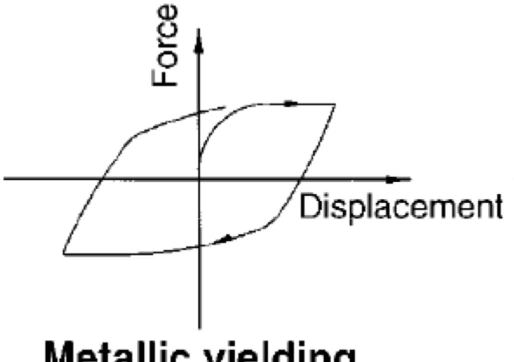


Passively Controlled Structure

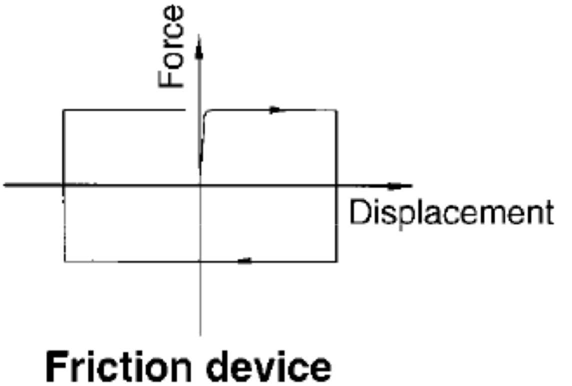


Displacement-Dependent Devices (1)

- Either rigid-plastic (friction devices), bilinear (metallic yielding devices) or trilinear hysteresis
- Force-displacement response is primarily function of relative displacement between each end of device
- Responses are independent of relative velocity between each end of device and/or frequency of excitation



Metallic yielding device



Friction device

Displacement-Dependent Devices (2)

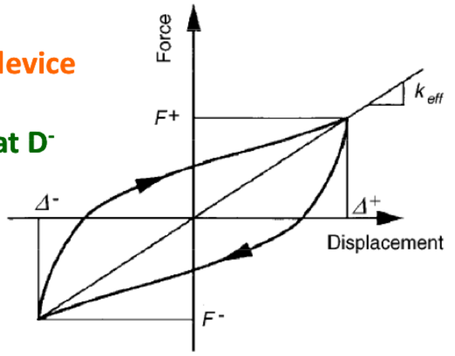
- Force $F = k_{eff} D$

  Relative displacement between each end of device

- Effective stiffness

  Force at D^+ Force at D^-

$$k_{eff} = \frac{|F^+| + |F^-|}{|D^+| + |D^-|}$$



- Damping effect

$$\beta_D = \frac{\sum_j W_{Dj}}{4\pi W_k}$$

Work done by device j in one complete cycle corresponding to floor displacement

- Maximum strain energy in the frame

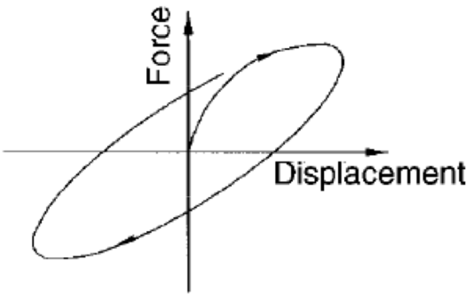
$$W_k = \frac{1}{2} \sum_i F_i u_i$$

F_i: Inertia force at floor level i

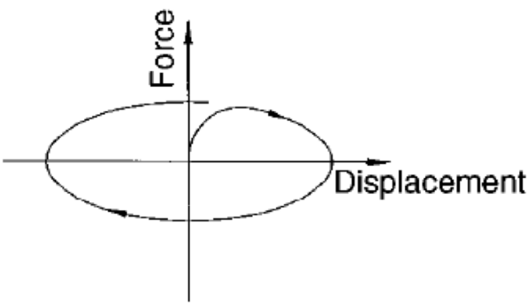
u_i: Displacement at floor level i

Velocity-Dependent Devices

- Solid viscoelastic, fluid viscoelastic, and fluid viscous devices
- Force-displacement response is primarily function of relative velocity between each end of device



Viscoelastic solid or fluid device



Viscous fluid device

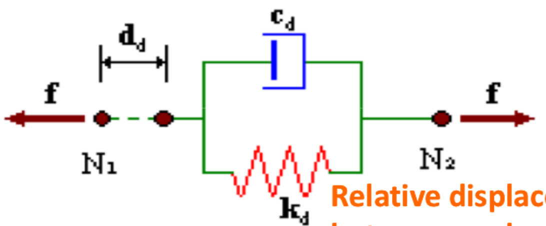
- Damping effect

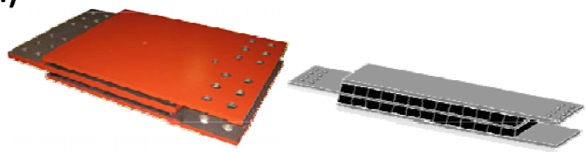
$$\beta_V = \frac{\sum_j W_{Vj}}{4\pi W_k}$$

Work done by device j in one complete cycle corresponding to floor displacement

Solid Viscoelastic Devices

- Spring and dashpot in parallel (Kelvin model)





Relative displacement between each end of device

Relative velocity between each end of device

- Force

$$F = k_{eff} D + C \left|\dot{D}\right|^{\alpha} \operatorname{sgn}(\dot{D})$$

Velocity exponent of device

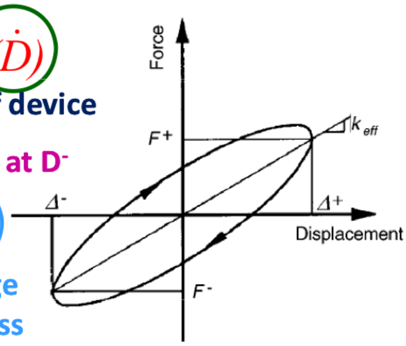
Force at D^+

Force at D^-

- Effective stiffness

$$k_{eff} = \frac{\left|F^+\right| + \left|F^-\right|}{\left|D^+\right| + \left|D^-\right|} = K'$$

Storage stiffness



Area enclosed by one complete cycle of device

- Damping coefficient

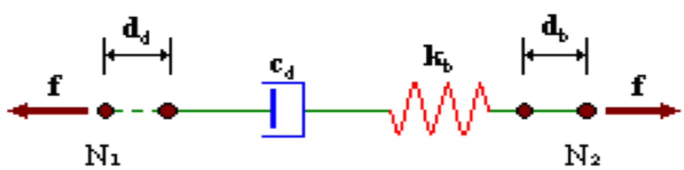
$$C = \frac{W_D}{\pi \omega_1 D_{ave}^2} = \frac{K''}{\omega_1}$$

Loss stiffness

Average of absolute values of D^+ and D^-

Fluid Viscoelastic Devices

- Spring and dashpot in series (Maxwell model)



Velocity exponent of device

Damping coefficient of device

Relative velocity between each end of dashpot

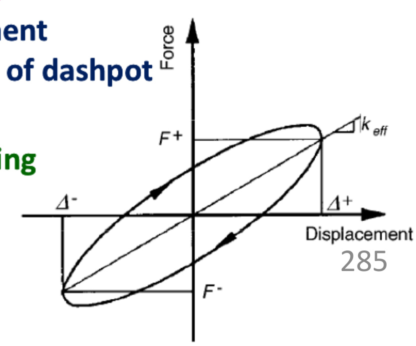
- Force

$$\begin{cases} F = k_{eff} D_k = C \left|\dot{D}_c\right|^{\alpha} \operatorname{sgn}\left(\dot{D}_c\right) \\ D = D_k + D_c \end{cases}$$

Relative displacement between each end of dashpot

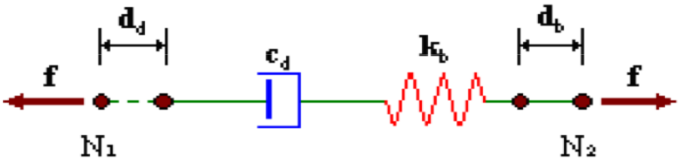
Relative displacement between each end of device

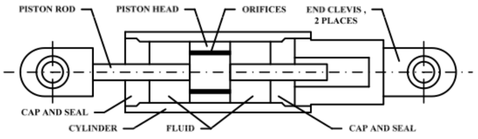
Relative displacement between each end of spring



Fluid Viscous Devices

- Spring and dashpot in series (Maxwell model)





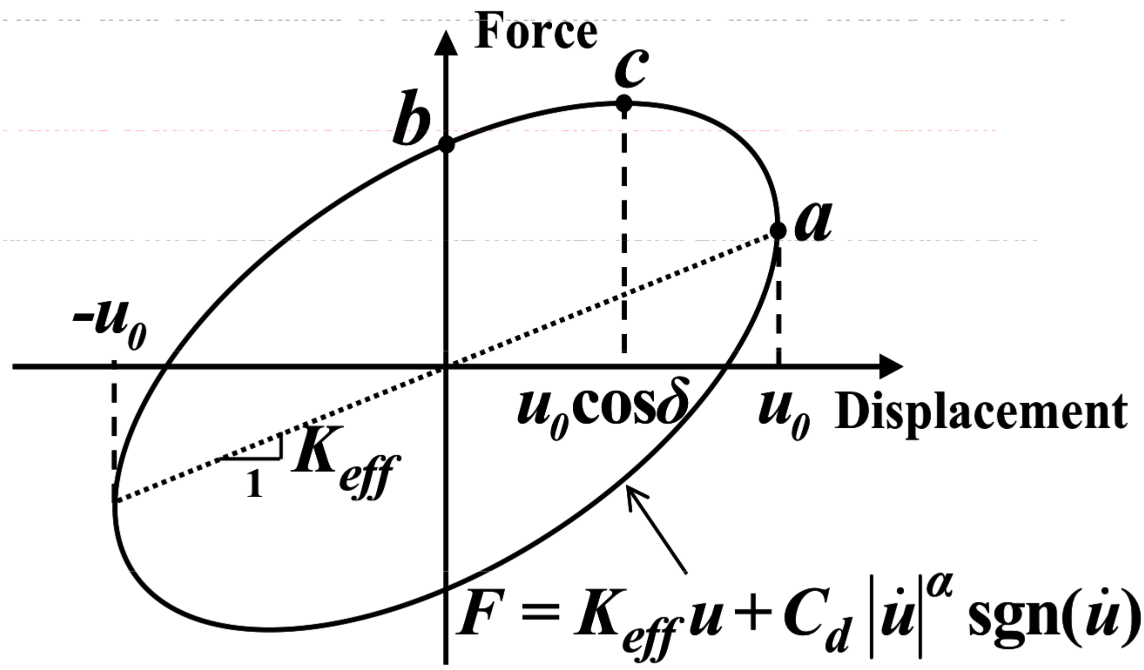
Velocity exponent of device

- Force $$F = C|\dot{D}|^{\alpha}\operatorname{sgn}(\dot{D})$$

Damping coefficient of device

Relative displacement between each end of device

Linear Analysis Procedure (1)



- Three distinct stages: (1) Maximum drift (zero viscous force); (2) Maximum velocity (zero drift); and (3) Maximum floor acceleration

Linear Analysis Procedure (2)

Step 1: Determine desired damping ratio afforded by energy dissipation devices

Step 2: Decide installation locations and numbers of energy dissipation devices at each story of building

Step 3: Design building incorporated with energy dissipation devices (framing system remains elastic when damping ratio afforded by energy dissipation devices is considered)

Step 4: Perform linear static or linear dynamic procedures

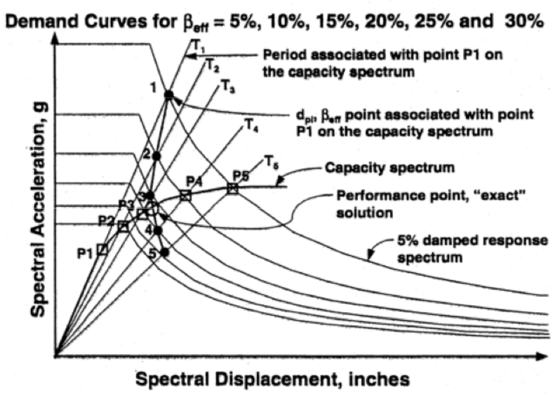
Step 5: Design mechanical properties of all energy dissipation devices at each story based on analysis results obtained from Step (4), and then confirm that if calculated equivalent damping ratio conforms to desired damping ratio determined in Step (1)

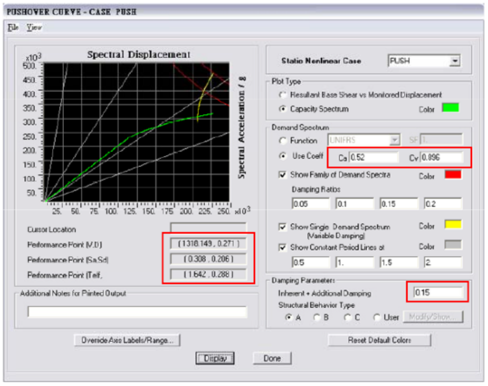
Step 6: Calculate maximum displacement and force demands for all energy dissipation devices at each story

Step 7: Check if design results meet all related requirements

Nonlinear Static Procedure (1)

- Capacity spectrum method in form of acceleration-displacement response spectrum (ADRS) can be performed using pushover analysis procedure in several commercially available computer programs





- Ratio of maximum resistance to story shear demand in each story should range between 80% and 120% of average value of ratios for all stories

- Maximum resistance of all energy dissipation devices should not exceed 50% of resistance of remainder of framing system

Nonlinear Static Procedure (2)

Step 1 : Determine desired damping ratio afforded by energy dissipation devices

Step 2 : Decide installation locations and numbers of energy dissipation devices at each story of building

Step 3 : Design building incorporated with energy dissipation devices (both ductility of framing system and damping ratio afforded by energy dissipation devices are considered)

Step 4 : Perform nonlinear static procedures

Step 5 : Obtain performance point under desired earthquake level using capacity spectrum method

Step 6 : Design mechanical properties of all energy dissipation devices at each story based on analysis results obtained from Step (5), and then confirm that if calculated equivalent damping ratio conforms to desired damping ratio determined in Step (1)

Step 7 : Calculate maximum displacement and force demands for all energy dissipation devices at each story

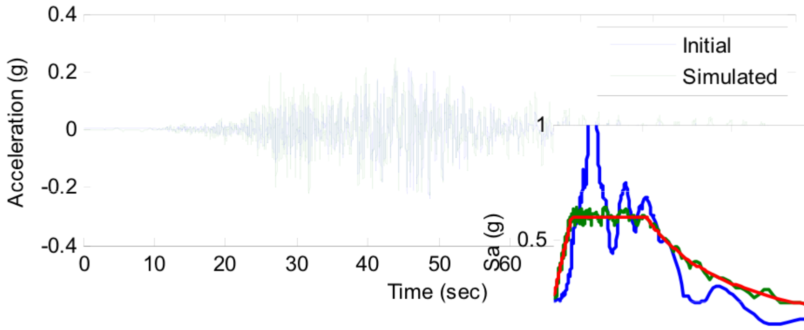
Step 8 : Check if maximum resistance of all energy dissipation devices satisfies related requirements

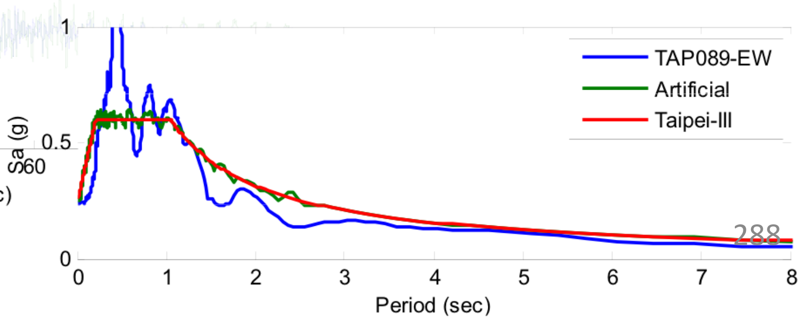
Step 9 : Check if ductility of structure is not greater than allowable capacity

Step 10: Check if design results meet all related requirements

Nonlinear Dynamic Procedure

- Not fewer than three simulated ground motions
- Selected from recorded events near site consistent with design basis (or maximum considered) earthquake
- If at least seven simulated ground motions, average value is used for design
- If fewer than seven simulated ground motions, maximum value is used for design





Detailed Requirements (1)

- Energy dissipation devices
  - Gravity, seismic, wind, thermal, or other cyclic loads
  - Adhesion of device parts
  - Exposure to environmental conditions
  - Should resist wind forces without slip, movement, or inelastic cycling subject to failure by low-cycle fatigue
- Connection points of energy dissipation devices
  - Should provide sufficient articulation to accommodate simultaneous longitudinal, lateral, and vertical displacements
- Wind forces
  - Should resist wind forces in linearly elastic range subject to failure by low-cycle fatigue
- Fire resistance
  - Fire resistance rating for energy dissipation system should be much stricter than that for other structural elements

Detailed Requirements (2)

- Inspection and periodic testing
  - Should provide access for inspection and removal of all energy dissipation devices
  - Registered design professional responsible for structural design should establish appropriate inspection and testing schedules for each type of energy dissipation devices
- Manufacturing quality control
  - Registered design professional responsible for structural design should establish quality control plans for manufacture of energy dissipation devices
- Maintenance
  - Registered design professional responsible for structural design should establish maintenance and testing schedules for energy dissipation devices

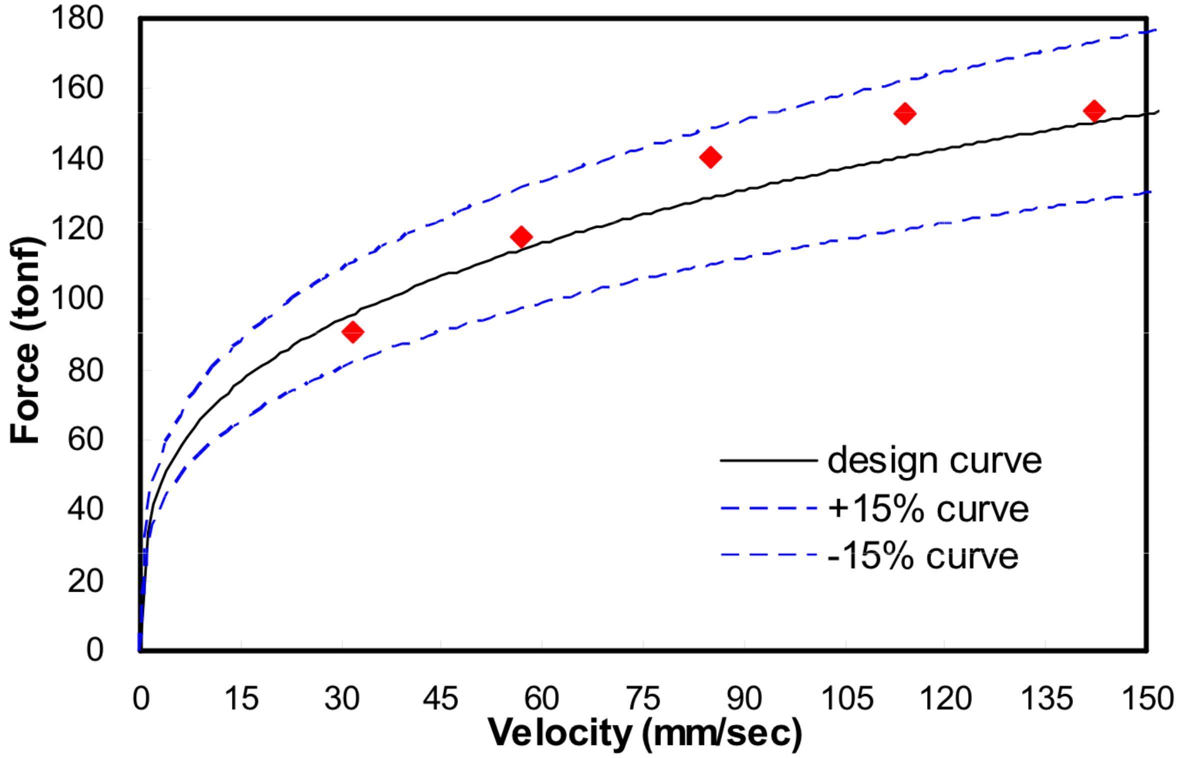
Prototype Tests

- Confirm force-velocity-displacement properties of passive energy dissipation devices assumed for design
- Demonstrate robustness of individual device subjected to extreme seismic excitations
- Test procedures should be approved by registered design professional prior to fabrication of devices
- Sampling rate for each cycle should not be less than 100
- Test data of first cycle can be negligible

Velocity-Dependent Devices (1)

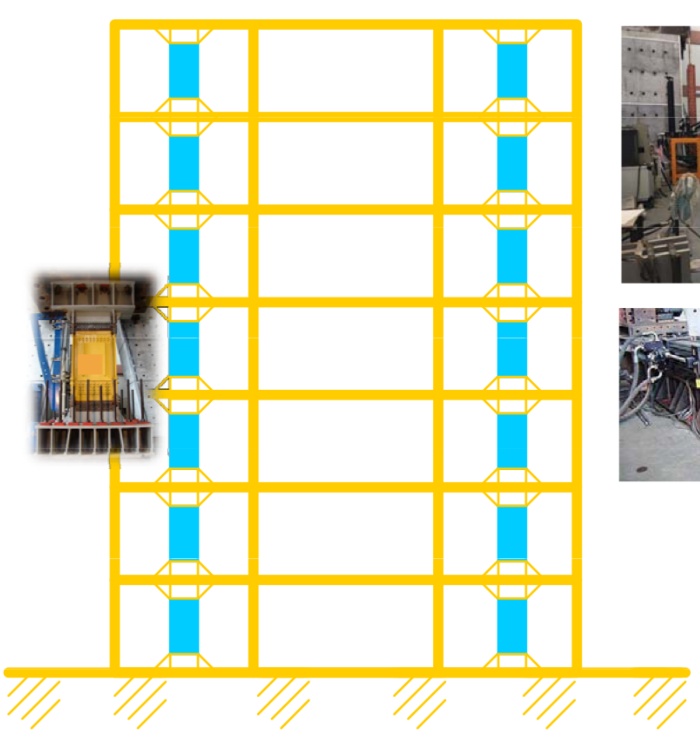
- Perform fully reversed cycles at different representative velocities and forces to find force-velocity relation
  - Test force corresponding to any representative velocity does not differ by more than 15% from design values specified by registered design professional responsible for design
- Perform five fully reversed cycles at maximum earthquake device force considering level of redundancy
  - Effective stiffness (k_{eff}) in any one cycle does not differ by more than 15% from average effective stiffness calculated from all cycles
  - Maximum force and minimum force at zero displacement in any one cycle do not differ by more than 15% from average maximum and minimum forces at zero displacement calculated from all cycles, respectively
  - Area of hysteresis loop (W_D) in any one cycle is not less than 85% of average area of hysteresis loops calculated from all cycles

Velocity-Dependent Devices (2)



NARLabs

Facilities for Testing Dampers at NCREE




High-performance
Damper Testing Facility
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