2015 NEHRP Recommended Seismic Provisions:

Instructional Material Complementing FEMA 1051, Design Examples:

Seismically Isolated Structures

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Includes some materials originally developed by Charles A. Kircher, P.E., Ph.D.
Presentation Objectives

• Present basic principles of seismic isolation: What?, Why?, Where?, How?

• Present an overview of the design requirements with background on major revisions

• Present an overview of a design example
Basic Principles

What is seismic isolation?

A **flexible, sliding or rolling** horizontal interface between the structure and the ground.

This interface **lengthens the period** of the structure away from dominant earthquake frequencies and is complemented with the **ability to absorb energy**.
Basic Principles

What is seismic isolation?

- Modern seismic design approaches: **Fixed-base building:**

  ![Diagram of fixed-base building](image)

  Allow damage in many controlled areas

  Inelastic action occurs over the height of the building

  Figure Courtesy DIS-Inc
Basic Principles

What is seismic isolation?

- Modern seismic design approaches: **Isolated building**

Protect the structure by using an “engineered soft-story”

Inelastic action and displacement concentrated in a single level

Figure Courtesy DIS-Inc
Basic Principles

What is seismic isolation?

• The response spectrum gives us a way to estimate the maximum response of a Single Degree of Freedom (SDOF) oscillator at a range of different periods.

• Isolated buildings (and many other structures) exhibit a response that is dominated by their first oscillating mode – as if it were a SDOF oscillator.

• Thus, by approximating an isolated building as a SDOF oscillator, the response spectrum can be used to estimate the maximum response.
Basic Principles

What is seismic isolation?

• Thus, looking at representative response spectra, what is the premise of seismic isolation?

Figure Courtesy DIS-Inc
Basic Principles

Why isolate?

- Isolation achieves a greatly improved seismic performance compared to most other conventional fixed-base seismic force resisting systems in a major earthquake.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Conventional</th>
<th>Isolated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaths</td>
<td>thumbs up</td>
<td>thumbs up</td>
</tr>
</tbody>
</table>
  Serious injury and life loss not expected  
| Dollars      | thumbs down  | thumbs up|  
  No or minimal structural and non-structural repair costs  
| Downtime     | thumbs down  | thumbs up|  
  No or minor loss of function for all facilities  

Basic Principles

Where to isolate?

Greatest benefits of isolation realized in areas which have high seismicity
Basic Principles

Where to isolate?

Natural candidates for isolation have been:

- **Essential facilities** such as emergency operation centers that require continued functionality for public health and safety.
Basic Principles
Where to isolate?

- **Historic structures and museums** that have low available ductility, valuable contents and require preservation.
Basic Principles

Where to isolate?

- **Business facilities** such as data centers and factories that have high-value or hazardous contents and/or require continued functionality.
Basic Principles

Where to isolate?

Almost any building can be isolated, however there are several factors where it is more or less effective:

1. **Buildings characteristics**
   - ✓ Short-period structures (say $T_1 < 1.0$ sec)
   - ✓ Heavy buildings
   - ? Overly flexible or tall structures
   - ? Slender buildings and Seismic Force Resisting System (SFRS) configurations that give large uplift forces
Basic Principles

Where to isolate?

2. **Site conditions**
   - ✓ Stiff soils
   - ? Sites susceptible to basin amplification
   - ? Sloping sites that requires a stepped isolation plane

3. **Space and installation**
   - ✓ Isolation plane is above grade level
   - ? Close adjacent buildings (moat clearance)
Basic Principles

Where to isolate?

4. **People**
   - Long-term building owners
   - Businesses or institutions with valuable contents, critical functions
   - Recognition of market demand for higher performance
Isolation System Definition:

“The collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes the wind-restraint system, energy-dissipation devices, and/or the displacement restraint system if such systems and devices are used to meet the design requirements of this chapter.”
Basic Principles

How to isolate?

• Isolation Interface

Instructional Material Complementing FEMA 1051, Design Examples
Basic Principles

How to isolate?

Isolator Units (or Bearings):

• Horizontally have **low stiffness, re-centring ability** and good energy dissipation.
• Are **vertically stiff and stable** under the weight of the building and large displacement.
• Have **well established** and repeatable **mechanical properties** with **limited degradation**.
Basic Principles

How to isolate?

• Two of the most common types:
  1. **Elastomeric (rubber)** Isolators
     Consist of alternating layers of rubber and steel shims.
     – Low- or high-damping rubber bearings
     – Lead-rubber (LR) bearings
Basic Principles

How to isolate?

• Two most common types:

2. **Sliding** Isolators

Utilize a low-friction sliding interface, commonly PTFE (Teflon) on polished stainless steel.

  – Concave sliding system
    • Single-concave sliding surface
    • Double-concave sliding surface
    • Triple-pendulum™ bearings
  – Flat sliding bearings (used with rubber isolators)
Basic Principles

Summary

• **What** is seismic isolation?
  Period shift and energy absorption (“engineered soft-story”)

• **Why** isolate?
  Improved seismic performance (deaths, dollars, downtime)

• **Where** to isolate?
  – Where continued functionality and avoidance of damage to structural/non-structural elements and contents is valued.
  – Most effective where a building has a short-period, on stiff soils with little constraints on moat clearance and location of isolation plane.

• **How** to isolate?
  Most common bearings are elastomeric (rubber) and sliding isolators (flat or concave).
Background of Seismic Provisions

Design Requirements Overview

- NEHRP Provisions
- ASCE 7 Standard (Seismic)
- International Building Code
- NFPA 5000 Building Code
- California Building Code
Background of Seismic Provisions

Design Requirements Overview

Chapter 17, ASCE 7-2016 (the *Standard*) is divided into eight sections:

- **17.1 & 17.2**: Definitions & General Requirements
- **17.3**: Ground Motion Criteria
- **17.4, 17.5, 17.6**: Analysis Procedures
- **17.7**: Design Review
- **17.8**: Testing
17.1 & 17.2: Definitions & General Requirements:

**Structural System**

- $I_e$, $\rho$, Irregularities?
- Different design actions for components above and below isolation system
- Permitted structural systems, *i.e.* OCBF up to 160ft
- Minimum building separations
Background of Seismic Provisions

Design Requirements Overview

17.1 & 17.2: Definitions & General Requirements:

- **Isolation System**

- Wind and Fire Resistance
- Minimum Restoring Force
- Vertical load combinations
- Overturning and uplift stability
- Inspection & replacement
- Upper- & lower-bound properties
17.3: Ground Motion Criteria

Question 1: **Is a site-specific hazard analysis necessary?**

- Yes, for Class A, B, C sites, where $S_1 \geq 0.6$
- Yes, for Class D and E sites, where $S_1 \geq 0.2$
- Yes, for Site Class F

Otherwise USGS website
17.3: Ground Motion Criteria

**Question 2: What level of analysis is necessary?**

- For **ELF** and **Response Spectrum** procedures, simply use the response spectrum determined by answering **Question 1**.
- For **Response History Analysis**, also have to select and scale ground motion records:
17.7: Design Review

- At least one registered design professional shall provide an independent review.
- Peer reviewer or panel should be formed before setting the design criteria (including site-specific ground motion criteria).
17.8: Testing

The *Standard* has extensive testing requirements compared to other structural systems, why?

Because *seismic isolators* are:

- typically custom designed and proprietarily constructed, and
- manufactured using non-traditional materials (lead, elastomers, Teflon)

*Much like baked bread, their behavior (taste) may vary significantly between projects (batches) and suppliers (bakers)*
17.8: Testing

The three categories are:

1. **Qualification testing**
   - Submitted by the manufacturer
   - Qualitative requirement, may be used in establishing the isolators properties, longevity, or to develop models to be used in analysis
17.8: Testing

2. Prototype testing

- Two isolators of each type require testing or may make use of previous test data from “similar” isolators
- Used to determine properties for design and modification factors $\lambda_{\text{test}}$
- Test sequences and cycles also check wind loading, durability and stability of the isolators
Background of Seismic Provisions

Design Requirements Overview

17.8: Testing

3. Production testing

– All isolators must be subjected to a combined compression and shear load cycle before being installed
– May be performed at slow-speed
– Verifies the quality of product
Background of Seismic Provisions

Revisions

• **Full replacement** of ASCE 7 Chapter 17 recommended
• Some major changes include:
  1. Having a MCE\(_R\)-only basis for analysis and design.
  2. A completely new section to systematically account for the variability in the isolation systems properties

**NEHRP Recommended Seismic Provisions for New Buildings and Other Structures**

FEMA P-1050-1/2015 Edition

FEMA
Background of Seismic Provisions

Revisions

3. Revision of ground motion criteria.
4. Expanded the range of applicability of the ELF procedure.
5. Revised equations for calculating the distribution of shear force over the height of the building.
6. Simplified approach for incorporating accidental mass eccentricity for NLRHA.
7. Additions and changes to the testing requirements.
Background of Seismic Provisions

Revisions

1. MCE$_R$-only basis for design
   • Modified the elastic base shear calculation from the DBE event to the MCE$_R$ event, but now using a consistent set of the upper- or lower-bound properties.
   • Consequently, the DBE event was removed completely from Ch 17.

Although not seeking damage-control as an objective, isolated buildings will have a better performance than other SFRS because:
   • The superstructure is designed to remain essentially elastic for the MCE$_R$ event.
   • Isolation system is designed and tested for the MCE$_R$ event.
2. Isolation System Properties

- Completely new section to systematically account for the variability and uncertainty in isolator properties.
- Process is to use the property modification ($\lambda$) factor approach.
- Two parallel upper- and lower-bound analyses are conducted, where the governing case for each response parameter of interest is used for design.
3. Ground Motion Criteria- NLRHA

- Only **seven** ground motions required (other structures in ASCE 7-16 require 11)
- Includes specific scaling requirements for amplitude and spectrally matched ground motions
- Need only apply motions to analysis model in **one** orientation.
- Clarified scaling for both FN and FP components at near-fault sites.
Background of Seismic Provisions

Revisions

4. ELF Procedure can be used to design more buildings
   • Relaxed permissible limits and criteria for the use of the equivalent lateral force (ELF) procedure.
   • This modification minimizes the need to perform complex and computationally expensive nonlinear response history analyses for many base isolated structures.
Background of Seismic Provisions

Revisions

5. ELF Procedure Structural Shear Distribution

- New, more realistic vertical distribution of lateral forces associated with the ELF method of design

ASCE 7-10  ASCE 7-16
6. Establishing amplifications to account for accidental mass eccentricities

- Only two additional analysis cases required, IIa and IIb:

<table>
<thead>
<tr>
<th>Case</th>
<th>Isolator Properties</th>
<th>Accidental Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Lower bound</td>
<td>No</td>
</tr>
<tr>
<td>IIa</td>
<td>Lower bound</td>
<td>Yes, X direction</td>
</tr>
<tr>
<td>IIb</td>
<td>Lower bound</td>
<td>Yes, Y direction</td>
</tr>
</tbody>
</table>

The following amplification factors (ratio of Case IIa or IIb response to Case I response) are computed:

a) isolator displacement at the plan location with the largest isolator displacement;

b) story drift in the structure at the plan location with the highest drift, enveloped over all stories;

c) frame-line shear forces at each story for the frame with to the maximum drift.
7. Testing Requirements

Some changes include:

- Move towards having dynamic testing (i.e. prototype testing now has dynamic sequences).
- Specific “similarity” criteria added to define when prototype testing may be waived.
- Production testing in combined compression in shear is now required for all (100%) of isolators.
Overview of Design Example

1. Project Information
2. Design Steps
3. Preliminary Design
4. Isolation System Properties
5. Equivalent Lateral Force (ELF) Procedure
6. Dynamic Analysis
   a) Vertical Response Spectrum
   b) Response History
7. Testing Requirements
Project Information

• **Structural Description**

Seismic Weight = 10,200 kip (D+0.5L_{\text{red}})
Project Information
Project Information

• This structure is purposely configured to the minimize uplift (tension) demands, through:
  – Increasing the number of bays with bracing at lower stories.
  – Locating braces at interior (rather than perimeter) gridlines since they have greater gravity loading.
  – Avoiding common end columns for bracing in the transverse and longitudinal directions.
Project Information
Design Steps

**Step I:**
Project & Ground Motion Criteria

**Step II:**
Preliminary Design

**Step III:**
Isolation System Properties and ELF Analysis

**Step IV:**
Vertical Earthquake Effects

**Step V:**
Revisit ELF Analysis & Optimize

**Step VI:** (if required)
Dynamic Analysis

**Step VII:**
Final Specifications
Project Information

Performance Criteria:

- Emergency Operation Center: Occupancy Category IV

Project specific goals are to:

1. Resist minor and moderate earthquakes without damage.
2. Resist major earthquakes without failure of the isolation system, or significant damage to structural and nonstructural components, or major disruption to facility function.

Implicitly achieved by using a Standard-compliant isolated building, accordingly:

- Occupancy Importance Factor: $I_e = 1.0$ for all isolated structures ($I_e = 1.5$ for other conventional Category IV structures)
Project Information

Ground Motion Criteria:

- Site Hazard and Soil Conditions
  - Region of high-seismicity
  - Seismic Design Category D
  - Soil site class D
- Spectral Accelerations
  - $S_{MS} = 1.4$
  - $S_{M1} = 0.9$
  - $S_1 = 0.5 \Rightarrow $§11.4.7 Site-specific hazard analysis required
Preliminary Design

• **Philosophy:**

Use information from previously manufactured and tested bearings, instead of doing theoretical optimizations which give atypical designs.

• Latest in knowledge: Constantinou et al 2007 & 2011 MCEER reports (recommend you download, free)
Preliminary Design

Elastomeric Isolation System:

- Select trial bearing dimensions and lower bound properties.
- Quickly estimate displacements (and rough compression forces) using the ELF procedure.
- Assess the bearing’s adequacy (stability) and iterate on bearing dimensions

<table>
<thead>
<tr>
<th>Properties (Section 15.4.1.2)</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Yield Stress of Lead ($\sigma_{yl}$)</td>
<td>1.45 ksi</td>
<td>1.45</td>
</tr>
<tr>
<td>Rubber Shear Modulus ($G$)</td>
<td>60 psi</td>
<td>60</td>
</tr>
</tbody>
</table>

**Bearing Dimensions (Step 1)**

<table>
<thead>
<tr>
<th>Property</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Core Diameter ($D_L$)</td>
<td>4.5 inch</td>
<td>5.125 inch</td>
</tr>
<tr>
<td>Bonded Rubber Diameter ($D_B$)</td>
<td>22.5 inch</td>
<td>26.5</td>
</tr>
<tr>
<td>Total Thickness of Rubber ($T_r$)</td>
<td>4.5 inch</td>
<td>5.125</td>
</tr>
<tr>
<td>Yield Displacement ($Y$)</td>
<td>0.60 inch</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Isolation System Force-Displacement Behavior (Step 2)**

<table>
<thead>
<tr>
<th>Property</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Post-elastic Stiffness ($k_{st,Total}$)</td>
<td>178 kip/in</td>
<td>218 kip/in</td>
</tr>
<tr>
<td>System Characteristic Strength ($Q_d,Total$)</td>
<td>807 kip</td>
<td>1047 kip</td>
</tr>
</tbody>
</table>

**Equivalent Lateral Force Procedure (MCEA) (Step 2)**

<table>
<thead>
<tr>
<th>Property</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Displacement ($D_M$)</td>
<td>13.6 inch</td>
<td>11.2</td>
</tr>
<tr>
<td>Effective Stiffness ($k_M$)</td>
<td>237 kip/in</td>
<td>311</td>
</tr>
<tr>
<td>Effective Period ($T_M$)</td>
<td>2.10 second</td>
<td>1.83</td>
</tr>
<tr>
<td>Effective Damping ($\beta_M$)</td>
<td>0.15</td>
<td>0.18</td>
</tr>
</tbody>
</table>

**Required Rubber Layer Thickness (Steps 3 and 4)**

(1.2 + 0.2Sm)D + 0.5 L + Q$_E$

<table>
<thead>
<tr>
<th>Property</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_u$</td>
<td>1156 kip</td>
<td>1199</td>
</tr>
<tr>
<td>Displacement with Torsion ($D_{dt}$)</td>
<td>16.3 inch</td>
<td>13.4</td>
</tr>
<tr>
<td>Rubber thickness for stability ($t$)</td>
<td>0.072 inch</td>
<td>0.074</td>
</tr>
<tr>
<td>Rubber Shear Strain ($D_{st}T_r$)</td>
<td>0.302 %</td>
<td>0.219</td>
</tr>
</tbody>
</table>

Not acceptable, need ≥ 0.25inch and ≤ 250%, iterate O.K.
ELF Procedure

1. Assume a displacement, say $D_M = 11.2$ inch

2. Calculate the effective stiffness $k_M$

   $$k_M = k_{d,\text{total}} + \frac{Q_{d,\text{total}}}{D_M} = 218 + \frac{1047}{11.2} = 311 \text{ kip/inch}$$

3. Calculate the effective period $T_M$

   $$T_M = 2\pi \sqrt{\frac{W}{k_M g}} = 2\pi \sqrt{\frac{10200}{311 \times 386}} = 1.83 \text{ seconds}$$

4. Calculate the effective damping $\beta_M$

   $$\beta_M = \frac{4Q_{d,\text{total}}(D_M - Y)}{2\pi k_M D_M^2} = \frac{4 \times 1047 \times (11.2 - 0.6)}{2\pi \times 311 \times 11.2^2} = 0.18$$

5. Interpolate the damping coefficient $B_M$ from Table 17.5-1

   $$B_M = 1.44$$

6. Check the displacement matches what was initially assumed in Step 1

   $$D_M = \frac{gS_{M1}T_M}{4\pi^2 B_M} = \frac{386 \times 0.9 \times 1.83}{4 \times \pi^2 \times 1.44} = 11.18 \text{ inch} \approx 11.2 \text{ inch : O.K.}$$
ELF Procedure

• Refine analysis with a 3-D model and optimise the isolation system design

• ELF force-deflection behaviour of the “optimized” solution
ELF Procedure

- **Check Minimum Requirements for** $V_S$
- $V_S = 3449$ kip (upper-bound properties)

Minimum Requirements of §17.5.4.3 for Reduced Lateral Force $V_s$

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Requirement</th>
<th>Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The lateral seismic force required by <em>Standard</em> §12.8 for a fixed-base structure of the same effective seismic weight, $W_S$, and a period equal to the period of the isolation system using the upper bound properties $T_{M}$.</td>
<td>$C_s = \frac{2}{3} \frac{S_{M1}}{T \left( \frac{R}{I_e} \right)} = \frac{2}{3} \times \frac{0.9}{1.5} \frac{3.25}{1.5} = 0.19$</td>
</tr>
<tr>
<td></td>
<td>$C_S \geq 0.044 \times \frac{2}{3} \times S_{MS} \times I_e \geq 0.01$</td>
<td>\geq 0.06</td>
</tr>
<tr>
<td></td>
<td>$V_S \geq C_S W = 1940$ kip O.K.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>The base shear corresponding to the factored design wind load.</td>
<td>O.K.</td>
</tr>
<tr>
<td>3</td>
<td>The lateral seismic force, $V_{st}$, calculated using Eq. 17.5-7, and with $V_b$ set equal to the force required to fully activate the isolation system utilizing the upper bound properties.</td>
<td>$F_y = Q_d + k_d Y = 1582 + 274 \times 0.6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1746 kip O.K.</td>
</tr>
<tr>
<td>3a</td>
<td>1.5 times the nominal properties, for the yield level of a softening system</td>
<td>N/A</td>
</tr>
<tr>
<td>3b</td>
<td>the ultimate capacity of a sacrificial wind-restraint system</td>
<td>N/A</td>
</tr>
<tr>
<td>3c</td>
<td>the break-away friction force of a sliding system, or</td>
<td>N/A</td>
</tr>
<tr>
<td>3d</td>
<td>the force at zero displacement of a sliding system following a complete dynamic cycle of motion at $D_M$.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
ELF Procedure

- **Bearing Vertical Loads**

  - Model the bearing (& soil) vertical stiffness, framing stiffness and mass distribution realistically in 3-D.

- The compression stiffness of a multi-layered elastomeric bearing can be approximated accordingly:

  \[
  K_v = A \left[ \sum_i t_i \left( \frac{1}{E_{ci}} + \frac{4}{3K} \right) \right]^{-1}
  \]
ELF Procedure

- **Total Maximum Displacements:**
  - Increase the maximum ($MCE_R$) displacement due to torsion to get the total maximum displacement
  - Minimum amplification factor:
    \[
    1 + \left( \frac{y}{P_T^2} \right) \frac{12e}{b^2 + d^2} \geq 1.15^* 
    \]
    *(in commentary)*

Where:

- $P_T =$ ratio of the effective translational to torsional period of the isolation system
- $y$ (or $x$) = distance in plan from center of rigidity to corner
- $e =$ actual plus accidental eccentricity
- $b, d =$ plan dimensions

**Plan View of Building**

- Total Maximum Displacement
  (maximum considered earthquake corner of building)
- Maximum Displacement
  (maximum considered earthquake center of building)
- Design Displacement
  (design earthquake center of building)

Removed from 2016 Standard
ELF Procedure

• P-delta Effects

\[ M_A = VH_1 + \Delta P/2 \]
\[ M_B = VH_2 + \Delta P/2 \]
\[ M_C = VH_3 \]
\[ M_D = VH_4 + \Delta P \]
\[ M_E = VH_5 + \Delta P/2 \]
\[ M_F = VH_6 + \Delta P/2 \]
\[ M_G = VH_7 \]
\[ M_H = VH_8 + \Delta P \]
Dynamic Analyses

• **Analysis Procedure Selection**

• ELF Procedure permitted for final design

• However, uplift is an issue and more sophisticated analysis may show improved responses

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**Table 15.5-11** Restrictive Requirements for ELF (and Response Spectrum) Analysis

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Requirement</th>
<th>Upper-bound</th>
<th>Lower-bound</th>
<th>Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The structure is located on a Site Class A, B, C and D.</td>
<td>Site Class D</td>
<td>O.K.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>The effective period of the isolated structure at the maximum displacement, $D_M$, is less than or equal to 5.0s.</td>
<td>1.5 sec</td>
<td>2.1 sec</td>
<td>O.K.</td>
</tr>
<tr>
<td>3</td>
<td>The structure above the isolation interface is less than or equal to 4 stories or 65 ft (19.8m) in structural height measured from the base level. Exception: These limits are permitted to be exceeded if there is no tension/uplift on the bearings.</td>
<td>4 stories with 50 ft height.</td>
<td>O.K.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>The effective damping of the isolation system at the maximum displacement, $D_M$, is less than or equal to 30%.</td>
<td>24%</td>
<td>16%</td>
<td>O.K.</td>
</tr>
</tbody>
</table>
| 5       | The effective period of the isolated structure $T_M$ is greater than three times the elastic, fixed-base period of the structure above the isolation system determined using a rational modal analysis. | $T_M = 1.5$ sec  
$T_M = 2.1$ sec | $T_B = 0.43$ s  
$3T_B = 1.3$ s | O.K.   |
| 6       | The structure above the isolation system does not have a structural irregularity, as defined in Section 17.2.2.                                                                                           | No structural irregularity, see Section 15.2.4.1 | O.K.        |
| 7a      | The effective stiffness of the isolation system at the maximum displacement, $D_M$, is greater than one-third of the effective stiffness at 20 percent of the maximum displacement. | $464 > 409$  
$239 > 164$ | O.K.        |
| 7b      | The isolation system is capable of producing a restoring force such that the lateral force at the corresponding maximum displacement is at least 0.025W greater than the lateral force at 50 percent of the corresponding maximum displacement. | $0.11W$     
$0.12W$     | O.K.        |
| 7c      | The isolation system does not limit maximum earthquake displacement to less than the total maximum displacement, $D_{1M}$.                                                                              | Assumed to have no restrictions less than $D_{1M}$ | O.K.        |
Dynamic Analyses

- **Response History Analysis**

Model Verification

![Graph showing base shear vs. displacement for different directions and procedures.](image-url)
Dynamic Analyses

- **Response History Analysis**

**Post-Processing**

![Graph showing displacement over time for X-displacement, Y-displacement, and SRSS.](image-url)
Dynamic Analyses

- **Response History Analysis**

Post-Processing – Lateral Forces

Base Shear, $V_b =$
- 2410 kip
- 2834 kip
- 3853 kip
Dynamic Analyses

• **Response History Analysis**

Post-Processing – Lateral Forces

• All elements **above** the isolation system shall be designed for lateral force **no less** than 80% of the ELF $V_b$ for this regular structure. Therefore increase NLRHA forces by:

  X-direction scale factor: $0.8 \times \frac{3853}{2834} = 1.09$

  Y-direction scale factor: $0.8 \times \frac{3853}{2410} = 1.28$

• All elements **below** the isolation system shall be designed for lateral force **no less** than 90% of the ELF $V_b$

  *i.e. increase scale factors above further by* $0.9/0.8 = 1.13$
7. Testing Requirements

- **Prototype testing of 2 isolators**

1. For setting acceptance criteria of production testing
2. To determine nominal properties and $\lambda_{test}$ factors
3. To check durability of isolator for multiple earthquake events
4. Stability of isolator in extreme conditions

<table>
<thead>
<tr>
<th>No. of Cycles</th>
<th>Standard Criteria</th>
<th>Example EOC Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical Load</td>
<td>Lateral Load</td>
</tr>
<tr>
<td>1.</td>
<td>Production Set of Tests, Performed Quasi-Statically on a Virgin Bearing</td>
<td></td>
</tr>
<tr>
<td>3 cycles</td>
<td>Typical 0.67$D_M$</td>
<td>290 kips 7.0 in.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Cyclic Load Tests to Establish Force-Deflection Behavior, Performed Dynamically</td>
<td></td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Typical 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>290 kips</td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Typical 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>290 kips</td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Maximum 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>590 kips</td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Maximum 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>590 kips</td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Minimum 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>30 kips</td>
</tr>
<tr>
<td>1 cycle at each increment of displacement</td>
<td>Minimum 0.25, 0.5, 0.67, 1.0$D_M$</td>
<td>30 kips</td>
</tr>
<tr>
<td>3 cycles</td>
<td>Typical 1.0$D_M$</td>
<td>290 kips 10.4 in.</td>
</tr>
<tr>
<td>3 cycles</td>
<td>Maximum 1.0$D_M$</td>
<td>590 kips 10.4 in.</td>
</tr>
<tr>
<td>3 cycles</td>
<td>Minimum 1.0$D_M$</td>
<td>30 kips 10.4 in.</td>
</tr>
<tr>
<td>3. Cyclic Load Tests to Check Durability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 cycles$^2$</td>
<td>Typical 0.75$D_M$</td>
<td>290 kips 7.8 in.</td>
</tr>
<tr>
<td>4. Load Test of Isolator Stability$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 cycle</td>
<td>Maximum 1.0$D_{TM}$</td>
<td>830 kips 12.0 in.</td>
</tr>
<tr>
<td>1 cycle</td>
<td>Minimum 1.0$D_{TM}$</td>
<td>-75 kips 12.0 in.</td>
</tr>
</tbody>
</table>
7. Testing Requirements

• Prototype units are acceptable if they have:

1. Positive incremental restoring force capacity for re-centering

2. Reliable force-deflection properties with limited manufacturing variations

3. & 4. Measured lateral force-displacement response that lies between the limits set forth by the engineer-of-record for the specified cycles of dynamic loading & is durable for multiple earthquakes.

5. Remain stable under worst case loading conditions
7. Testing Requirements

• Production testing of all (100%) isolators

Example Production Test Requirements¹

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<td>Lateral Load</td>
</tr>
<tr>
<td>3 cycles</td>
<td>Typical</td>
<td>$0.67D_M$</td>
</tr>
</tbody>
</table>

1. Testing performed quasi-statically
Presentation Objectives

• Present basic principles of seismic isolation: What?, Why?, Where?, How?

• Present an overview of the design requirements with background on major revisions

• Present an overview of a design example
Questions?