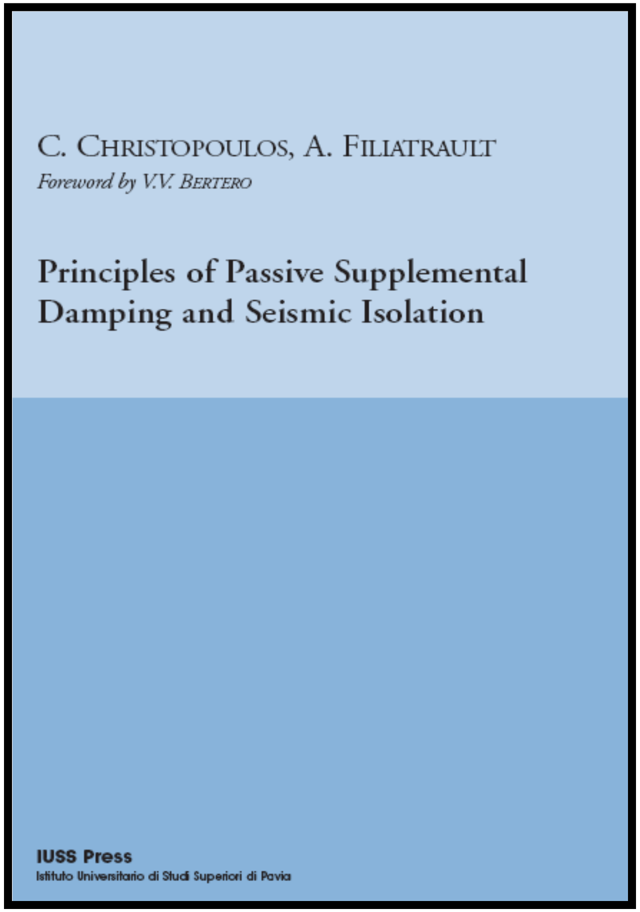
Chapter 11
The AASHTO Design Guide Specifications for Seismically Isolated Bridges

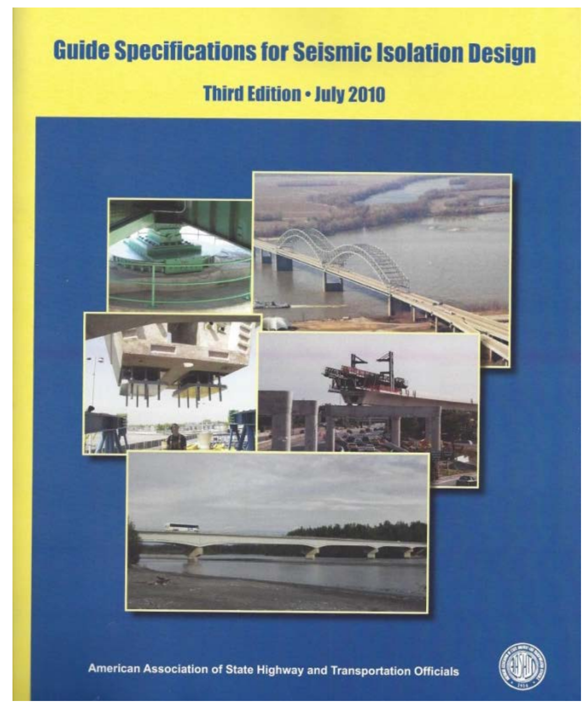
CONTENT

Major References

- Section 9.4

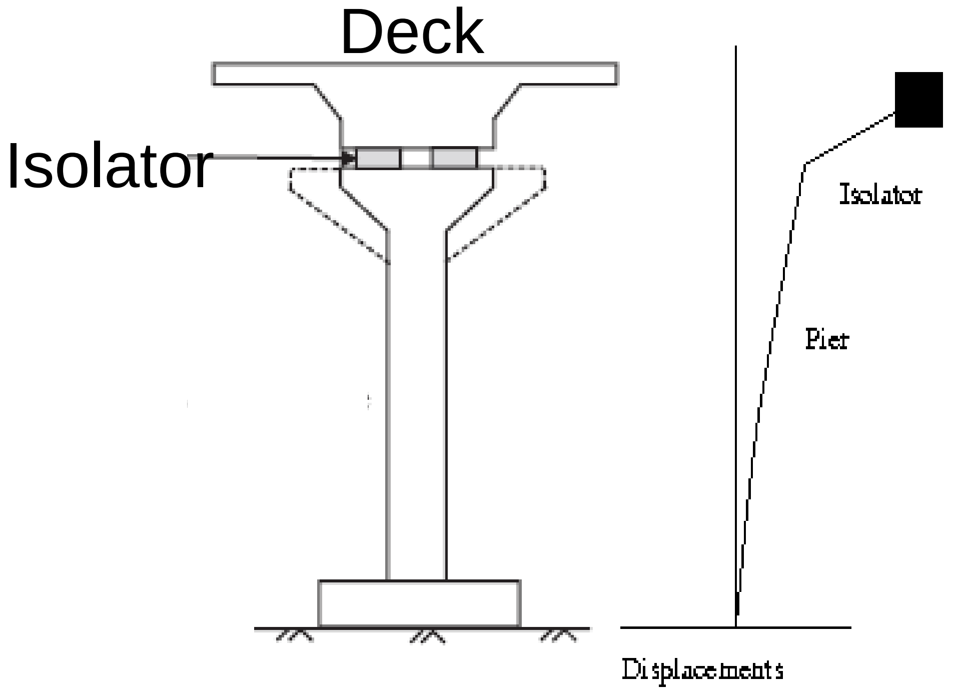


- AASHTO Guide Specifications for Seismic Isolation Design



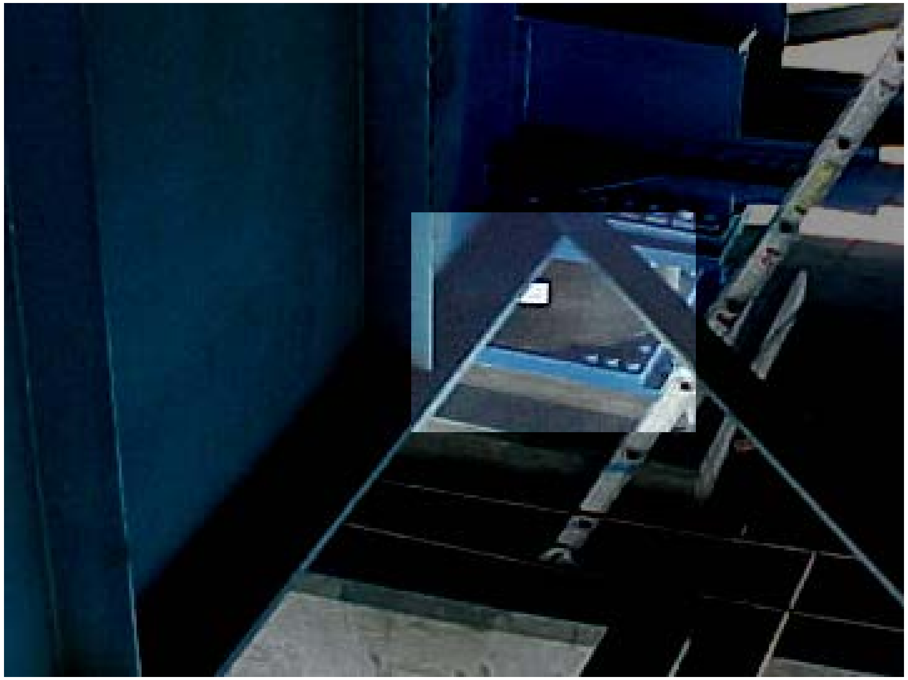
1. Introduction

- Base isolation in bridges separate the deck from the piers.
- Isolators usually positioned at top of piers or bents with deck supported above to reduce overturning moment on isolators and reduce superstructure flexibility.
- Deck designed as a simply supported (or continuous over simple supports) beam or slab-on beam.



1. Introduction

- Coronado Bridge, San Diego, CA



1. Introduction

- Codified Design Methods
  - Several hundreds of bridges in New Zealand, Japan, Italy, Greece and United States designed using seismic isolation principles and technology (see textbook Appendix D)
  - Most recent design provisions for seismically isolated bridges:
    - AASHTO Guide Specifications for Seismic Isolation Design, 3rd Edition
      - Design procedures based on equivalent linearization procedure
      - Stiffness of isolation system described as effective linear stiffness at design displacement
      - Energy dissipation of isolation system modeled as equivalent viscous damping

2. Design Methods

- Four possible design methods:
  1. Equivalent Static Force Method
     - Must be conducted in all cases.
     - For isolated bridge structures responding mainly as single-degree-of-freedom systems in each principal direction
     - No displacement coupling between the principal directions.
     - Independent analysis in each principal direction and combination of the results according to AASHTO Guide Specifications.

2. Design Methods

- Four possible design methods:
  2. Single mode spectral method
     - For isolated bridge structures responding mainly as single-degree-of-freedom systems in each principal direction
     - No displacement coupling between the principal directions.
     - Independent analysis in each principal direction and combination of the results according to AASHTO Guide Specifications.
     - The effective stiffness of the isolation system must correspond to the design displacement.
       - Equivalent force method can be used as starting point.
       - Iterations required.

2. Design Methods

- Four possible design methods:

3. Multiple modes spectral method
   - For isolated bridge structures with displacement coupling between the principal directions.
   - Design spectrum at 5% damping similar to the ASCE 7-10 design spectrum.
   - Spectral responses for periods longer than $0.8T_{eff}$, where T_{eff} is the effective period of the isolation system, must be divided by the damping reduction factor B_D.
   - Independent analysis in each principal direction and combination of the results according to AASHTO Guide Specifications.
   - The effective stiffness of the isolation system must correspond to the design displacement.
     - Equivalent force method can be used as starting point.
     - Iterations required.

2. Design Methods

- Four possible design methods:

4. Time-history analysis
   - Linear or nonlinear analysis.
   - For linear analysis, the effective stiffness of the isolation system must correspond to the design displacement.
     - Equivalent force method can be used as starting point.
     - Iterations required.
   - For nonlinear analysis, the nonlinear behavior of the isolation system must be modeled.
   - The selection of ground motion time-histories follow the same rules as that of ASCE 7-10 (see Section 3).

3. Equivalent Static Force Method

For all seismic isolation designs, it is first necessary to determine an equivalent static design force for the superstructure above the isolation system. The statically equivalent seismic design force V is given by:

$$V = C_d W \tag{9.72}$$

where W is the total vertical load for design of the isolation system (dead and live loads) and C_d is a seismic response demand coefficient given by:

$$C_d = \frac{k_{eff}\,\Delta}{W} = \frac{F_v\, S_1}{T_{eff}\, B_D} \tag{9.73}$$

where k_{eff} is the effective linear stiffness of the base isolation system and substructure supporting the superstructure at the total deck design displacement Δ at the center of rigidity of the isolation system, F_v is the site soil coefficient.

S_1 is the one-second period spectral acceleration.

T_{eff} is the effective period of the isolation system at the design displacement Δ, and B_D is the same damping reduction factor given by Equation (9.61) and Table 9-1.

3. Equivalent Static Force Method

The effective period of the isolation system in Equation (9.73) is given by:

$$T_{eff} = 2\pi \sqrt{\frac{W}{k_{eff}\, g}} \tag{9.74}$$

Substituting Equation (9.74) into Equation (9.73) yields an expression for the total deck displacement Δ (in meters):

$$\Delta = \frac{0.25 F_v S_1 \boldsymbol{T_{eff}}}{B_D} \tag{9.75}$$

3. Equivalent Static Force Method

Table 9-1 : Damping Reduction Factors, B_D

ξ	B_D	$\left(\frac{\zeta}{0.05}\right)^{0.3}$
< 0.02	0.8	0.77
0.05	1.0	1.00
0.10	1.2	1.23
0.20	1.5	1.52
0.30	1.7	1.71
0.40	1.9	1.87
≥ 0.50	2.0	2.00

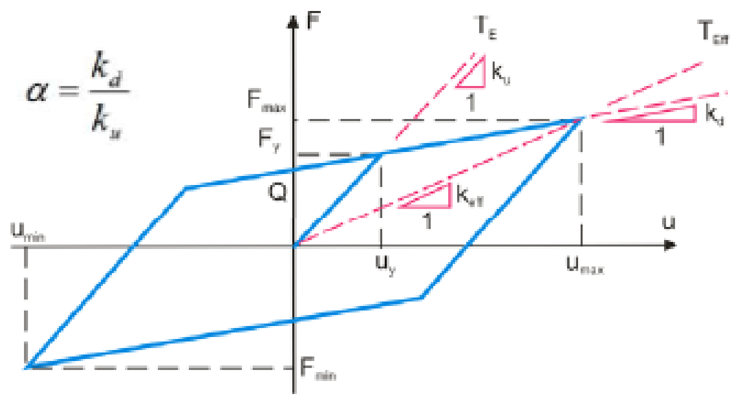
3. Equivalent Static Force Method

- Effective damping coefficient

$$\zeta_{eff} = \frac{1}{4\pi}\cdot\frac{Eh}{Es} = \frac{2}{\pi}\cdot\frac{Q\cdot(u_{max}-u_y)}{k_{eff}\cdot u_{max}^{2}} = \frac{2}{\pi}\cdot\frac{(\mu-1)\cdot(1-\alpha)}{\mu\cdot(1+\alpha\mu-\alpha)}$$

$$T_{eff} = T_e\cdot\sqrt{\frac{\mu}{1+\alpha\mu-\alpha}}$$

$$\alpha = \frac{k_d}{k_u}$$



  - Must consider all sources of damping
    - Isolation system + parallel dampers

3. Equivalent Static Force Method

- Flexibility of sub-structure must be considered in design and analysis of an isolated bridge

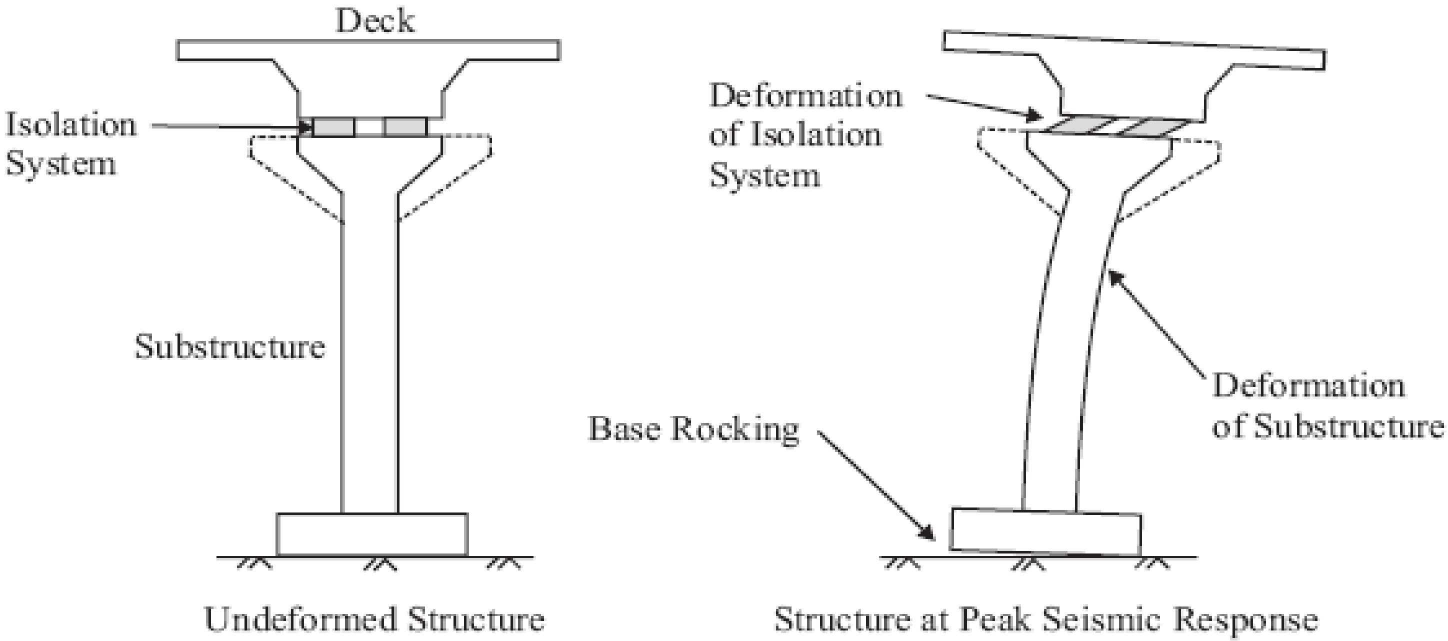


Figure 9.8 Effective Lateral Stiffness of Combined Isolation System and Substructure

3. Equivalent Static Force Method

Note that in calculating the effective stiffness k_{eff}, both the effective stiffness of the isolation system and of the substructure supporting the isolators must be considered.

$$k_{eff} = \frac{k_{sub}\, k_{iso}}{k_{sub} + k_{iso}} \tag{9.76}$$

where k_{iso} is the effective lateral stiffness of the isolation system at the design displacement Δ_i (as illustrated in Figure 9.9) and k_{sub} is the effective lateral stiffness of the substructure at the corresponding displacement Δ_{sub}.

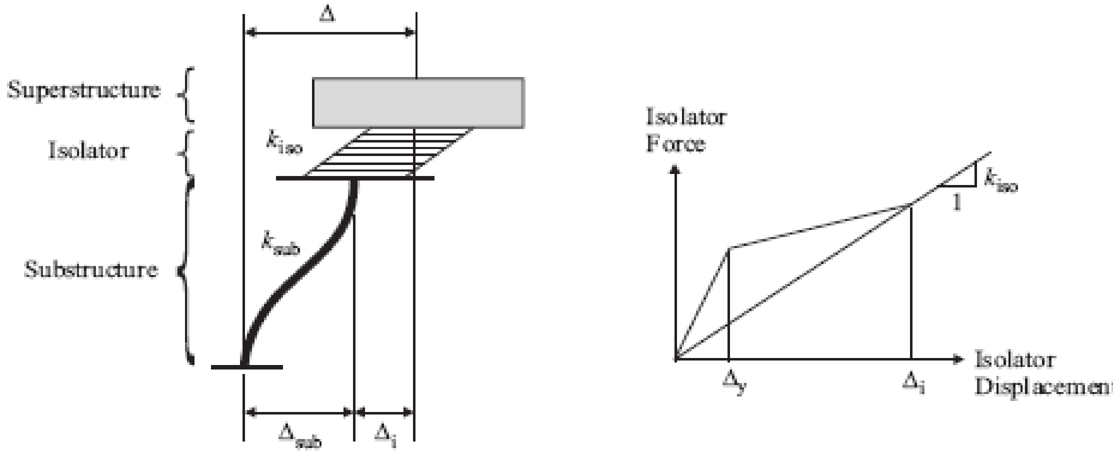


Figure 9.9 Effective Lateral Stiffness of Combined Isolation System and Substructure

3. Equivalent Static Force Method

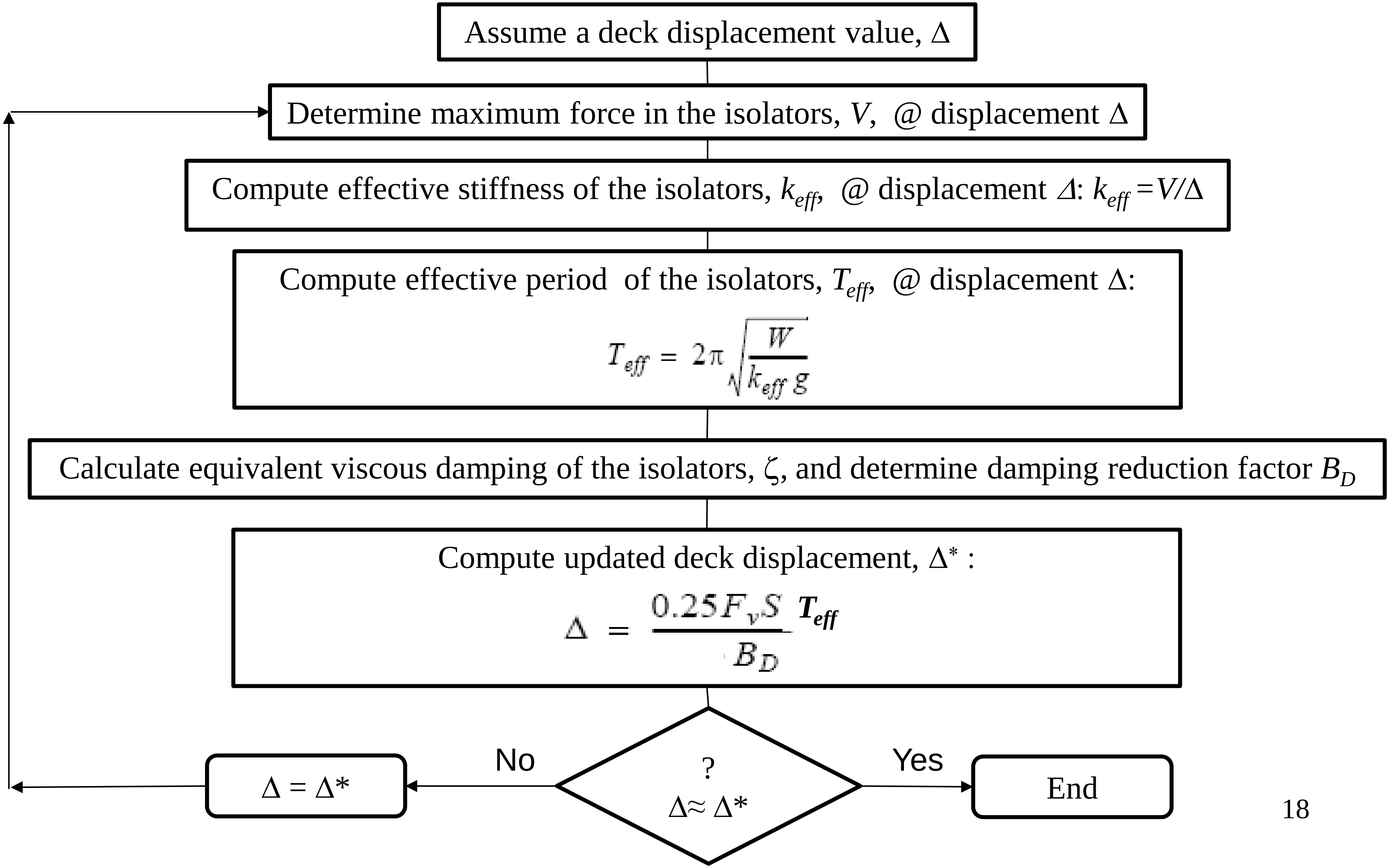
Depending on the complexity of the bridge, the design lateral force given by Equation (9.72) is distributed in each orthogonal direction as either a uniform load (single mode) or according to a spectral analysis (multi-mode) using a response spectrum scaled by the damping coefficient B_D. Alternatively, a nonlinear time-history dynamic analysis can be performed according to the same recommendations given in Section 9.3.3.

The design force V_A for the connections between the superstructure and substructure at each bearing is given by:

$$V_A = k_{iso}\,\Delta_t \tag{9.77}$$

where Δ_t is the total design displacement of the isolation system including torsional effects (see Section 9.3.2).

- Iterative Design Flow Chart



4. Design Properties of Seismic Isolation System

- AASHTO guide specifications require bounding analyses:
  - Determine variations in design forces resulting from minimum and maximum effective stiffness values and damping of isolation system.
- Guidelines define property modification factors:
  - Established from characterization tests on prototype isolation bearings.
  - Consider variations of effective stiffness and damping of isolation system.
  - Effects considered:
    - Temperature;
    - Aging (including corrosion);
    - Velocity;
    - Wear;
    - Contamination (sliding systems only); and
    - Scragging (elastomeric systems).
  - Proposed values developed by Constantinou et al. (1999).

4. Design Properties of Seismic Isolation System

- Concept of Property Modification Factors

Once a nominal value of a property P_n of a seismic isolation system has been established for references conditions (e.g. ambient temperature, fresh bearing conditions, reference normal loading, etc.), the maximum and minimum values of this property, P_{max} and P_{min}, can be established by multiplying the nominal value by a series of property modification factors, λ_{max} and λ_{min}, as follows:

$$\begin{aligned} P_{max} &= \lambda_{max} P_n \\ P_{min} &= \lambda_{min} P_n \end{aligned} \tag{9.78}$$

where:

$$\lambda_{max} = \prod_i \lambda_{max\,i} \geq 1.0 \quad \text{and} \quad \lambda_{min} = \prod_i \lambda_{min\,i} \leq 1.0 \tag{9.79}$$

4. Design Properties of Seismic Isolation System

- Concept of Property Modification Factor

Constantinou et al. (1999) recognized that the values of P_{max} and P_{min} given by Equation (9.78) could be conservative because of the low probability that all extreme values of property modification factors occur simultaneously in a real earthquake situation. For this purpose, they recommended the use of adjusted property modification factors, $\lambda_{max\ \mathrm{adjusted}}$ and $\lambda_{min\ \mathrm{adjusted}}$, given by:

$$\begin{aligned} \lambda_{max\ \mathrm{adjusted}} &= 1 + (\lambda_{max} - 1)a \\ \lambda_{min\ \mathrm{adjusted}} &= 1 + (1 - \lambda_{min})a \end{aligned} \tag{9.80}$$

where a is an adjustment factor that depends on the importance of the bridge under consideration. Constantinou et al. (1999) recommended values of $a = 1$ for critical bridges, $a = 0.75$ for essential bridges and 0.66 for all other bridges.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Coefficient of Friction of Sliding Bearings

The maximum and minimum values of the coefficient of friction of sliding bearings, μ_{max} and μ_{min}, can be established from the nominal value of the coefficient of friction, μ_n, as follows:

$$\mu_{max} = \lambda_{max\,\mathrm{a}}\,\lambda_{max\,\mathrm{c}}\,\lambda_{max\,\mathrm{w}}\,\lambda_{max\,\mathrm{t}}\,\mu_n$$
$$\mu_{min} = \mu_n \qquad (9.81)$$

where $\lambda_{max\,\mathrm{a}}$, $\lambda_{max\,\mathrm{c}}$, $\lambda_{max\,\mathrm{w}}$ and $\lambda_{max\,\mathrm{t}}$ are the property modification factors for aging, contamination, wear, and temperature, respectively.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Coefficient of Friction of Sliding Bearings

$$\mu_{max} = \lambda_{max\,a}\,\lambda_{max\,c}\,\lambda_{max\,w}\,\lambda_{max\,t}\,\mu_n$$

$$\mu_{min} = \mu_n$$

Table A.1.2.1-1—Maximum Value of Property Modification Factor for Aging, $\lambda_{max,a}$

	Unlubricated PTFE		Lubricated PTFE		Bimetallic Surfaces	
Condition/Environment	Sealed	Unsealed	Sealed	Unsealed	Sealed	Unsealed
Normal	1.1	1.2	1.3	1.4	2.0	2.2
Severe	1.2	1.5	1.4	1.8	2.2	2.5

Note:

- Values are for 30-yr exposure of stainless steel. For chrome-plated carbon steel, multiply values by 3.0.
- Unsealed conditions assumed to allow exposure to water and salt, thus promoting further corrosion.
- Severe environments include marine and industrial environments.
- Values for bimetallic interfaces apply for stainless steel and bronze interfaces.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Coefficient of Friction of Sliding Bearings

$$\mu_{max} = \lambda_{max\ a}\lambda_{max\ c}\lambda_{max\ w}\lambda_{max\ t}\ \mu_n$$

$$\mu_{min} = \mu_n$$

Table A.1.2.3-1—Maximum Value of Property Modification Factor for Contamination, $\lambda_{max,c}$

	Unlubricated PTFE	Lubricated PTFE	Bimetallic Surfaces
Sealed with stainless steel surface facing down	1.0	1.0	1.0
Sealed with stainless steel surface facing up [a]	1.1	1.1	1.1
Unsealed with stainless steel surface facing down	1.1	3.0	1.1
Unealed with stainless steel surface facing up	Not allowed	Not allowed	Not allowed

a Use factor of 1.0 if bearing is galvanized or painted for 30-yr lifetime.

Values shown in Table A.1.2.3-1 assume that the sliding interface will not be separated.

Sealed bearings shall have a protective barrier to prevent contamination of the sliding interface. The protective barrier shall remain effective at all service load displacements.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Coefficient of Friction of Sliding Bearings

$$\mu_{max} = \lambda_{max\,a}\,\lambda_{max\,c}\,\lambda_{max\,w}\,\lambda_{max\,t}\,\mu_n$$

$$\mu_{min} = \mu_n$$

Table A.1.2.4-1—Maximum Value of Property Modification Factor for Travel (Wear), $\lambda_{max,tr}$

Cumulative Travel (ft)	Unlubricated PTFE [a]	Lubricated PTFE	Bimetallic Interfaces
<3300	1.0	1.0	To be established by test
<6600	1.2	1.0	To be established by test
>6600	To be established by test	To be established by test	To be established by test

a Test data based on 1/8-in. sheet, recessed by 1/16 in. and bonded.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Coefficient of Friction of Sliding Bearings

$$\mu_{max} = \lambda_{max\ a}\ \lambda_{max\ c}\ \lambda_{max\ w}\ \lambda_{max\ t}\ \mu_n$$

$$\mu_{min} = \mu_n$$

Table A.1.2.5-1—Maximum Value of Property Modification Factor for Temperature, $\lambda_{max,t}$

Minimum Temp for Design (°F)	Unlubricated PTFE	Lubricated PTFE	Bimetallic Interfaces
70	1.0	1.0	To be established by test
32	1.1	1.3	
14	1.2	1.5	
–22	1.5	3.0	

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Elastomeric Bearings

The maximum and minimum values of the properties of elastomeric bearings can be established from the nominal values of the properties as follows:

$$P_{max} = \lambda_{max\,a}\,\lambda_{max\,s}\,\lambda_{max\,t}\,P_n \qquad P_{min} = P_n \tag{9.82}$$

where $\lambda_{max\,a}$ $\lambda_{max\,s}$ and $\lambda_{max\,t}$ are the property modification factors for aging, scragging, and temperature, respectively.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Elastomeric Bearings

$$P_{max} = \lambda_{max\ a} \lambda_{max\ s} \lambda_{max\ t} P_n$$
$$P_{min} = P_n$$

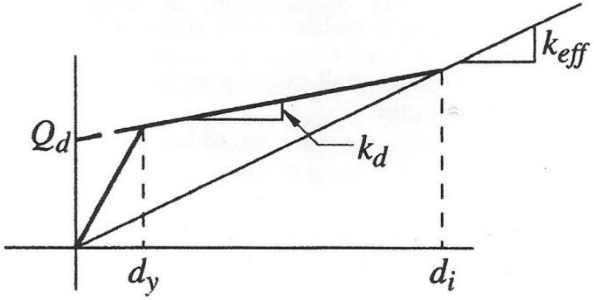


Table A.2.2.1-1—Maximum Value of Property Modification Factor for Aging, $\lambda_{max,a}$

	K_d	Q_d
Low-damping natural rubber	1.1	1.1
High-damping rubber with small difference between scragged and unscragged properties	1.2	1.2
High-damping rubber with large difference between scragged and unscragged properties	1.3	1.3
Lead	—	1.0
Neoprene	3.0	3.0

Note:

A large difference is one in which the unscragged properties are at least 25 percent more than the scragged ones.

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Elastomeric Bearings

$$P_{max} = \lambda_{max\ a}\,\lambda_{max\ s}\,\lambda_{max\ t}\,P_n$$
$$P_{min} = P_n$$

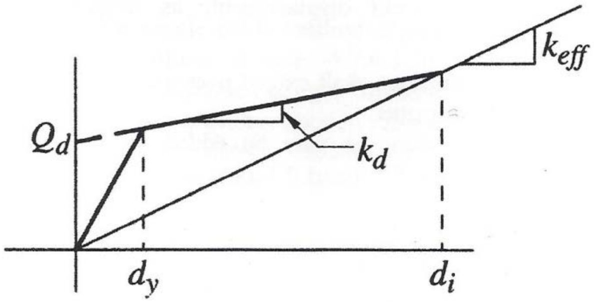


Table A.2.2.6-1—Maximum Value of Property Modification Factor for Scragging, $\lambda_{max,\ scrag}$

Q_d			K_d		
LDRB	HDRB with $\xi < 0.15$	HDRB with $\xi > 0.15$	LDRB	HDRB with $\xi < 0.15$	HDRB with $\xi > 0.15$
1.0	1.2	1.5	1.0	1.2	1.8

LDRB: Low Damping Rubber Bearings
HDRB: High Damping Rubber Bearings

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Elastomeric Bearings

$$P_{max} = \lambda_{max\,a}\,\lambda_{max\,s}\,\lambda_{max\,t}\,P_n$$
$$P_{min} = P_n$$

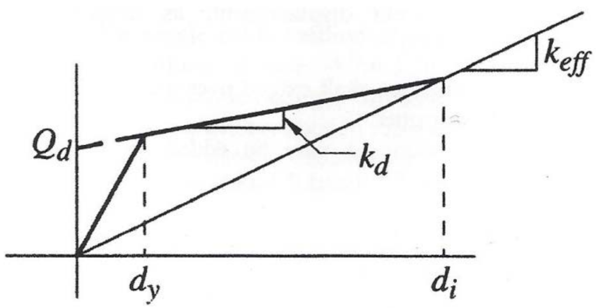


Table A.2.2.5-1—Maximum Value of Property Modification Factor for Temperature, $\lambda_{max,t}$

Minimum Temp for Design (°F)	Q_d			K_d		
	HDRB [a, c]	HDRB [b, c]	LDRB [b, d]	HDRB [a, c]	HDRB [b, c]	LDRB [b, d]
70	1.0	1.0	1.0	1.0	1.0	1.0
32	1.3	1.3	1.3	1.2	1.1	1.1
14	1.4	1.4	1.4	1.4	1.2	1.1
–22	2.5	2.0	1.5	2.0	1.4	1.3

Notes:

a Large difference between scragged and unscragged properties. A large difference is one in which the unscragged properties are at least 25 percent more than the scragged ones.

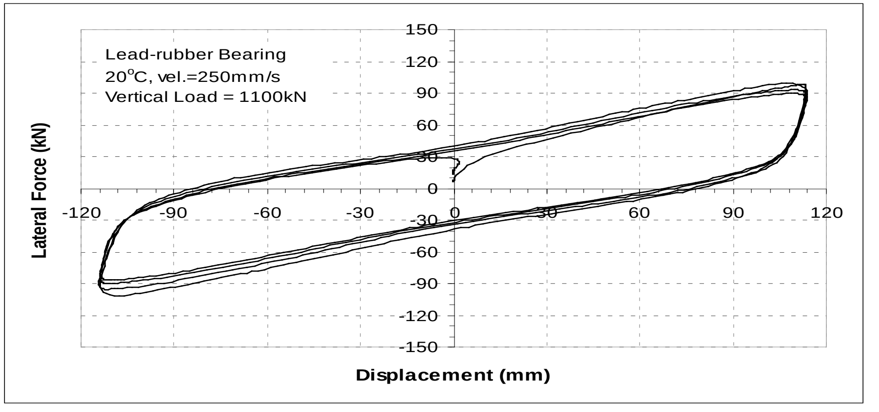
b Small difference between scragged and unscragged properties.

c HDRB = High-Damping Rubber Bearing

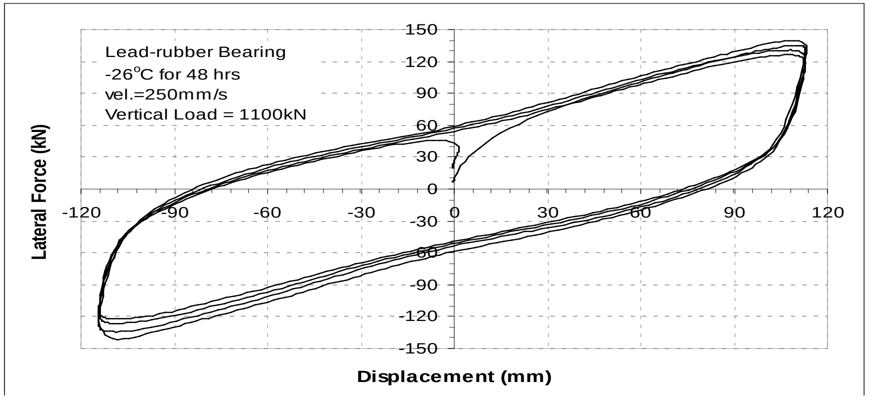
d LDRB = Low-Damping Rubber Bearing

4. Design Properties of Seismic Isolation System

- Property Modification Factors for Elastomeric Bearings



TEMP=20^{O}C



TEMP=-25^{O}C

Courtesy of M. Constantinou

LEAD-RUBBER BEARING, UNIVERSITY AT BUFFALO
LOAD=1100kN, DISPLACEMENT=100mm, VELOCITY=250mm/sec

5. Minimum Clearances

- The clearance between the bridge deck and any surrounding structure in each principal direction must be at least equal to the total maximum. displacement of the deck obtained from analysis.
- However, the clearance cannot be less than 80% of the total maximum displacement obtained from the equivalent static force procedure.

$$\Delta_{cmin} = \frac{0.20 F_v S_1 T_{eff}}{B_D}$$

6. Required Testing Program for Isolation Bearings

- AASHTO guide specifications require that all isolation systems have design properties and seismic performance verified by testing.
- Three different types of tests:
  - i) System characterization tests;
  - ii) Prototype tests; and
  - iii) Quality control tests.
- If seismic isolation system has undergone similar testing program, not need to be re-tested, design properties based on pre-approved certified test data from manufacturer of isolation system.

6. Required Testing Program for Isolation Bearings

I. System characterization tests

- Cyclic tests on individual isolators according to nationally recognized standards (e.g. HITEC, 2002; NIST, 1996).
- Shake table tests on isolated bridge models with a scale factor of at least 1:4.
- Low temperature tests
  - For cold regions applications.
  - Stability tests at temperatures of -7^{o}C to -26^{o}C depending on the temperature application zone given by the AASHTO Bridge Design Standard.
  - One static loading cycle at the displacement caused by the gravity load given below plus 1.1 times the maximum total MCE displacement (return period of 1000 years).
  - Gravity load equals to 1.2 times the dead load plus 1.0 time the live load and all the non-seismic load causing a rotation of the isolators.
- Wear and fatigue tests
  - Thermal and rotational displacements corresponding to 30 years of service.
  - Minimum cumulative displacements:
    - Isolators with dampers connected at the neutral axis of the beams: 1.6 km (1 mile)
    - Isolators with dampers connected to the inferior portion of the bridge deck: 3.2 km (2 miles)
  - For cold regions applications, the tests must be conducted at temperatures of -7^{o}C to -26^{o}C depending on the temperature application zone given by the AASHTO Bridge Design Standard.

6. Required Testing Program for Isolation Bearings

II. Prototype tests

- On at least two full-scale isolators.
- Tests on reduced scale isolators can be performed only if the capacities of the existing testing machines are not sufficient. Requires a special permission from the engineer of record.
- Isolators successfully tested can be used in construction.
- Thermal tests
  - Three reversed cycles at the anticipated thermal displacement.
  - Loading rate must be at least 0.076 mm/min.
- Wind and breaking tests
  - 20 reversed cycles at he anticipated wind and breaking displacements.
  - Total duration of each test must be at least 40 seconds.
  - Following the cyclic tests, the total load must be maintained for 1 minute.
- Seismic tests
  - Three reverse cycles for the following sequence of multiples of the maximum total design displacement (pier + isolator): 1.0, 0.25, 0.50, 0.75, 1.0 and 1.25.
- Post-seismic wind and breaking tests
  - Similar to the pre-seismic wind and breaking tests described above.
- Seismic performance tests
  - Three reverse cycles at the maximum total design displacement (pier + isolator).
  - For bi-directional isolators, the tests must be conducted in the orthogonal direction of the seismic tests described above.
- Stability tests
  - One static loading cycle at the displacement caused by the gravity load as defined below plus 1.1 time the maximum total MCE displacement (return period of 1000 years).
  - Gravity load equals to 1.2 times the dead load plus 1.0 time the live load and all the non-seismic load causing a rotation of the isolators.

6. Required Testing Program for Isolation Bearings

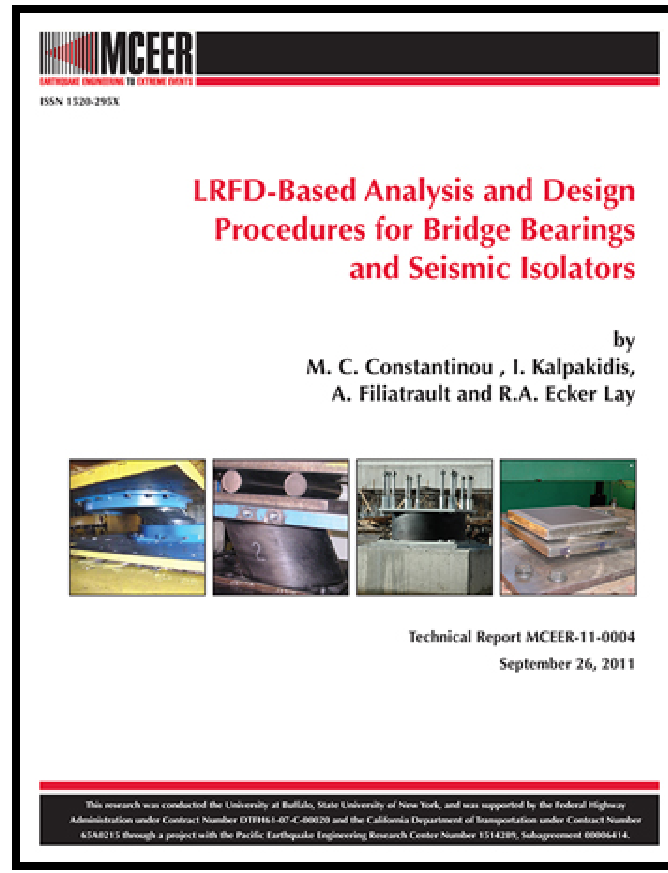
III. Quality control tests

- Compression tests
  - Five minutes at a compression load equals to 1.5 times the maximum anticipated gravity load (dead plus live load).
- Compression and shear tests
  - Two isolators can be tested simultaneously.
  - Three reversed cycles at the total maximum displacement (pier + isolator) or at 50% of the total rubber thickness (for rubber bearings).
  - Average compressions dead load.
  - Average effective stiffness (K_{eff}) and energy dissipated per cycle (EDC) must not deviate more than the values tabulated below.

	K_{eff}	*EDC*
Each bearing	± 20%	-25%
Average of the group	± 10%	-15%

7. Adequacy Assessment of Bearings

- See Chapter 9



http://mceer.buffalo.edu/publications/catalog/reports/LRFD-Based-Analysis-and-Design-Procedures-for-Bridge-Bearings-and-Seismic-Isolators-MCEER-11-0004.html

Questions/Discussions