SEISMIC PROTECTION OF STRUCTURES WITH MODERN TECHNOLOGIES

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Seismic Isolation

A flexible interface between the superstructure and the foundation that consists of well engineered devices (Isolation Bearings) which decouple the motion at the expense of large displacements; therefore, reducing the inertia forces that develop in the superstructure.
Seismic Design and Retrofit with Isolation Bearings

Seismic Retrofit of Richmond San Rafael Bridge, CA

Seismic Retrofit of American River Bridge, CA

Seismic Design and Retrofit with Fluid Dampers
Prototype and production testing of bearings and dampers

Modern seismic protection technologies consist of well engineered devices that have been tested extensively and when properly installed may lead to sustainable engineering.

Sustainable Engineering: The design and construction of structures that meet acceptable performance levels at present and in the years to come without compromising the ability of future generations to use them, maintain them and benefit from them.
Outline

The Concept of Seismic Isolation
Accommodating Forces and Displacements
Examples from the Implementation of Seismic Protection Systems in Bridges
Isolation Bearings
  • Elastomeric Bearings (NRB, HDRB, LRB)
  • Sliding Bearings (FPS)
Definition of the Isolation Period
The Linear Viscoelastic Behavior
The Bilinear Behavior
Fluid Dampers
Nonlinear Viscous Behavior
The Concept of Seismic Isolation

• Use some type of support that uncouples the motion of the super-structure from the ground

• Basic Properties of an Isolation System

  • Horizontal Flexibility: to increase structural period and reduce spectral demands

  • Energy Dissipation: to reduce displacements

  • Sufficient Stiffness/Rigidity at Small Displacements
Types of Isolation Bearings

Laminated Elastomeric Bearings
Natural Rubber Bearings (NRB)
High Damping Bearing (HDRB)

Lead Rubber Bearings (LRB)
(lead diameter 60 to 150 mm)

Sliding Bearing

$u_y \approx 2cm$

$u_y \approx 0.2mm$
Egnatia Highway
Northern Greece
View of 91/5 overcrossing located in Orange County in Southern California. The deck is supported at mid-span by an outrigger prestressed beam, while at each abutment it rests on four elastomeric pads and is attached with four fluid dampers.
91/5 overcrossing
Orange County in Southern California

View of 91/5 overcrossing located in Orange County, Southern California.
91/5 overcrossing
Orange County in Southern California
91/5 overcrossing
Orange County in Southern California

Photo showing four dampers installed at the south end of the 91/I5 overpass.
Seismic Isolation: Examples of Retrofitted Bridges

I-40 Mississippi River Bridge
Memphis, Tennessee

It was retrofitted with Friction Pendulum™ isolation bearings designed to withstand a magnitude 7 earthquake occurring on the New Madrid fault.

Use of Friction Pendulum™ bearings allows the 40 year old bridge to remain operational after an extreme earthquake event.
Seismic Isolation: Examples of Retrofitted Buildings

U.S. Court of Appeals
San Francisco, California

Friction Pendulum™ seismic isolation saves $7.6 million and wins National Award
Seismic Isolation: Examples of New Projects

San Francisco Airport International Terminal

*World’s Largest Isolated Building*

The Friction Pendulum™ bearings provide a 3 sec. isolated period.

Each bearing can displace up to 20 inches in any horizontal direction while supporting buildings and seismic loads of up to 6 million pounds.
Seismic Isolation: Examples of New Projects

Tokyo Rinkai Hospital
Tokyo, Japan
Reduce forces at the expense of accommodating large displacements

Various types of isolation bearings

How is the isolation period $T_I$, $T_0$ defined?
The Confusion!

Offered by established Design Codes (see ASSHTO 1998, FEMA-274 1997)

**Nearly Viscoelastic**

![Diagram of Nearly Viscoelastic Behavior]

\[ K_{\text{eff}} = \frac{|F^+| + |F^-|}{|A^+| + |A^-|} \]

\[ T_I = T_{\text{eff}} = 2\pi \sqrt{\frac{m}{K_{\text{eff}}}} \]

Theoretically correct!

Why?

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**Bilinear Behavior**

![Diagram of Bilinear Behavior]

\[ K_{\text{eff}} \]

What most seismic codes use

\[ T_I = T_{\text{eff}} = 2\pi \sqrt{\frac{m}{K_{\text{eff}}}} \]

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**Rigid Elastic Behavior**

![Diagram of Rigid Elastic Behavior]

\[ K_2 = \frac{mg}{R} = \frac{W}{R} \]

There exists a very small \( u_y = 0.025 \text{cm} \)

\[ T_I = 2\pi \sqrt{\frac{R}{g}} \]

(R = radius of curvature of spherical surface)

The concept of \( T_{\text{eff}} \) is abandoned

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**Theoretically Unsubstantiated!**

Why?

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**Theoretically Correct!**

Why?
The Linear Viscoelastic Behavior

Cyclic loading with frequency $\Omega$

Imposed Displacement

$$u(t) = u_0 \sin(\Omega t)$$
$$\dot{u}(t) = \Omega u_0 \cos(\Omega t)$$

Recorded Force

(force needed to support the motion)

$$F(t) = F_0 \sin(\Omega t + \varphi)$$

Expansion of the argument

$$F(t) = F_0 \sin(\Omega t) \cos \varphi + F_0 \cos(\Omega t) \sin \varphi$$

$$F(t) = F_0 \frac{u_0}{u_0} \sin(\Omega t) \cos \varphi + F_0 \frac{1}{u_0 \Omega} \cos(\Omega t) \sin \varphi$$

$$F(t) = \frac{F_0}{u_0} \cos(\varphi) u(t) + \frac{F_0}{u_0 \Omega} \cdot \sin(\varphi) \dot{u}(t)$$

(1)
The Linear Viscoelastic Behavior cont’

\[ F(t) = \frac{F_0}{u_o} \cos(\varphi) \, u(t) + \frac{F_0}{u_o} \frac{1}{\Omega} \cdot \sin(\varphi) \, \dot{u}(t) \]

\[ K_1(\Omega) = \frac{F_0}{u_o} \cos \varphi = \text{storage stiffness} \]

\[ C(\Omega) = \frac{F_0}{u_o} \frac{1}{\Omega} \sin \varphi = \text{damping coefficient} \]

\[ K_2(\Omega) = \Omega C(\Omega) = \frac{F_0}{u_o} \sin \varphi = \text{loss stiffness} \]

Note that:

\[ K_1^2(\Omega) + K_2^2(\Omega) = \left( \frac{F_o}{u_o} \right)^2 \left[ \cos^2 \varphi + \sin^2 \varphi \right] = \left( \frac{F_o}{u_o} \right)^2 \]

So:

\[ K_o(\Omega) = \sqrt{K_1^2(\Omega) + K_2^2(\Omega)} = \frac{F_o}{u_o} : \text{total stiffness} \]

Returning to equation (1):

\[ F(t) = K_1(\Omega) \, u(t) + C(\Omega) \, \dot{u}(t) \]

\[ \begin{align*}
1. \text{A single frequency } \Omega \\
2. \text{Steady State Motion.}
\end{align*} \]
The Linear Viscoelastic Behavior cont'

Work done per cycle:

\[ W_D = \int_o^T F(t) \frac{du}{dt} dt \]

\[ F(t) = K_1(\Omega)u(t) + C(\Omega)u(t) \]

\[ \Rightarrow W_D = \int_o^T F(t) \dot{u}(t) dt \ldots \ldots \]

\[ \ldots \ldots \Rightarrow W_D = \pi C(\Omega)\Omega u_o^2 \]

\[ C(\Omega) = \frac{W_D}{\pi \Omega u_o^2} \]
Evaluation of Mechanical Properties from Experiments

\[ K_{\text{eff}} = K_1(\Omega) \]

\[ C(\Omega) = \frac{W_D}{\pi \Omega u_o^2} \]

\[ K_2(\Omega) = \Omega C(\Omega) = \frac{W_D}{\pi u_o^2} \]

\[ K_o = \frac{P_o}{u_o} \]

\[ K_1(\Omega) = \sqrt{K_o^2 - K_2^2} = \sqrt{\left(\frac{F_o}{u_o}\right)^2 - \left(\frac{W_D}{\pi u_o^2}\right)^2} \]

now: \( K_I = K_1(\Omega) \)

and: \( T_I = 2\pi \sqrt{\frac{m}{K_1}} \)

We measure three quantities:

\[ \begin{align*}
F_o \\
u_o \\
W_D
\end{align*} \]
Equivalent Damping Coefficient and Viscous Damping Ratio

Equivalent Damping Coefficient \( \beta \) is a measure for the ability of a bearing or any structural components to dissipate energy.

\[
\beta = \frac{1}{2} \frac{K_2(\Omega)}{K_1(\Omega)} = \frac{1}{2} \frac{W_D(\Omega)}{\pi K_1 u_0^2}
\]

Viscous Damping ratio \( \zeta_I \) is modal damping of an isolated mass:

\[
2\zeta_I m\omega_I = C(\Omega) = \sum_i \frac{W_{D_i}}{\pi \Omega u_0^2}
\]

\[
\Rightarrow \zeta_I = \frac{1}{2\pi m\omega_I \Omega u_0^2} \Rightarrow \zeta_I = \frac{1}{2\pi} \frac{\omega_I}{\Omega} \frac{1}{2} \frac{\sum W_{D_i}(\Omega)}{\sum K_i u_0^2}
\]

\[
\zeta_I = \frac{1}{2\pi} \frac{\omega_I}{\Omega} \frac{\sum W_{D_i}(\Omega)}{\sum K_i u_0^2} = \frac{\omega_I}{\Omega} \beta
\]
What the Code Offers as Effective Damping Ratio

\[ \zeta_{\text{eff}} = \xi = \frac{1}{2\pi} \sum_{i} \frac{W_{Di}(\Omega)}{K_{eff}u_{o}^{2}} \quad \left( \text{indeed} \quad \frac{\omega_{1}}{\Omega} = 1 \right) \]

In this case the areas \( W_{Di} \) need to be taken from experiments performed at \( \Omega = \omega_{1} \) (say \( \omega_{1} = 2 \text{ sec} \))
Examples

Elastic Springs

\[ F(t) = ku(t) \]

\[ C(\Omega) = 0 \]

\[ K_2(\Omega) = 0 \]

\[ K_1(\Omega) = \sqrt{\frac{F_o}{u_o^2}} - 0 = \frac{F_o}{u_o} = K_0 \]

Viscous Dashpot

\[ F(t) = k\dot{u}(t) \]

\[ W_D = \pi u_o F_o \]

\[ C(\Omega) = \frac{W_D}{\pi \Omega u_o^2} \Rightarrow C(\Omega) = \frac{F_o}{\Omega u_o} \]

\[ K_2(\Omega) = \frac{F_o}{u_o} \]

\[ K_1(\Omega) = \sqrt{\left(\frac{F_o}{u_o}\right)^2 - \left(\frac{F_o}{u_o}\right)^2} = K_1(\Omega) = 0! \]

\[ K_o = \frac{F_o}{u_o} \rightarrow \text{no physical meaning} \]
Restoring and Dissipation Mechanisms of Isolation Bearings

<table>
<thead>
<tr>
<th>Restoring Mechanism</th>
<th>Dissipation Mechanism</th>
<th>Idealized Mechanical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image of restoring mechanism" /></td>
<td><img src="image2" alt="Image of dissipation mechanism" /></td>
<td><img src="image3" alt="Image of idealized mechanical model" /></td>
</tr>
</tbody>
</table>
Question: Is \( T_{eff} \) indeed the time needed for a bilinear oscillator to complete one cycle?
Small to Moderate ductility values

Iwan and Gates (1979)\[ T_{eff} = [1 + 0.121 (\mu - 1)^{0.939}] T_1, \quad \mu \leq 8 \]

Guyader and Iwan (2006)\[ T_{eff} = [1 + 0.1145 (\mu - 1)^2 - 0.0178 (\mu - 1)^3] T_1, \quad \text{for} \quad \mu < 4.0 \]
\[ T_{eff} = [1 + 0.1777 + 0.1240(\mu - 1)] T_1, \quad \text{for} \quad 4.0 \leq \mu \leq 6.5 \]

Large ductility values

Hwang and Sheng (1993, 1994)\[ T_{eff} = \{1 + \ln[1 + 0.13(\mu - 1)^{1.137}]\} T_1 \]

Hwang and Chiou (1996)\[ T_{eff} = \frac{\mu}{\sqrt{1 + \alpha(\mu - 1)}} \left(1 - 0.737 \frac{\mu - 1}{\mu^2}\right) T_1 \]
\[ \alpha = \frac{K_2}{K_1} = 0.15 = 1/6.5 \]

Upper bound: \( T_2/T_1 = 1/\sqrt{\alpha} = 2.58 \)

\[ \alpha = \frac{K_2}{K_1} = 0.0039 = 1/256 \]

Upper bound: \( T_2/T_1 = 1/\sqrt{\alpha} = 16 \)

\[ K_2 = \alpha K_1 \]

\[ K_{\text{eff}} = K_2 \frac{1 + \alpha(\mu - 1)}{\alpha \mu} \]

\[ T_{\text{eff}} = T_2 \sqrt{\frac{\alpha \mu}{1 + \alpha(\mu - 1)}} \]
Geometric relation for large $\mu$ gives

\[
T_{\text{eff}} = \frac{1}{\sqrt{1 + \frac{Q}{K_2 u_{\text{max}}}}} T_2
\]

or

\[
\frac{T_{\text{eff}}}{T_2} = 1 - \frac{1}{2} \frac{Q}{K_2 u_{\text{max}}} + \frac{3}{8} \left( \frac{Q}{K_2 u_{\text{max}}} \right)^2 + \cdots
\]
Free-Vibration Period of a Bilinear System

\[ T_I = f\left(\frac{Q}{m}, u_y, \frac{K_2}{m}\right) \]

\[ \frac{T_I}{2\pi \sqrt{\frac{m}{K_2}}} = \varphi\left(\frac{Q}{K_2u_y}\right) \Rightarrow T_I = \varphi\left(\frac{Q}{K_2u_y}\right)T_2 \]
Free-Vibration Period of a Bilinear System

$T = 2.5s, Q/m = 3\%g, u_0 = 30cm$

$T = 2.5s, Q/m = 3\%g, u_0 = 40cm$

$T = 2.5s, Q/m = 4\%g, u_0 = 30cm$

$T = 2.5s, Q/m = 4\%g, u_0 = 40cm$
Free-Vibration Period of a Bilinear System

\[ \Pi_Q = \frac{Q}{(K_2 u_y)} = \left( \frac{K_1}{K_2} \right) - 1 = \frac{1}{\alpha} - 1 \]
Free-Vibration Period of a Bilinear System

\[ T = 2.5s, \frac{Q}{m} = 3\%g, u_0 = 30\text{cm} \]

\[ T = 2.5s, \frac{Q}{m} = 3\%g, u_0 = 40\text{cm} \]

\[ T = 2.5s, \frac{Q}{m} = 4\%g, u_0 = 30\text{cm} \]

\[ T = 2.5s, \frac{Q}{m} = 4\%g, u_0 = 40\text{cm} \]
Free-Vibration Period of a Bilinear System

Conclusions

When the response history of the bilinear system exhibits a coherent oscillatory trace with a narrow frequency band as in the case of free vibration of forced vibrations from most pulselike excitations, the talk shows that the “effective period” $T_{\text{eff}}$ of the bilinear isolation system is a dependable estimate of its vibration period.

At the same time the talk concludes that the period associated with the second slope of the bilinear system $T_2$ is an even better approximation of the vibration period regardless of the value of the dimensionless strength $\frac{Q}{(K_2u)}=\frac{1}{a}$ of the system. Consequently, this talk concludes that whenever the concept of associating a vibration period is meaningful the “effective” period, $T_{\text{eff}}$ can be replaced with $T_2$ which is a period that is known a priori (no iterations are needed) and offers in general superior results.
Conclusions

This finding serves both simplicity and a more rational estimation of maximum displacement. Simplicity is served because instead of looking for Teff - a quantity that derives from the non-existing Keff, for which iterations are needed to be approximated, the paper shows that the period associated with the second slope of the bilinear system = $T_2$ (that is known a priori - no iterations are needed) is a better single-value descriptor of the frequency content of the dynamic response of a bi-linear isolation system. Given that $T_2$ is always longer than Teff the peak inelastic displacement does no run the risk to be underestimated.