SIMPLIFIED DESIGN METHOD FOR FRAMES WITH NONLINEAR VISCOUS DAMPERS

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Transformation of Vibration-control System

Hysteresis Curves of Frames (Left) and Dampers (Right) Considered

Various performance curves and design methods have been developed since the publication by Kasai, K., Fu, Y., and Watanabe A.: Passive Control Systems for Seismic Damage Mitigation, J. Str. Eng., ASCE, 1998.5
Introduction

- Our method determines the **damper properties** required to satisfy the **drift limit** under the design earthquake (spectrum).
- It uses SDOF **performance curves** of only a few parameters characterizing the **damper**, its connected members (brace), and the **frame**.
- When the **frame** is inelastic (bilinear, slip, degrading, etc.), more parameters and more curves become necessary.
- The **proposed alternative approach** repeats SDOF time-history analysis, by simply increasing damper capacity until the drift goes under the limit.
- Under typical **Japanese drift angle limit 0.01** or less, the frame is almost elastic. The limits 0.01 and 0.02 will be considered to check the **accuracy** of the design method, extent of **frame yielding**, and to compare **damper capacities required**.
- Ramirez et al.’s three-story frame with **brace-type nonlinear viscous dampers** will be considered (often included as an example in the US guidelines).
Simplified Design Method for Frames with Nonlinear Viscous Dampers

Types of vibration-controlled frame

\[ F_d(t) = C_d \, \text{sgn}(\dot{u}_d(t)) \left| \ddot{u}_d(t) \right|^\alpha, \quad W_d = 4e^{-0.24\alpha} F_{d,\text{max}} u_{d,\text{max}} \]
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Simplified model of the system (e.g., \( \alpha = 0.4 \))

**Approximation of \( K_a' \) and \( K_a'' \) by interpolation between \( \alpha = 0 \) and 1**

\[
K_d' = 0, \quad K_d'' = C_d \omega^\alpha u_d^{\alpha-1}
\]

\[
K_a' = \frac{\lambda^{1+\alpha}}{1 + \lambda^{1+\alpha}} K_b^*
\]

\[
K_a'' = \min(\lambda, \lambda^\alpha) \frac{K_b^*}{1 + \lambda^{1+\alpha}}
\]

where

\[
\lambda = \frac{K_d''}{K_b^*}
\]

= brace-to-damper deformation ratio
Design Procedures Using Nonlinear Viscous Dampers

\[ H_{eff} = \frac{\sum_{i=1}^{N} (m_i \cdot H_i^2)}{\sum_{i=1}^{N} (m_i \cdot H_i)} \]

Step 1 - Static push-over analysis of frame only. Bilinear approximation. Get an equiv. bilinear SDOF system when the frame drift angles equal the uniform target value.

Step 2 - Repeat time-history analysis of the SDOF system, by simply increasing damper capacity until the drift goes below the limit.

Step 3 – Conversion from SDOF to MDOF (next page)
Simplified Design Method for Frames with Nonlinear Viscous Dampers

Standard Type
Soft Upper-story Type
Soft Lower-story Type

From SDOF Analysis

Damper Forces Required for Various Frame Shear Distributions
Example:
3-story frame with brace-type nonlinear viscous dampers

Push-over curves for frame without dampers
(symbols = timing of each member yielding)
Hysteresis of SDOF models designed for two different target drift angles

Properties of the frame and added components for two different target drift angles

<table>
<thead>
<tr>
<th>Story</th>
<th>Frame</th>
<th>Design for $\theta_i = 0.01$ rad.</th>
<th>Design for $\theta_i = 0.02$ rad.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_f$</td>
<td>$p_f$</td>
<td>$\theta_{yi}$</td>
</tr>
<tr>
<td>3</td>
<td>69.5</td>
<td>0.419</td>
<td>0.0087</td>
</tr>
<tr>
<td>2</td>
<td>127.9</td>
<td>0.499</td>
<td>0.0100</td>
</tr>
<tr>
<td>1</td>
<td>240.4</td>
<td>0.209</td>
<td>0.0094</td>
</tr>
</tbody>
</table>
Hysteresis curves of frame, added component, and system
(design for $\theta_t = 0.02$ rad)
Simplified Design Method for Frames with Nonlinear Viscous Dampers

- **Acceleration**: 
  - \( \ddot{u}_{i,\text{tot}} \) (cm/s²)

- **Story Drift Angle**: 
  - \( \theta_i \), \( \theta_t = 0.01 \text{ rad.} \), \( \theta_t = 0.02 \text{ rad.} \)

- **Story Shear Force**: 
  - \( V_i \) (kN)

**Graphs**:
- Story number
- No Damper.

**Legend**:
- Story number
- \( \theta_i \) (rad.)

**Table**:
- No Damper.

**Note**:
- Kasai Laboratory, Tokyo Institute of Technology
Drift angles at the effective height of Vib. Control Systems (SDOF vs. Multi-Story Frame)
Avg. of twenty earthquakes used by Ramirez. ≈ NEHRP spectrum (1997).
≈ BCJ-L2 spectrum.
Designed the 3-story using the smoothed BCJ-L2 spectrum;
Did its time-history analyses using the twenty earthquakes.
Summary and Conclusion

Design approach for multi-story inelastic frame w. nonlinear viscous dampers:
(1) Reduce the inelastic frame to the SDOF inelastic system,
(2) Get damper capacity to satisfy drift limit via SDOF time history analysis
(3) Convert the SDOF damper capacity to MDOF story-by-story.

Reasonably accurate: justified the dominance by the first mode (in contrast to Ramirez et al. method to consider significant higher mode contributions in characterizing the damper effect).
Control Performance Comparison between Test Results and Evaluations by Performance Curves
## Major Damper Types Used in Japan

<table>
<thead>
<tr>
<th>Viscous</th>
<th>Oil</th>
<th>Viscoelastic</th>
<th>Steel</th>
<th>Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear/Flow Resist. Panel, Box Cylinder</td>
<td>Flow Resist. Cylinder</td>
<td>Shear Resist. Brace, Panel, etc.</td>
<td>Axial/Shear Yielding Brace, Panel, etc.</td>
<td>Slip Resist. Brace, Panel</td>
</tr>
<tr>
<td>$F = C \cdot \dot{u}^2$</td>
<td>$F = C_1 \cdot \dot{u}$ or $C_2 \cdot \dot{u}$</td>
<td>$F = K(\omega) \cdot u + C(\dot{\omega}) \cdot \dot{u}$</td>
<td>$F = K \cdot f(\omega)$</td>
<td>$F = K \cdot f(u)$</td>
</tr>
</tbody>
</table>

**Fig. 4** Five Types of Dampers Considered by JSSI Manual

Manual by JSSI (Japan Society for Seismic Isolation)
Step 1 - Conversion of multi-story frame w/o dampers to SDOF model

Figure 2 (b) Push-over curve (i-th story) and bilinear approximation

\[ K_f = \sum_{i=1}^{N} \frac{K_{fi} h_i^2}{H_{eff}^2} \]
\[ p_f = \left[ -1 + 2\mu \sum_{i=1}^{N} \frac{W_{fi}}{K_f (H_{eff} \theta_i)^2} \right] / (\mu - 1) \]
\[ \mu = 4 \left\{ -K_f (H_{eff} \theta_i)^2 - 2 \sum_{i=1}^{N} W_{fi} \right\} / \sum_{i=1}^{N} \Delta W_{fi} \]  

Using such bilinear story properties of the multi-story frame, the bilinear SDOF model of the frame having equivalent dynamic properties are obtained using the two constraints: (1) their strain energies are equal when the frame is elastic, and; (2) their strain energies (defined by the secant stiffnesses) and dissipated energies, respectively, are equal at the full inelastic cycle of \( \pm \theta_t \).
Step 2 – Finding required damper capacity for SDOF model

\[ K_d = \beta_{\text{eff}} C_d \quad K_b = 0.5 K_d \quad \beta_{\text{eff}} = \left( \frac{H_{\text{eff}}}{H_0} \right)^{\alpha-1} \cos^{\alpha-1} \phi_0 \hat{\beta} \quad (9a-c) \]

A series of time-history analyses are conducted by gradually increasing the value of \( C_d \), with those of \( K_d \) and \( K_b \) satisfying Eq. 9. The analyses are performed several times until the drift angle almost equals the target value \( \theta_t \).
Step 3 – Conversion of damper properties from SDOF model to multi-story system (part 1)

The conversion rule satisfies the following two constraints: (1) the equivalent damping ratios of the SDOF model and the multi-story vibration-controlled system are equal, and; (2) the story drift angle of the multi-story system obtained from the static lateral force and system equivalent stiffness uniformly equals the target drift angle $\theta_t$.

$$ K_{di}'' = \frac{B}{\lambda^\alpha} \left[ \frac{O_i}{\gamma_i} \sum_{i=1}^{N} \gamma_i K_{fi} h_i^2 + \frac{(A_1 - A_2)\lambda^\alpha}{A_3 B} \right] \left( \frac{\sum_{i=1}^{N} Q_i h_i}{\sum_{i=1}^{N} Q_i h_i} - \gamma_i K_{fi} \right) $$

$$ A_1 = \left\{ K_f (1 - \gamma) / \mu + e^{-0.24\alpha} K_d'' \right\} \sum_{i=1}^{N} \gamma_i K_{fi} h_i^2 $$

$$ A_2 = \left\{ \gamma K_f + (\lambda^\alpha / B) K_d'' \right\} \sum_{i=1}^{N} (1 - \gamma_i) K_{fi} h_i^2 / \mu_i $$

$$ A_3 = K_f \left\{ e^{-0.24\alpha} \gamma B^{\alpha-2} - (\lambda^\alpha / B) (1 - \gamma) / \mu \right\} \quad \quad B = 1 + \lambda^{1+\alpha} \quad (10a-e) $$

$$ \gamma = (1 + p_f \mu - p_f) / \mu $$

$$ \gamma_i = (1 + p_{fi} \mu_i - p_{fi}) / \mu_i \quad (11a,b) $$
Step 3 – Conversion of damper properties from SDOF model to multi-story system (part 1)

The properties are transformed to the inclined (axial) direction of each damper.

\[ u_{di,\text{max}} = h_i \theta_i / (1 + \lambda^{1+\alpha})^{1-0.5\alpha} \]

\[ C_{di} = K_{di} u_{di,\text{max}}^{1-\alpha} / \omega_{eq}^\alpha \]

\[ K_{bi}^* = K_{di}^2 / \lambda \quad (12\text{a-c}) \]

\[ \hat{C}_{di} = C_{di} / \cos^{1+\alpha} \phi_i \]

\[ \hat{K}_{di} = \beta \hat{C}_{di} \]

\[ \hat{K}_{bi}^* = K_{bi}^* / \cos^2 \phi_i \]

\[ \hat{K}_{bi} = \hat{K}_{di} \hat{K}_{bi}^* / (\hat{K}_{di} - \hat{K}_{bi}^*) \quad (13\text{a-d}) \]