Guidelines for Seismic Retrofit of Weak-Story Wood-Frame Buildings
Learning Objectives

1. Understand the vulnerabilities and failure modes of weak-story buildings under EQ demands.

2. Recognize the influence of “non-structural” finishes on the capacity of wood buildings.

3. Learn how to determine the capacity at “near” collapse.

4. Learn how to determine the optimal retrofit.

5. Understand the use of the Weak Story Tool.
Background and Theory

Nuts and Bolts

Making it Simple
4,400 Dangerous Multi-unit Buildings: 8% of population
Create Seismic Retrofit Program for Weak-Story Wood-framed Apartment Buildings in Western US
The Scope
Inexpensive to Construct
(Work Only In Ground Story)

Inexpensive to Design
(Unsophisticated Engineers)

Performs Well
(Shelter-In-Place)
Typically:
Non-Engineered
No Plans
Archaic Materials
Archaic Construction Practices
The Problem
San Francisco, CA, Loma Prieta Earthquake 11/17/1989
Beach and Divisadero in the Marina District. U.S.G.S. by Nakata, J.K.
Northridge, CA: Northridge earthquake
FEMA News Photo
Design for a Population of Buildings, not an Individual Building
Pattern Recognition
Pattern Recognition

Strong but Brittle
Upper Structure

Weak and Brittle
Lower Structure
Pattern Recognition

Limited Damage to Upper Structure

Damage Concentrated in Lower Structure
RELATIVE
STRENGTH
METHOD
The Relative Strength Method

- Optimize benefits of ground story retrofits
- Retrofit to add both strength and displacement capacity, and reduce torsion
- Strength limit established by the upper structure
- Create a damage and deformation absorption level
- The tough ground story protects the upper stories
- If too strong, no damage absorption – forces are transmitted to upper structure
The Relative Strength Method

![Diagram showing the relative strength method for seismic evaluation and retrofit of multi-unit wood-frame buildings with weak first stories. The diagram includes graphs and lines representing different retrofit scenarios such as optimal-performance, overly strong, and optimal-cost retrofit.](image-url)
Can a Building’s Capacity be Determined from a Few Parameters?
Local Seismicity

![Graph showing spectral acceleration vs. period for local seismicity with mean, median, and geomean lines.](image)
Translational Weakness
Analysis Methodology - Material Forms

Sheathing material with $C_D = 0.0$

Sheathing material with $C_D = 1.0$

$\Delta L = 1.25\%$

$\Delta L = 4.0\%$
Damping and Hysteretic Models

Hysteresis of idealized high displacement capacity material “ductile” form

Hysteresis of idealized low displacement capacity material “brittle” form
Torsional Weakness
Characteristic Structural Coefficients

\[ C_{s,x} = \frac{V_{1,x}}{\sum_{j=1}^{N_x} W_j} \quad \text{Ground-story Strength} \]

\[ C_{U,x} = \min \left\{ \frac{V_{i,x}}{\sum_{j=i}^{N_x} W_j} \right\} \quad \text{Upper-story Strength} \]

\[ C_{W,x} = \frac{C_{s,x}}{C_{U,x}} \quad \text{Upper to Ground Strength Ratio} \]

\[ C_{D,x} = \frac{F_{1,x} (\delta = 3\%)}{V_{1,x}} \quad \text{Strength Degradation} \]

\[ C_T = \frac{\tau}{T} \quad \text{Torsional Imbalance} \]
Create a Controlled Experiment
Determine the Influence of Each Characteristic
Analytical Engine: Surrogate Structure Concept

Material forms:
(2) total

Upper-story strength ratios, $A_u$:
(4) per mat'l form

Weak-story ratios, $A_w$:
0.6 to 1.1 by 0.1
(6) per upper-story strength

Retrofit strengths:
$A_w$ to 1.6
(51) per upper-story strength ratio

TOTAL NUMBER OF BUILDINGS: 612

Time-history seed records:
(22) Bi-directional records = (44) individual
Scaled so that median $S_a(T = 0.3\text{ sec}) = 1.0g$

(35) intensities per seed record varying from 0.1 to 3.5 by 0.1
Recover peak interstory drift ratios for each analysis

Given drift criteria, fit log-normal CDF

Earthquake Intensity

0 1.0 $S_a = 1g$ 3.5
Simplified Building Model

HORIZ. D.O.F.

<table>
<thead>
<tr>
<th>W</th>
<th>50 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>100 in.</td>
</tr>
<tr>
<td>L</td>
<td>111.8 in.</td>
</tr>
<tr>
<td>q</td>
<td>1.107 rad, 63.4 deg.</td>
</tr>
<tr>
<td>cos(q)</td>
<td>0.447</td>
</tr>
<tr>
<td>Astrut</td>
<td>1 in²</td>
</tr>
<tr>
<td>Mg</td>
<td>1 kip (total weight of building)</td>
</tr>
</tbody>
</table>

F (fraction of weight)

M = 1 kip/g
Mg = 1 kip

σ = f*Mg*cos(θ)/A
ε = d4H*cos(θ)/L

PERFORM INPUT
Analytical Engine: Surrogate-Structure Concept

612 surrogate structures x 44 EQs x 35 intensities

1 million nonlinear response-history analyses
Analysis Results

FEMA P-807: Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories
Analysis Results

\[ S_{c,20} = (0.34 + 1.47 A_{w,x}) A_{u,x}^{0.48} \]

Curve fit for Incremental Dynamic Analysis
Structural Capacity

\[ S_{c1,x} = 0.66\left(0.525 + 2.24 A_{W,x}\right)\left(1 - 0.5 C_T\right)Q_s A_{U,x}^{0.48} \quad C_D = 1.0 \]

\[ S_{c0,x} = 0.60\left(0.122 + 1.59 A_{W,x}\right)\left(1 - 0.5 C_T\right)Q_s A_{U,x}^{0.60} \quad C_D = 0.0 \]
Limitations on the Guidelines

• Up to four stories
• Strong basement and strong sloped base can be accommodated
• Wood-framed stud walls and existing steel moment frames
• No concrete or masonry walls or steel braced frames
• 8’ – 12’ floor heights for upper structure
• 8’ – 15’ floor heights for ground floor
• Sloped sites can be accommodated
• Torsionally regular upper structure
• No vertical irregularities in upper structure
Characteristic Structural Coefficients

Ground-story Strength \[ C_{s,x} = \frac{V_{1,x}}{\sum_{j=1}^{N_x} W_j} \]

Upper-story Strength \[ C_{U,x} = \min \left( \frac{V_{i,x}}{\sum_{j=1}^{N_x} W_j} \right) \]

Upper to Ground Strength Ratio \[ C_{W,x} = \frac{C_{s,x}}{C_{U,x}} \]

Toughness \[ C_{D,x} = \frac{F_{1,x}(\delta = 3\%)}{V_{1,x}} \]

Torsional Imbalance \[ C_T = \frac{\tau}{T} \]
STORY

STRENGTH
Structural Use of Non-conforming Materials

- Stucco
- Horizontal wood sheathing
- Diagonal wood sheathing
- Brick veneer
- Plaster on wood lath
- Plywood panel siding
- Gypsum wall board
- Plaster on gypsum lath
- Wood structural panel 8d@6
- Wood structural panel 8d@4
- Wood structural panel 8d@3
- Wood structural panel 8d@2
- Wood structural panel 10d@6
- Wood structural panel 10d@4
- Wood structural panel 10d@3
- Wood structural panel 10d@2

Unit Force, plf

Drift Ratio, %
**Deflection Criteria**

### Brittle Backbone Curves

<table>
<thead>
<tr>
<th>Name</th>
<th>Ground Story</th>
<th>Upper Stories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset of Strength Loss, Original Condition</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Onset of Strength Loss, Retrofitted</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Ductile Backbone Curves

<table>
<thead>
<tr>
<th>Name</th>
<th>Ground Story</th>
<th>Upper Stories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset of Strength Loss, Original Condition</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Onset of Strength Loss, Retrofitted</td>
<td>4.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>
Perforated Shearwalls

\[ Q_{perf} = 0.92\alpha - 0.72\alpha^2 + 0.80\alpha^3 \]

\[ \alpha = \frac{1}{1 + \frac{\sum A_i}{H\sum L_i}} \]

\[ \Sigma A_i = A_1 + A_2 \]

\[ \Sigma L_i = L_1 + L_2 + L_3 \]
Story Height Adjustment Factor

Linear fit for Story-Height Adjustment Factor, $Q_s$:

$$Q_s = 0.55 + 0.0045H$$

where $H$ is the mean ground-story height in inches.
Wall Height Adjustment Factor

\[ D_h = \frac{H_{\text{wall}}}{H} \]

Drift ratio, \( \delta = \frac{\Delta}{H} \)

Actual Drift Ratio

Normalized Drift Ratio

Adjusted load-deflection curve

Assembly unit load-deflection curve

Unit load-deflection curve adjusted for height of Wall 1

Unit load-deflection curve adjusted for height of Wall 2

Taller walls

Shorter walls

Unit Force, plf

Drift Ratio, %

Wall 1

Wall 2

Normalized wall in ground story

Wall 2

Wall 1

Tallest wall in ground story

\( H \)

\( H_1 \)

\( H_2 \)
Pushover Curve to Find Peak Strength

$$f_w(\delta_j) = v_w(\delta_j)L_w Q_{perf} Q_{ot}$$
SIMPLIFIED
OVERTURNING
ADJUSTMENT
Overturning Reduction Factor

<table>
<thead>
<tr>
<th>Level</th>
<th>Perpendicular to Framing</th>
<th>Parallel to Framing</th>
<th>Unknown or mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two or more stories above</td>
<td>0.95</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>One story above</td>
<td>0.85</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Top story</td>
<td>0.75</td>
<td>0.8</td>
<td>0.75</td>
</tr>
</tbody>
</table>
STRENGTH DEGRADATION RATIO
Strength Degradation Ratio

\[ C_D = \frac{V_{3\%}}{V} \]

- Peak Strength, \( V \)
- Load-Deflection Curve
- Strength at 3% Drift, \( V_{3\%} \)

Drift Ratio, %

Unit Force, plf

Strength Degradation Ratio, \( C_D = \frac{V_{3\%}}{V} \)
TORSIONAL IMBALANCE
Torsion Demand

\[ \tau = e_x V_{1,y} + e_y V_{1,x} \]

\[ e_x = |COS_{2,x} - COS_{1,x}| \]

\[ e_y = |COS_{2,y} - COS_{1,y}| \]
Torsion Capacity

Torsional moment that causes a twist of \( \theta_j \) for the Ground Story, \( t_j(\theta_j) \)

Maximum twist angle to consider for the Ground Story

Torsion Backbone Curve

\[
t(\theta_j) = \sum_{w=1}^{N_{wall}} d_{w,y} f_{w,x} \left( \frac{d_{w,y} \theta_j}{H_1} \right) + d_{w,x} f_{w,y} \left( \frac{d_{w,x} \theta_j}{H_1} \right)
\]

\[T = \max[t(\theta_j)]\]
Accounting for Torsion

\[ C_T = \frac{\tau}{T} \]
CALCULATE
SPECTRAL CAPACITY
Spectral Capacity, $S_{c}$

\[ S_{c1,x} = 0.66 \left( 0.525 + 2.24 A_{W,x} \right) \left( 1 - 0.5 C_T \right) Q_s A_{U,x}^{0.48} \quad C_D = 1.0 \]

\[ S_{c0,x} = 0.60 \left( 0.122 + 1.59 A_{W,x} \right) \left( 1 - 0.5 C_T \right) Q_s A_{U,x}^{0.60} \quad C_D = 0.0 \]

\[ S_{c,x} = C_D^3 S_{c1,x} + \left( 1 - C_D^3 \right) S_{c0,x} \quad \text{for intermediate values} \]

\[ S_{c,x} \geq S_{MS} \quad \text{if true - no retrofit required} \]

Onset of Strength Loss drift criteria, OSL

20% Probability of Exceedance, POE

Modifier for POE = 0.2

Mean spectral capacity, $S_m$
CALCULATE
OPTIMAL RETROFIT
Range of Retrofit Strength

For buildings with strong upper structures ($V_{r_{\text{max}}} > V_{re}$)

$$
V_{r_{\text{max},x}} = \left(0.11 A_{U,x} + 1.22\right) V_{U,x}
$$

\hspace{1cm}

For buildings with weak upper structures ($V_{r_{\text{max}}} < V_{re}$)

\hspace{1cm}

use 90% - 110% of upper limit

$$
V_{r_{\text{max},x}} = \left(0.11 A_{U,x} + 1.22\right) V_{U,x}
$$

If the upper structure is extremely weak, such that $S_{cr,x} \geq \frac{2}{3} S_{MS}$, then $S_{cr,x} = \frac{2}{3} S_{MS}$ this corresponds to a 50% POE at the MCE

the Guidelines are not applicable - use alternative methodology
Range of Retrofit Strength

Strength of Retrofitted Ground-Story

Minimum Strength, \( V_{r,\text{min}} \) (Adequate Performance)

Maximum Strength, \( V_{r,\text{max}} \) (Best Performance)

Acceptable Retrofit Range

\[ V_{r,\text{max},x} = (0.11A_{U,x} + 1.22) \cdot V_{U,x} \]

\[ V_{r,\text{min},x} = \frac{S_{MS} - X_2C_D^3 - Y_2(1-C_D^3)}{X_1C_D^3 + Y_1(1-C_D^3)} \]

\( S_c = S_{MS} \)

\( A_u = 0.4, A_w = 0.6 \)
Range of Retrofit Strength

- Acceptable Retrofit Range
- Estimated Minimum Strength, \( V_{re} \)
- Maximum Strength, \( V_{r max} \)
- Minimum Strength, \( V_{r min} = 0.9V_{r max} \)

\[ V_{r max} = \left(0.11A_{U,x} + 1.22\right) \cdot V_{U,x} \]

Strength of Retrofitted Ground-Story

Spectral Capacity, \( S_c \)

- \( S_{MS} \)
- \( 2/3 \cdot S_{MS} \)
- \( S_c \)

Au = 0.1, Aw = 0.6
Retrofit
Regularizing Diaphragms

Aspect ratios

Cantilevers

Openings

Re-entrant corners

Chord capacity must be checked if $L > 10$ feet.

Depending on the width, this portion may be considered a separate sub-diaphragm, $D_3$. 

This frame must support lateral loads from both diaphragms $D_1$ and $D_2$.

$x_1 : y > 2 : 1$  
$x_1 : y < 2 : 1$  
$x_2 : y < 2 : 1$

$x : y > 2 : 1$  
$y : x_1 < 2 : 1$  
$y : x_2 < 2 : 1$

$x : y < 0.25$  
$0.25x$  
$0.25y$

Direction of motion considered

North-South Analysis
Retrofit Placement to Minimize Torsion

Added retrofit strength -

$$\Delta V_{1,x} = V_{r,x} - V_{l,x}$$

Place to eliminate torsion, limited by building dimension

$$e_{x,y} = \frac{e_{x,y}}{\Delta V_{1,y}} \leq (L_x - COS_{2,x})$$

Range of acceptable eccentricity -

$$e_{\text{min},x} = e_{x} - \frac{\Delta V_{1,y}}{V_{r,y}} \left( e_{x} + e_{x,y} \right)$$

$$e_{\text{max},x} = e_{\text{min},x} + 0.05L_x$$
MAKING IT SIMPLE
WST
weak-story tool

Evaluation and Retrofit Guidelines for Weak-Story Wood Buildings