Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories
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
BACKGROUND

&

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

Inexpensive to Design
(Prescriptive)

Performs Well
(Shelter-In-Place)
Typically:
Non-Engineered
No Plans
Archaic Materials
Archaic Construction Practices
The Problem
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

Floor Displacement, in.

Elevation, in.

Drift Ratio

Least-cost retrofit

Best-performance retrofit

Overly strong retrofit

(E) Structure

Optimally strong retrofit

Optimally performance retrofit

Overly weak retrofit
Can a Building’s Capacity be Determined from a Few Parameters?
Local Seismicity
Translational Weakness
Displacement Capacity

Sheathing material with $C_D = 0.0$

$\Delta L = 1.25\%$

Sheathing material with $C_D = 1.0$

$\Delta L = 4.0\%$
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

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

- Upper-story Strength: 
  \[ C_{U,x} = \min \left\{ \frac{V_{i,x}}{\sum_{j=1}^{N} W_j} \right\}_{i=2 \rightarrow N} \]

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

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

- Torsional Imbalance: 
  \[ C_T = \frac{\tau}{T} \]
Create a Controlled Experiment

Determine the Influence of Each Characteristic
Analytical Engine: Surrogate Structure Concept

Material forms:
(2) total

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

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

Retrofit strengths:
Aw 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 Sa( T = 0.3 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 (Sa = 1g) 3.5
Simplified Building Model

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

612 surrogate structures x 44 EQs x 35 intensities
1 million nonlinear response-history analyses
Analysis Results

![Graph showing spectral capacity versus total ground floor strength/upper floor strength for different values of Au and Aw.]

Legend:
- **Au = 0.1**
- **Au = 0.2**
- **Au = 0.4**
- **Au = 0.6**

- **Aw = 0.6**
- **Aw = 0.8**
- **Aw = 1.1**
Structural Capacity

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

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

• Three or 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 \( c_{s,x} = \frac{V_{i,x}}{\sum_{j=1}^{N} W_j} \)

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

Upper to Ground Strength Ratio \( c_{w,x} = \frac{c_{s,x}}{c_{U,x}} \)

Toughness \( c_{D,x} = \frac{F_{l,x} (\delta = 3\%)}{V_{l,x}} \)

Torsional Imbalance \( c_T = \frac{T}{T} \)
STORY
STRENGTH
Structural Materials
Conforming & Non-conforming

Graph showing the relationship between unit force (plf) and drift ratio (%) for various structural 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
Deflection Criteria

<table>
<thead>
<tr>
<th>Name</th>
<th>High Displacement Capacity (Hd)</th>
<th>Low Displacement Capacity (Ld)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Ground Story</td>
<td>Upper Stories</td>
</tr>
<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>
Perforated Shearwalls

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

\[ \alpha = \frac{1}{\left(1 + \frac{\sum A_i}{H\sum L_i}\right)} \]
Story Height Adjustment Factor

Normalized Mean Spectral Capacity

Perform Model

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

$$Q_s = 0.55 + 0.0045 \times H$$

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

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

Drift ratio, \( \delta \), is calculated as:

\[ \delta = \frac{\Delta}{H} \]

- **Adjusted load-deflection curve**
- **Normalized Drift Ratio**
- **Actual Drift Ratio**
- **Unit load-deflection curve adjusted for height of Wall 1**
- **Unit load-deflection curve adjusted for height of Wall 2**
- **Unadjusted assembly unit load-deflection curve**
Pushover 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>
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STRENGTH DEGRADATION RATIO
Strength Degradation Ratio

![Graph showing Load-Deflection Curve](image)

**Peak Strength, V**

**Strength at 3% Drift, V₃%**

**Strength Degradation Ratio, C_D = V₃% / V**

- **Unit Force, plf**
- **Drift Ratio, %**
TORSIONAL IMBALANCE
Torsional Weakness
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

Torsion Backbone Curve

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

\[ T = \max [t(\theta_j)] \]
Torsion Adjustment Factor, $C_T$

$$C_T = \frac{\tau}{T}$$
CALCULATE SPECTRAL CAPACITY
Spectral Capacity, $S_c$

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

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

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

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

Onset of Strength Loss drift criteria, OSL

20% Probability of Exceedance, POE
CALCULATE

OPTIMAL RETROFIT
Range of Retrofit Strength

For buildings with strong upper structures \( (V_{\text{max}} > V_r) \)

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

lower limit \[ V_{re,x} = \frac{S_{MS} - X_2 C_D^3 - Y_2 (1-C_D^3)}{X_1 C_D^3 + Y_1 (1-C_D^3)} \]

Estimate of the minimum ground-story strength that gets POE below 0.2

For buildings with weak upper structures \( (V_{\text{max}} < V_r) \)

use 90% – 110% of upper limit \[ V_{\text{max},x} = (0.11A_{U,x} + 1.22) \cdot V_{U,x} \]

If the upper structure is extremely weak, such that

\[ S_{cr,x} \geq \frac{2}{3} S_{MS} \] this corresponds to a 50% POE at the MCE

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

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

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

\[ S_c = S_{MS} \]

\[ \text{Acceptable Retrofit Range} \]

\[ \text{Minimum Strength, } V_{r_{\text{min}}} \]

\[ \text{(Adequate Performance)} \]

\[ \text{Maximum Strength, } V_{r_{\text{max}}} \]

\[ \text{(Best Performance)} \]

\[ \text{Strength of Retrofitted Ground-Story} \]

\[ \text{Spectral Capacity, } S_c \]

\[ \text{Au = 0.4, Aw = 0.6} \]
Range of Retrofit Strength

\[ V_{r_{\max, x}} = (0.11A_{U,x} + 1.22) \cdot V_{U,x} \]
Retrofit
Regularizing Diaphragms

Aspect ratios

This frame must support lateral loads from both diaphragms D₁ and D₂

Chord capacity must be checked if L > 10 feet.

Re-entrant corners

North-South Analysis

Openings

Depending on the width, this portion may be considered a separate sub-diaphragm, D₃

Cantilevers
Retrofit to Minimize Torsion

Added retrofit strength -

\[ \Delta V_{1,x} = V_{r,x} - V_{1,x} \]

Place to eliminate torsion, limited by building dimension

\[ e_{\Delta V_{1,y}} = \frac{e_{x} V_{1,y}}{\Delta V_{1,y}} \leq (L_x - COS_{z,x}) \]

Range of acceptable eccentricity -

\[ e_{min,x} = e_{x} - \frac{\Delta V_{1,y}}{V_{r,y}} (e_{x} + e_{\Delta V_{1,y}}) \]

\[ e_{max,x} = e_{min,x} + 0.05 L_x \]
MAKING IT SIMPLE
www.atcouncil.org