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

BACKGROUND

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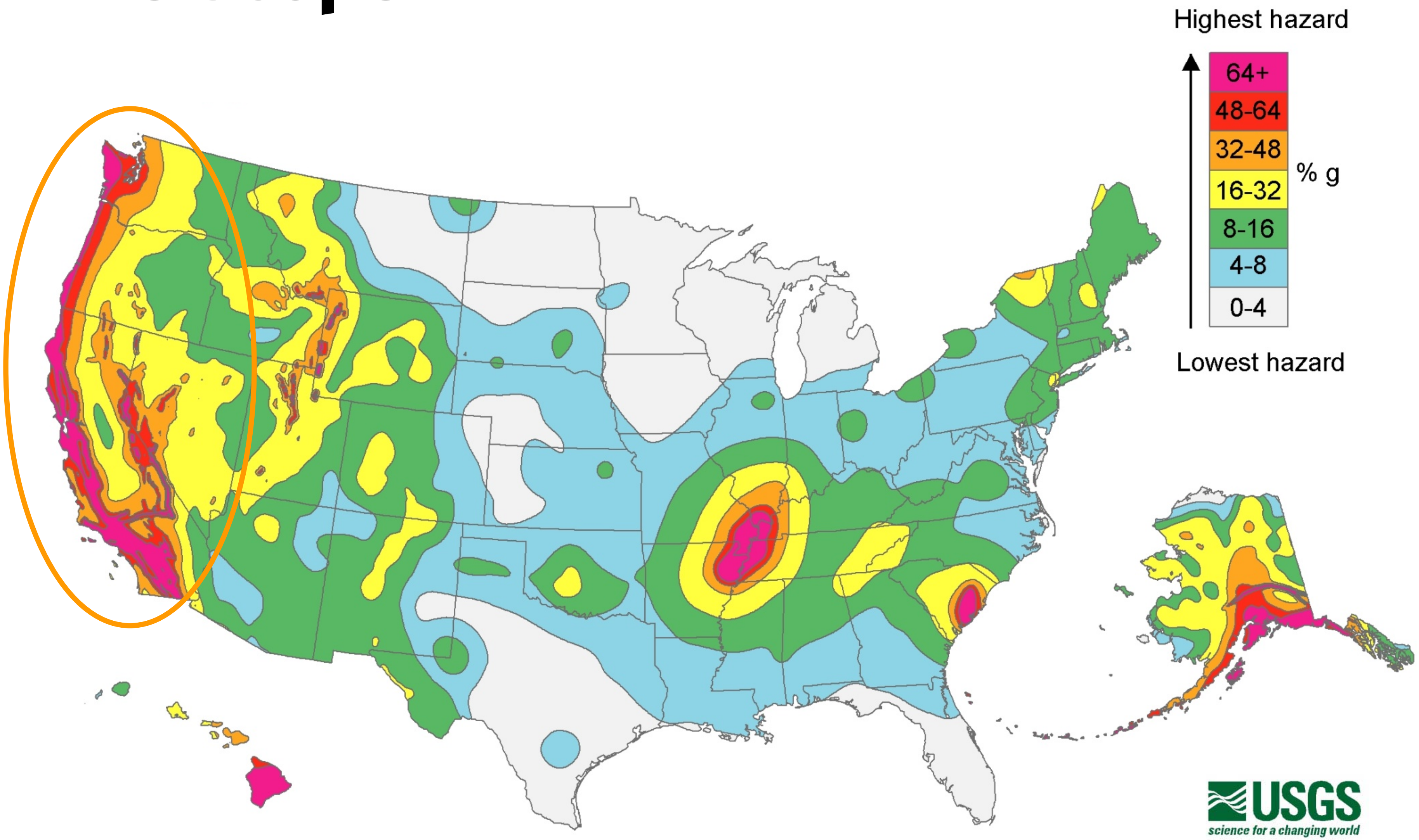
THEORY

4,400 Dangerous Multi-unit Buildings: 8% of population

Create Seismic Retrofit Program for Weak-Story Wood-framed Apartment Buildings in Western US

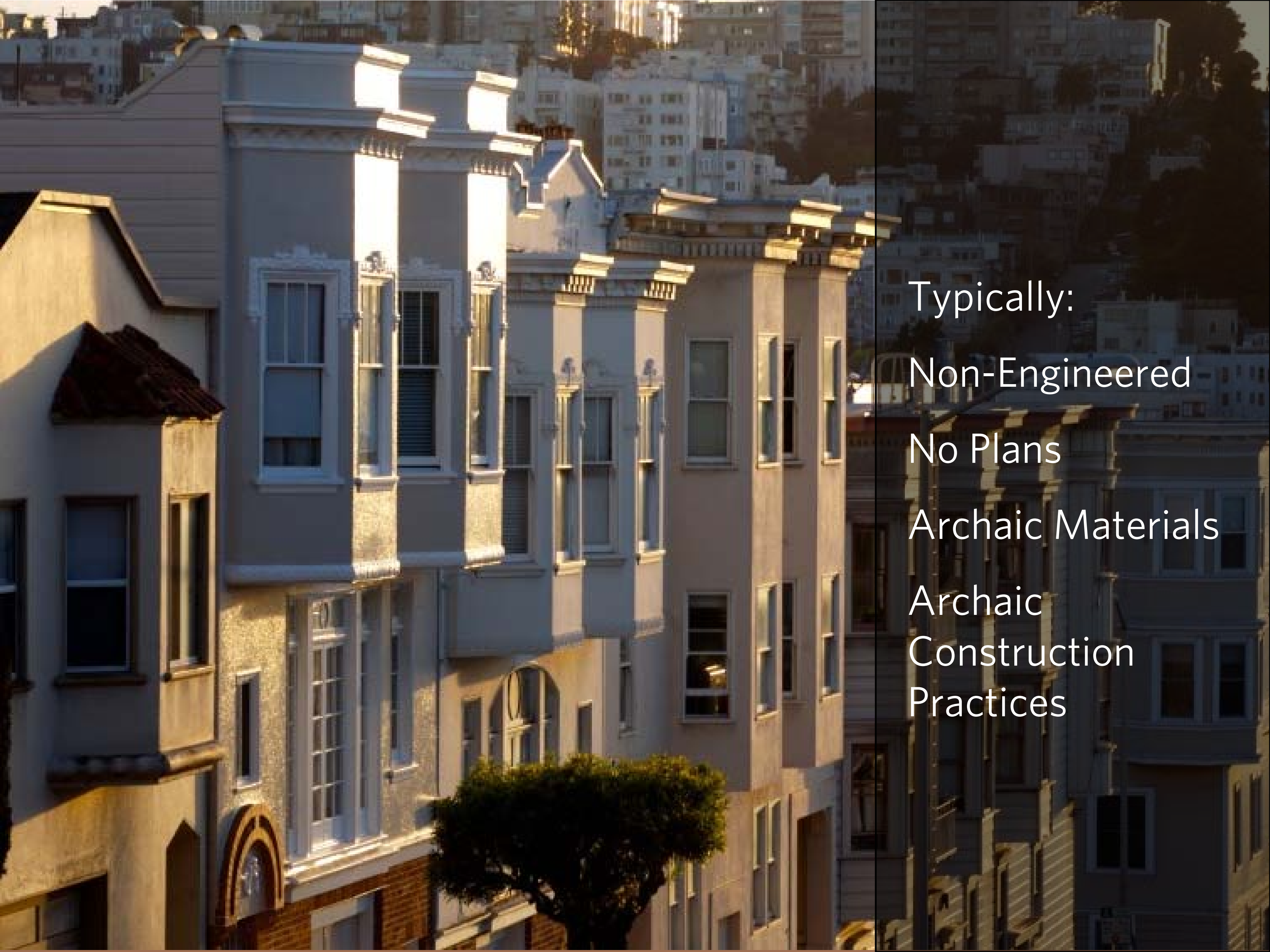
The Scope


Highest hazard
64+
48-64
32-48
16-32
8-16
4-8
0-4
% g
Lowest hazard
USGS
science for a changing world

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

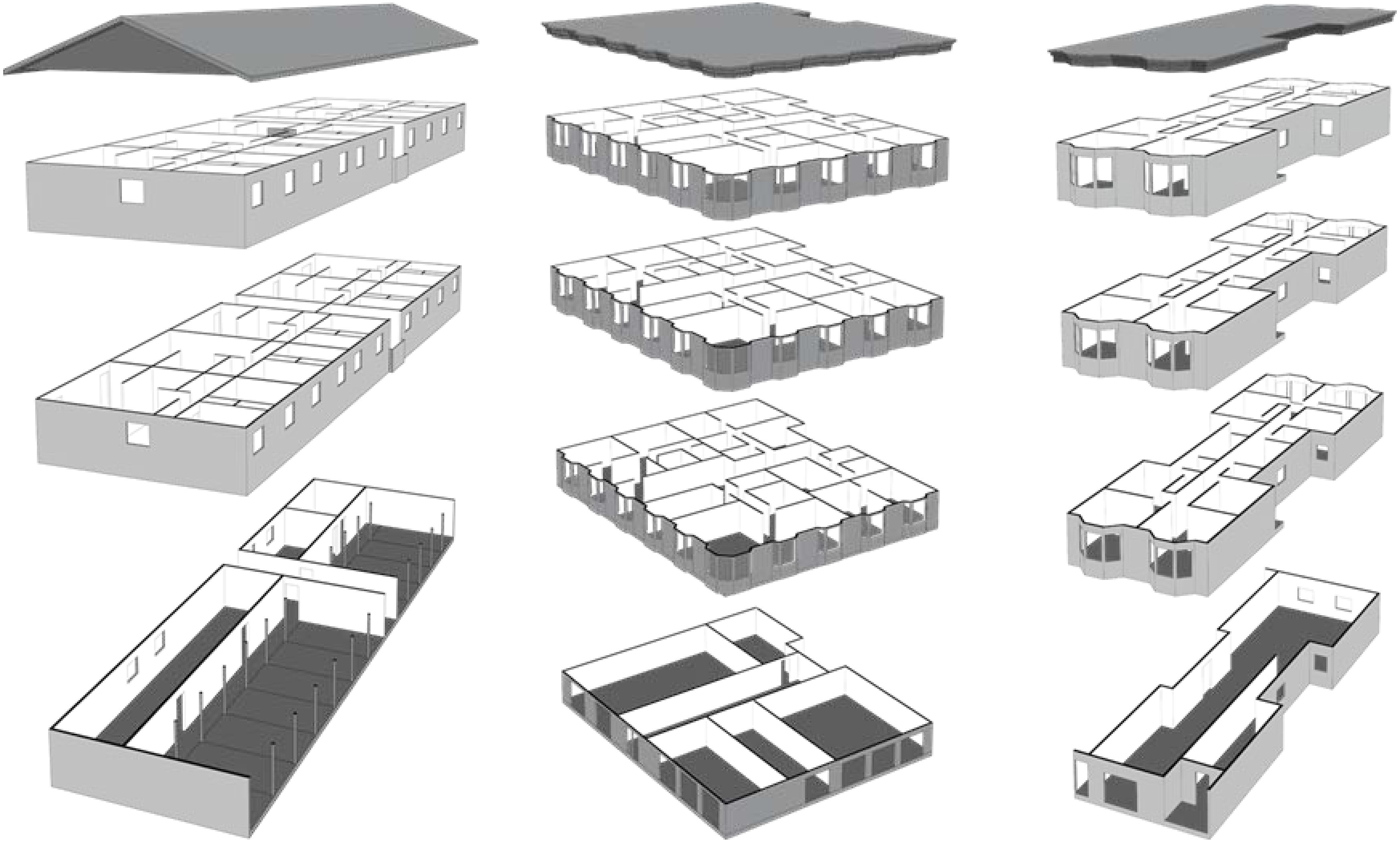
1989 Loma Prieta earthquake
Image by Raymond B. Seed
National Information Service for Earthquake Engineering
University of California, Berkeley.

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

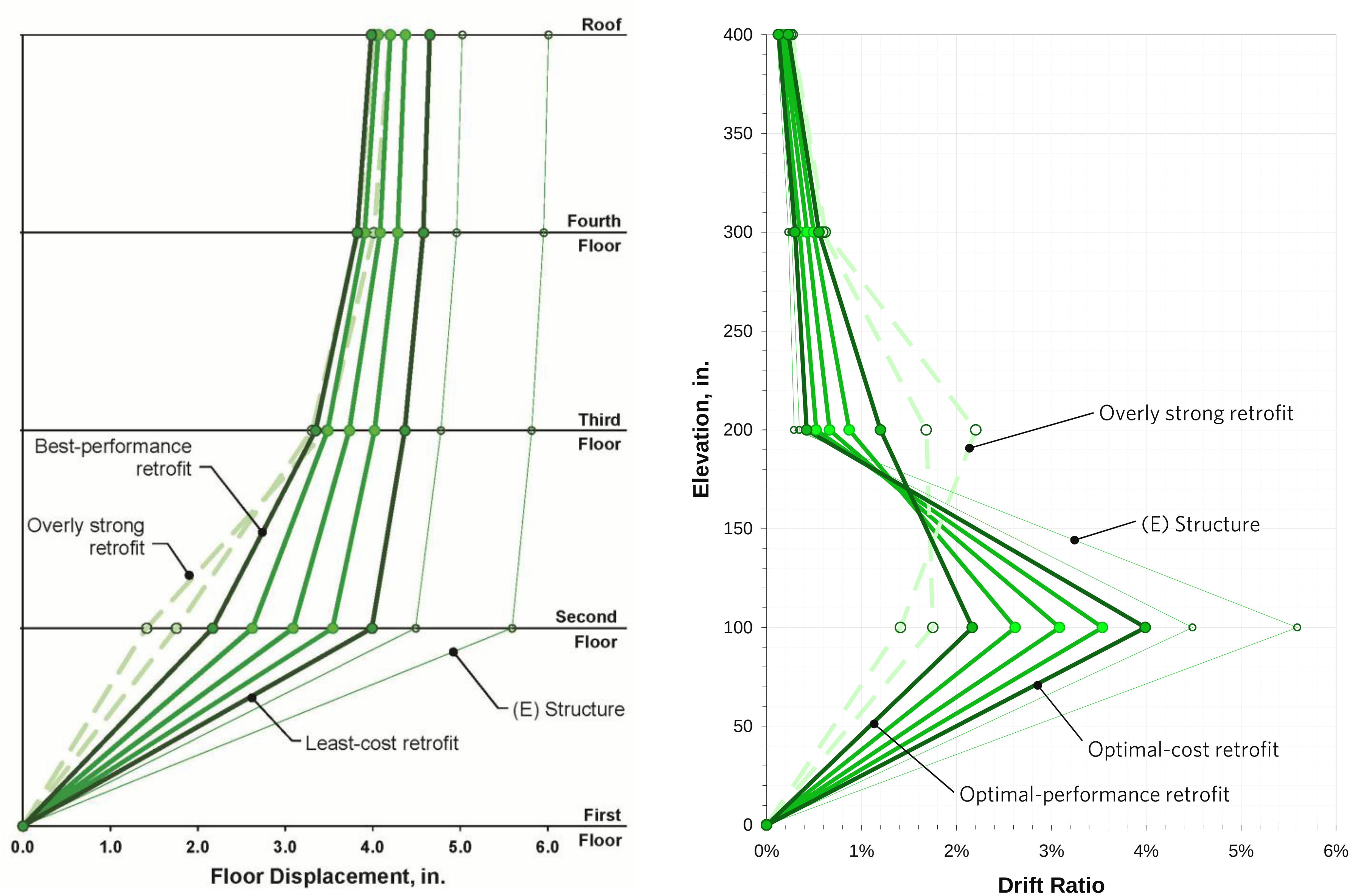
Damage Concentrated in Lower Structure

RELATIVE STRENGTH METHOD

The Relative Strength Method

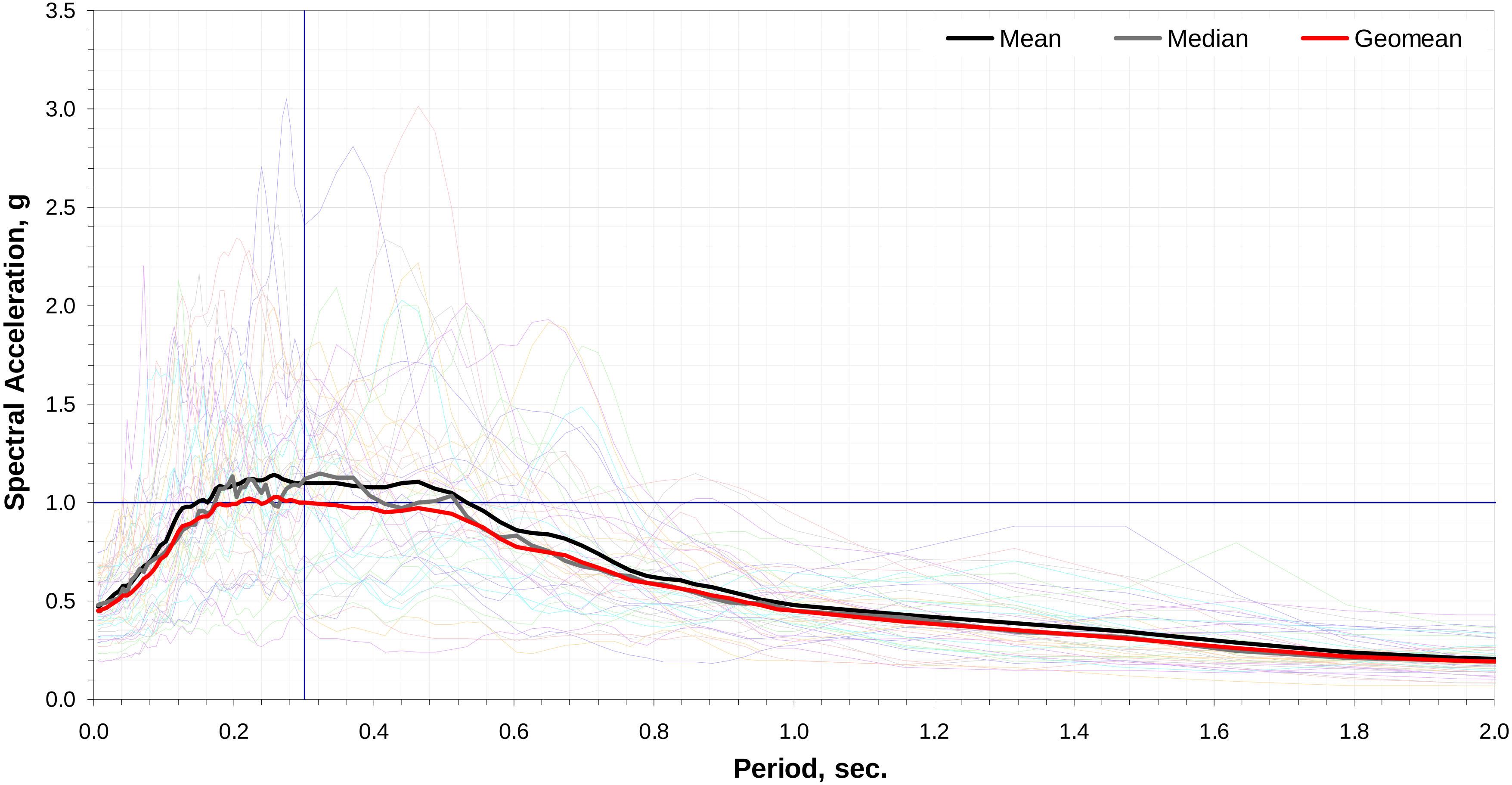
- **Optimize** benefits of ground story retrofits
- Retrofit to add both **strength and displacement capacity**, and **reduce torsion**
- Strength **limit** established by the **upper structure**
- Create a damage and **deformation absorption level**
- The tough ground story **protects the upper stories**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

The Relative Strength Method

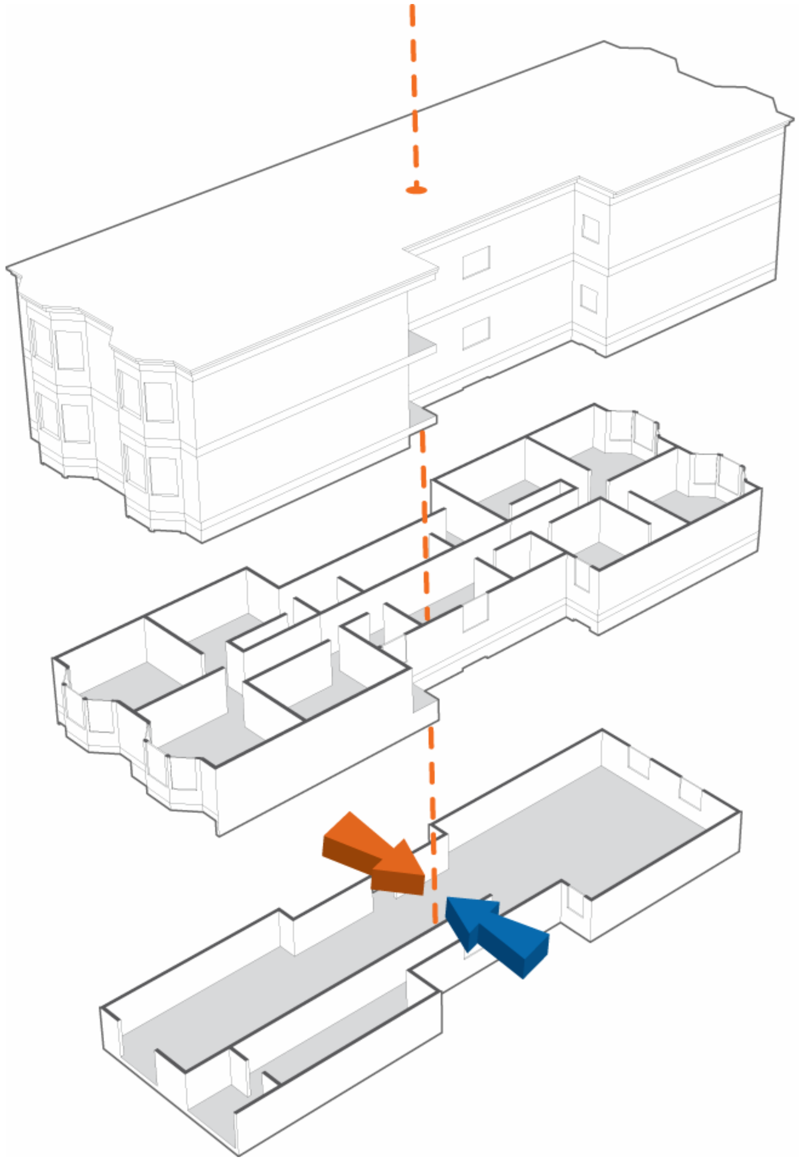


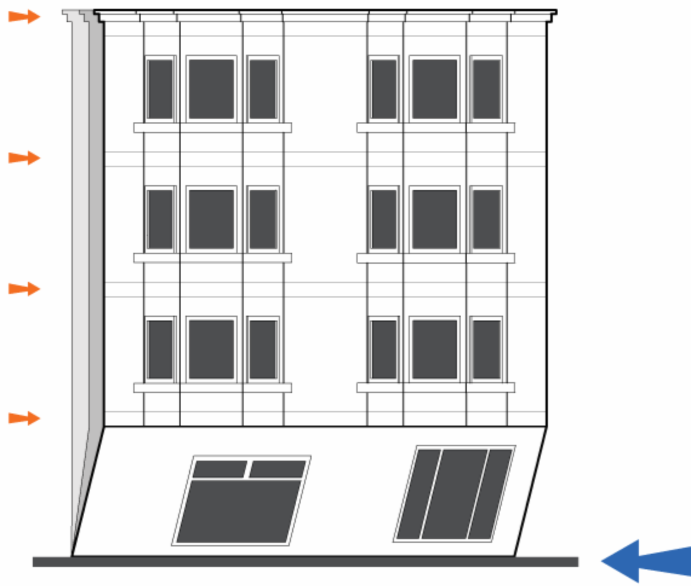
Can a Building's Capacity be Determined from a Few Parameters?

Local Seismicity

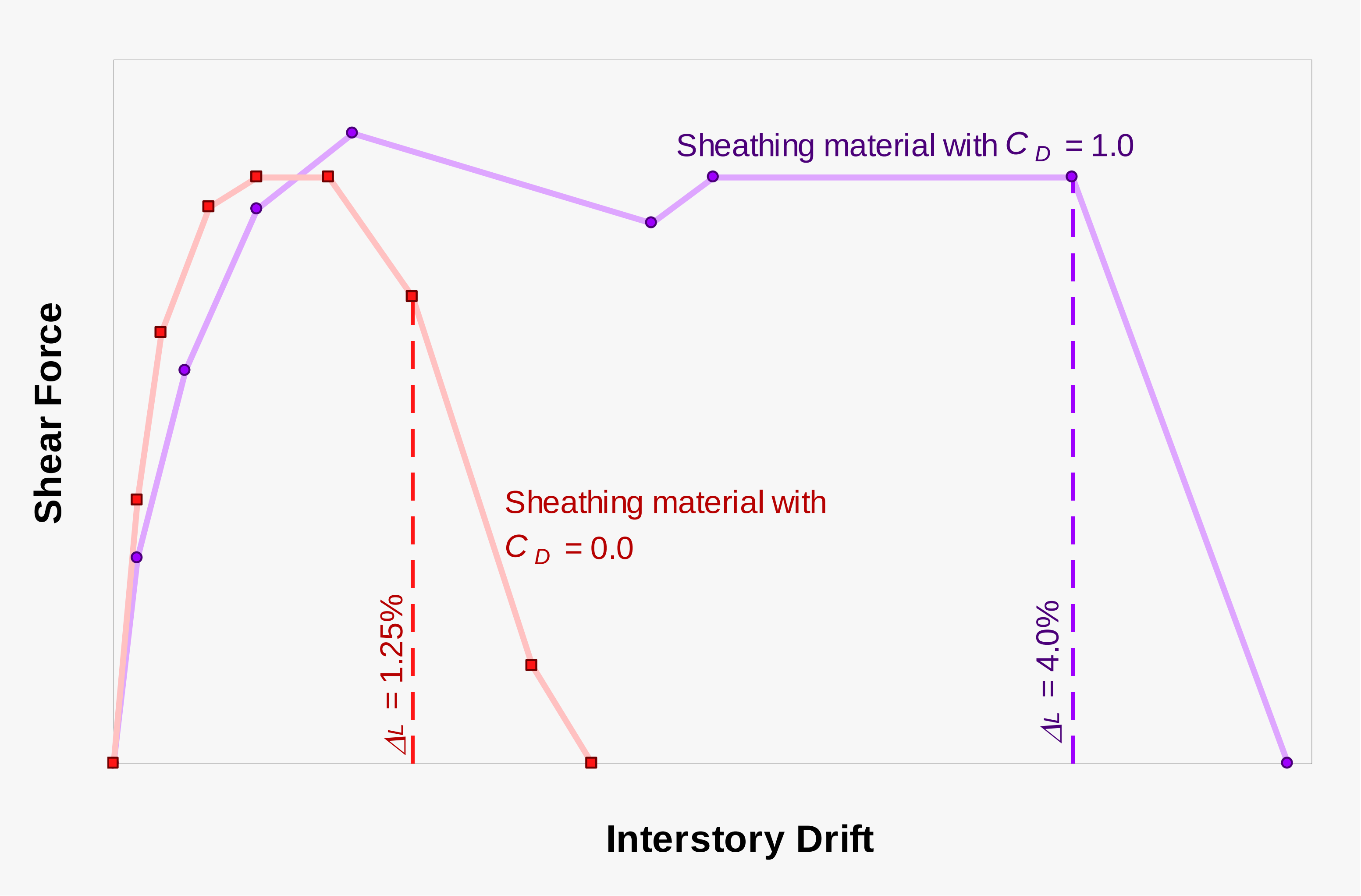


Translational Weakness



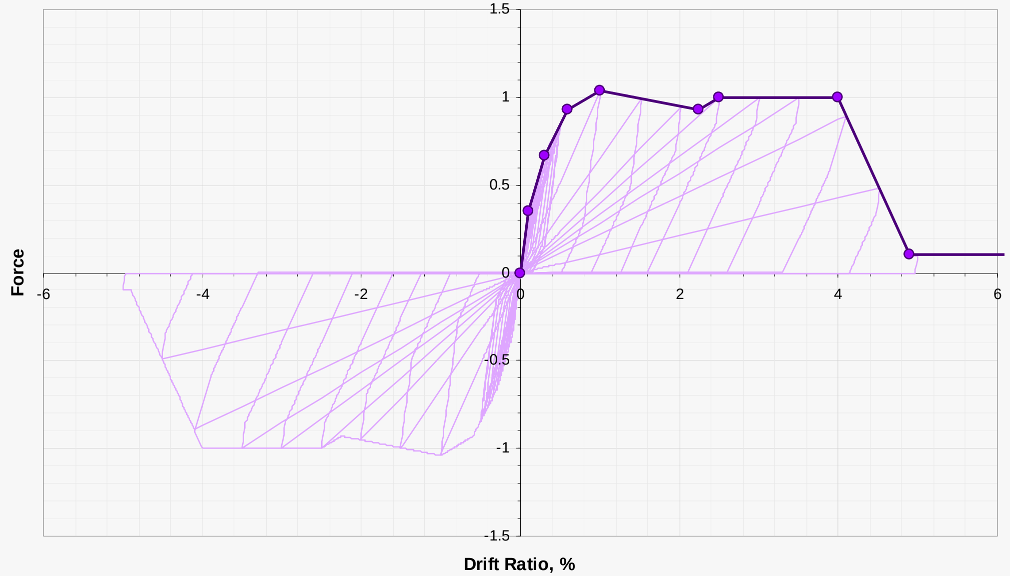


Analysis Methodology - Material Forms

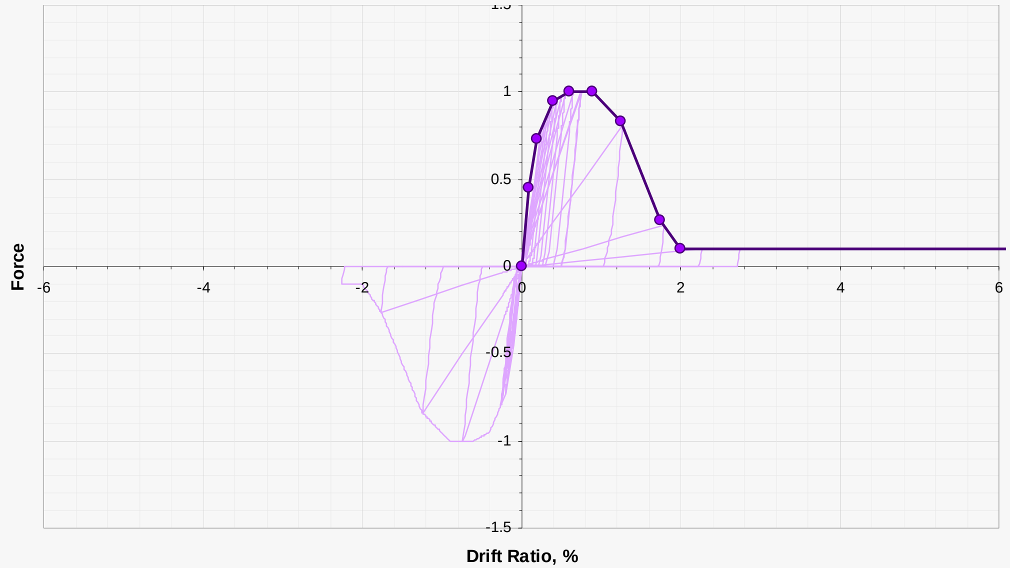


Damping and Hysteretic Models

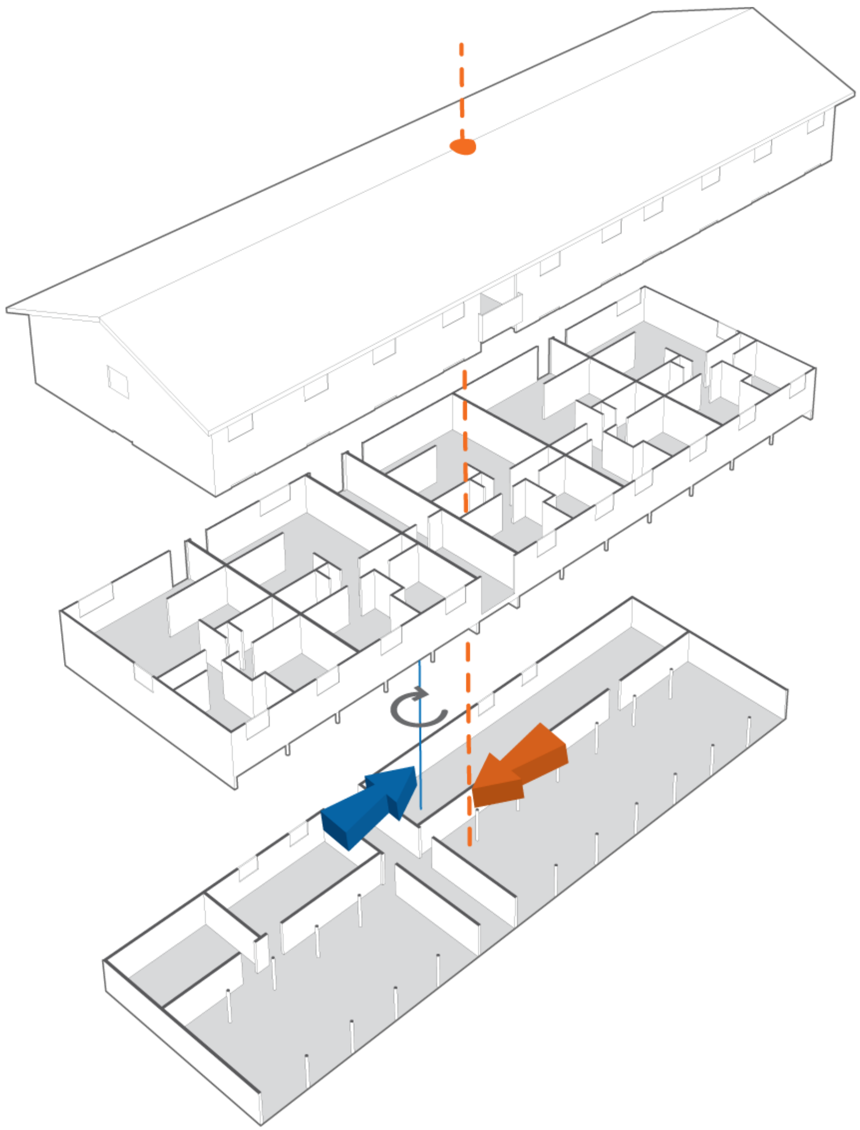
Hysteresis of idealized high displacement capacity material "ductile" form

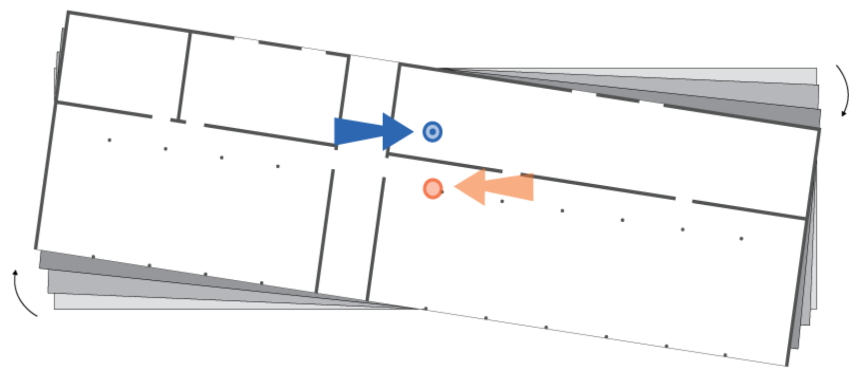


Hysteresis of idealized low displacement capacity material "brittle" form



Torsional Weakness





Characteristic Structural Coefficients

$$C_{s,x} = \frac{V_{1,x}}{\sum_{j=1}^{N_s} W_j}$$

Ground-story Strength

$$C_{U,x} = \min\left(\frac{V_{i,x}}{\sum_{j=i}^{N_s} W_j}\right)_{i=2\rightarrow N_s}$$

Upper-story Strength

$$C_{W,x} = \frac{C_{s,x}}{C_{U,x}}$$

Upper to Ground Strength Ratio

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

Strength Degradation

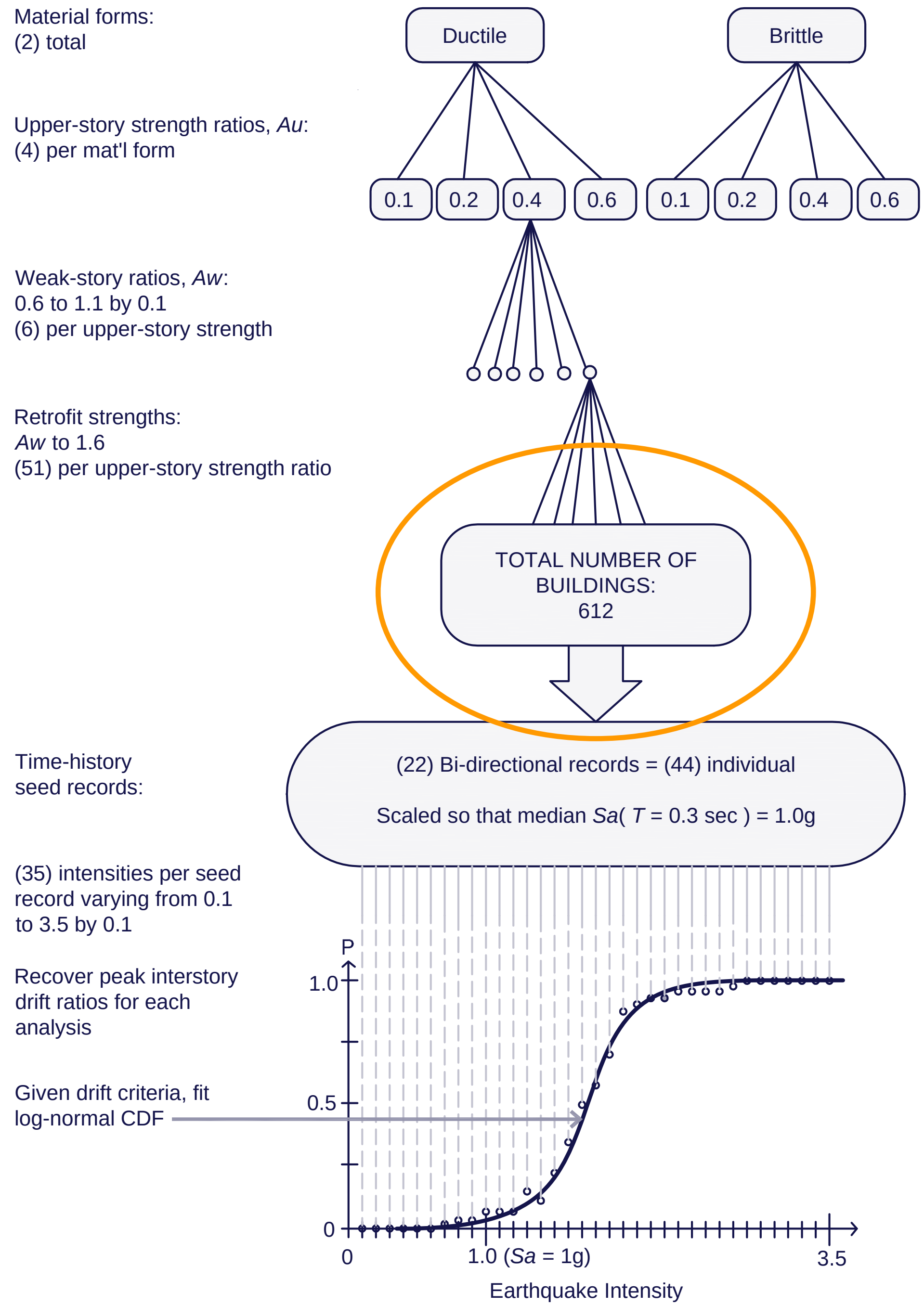
$$C_T = \frac{\tau}{T}$$

Torsional Imbalance

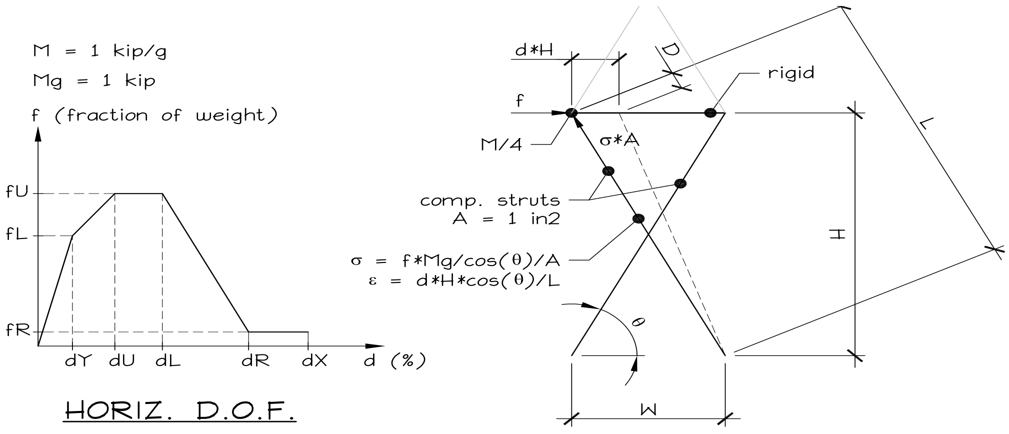
Create a Controlled Experiment

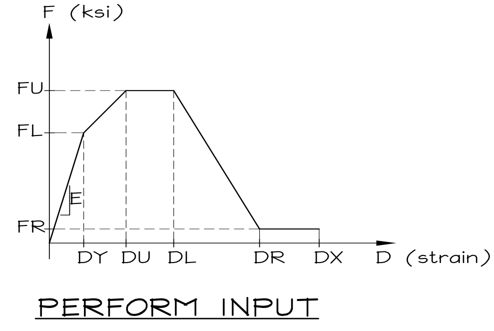
Determine the Influence of Each Characteristic

Analytical Engine: Surrogate Structure Concept

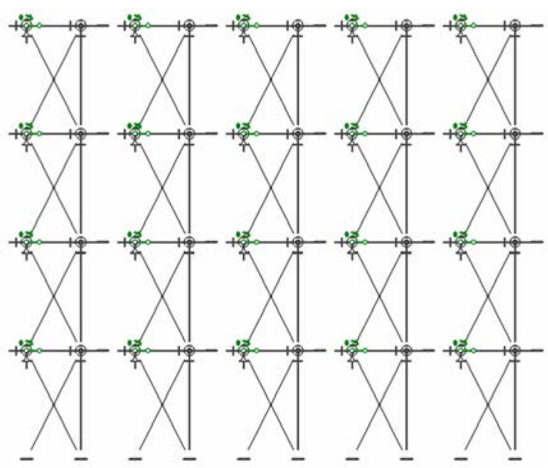


Simplified Building Model

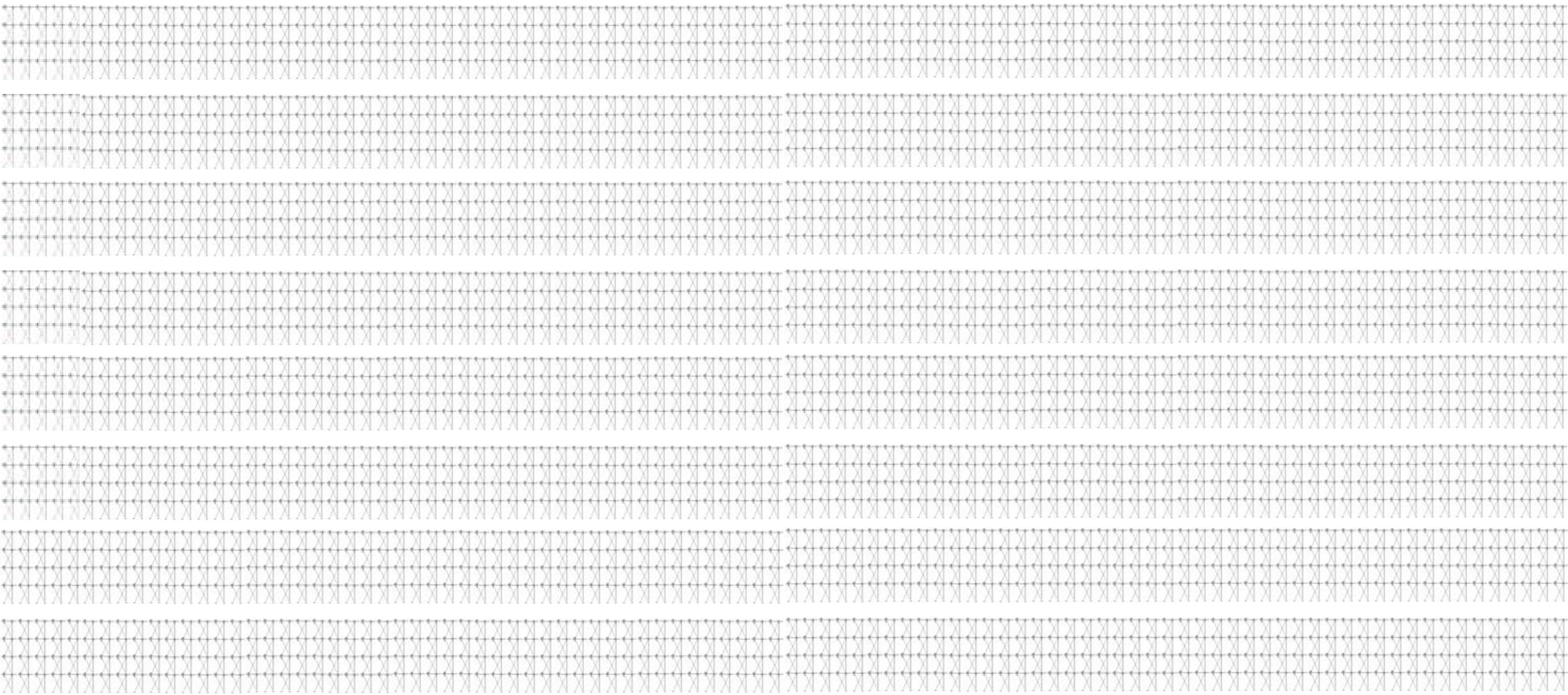




W	50	in.	
H	100	in.	
L	111.8		
q	1.107	rad,	
	63.4	deg.	
cos(q)	0.447		
Astrut	1	in2	
Mg	1	kip	(total weight of building)



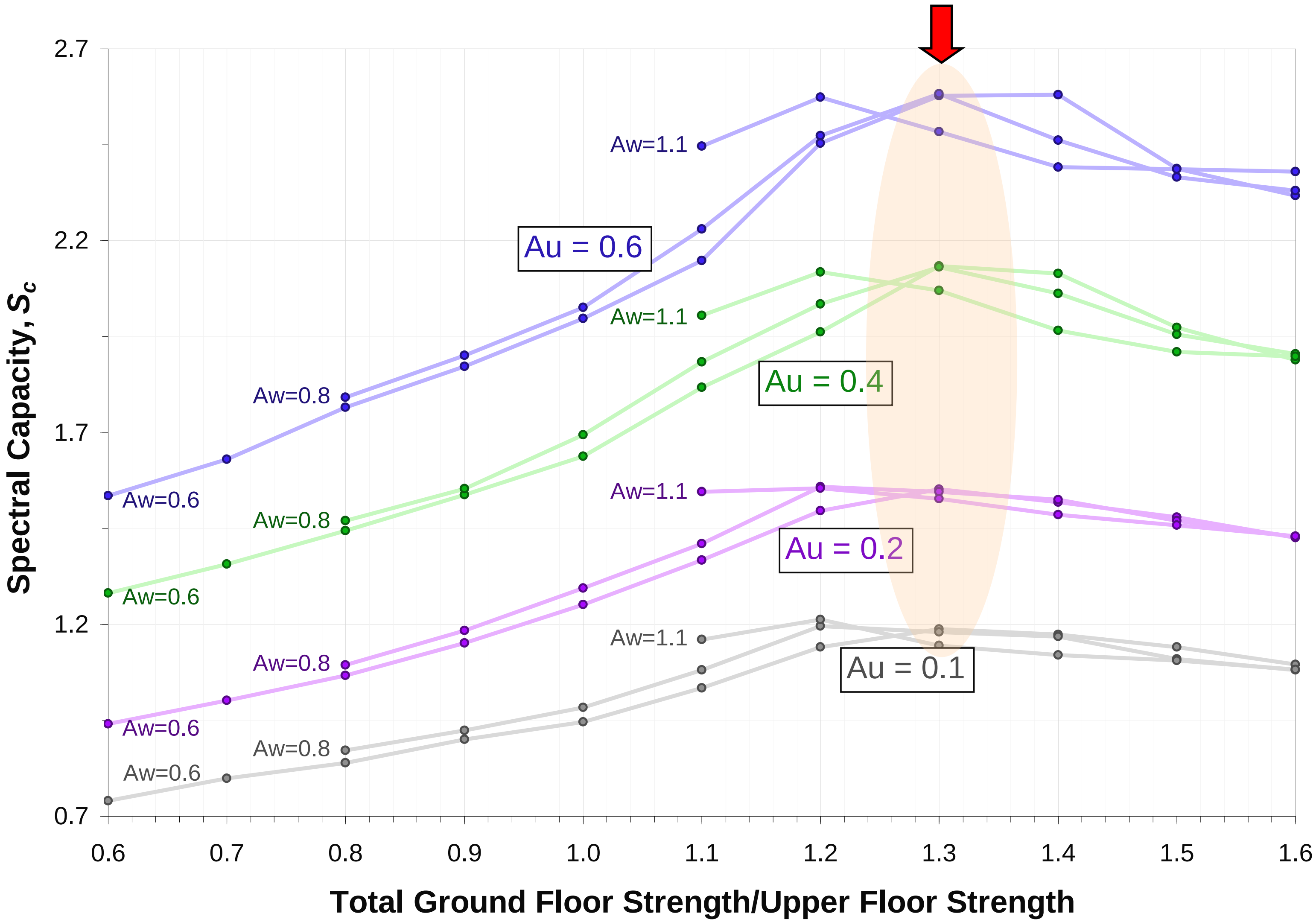
Analytical Engine:
Surrogate-Structure Concept



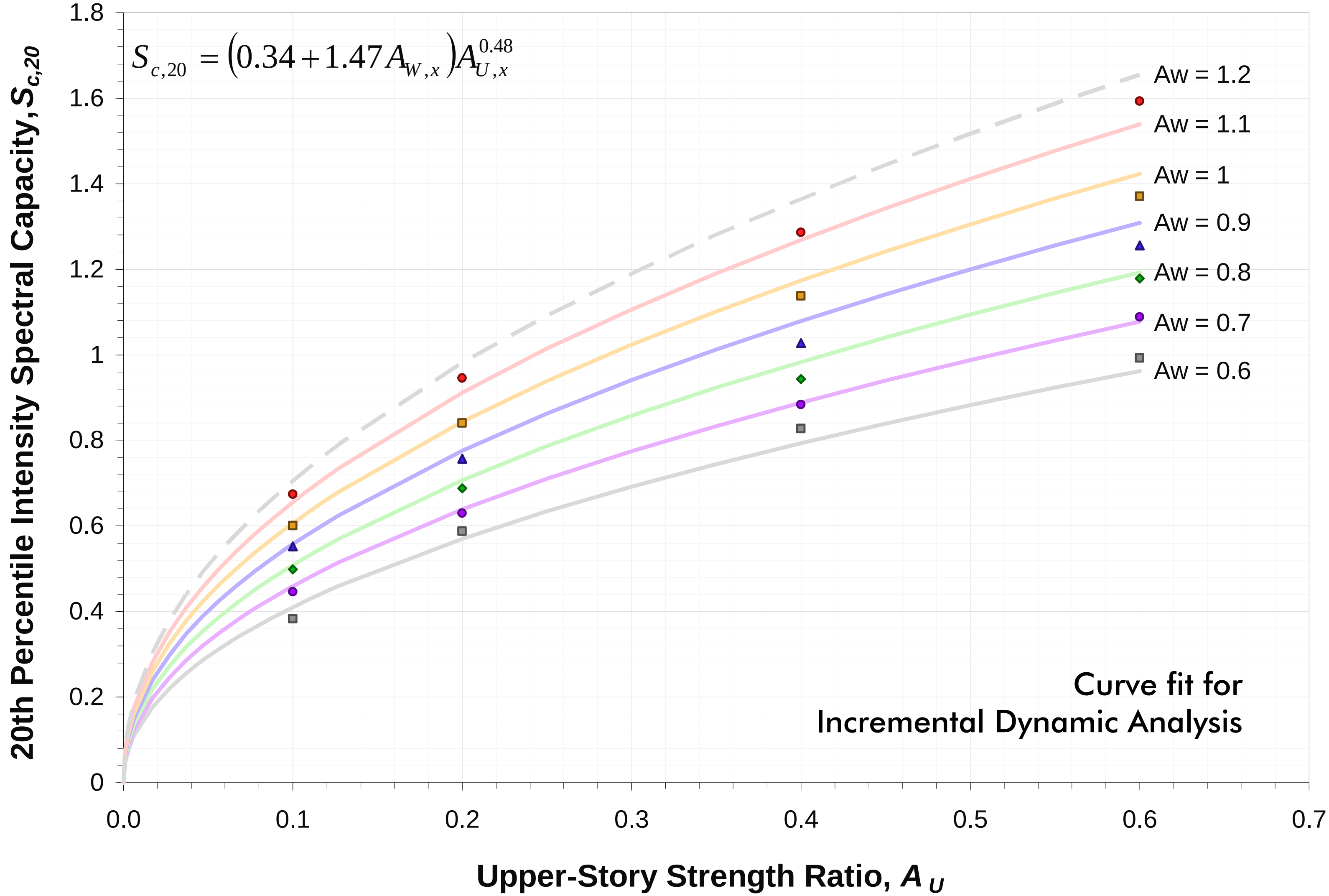
612 surrogate structures x 44 EQs x 35 intensities

1 million nonlinear response-history analyses

Analysis Results



Analysis Results



Structural Capacity

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

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

NUTS

&

BOLTS

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 $C_{s,x} = \frac{V_{1,x}}{\sum_{j=1}^{N_s} W_j}$

Upper-story Strength $C_{U,x} = \min\left(\frac{V_{i,x}}{\sum_{j=i}^{N_s} W_j}\right)_{i=2 \to N_s}$

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

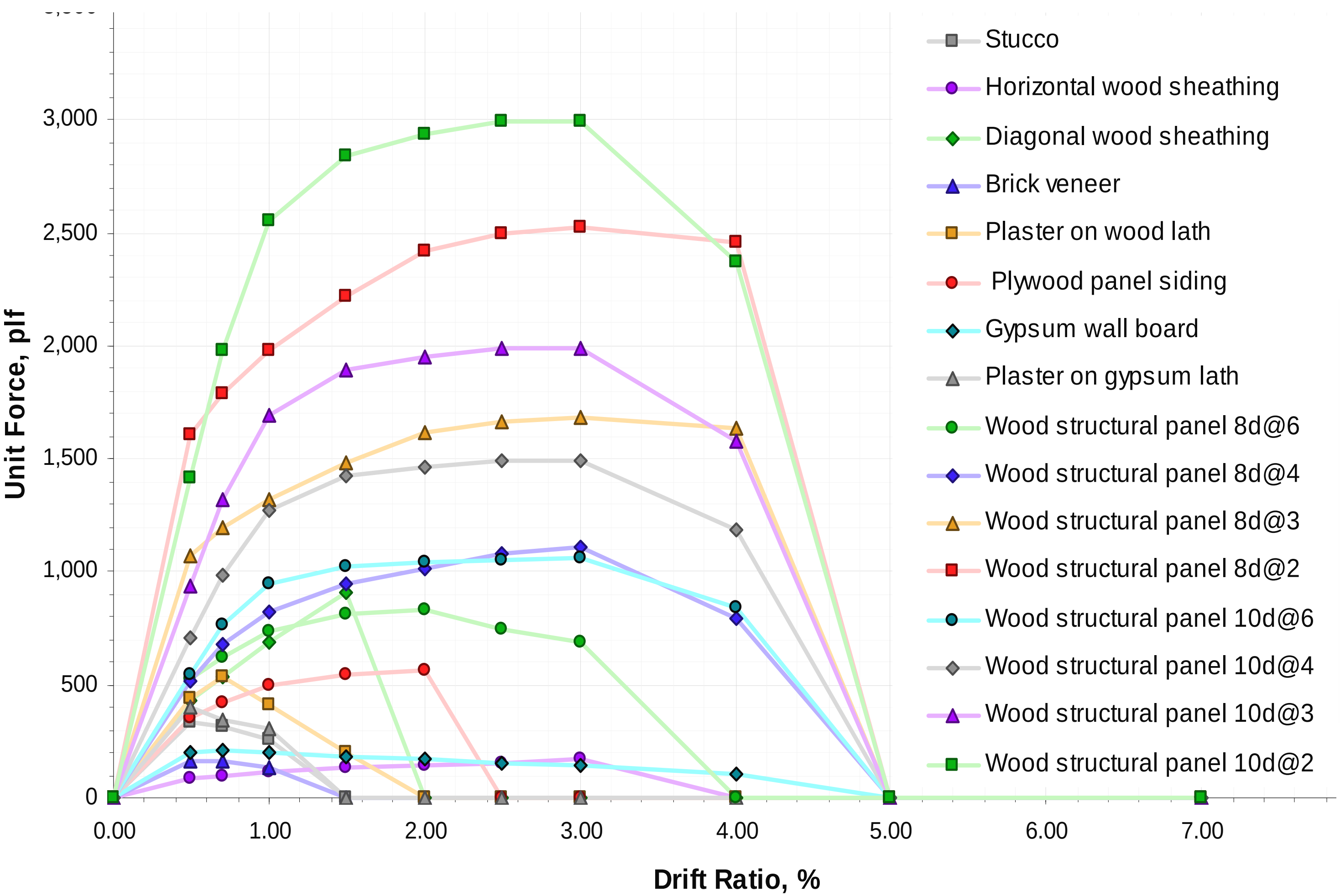
Toughness $C_{D,x} = \frac{F_{1,x}(\delta = 3\%)}{V_{1,x}}$

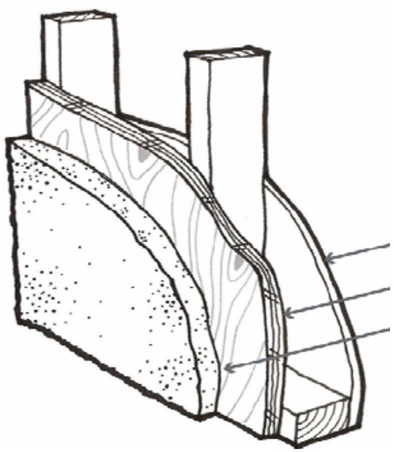
Torsional Imbalance $C_T = \frac{\tau}{T}$

STORY

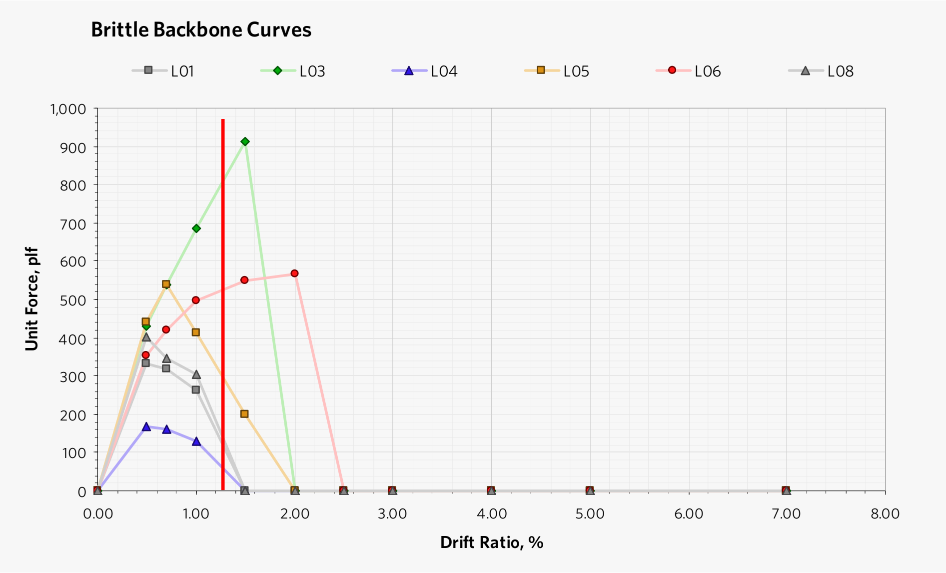
STRENGTH

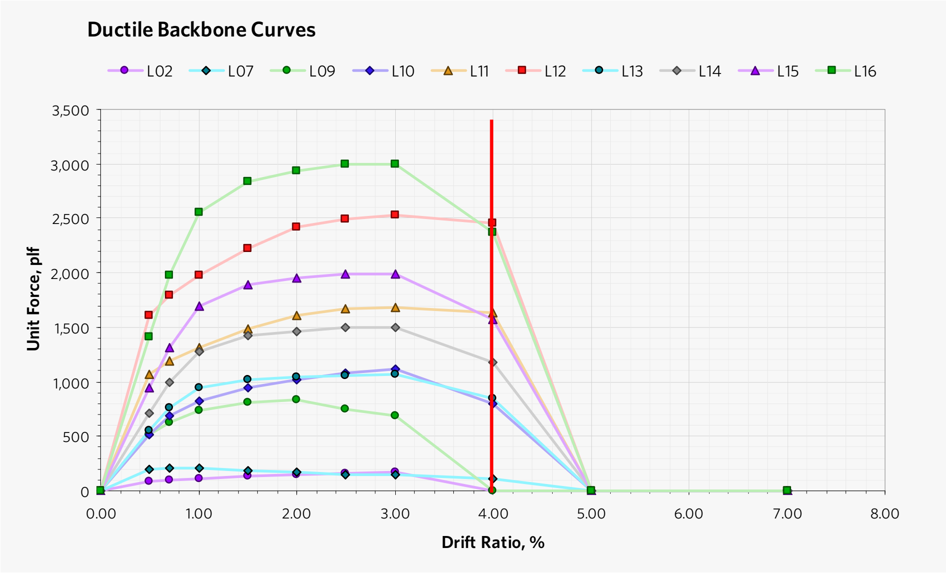
Structural Use of Non-conforming Materials





Deflection Criteria



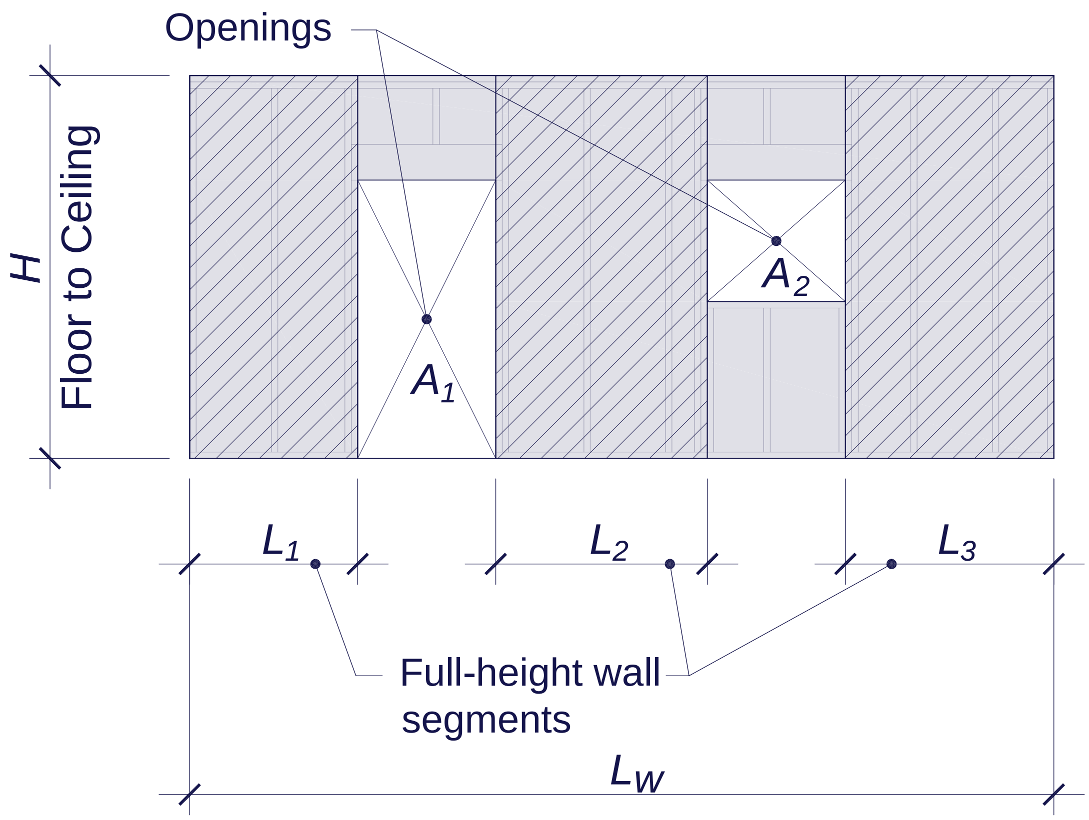


Name	High Displacement Capacity (Hd)		Low Displacement Capacity (Ld)	
	Ground Story	Upper Stories	Ground Story	Upper Stories
Onset of Strength Loss, Original Condition	4.0	4.0	1.25	1.25
Onset of Strength Loss, Retrofitted	4.0	4.0	4.0	1.25

Perforated Shearwalls

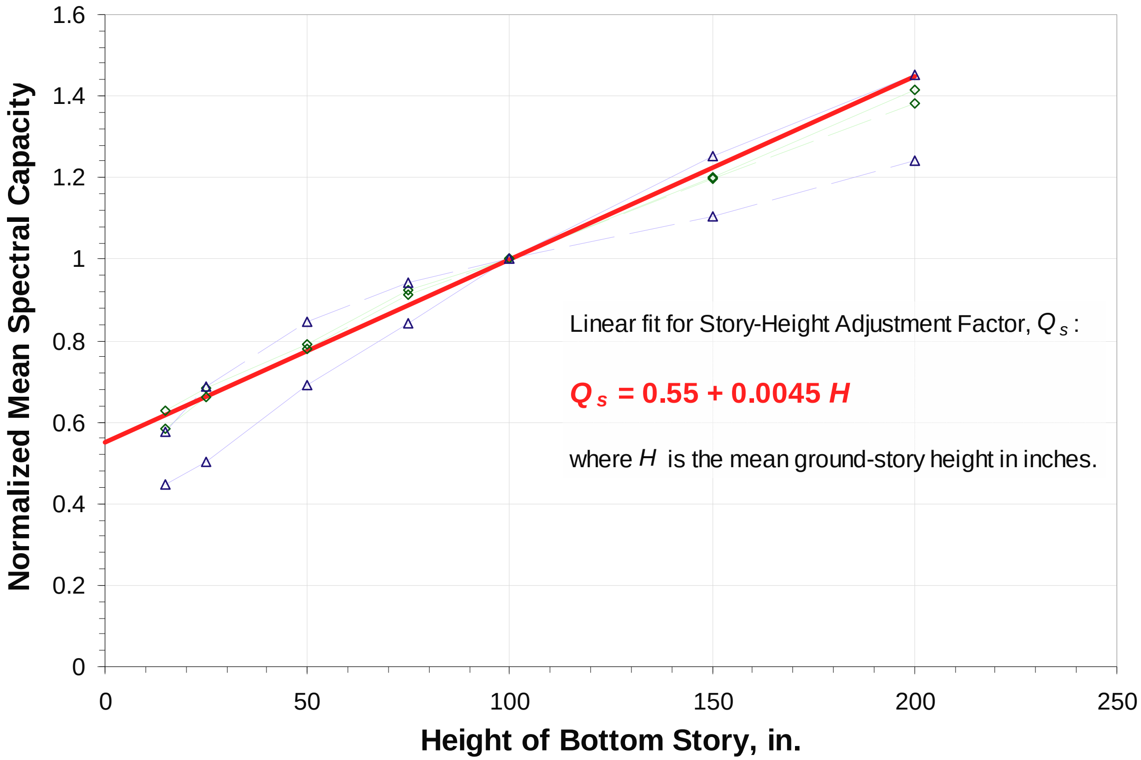
$$Q_{perf} = 0.92\alpha - 0.72\alpha^2 + 0.80\alpha^3$$

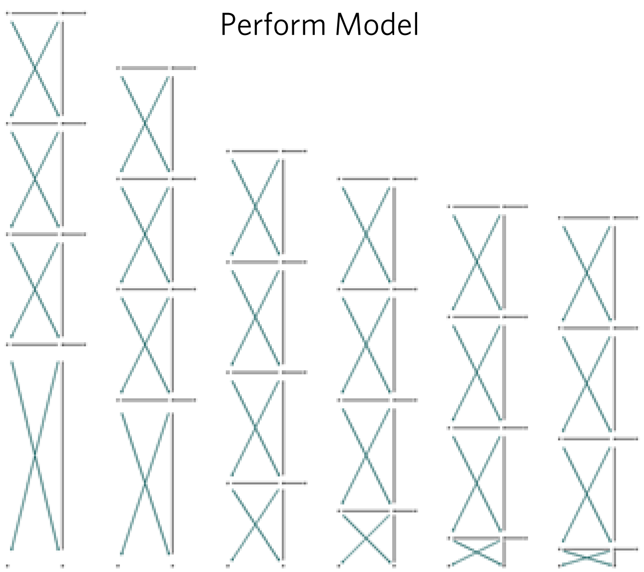
$$\alpha = \frac{1}{\left(1 + \frac{\sum A_i}{H \sum L_i}\right)}$$



$\Sigma A_i = A_1 + A_2$ $\Sigma L_i = L_1 + L_2 + L_3$

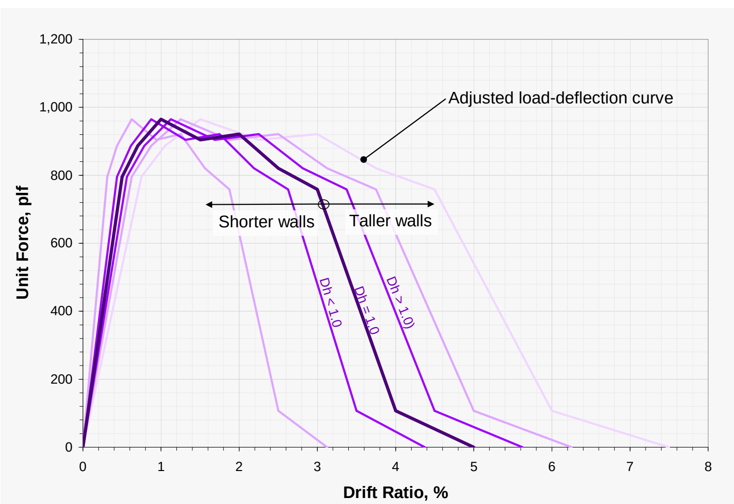
Story Height Adjustment Factor

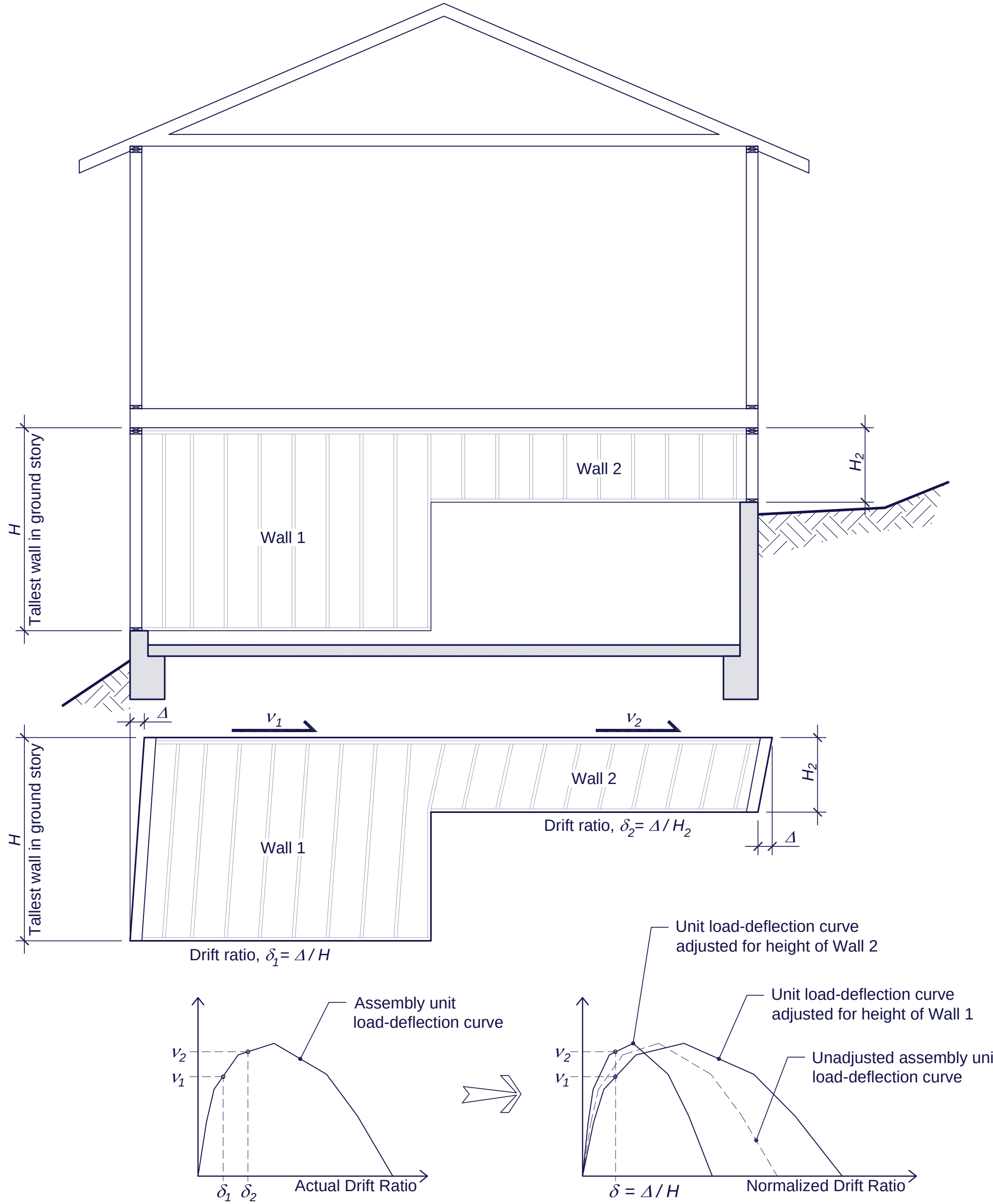




Wall Height Adjustment Factor

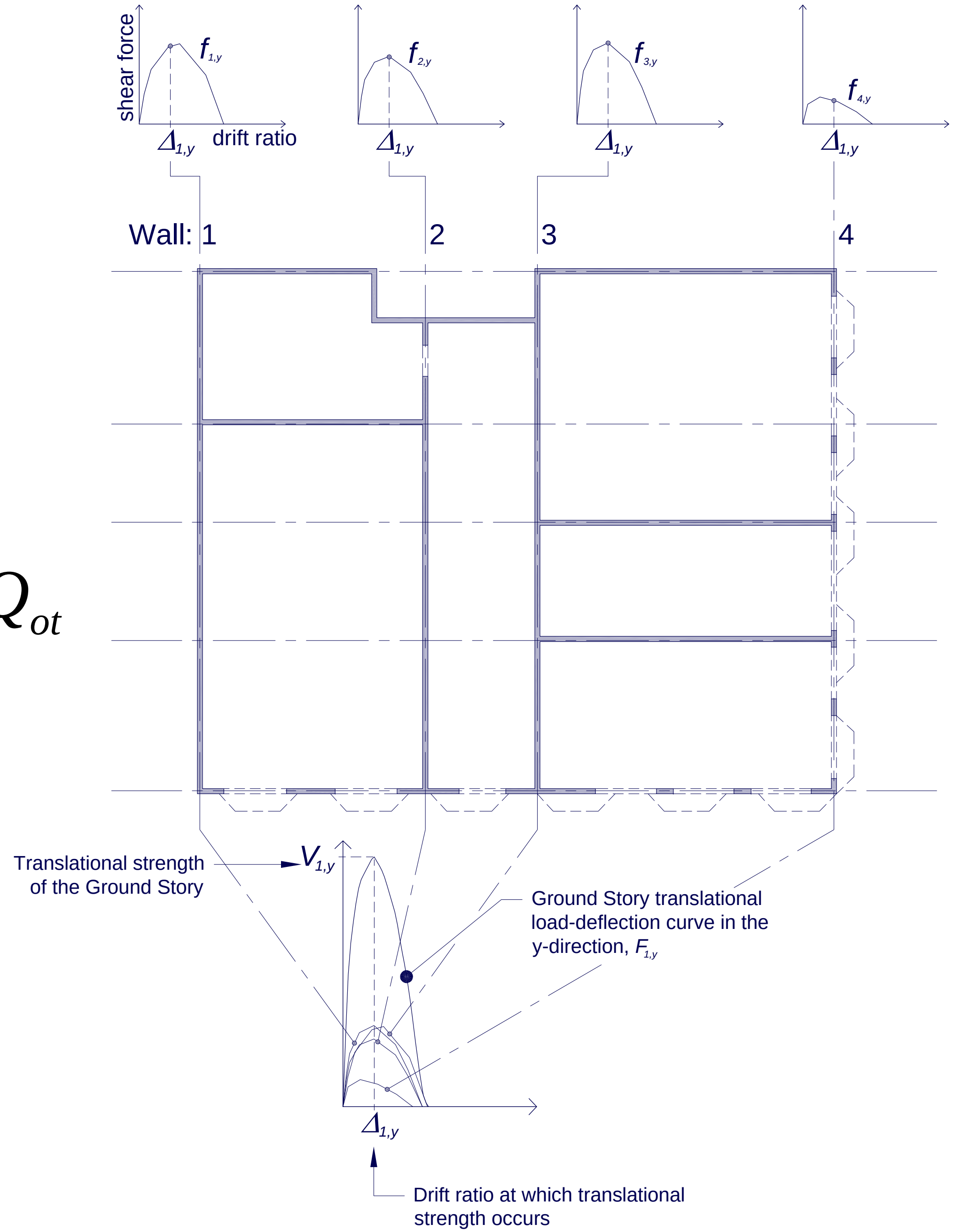
$$D_h = \frac{H_{wall}}{H}$$





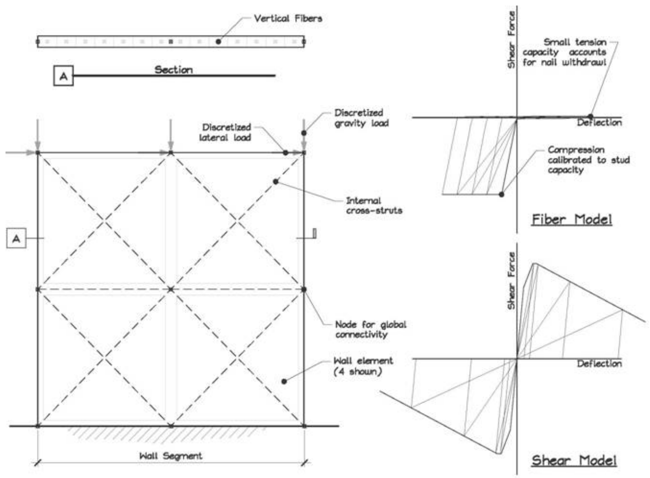
Pushover Curve to Find Peak Strength

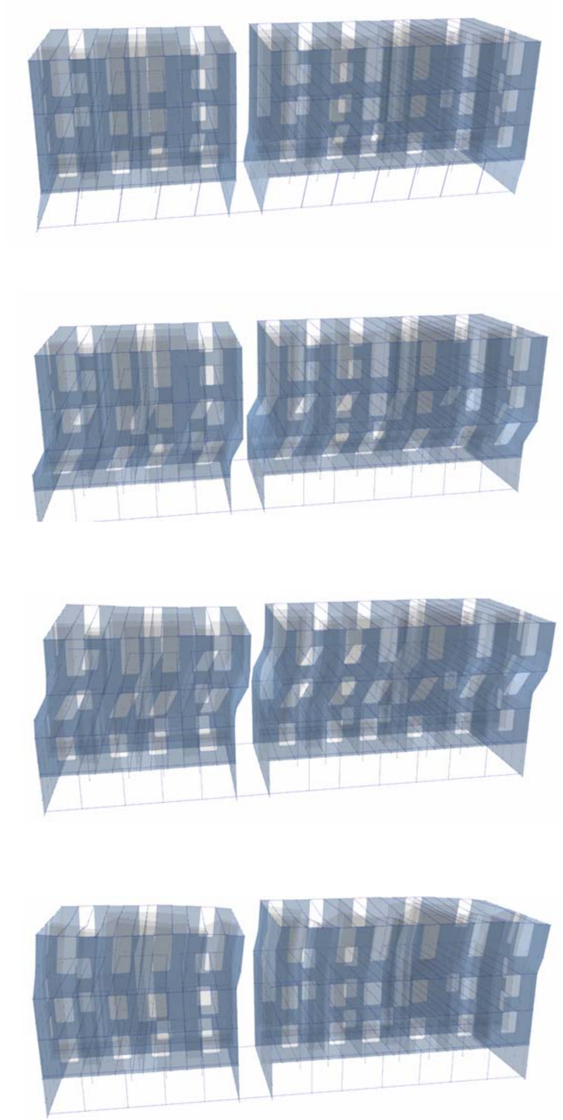
$$f_w(\delta_j) = v_w(\delta_j) L_w Q_{perf} Q_{ot}$$

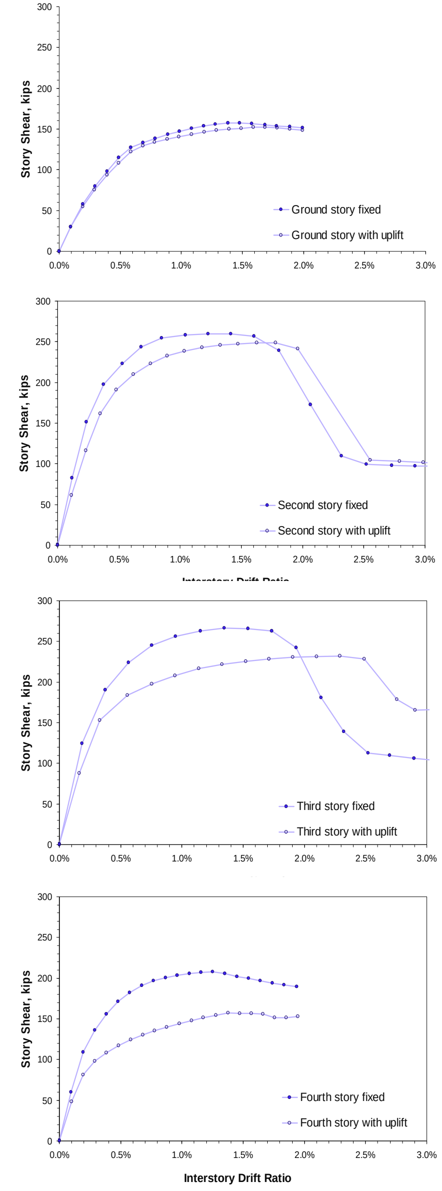


SIMPLIFIED OVERTURNING ADJUSTMENT

Overturning Reduction Factor







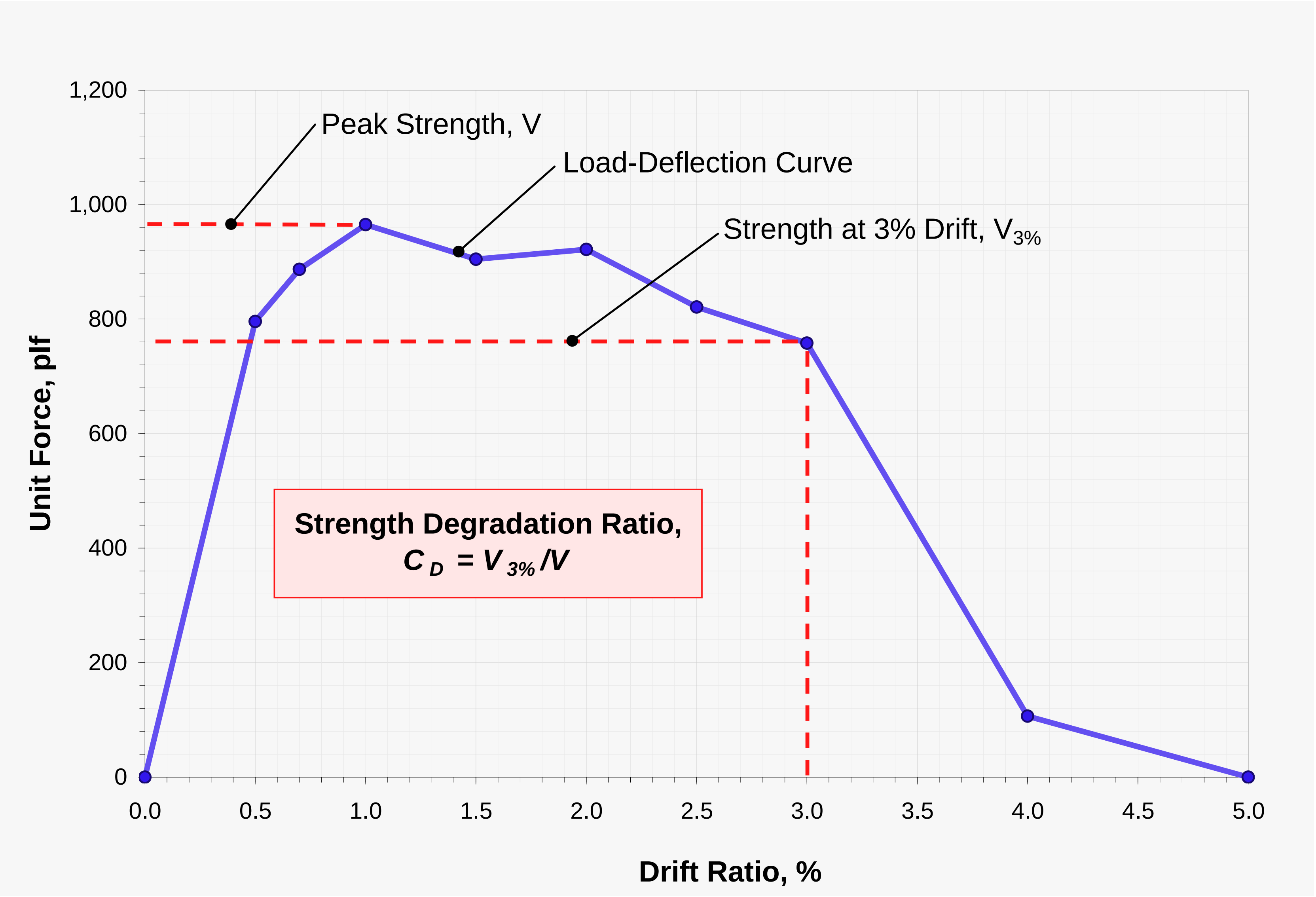
Overturning Reduction Factor Q_{ot}, for Upper Structure			
Level	Perpendicular to Framing	Parallel to Framing	Unknown or mixed
Two or more stories above	0.95	0.85	0.85
One story above	0.85	0.8	0.8
Top story	0.75	0.8	0.75

STRENGTH

DEGRADATION

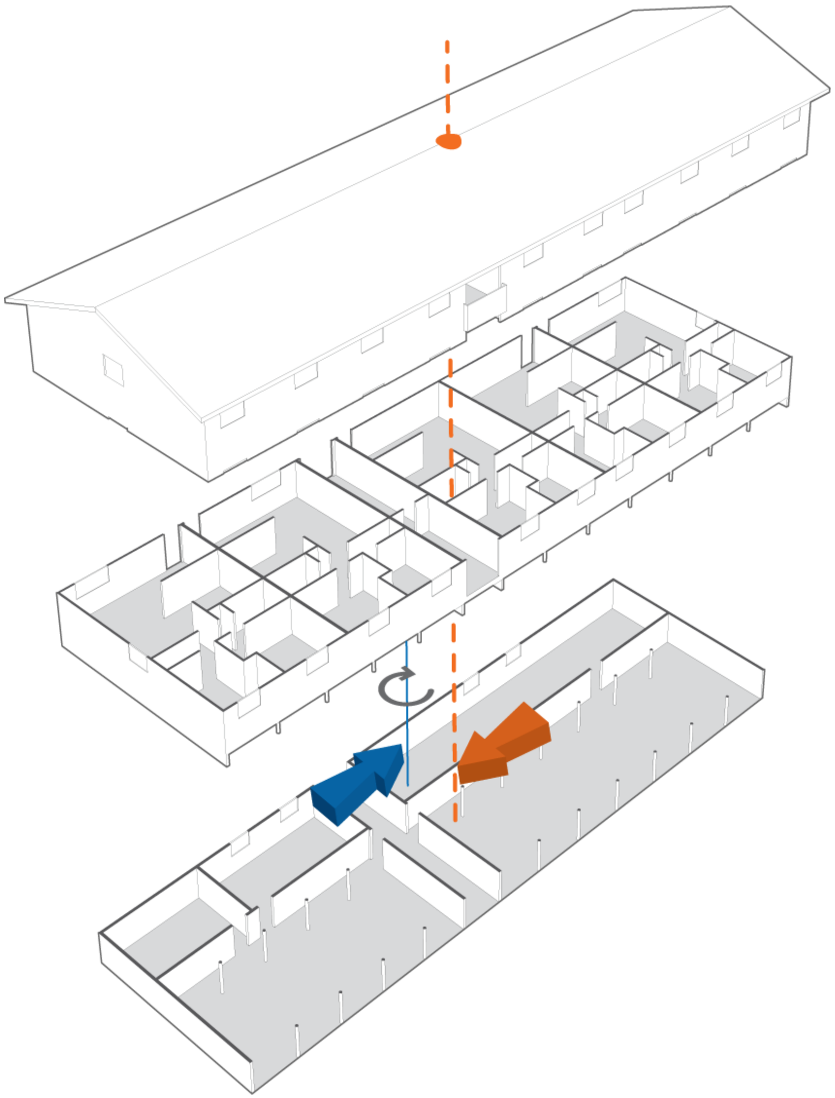
RATIO

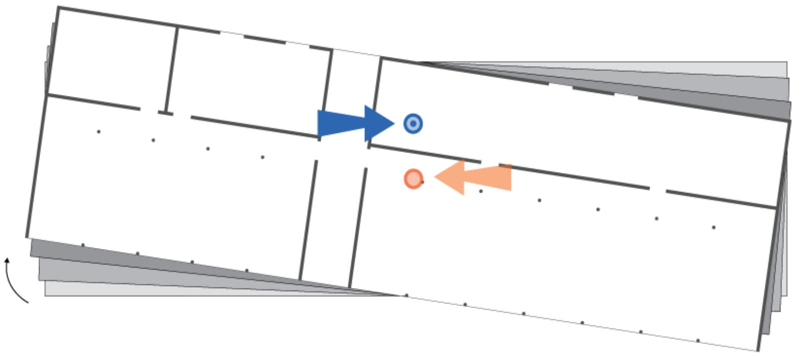
Strength Degradation Ratio



TORSIONAL IMBALANCE

Weak-Story Wood-Frame Buildings



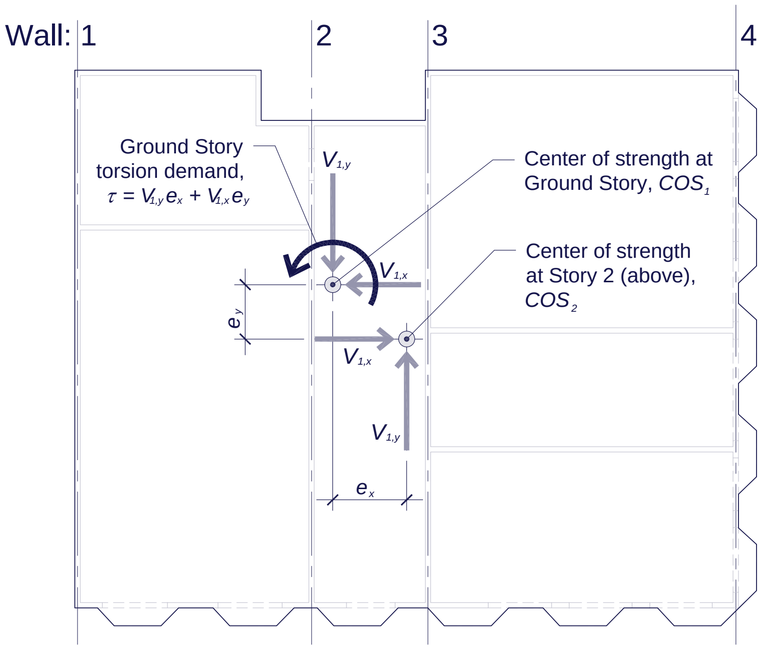


Torsion Demand

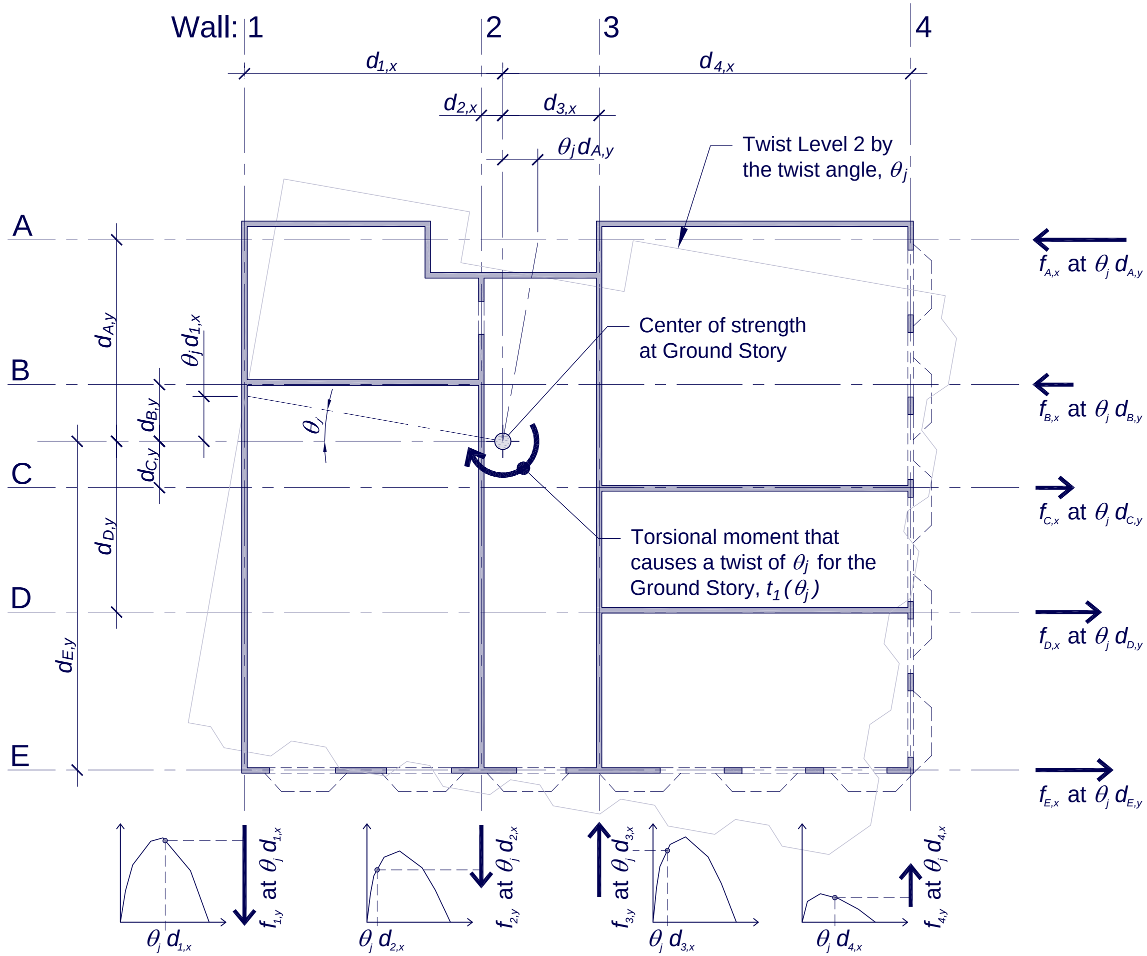
$$\tau = e_x V_{1,y} + e_y V_{1,x}$$

$$e_x = \left| COS_{2,x} - COS_{1,x} \right|$$

$$e_y = \left| COS_{2,y} - COS_{1,y} \right|$$



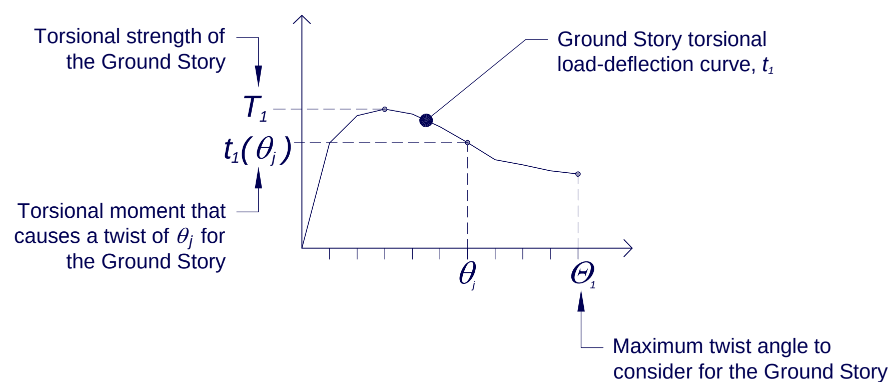
Torsion Capacity



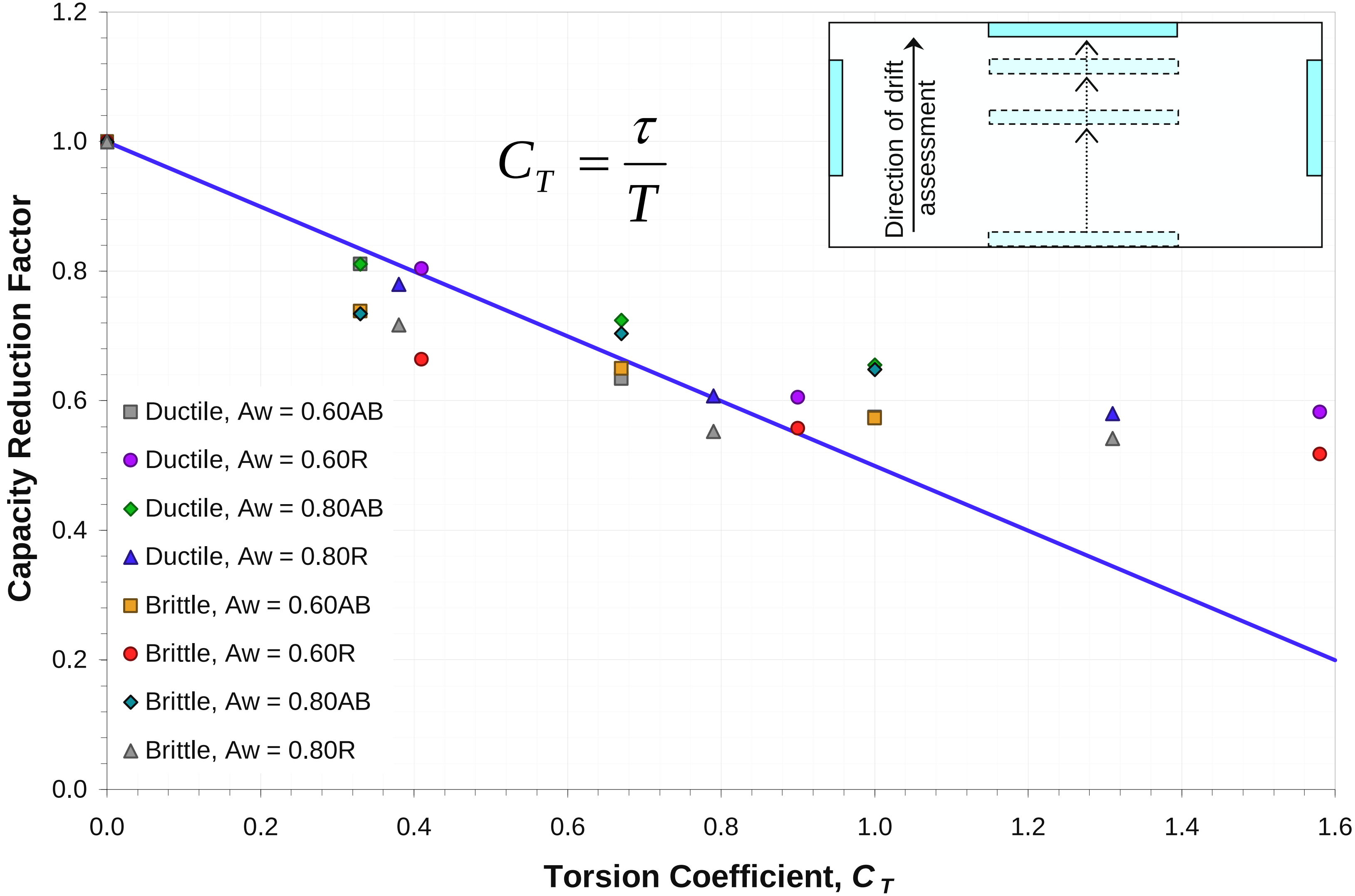
Torsion Backbone Curve

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

$$T = \max\left[t(\theta_j)\right]$$



Accounting for Torsion



CALCULATE

SPECTRAL CAPACITY

Spectral Capacity, Sc

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

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

Modifier for *POE* = 0.2

Mean spectral capacity, S_m

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

$$S_{c,x} \geq S_{MS}$$ 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 ($V_{rmax} > V_{re}$)

upper limit $$V_{r\max,x} = \left(0.11A_{U,x} + 1.22\right)\cdot V_{U,x}$$

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

$$X_0 = A_U^{0.48} Q_s\left(1 - 0.5C_T\right) \quad X_1 = 1.48X_0 \quad X_2 = 0.35X_0$$
$$Y_0 = A_U^{0.6} Q_s\left(1 - 0.5C_T\right) \quad Y_1 = 0.96Y_0 \quad Y_2 = 0.07Y_0$$

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

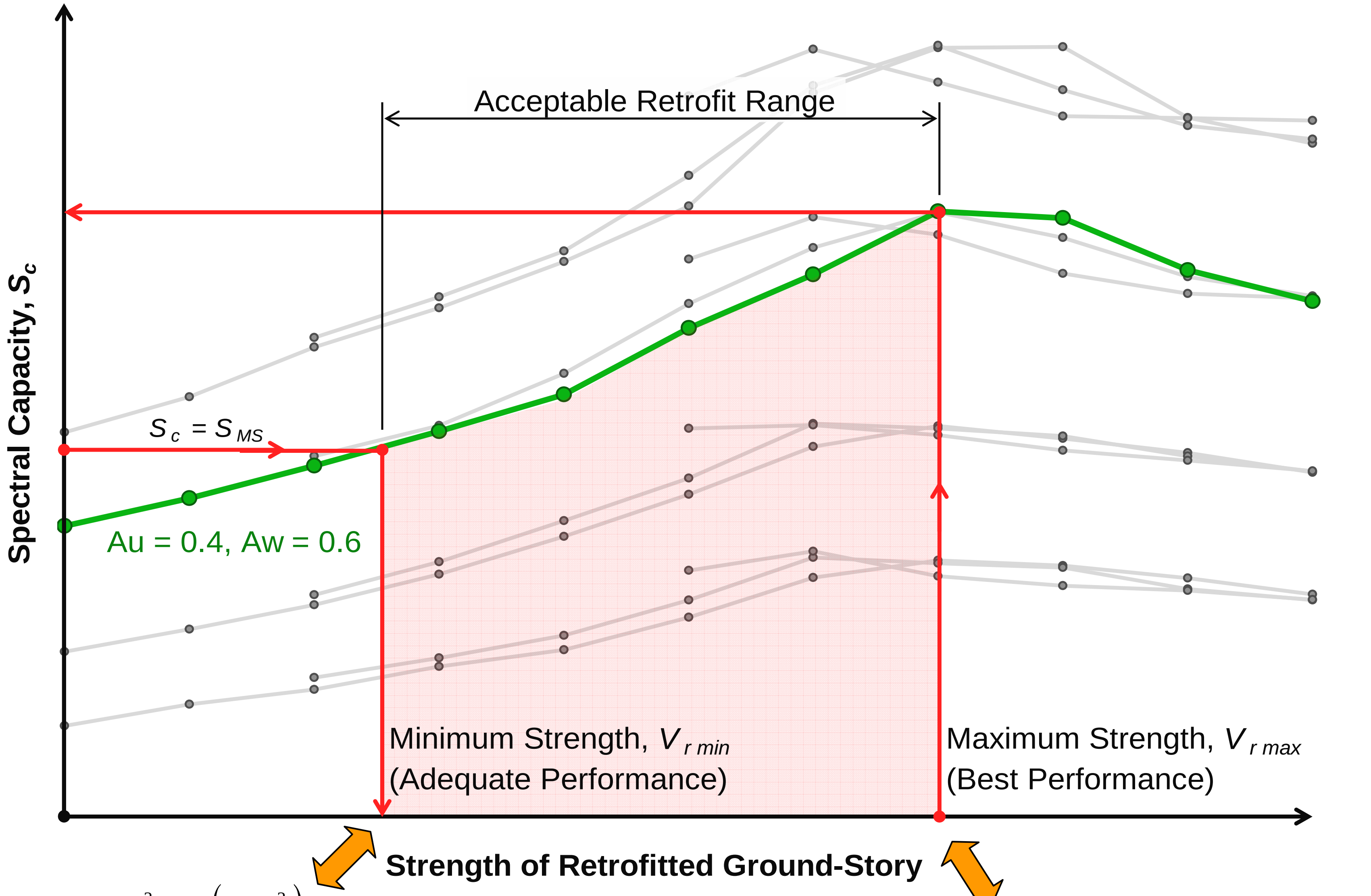
For buildings with weak upper structures ($V_{rmax} < V_{re}$)

use 90% – 110% of upper limit $$V_{r\max,x} = \left(0.11A_{U,x} + 1.22\right)\cdot V_{U,x}$$

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

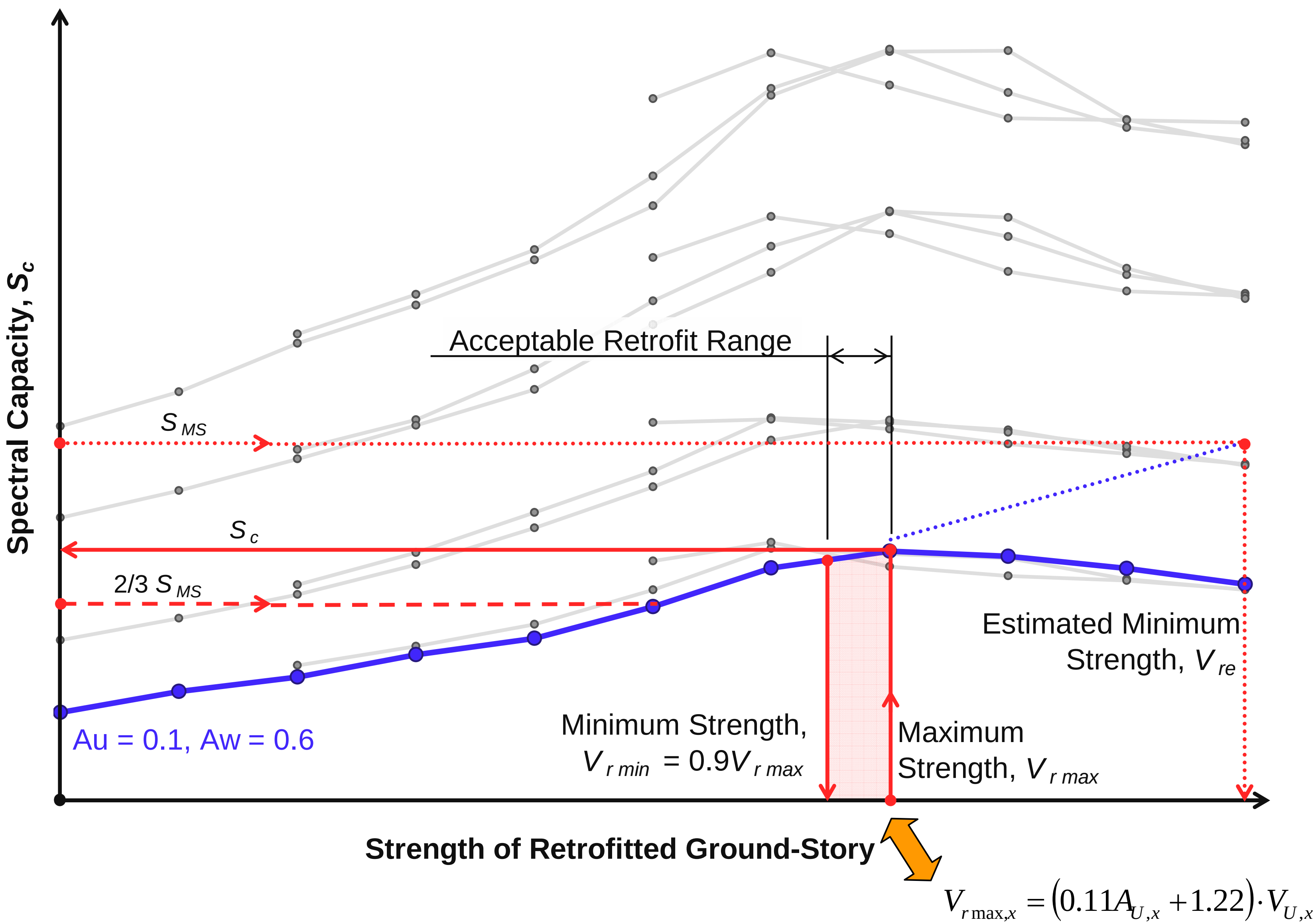
Range of Retrofit Strength



$$V_{re,x} = \frac{S_{MS} - X_2 C_D^3 - Y_2\left(1 - C_D^3\right)}{X_1 C_D^3 + Y_1\left(1 - C_D^3\right)}$$

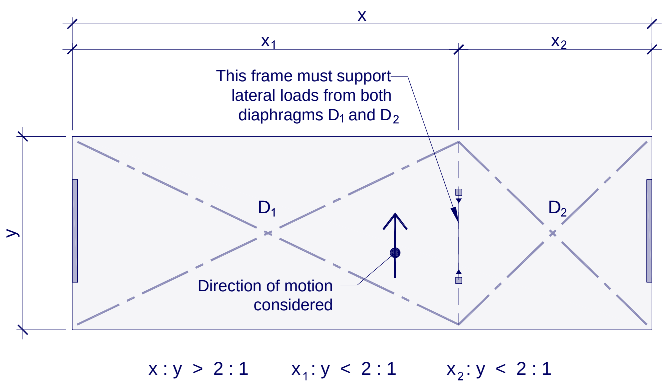
$$V_{r\max,x} = \left(0.11 A_{U,x} + 1.22\right) \cdot V_{U,x}$$

Range of Retrofit Strength

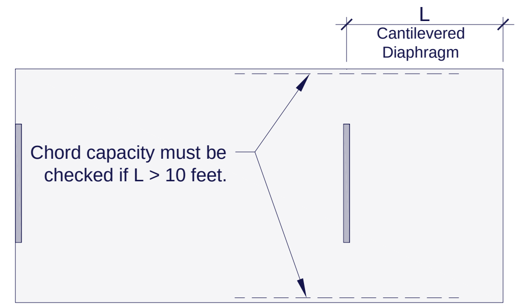


Retrofit

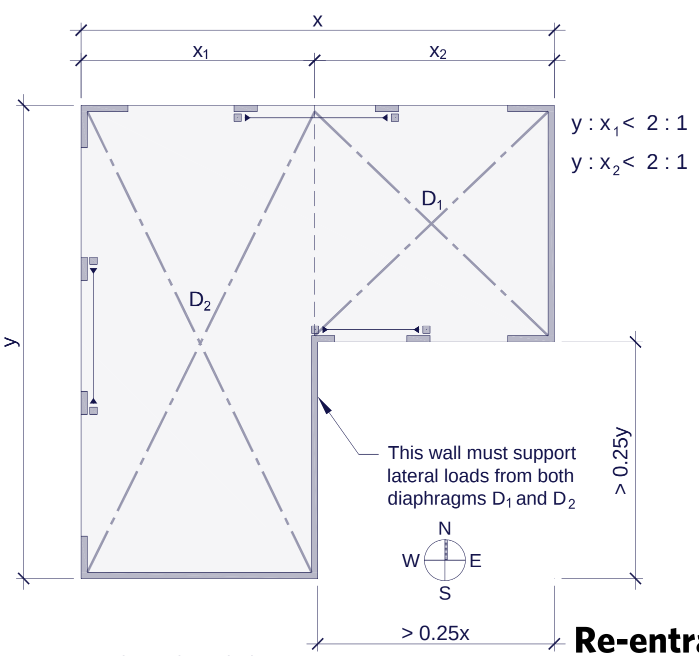
Regularizing Diaphragms



Aspect ratios

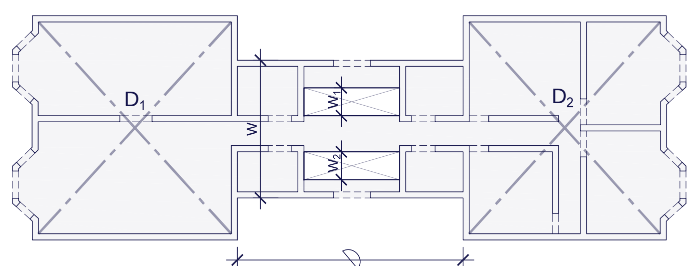


Cantilevers



North-South Analysis

Re-entrant corners



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

Openings

Retrofit Placement to Minimize Torsion

Added retrofit strength -

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

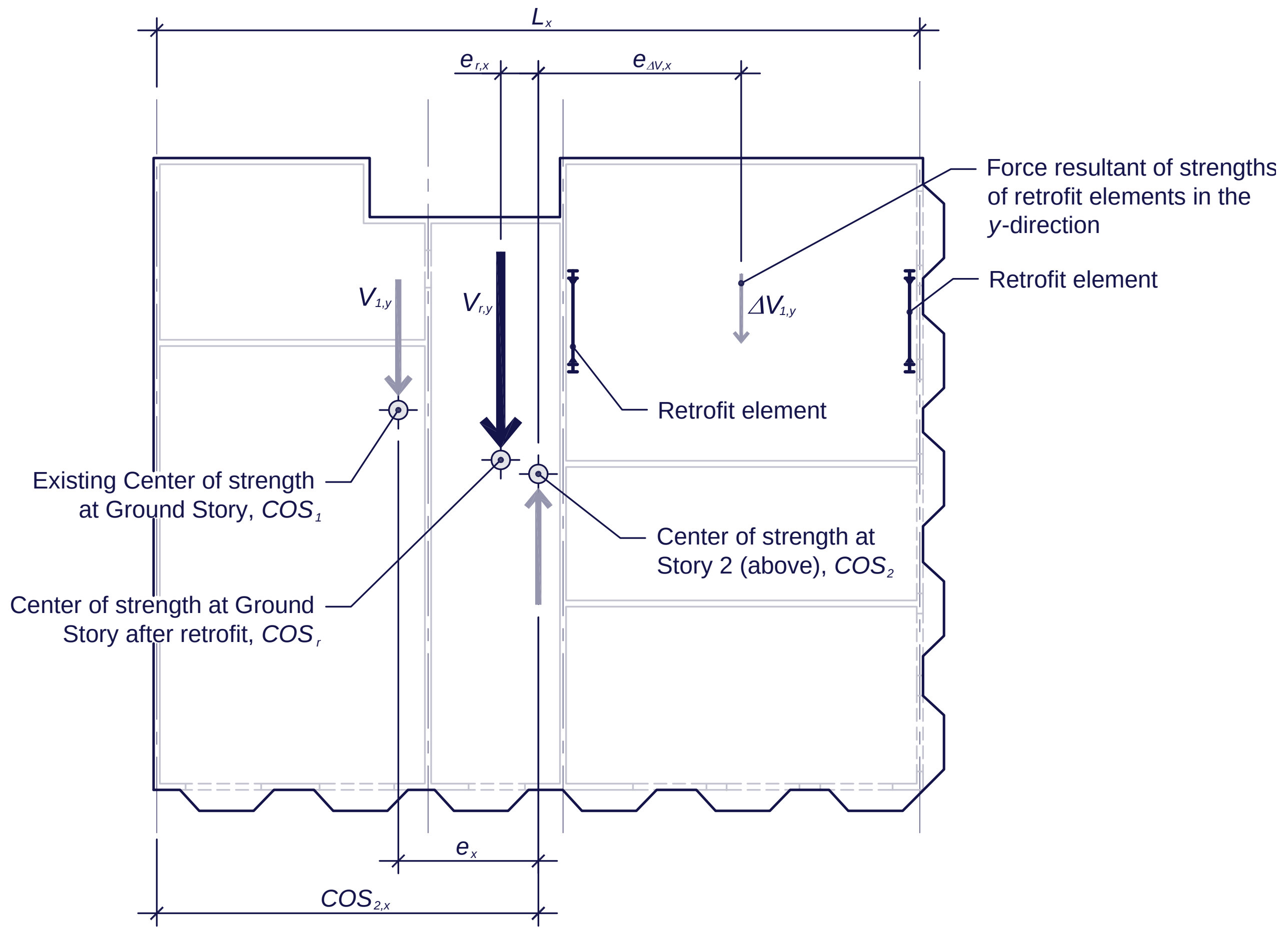
Place to eliminate torsion, limited by building dimension

$$e_{\Delta V,x} = \frac{e_x V_{1,y}}{\Delta V_{1,y}} \le \left(L_x - COS_{2,x}\right)$$

Range of acceptable eccentricity -

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

$$e_{\max,x} = e_{\min,x} + 0.05L_x$$



MAKING

IT

SIMPLE

wst

weak-story tool

FEMA

Evaluation and Retrofit Guidelines for Weak-Story Wood Buildings