FEMA P-807: Guidelines for Seismic Retrofit of Weak-Story Wood-Framed Buildings

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SUMMARY:
The *FEMA P-807 Guidelines for Seismic Retrofit of Weak-Story Wood-framed Buildings* are cost-effective retrofit procedures for a vulnerable class of buildings with a history of poor performance in earthquakes in the United States.

The *Guidelines'* cost-effective retrofit solutions limit work to the ground story. The Relative Strength Method optimizes the expected seismic performance by increasing the strength and ductility of the ground story without over-strengthening. Extensive modeling, using a broad scope incremental dynamic analysis (IDA), examines a population of around six hundred (600) simple surrogate structures. The population was created from permutations of five normalized parameters: ground story strength, upper structure strength, ground to upper story strength ratio, ductility and torsional imbalance.

The procedure itself is straightforward and prescriptive. The engineer needs only to characterize the subject building (i.e. determine the strength, weight, and other relevant parameters) to calculate if and what kind of retrofit is required.

1. BACKGROUND

1.1. Scope

Weak-story, wood-framed, multi-unit apartment buildings (three or four stories), are prevalent in the seismically active regions of California and the Pacific Northwest of United States. In San Francisco, California, 8% of the population is housed in 4,400 potentially dangerous multi-unit buildings. These structures have a history of poor performance in recent earthquakes since they were typically constructed between the 1940s and 1970s, and predate the use of modern seismic codes.

The upper structure tends to be strong, but brittle. This is because there are numerous interconnected walls that are sheathed with finish material, such as gypsum wallboard or lath and plaster. However, the ground story has relatively few walls due to parking or commercial uses. This strength irregularity tends to concentrate lateral deformations in the ground story. Building codes for new construction are poorly suited for the evaluation and retrofit of these types of buildings. Code procedures for evaluation of existing buildings such as ASCE 41 exist, but optimizing performance relative to cost requires expertise in nonlinear analysis that can be expensive to implement.

There is need for design guidelines that improve life safety, while being cost-effective. One way to achieve economies on construction would be to confine retrofit construction to the ground floor. Significant study was required in order to quantify potential improvements in seismic performance given this limited retrofit scope. The Federal Emergency Management Agency of the United States (FEMA) funded the Applied Technology Council (ATC), to perform the studies necessary and to create a document summarizing the findings and enumerating design guidelines.

Figure 1.1. Multi-unit apartment building that suffered a weak-story failure in the 1989 Loma Prieta earthquake. Note the presence of garage doors at the ground story. (Raymond B. Seed, National Information Service for Earthquake Engineering, University of California, Berkeley)

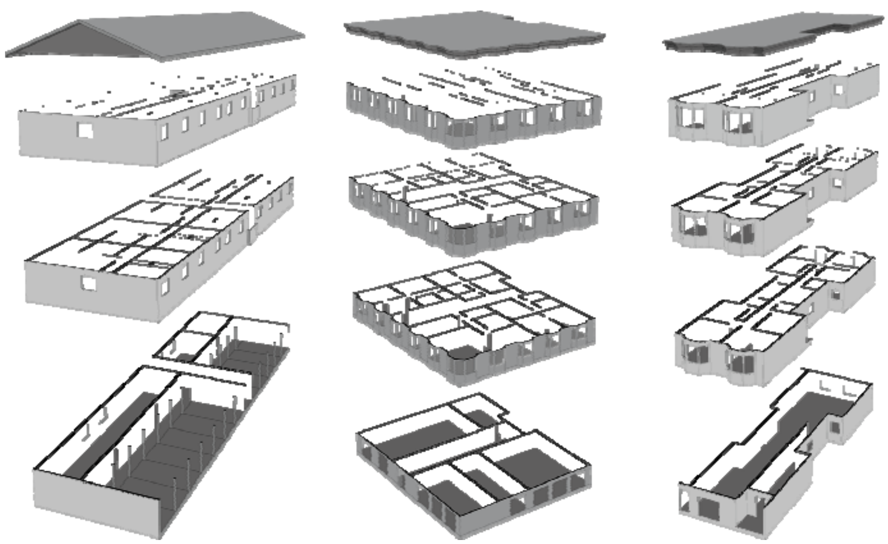

Figure 1.2. Diagrams of three archetype weak-story structures show the upper structure with numerous interconnected walls. Note lack of walls in the ground story, due to parking and commercial uses.

1.2. Dominant Deformation Mode

As seen in the photograph in Figure 1.1, weak-story buildings tend to fail in side sway of the ground story due to a lack of shear strength. This effect is exacerbated in some cases by torsional irregularity. Because the upper structure can be relatively strong, it tends to remain relatively undamaged, as deformation is concentrated in the ground story. Stiffness is often the focus of conventional methods of seismic analysis, yet the relative strength between the ground and upper stories is much more critical in determining the presence of the sort of vulnerability shown in Figure 1.1. As such, the buildings are termed *weak*-story structures rather than *soft*-story.

The strength of the upper structure derives from numerous wood stud walls that are the partitions of the living units, as illustrated in Figure 1.2. These walls may be sheathed with an assortment of materials including both structural wood panels, such as plywood, and "non-structural" finishes, such as gypsum wallboard, lath and plaster, cement stucco, etc. The presence of finishes greatly affects the lateral strength and overall behaviour. It is not conservative to neglect this material, as doing so may lead to an improper assessment of the propensity toward weak-story behaviour. The walls are interconnected elements, both load bearing and non-load bearing that form a grillage of elements. Consequently, a story with dense walls can resist high levels of lateral loads, despite the lack of modern hardware used to ensure continuous load paths.

2. RELATIVE STRENGTH METHOD

2.1. Basic Concept

The Relative Strength Method was developed for the *Guidelines* as a means of optimizing the seismic performance under the constraint of adding retrofit elements only to the ground floor. The new elements add strength and deformation capacity to create a ductile, energy absorbing story, but they do not prevent the ground floor side-sway mechanism. This is illustrated in Figure 2.1. By using a capacity design to determine the upper structure's strength, a retrofitted ground story is proportioned to be weaker than the upper stories yet ductile so that lateral stability is maintained through large deformations. This strategy utilizes the capacity of the upper structure, keeping it within its elastic range, thus protecting the brittle upper stories. This retrofit approach yields high value by optimizing performance while controlling costs and minimizing disruption.

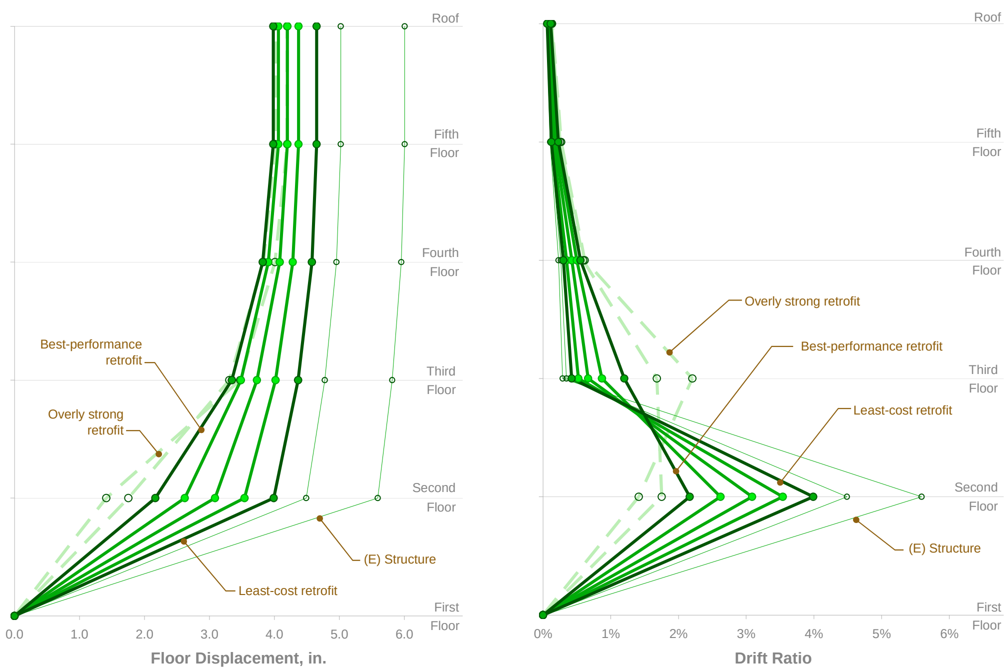

Figure 2.1. Displacements (left) and interstory drift ratios (right) are plotted for an archetype building, showing the unretrofitted condition and that of several retrofit options. The retrofits are new ductile elements of various strengths, located only in the ground story. The Relative Strength Method recognizes that there is a limit of capacity set by the upper structure.

2.2. Analytical Framework

The Relative Strength Method was developed through extensive analytical modeling using incremental dynamic analysis (IDA). The analysis scope examines a population of over six hundred (600) surrogate structures. The population (see Figure 2.2) was created from permutations of five normalized parameters: ground story strength, upper structure strength, ground to upper story strength ratio, ductility, and torsional imbalance. Hysteretic properties and lateral strength were based on the available results from testing for a broad array of structural and non-structural walls. The surrogate structures were subjected to an incremental dynamic analysis (IDA) using the FEMA P-695 far field record set (2 components of 22 events at 35 increments of intensity). The results are fitted to a lognormal distribution, and design equations were created empirically through regression considering the five key parameters listed above.

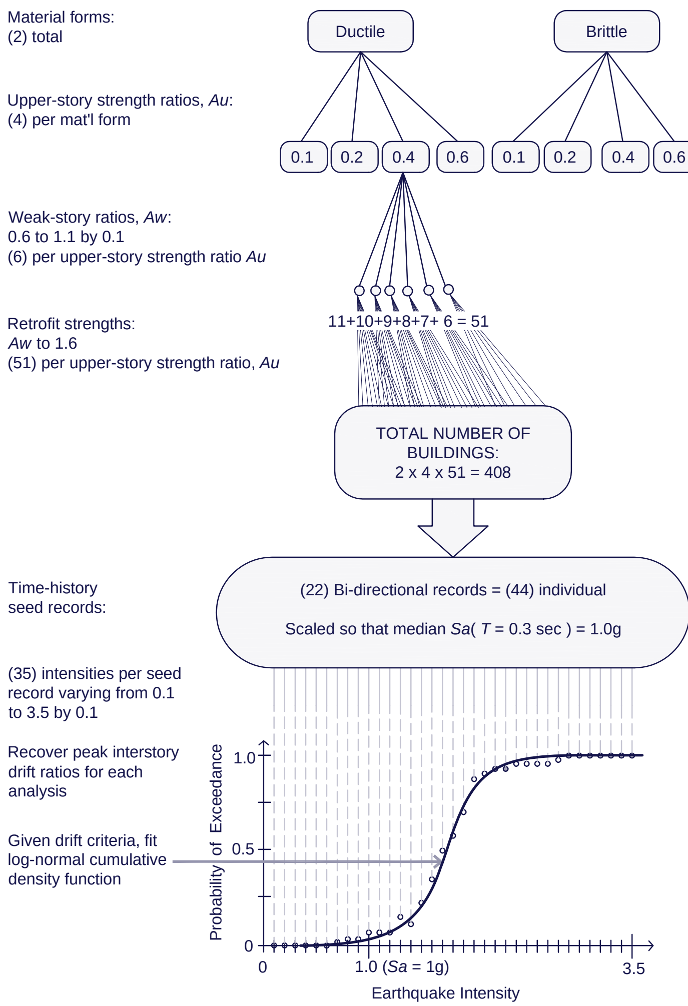

Figure 2.2. Illustration of 2-D analysis framework.

Many of the models themselves are simple two-dimensional towers as illustrated in Figure 2.3. These models emulate the strength and backbone shape and hysteretic loop characteristics of story shears for the archetype buildings. The models were created with the software *CSI Perform 3D*. The analysis results were also verified using the software *SAWS*. Both ductile and brittle forms of the backbone curve were considered as shown in Figure 2.4, based on wall test results and realistic distributions of sheathing material found in the archetype buildings.

We quantify seismic performance by defining the "median spectral capacity" of a model as the spectral acceleration at which any story in the model reaches a preset drift limit for 50% of the records. For models with high displacement capacity (those with the ductile form), the drift limit is set at 4%. For models with low displacement capacity (those with the brittle form), the drift limit is set at 1.25%. These limits correspond to what is considered to be a near collapse state, referred to as the Onset of Strength Loss (OSL), where story shear strength is reached for the ductile and brittle forms of the models. With the median spectral capacity and the standard deviation, one may derive the capacity relative to any probability of exceedance. We account for the presence of torsional irregularity and ground story height by applying adjustment factors.

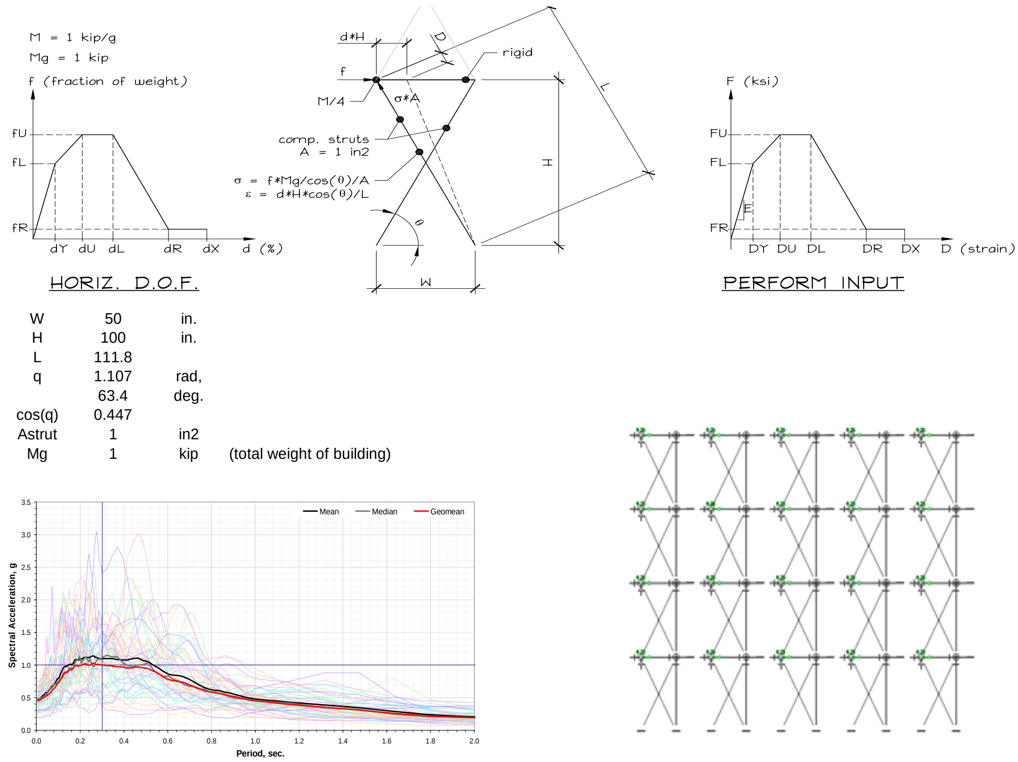

Figure 2.3. Illustration of models used in the incremental dynamic analysis. The vertical elements in the five structures in the lower right are for dead load to capture P-delta effects. These models were built in CSI Perform. The earthquake inputs were the FEMA P-695 far field record set shown in the lower left.

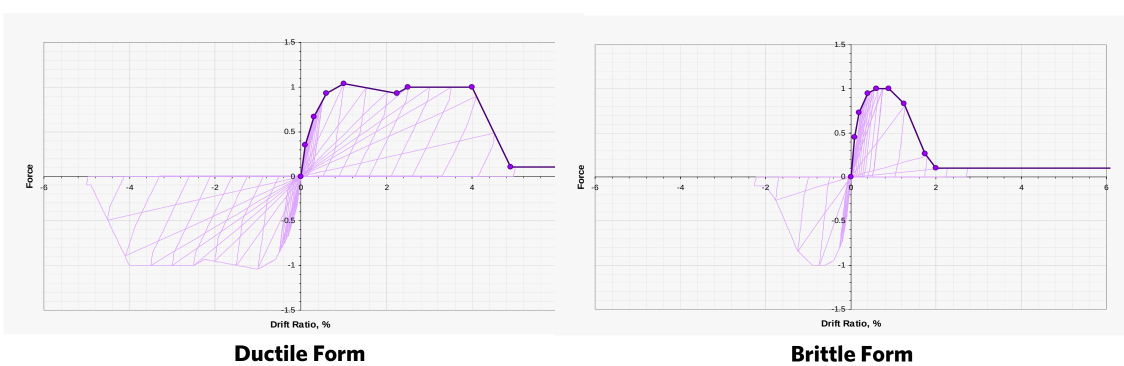

Figure 2.4. The backbone curves and hysteretic loops used in the IDA for the ductile form (left) and brittle form (right) of the structures.

2.3. Analysis Results

The population of surrogate structures is subjected to the suite of earthquake records for the 35 intensities. The results for each building are processed to determine the "median spectral capacity" (see Section 2.2 above). A given surrogate structure representing the existing condition without retrofit is analyzed. Ground-floor retrofit is added to the model of the existing condition, and for subsequent models, the retrofit strength is increased until the greatest spectral capacity is reached (see Figure 2.5). The Relative Strength Method postulates that there will be an upper limit of capacity for possible ground floor retrofits that depends upon the strength of the upper structure. That is, when the retrofit is too strong, the concentration of deformations will move into the upper stories (Figure 2.1).

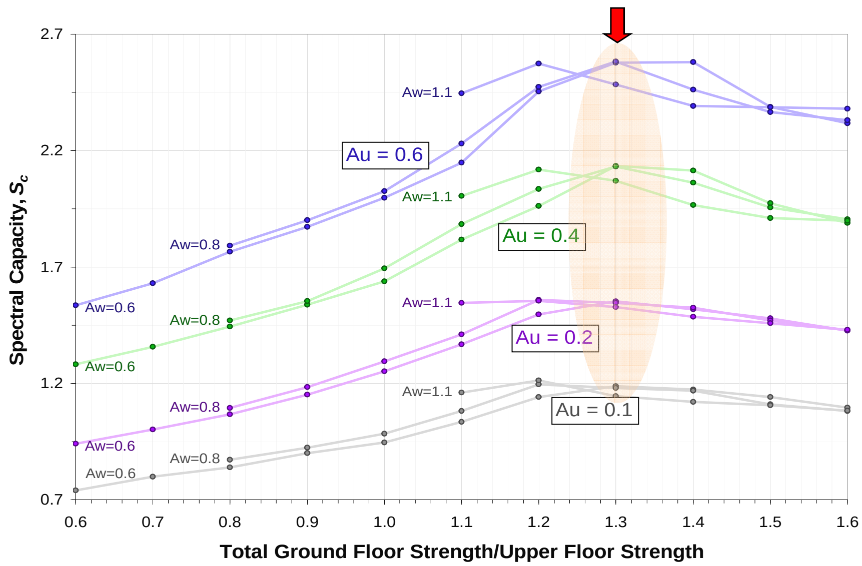

Figure 2.5. A plot showing the trend of Spectral Capacity with increasing ground-story retrofit (quantified by weak-story ratio, Aw) for various families of upper structure strength ratio Au. Peak spectral capacity for all families occurs around Aw = 1.3.

Figure 2.5 illustrates the effect of increasing ground-story retrofit strength for various values upper-structure strength and relative strength between the upper and ground stories. The vertical axis is the spectral capacity of the surrogate structures. The horizontal axis is ratio of ground-story to upper-story strength. There are four connected series of results representing structures with different values of upper story strength relative to total structural. For example, $A_U = 0.6$ is a family of buildings with an upper structure lateral strength capacity of 0.6 times its total mass. To the left of each series of buildings in each family is the ratio of upper-story to ground-story strength, termed A_w. As structure with $A_w = 0.6$ implies that the ground story is 60% as strong as the upper story. The spectral capacity increases with each increment of retrofit strength, up to a peak capacity. The peak capacity for each series occurs near the point where the ground-story strength is 1.3 times the upper-story strength.

2.4. Adjustments for Torsion and Story Height

To study the effect of torsional irregularity, a series of analytical models were created with each building represented by four four-story towers. A parameter relating the shape of the building setback of one line of lateral resistance was constructed. We create an array of models varying this parameter and subject them to bi-directional nonlinear response history analysis in the IDA framework. The overall spectral capacity was determined in the same manner as the 2-D analyses, but considering drift in both directions. The plot in Figure 2.6 shows the capacity reduction of each building with increased torsional irregularity (represented by the torsion coefficient, C_T), relative to the case 2-D analysis without consideration of torsion. The linear fit of the data represents the adjustment factor for torsional irregularity.

Another series of analytical models were created with various ground story heights to account for this effect. The incremental dynamic analysis (IDA) was performed and the spectral capacity determined based on the drift limits used for the base analysis. The plot in Figure 2.7 shows the capacity adjustment versus story height, relative to the base case. The straight-line fit of the data represents a capacity adjustment factor.

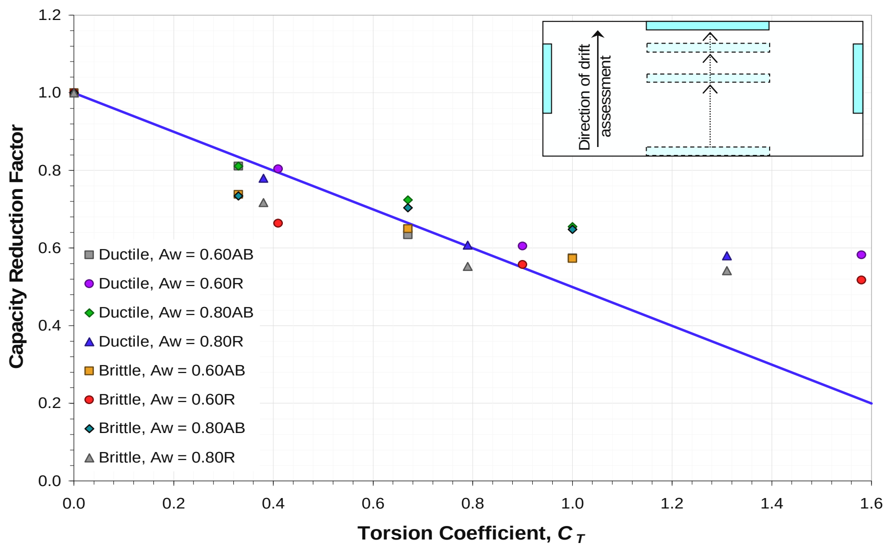

Figure 2.6. Plot of Torsion Coefficient, C_T versus reduction factor (relative to the base case with no torsion). Analytical models with various amounts of torsional imbalance were subjected to bi-directional input for the incremental dynamic analysis (IDA). The straight line conservatively applies a capacity reduction at very high level of torsional imbalance.

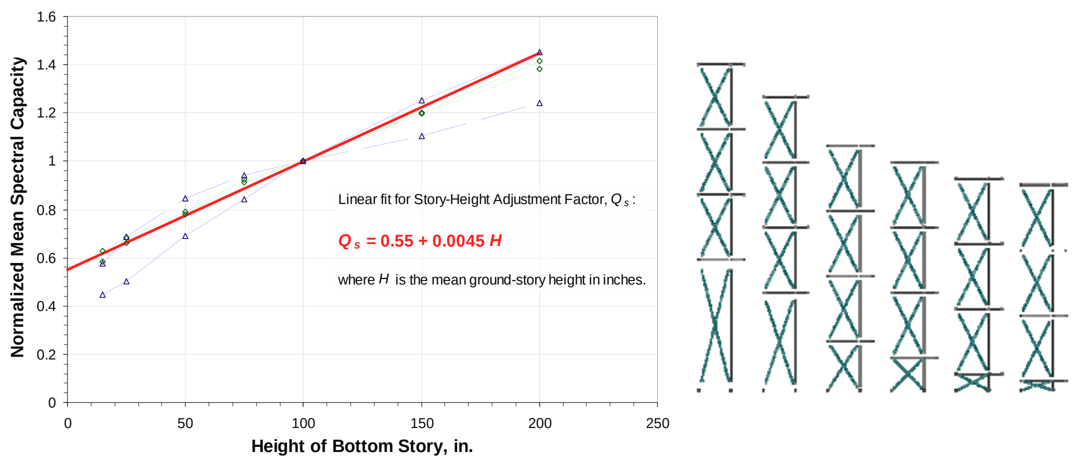

Figure 2.7. Story Height Adjustments based on IDA.

3. EVALUATION AND RETROFIT

3.1. Backbone curves

Calculating the realistic strength of each story is the critical step determining the characteristic coefficients. The first step is to determine the length and composition of sheathing for all walls at each floor. All walls are structural, even those typically considered to be "non-structural." It is not conservative to neglect walls, especially at the ground story where over-strengthening is to be avoided in order to achieve the ductile ground floor response.

Backbone curves for various sheathing materials are shown in Figure 3.1. These values are derived from tests, and have been reconciled to be internally consistent. Some tests were cyclic, with various loading protocols and some were monotonic. Reconciling these data required engineering judgement on the part of the authors.

To characterize the composite of sheathing materials used in a given wall assembly, the contribution from each layer is combined by means of a pushover curve. The load-deflection relationship of a wall assembly is typically estimated by adding the force ordinates of the individual sheathing materials. There is some adjustment required where structural wood panels are used in composite with non-structural finishes. The strength of the assembly is the peak force of the backbone curve.

The backbone curve for a given wall is obtained by multiplying the force ordinate of the assembly backbone curve by the length of the wall. The backbone curve of the wall is adjusted for perforations, recognizing the contributions of sections of wall around openings. Most structures of this vintage lack hardware used in modern wood construction to ensure an adequate load path. Adjustment values were developed based on modelling of archetype buildings and comparing pushover capacities of versions with and without overturning restraints. The backbone curves of the various walls are combined to determine backbone curve of the entire story in each direction, as shown in Figure 3.3, left.

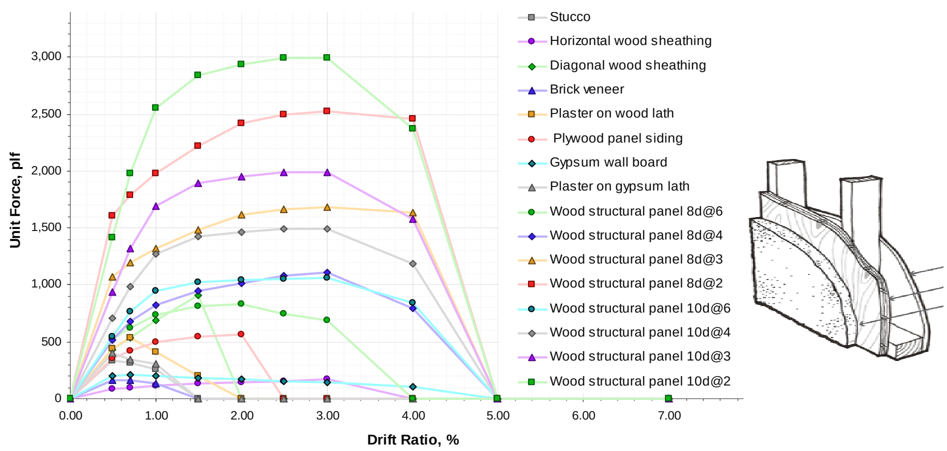

Figure 3.1. Backbone curves for various sheathing materials.

3.2. Coefficients

One must calculate the parameters shown in Figure **3.2** to characterize the structure and to link it with the under-girding analytical framework. The coefficients are the inputs for regression equations may be used to quantify seismic performance.

$C_{1,x} = A_{1,x} = \dfrac{V_{1,x}}{\sum_{j=2}^{N_s+1} W_j}$	$A_{U,x} = \dfrac{V_{U,x}}{W}$	$A_{W,x} = \dfrac{V_{1,x}}{V_{U,x}}$	$C_{D,x} = \dfrac{F_{1,x}(\delta = 3\%)}{V_{1,x}}$	$C_T = \dfrac{\tau}{T}$
Ground-story strength	Upper-story strength	Relative strength	Ductility	Torsion

Figure 3.2 Characteristic parameters.

The process of combining backbone curves physically represents translating the structure at the ground story without letting it twist and recording the strength required at each increment of displacement. This characterizes the structure in 2-D, allowing one to compute the various coefficients related to the strength of the upper structure (A_U) and ground story (A_1, C_1). We characterize the tendency of the ground story to degrade by relating its peak strength to that at a drift ratio of 3% (C_D). We calculate the relative strength to define the propensity toward weak-story behaviour (A_W).

Similarly to the process of computing the translational backbone curve of the ground story, we characterize the torsional irregularity using a torsional backbone curve. Physically, this would be like rotating the upper structure about the center of strength of the ground story and recording the required torque at each increment of twist angle. We define the concept of torsional demand as the product of the distance between the center of strength and the center of mass times the lateral strength of the ground story. The torsional coefficient, *(C_T)* is the ratio torsional demand to torsional capacity.

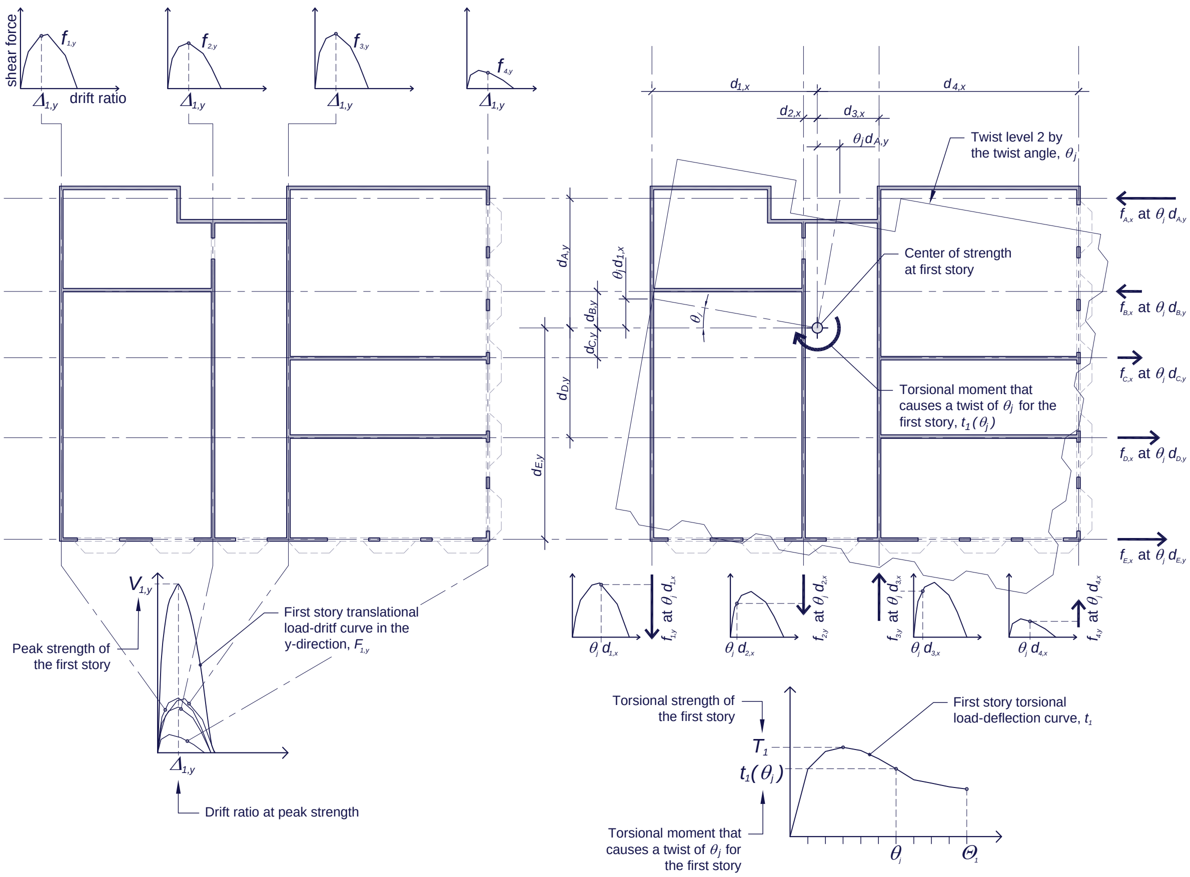

Figure 3.3. Left, illustration of procedure to compute translational backbone curve. Right, illustration of procedure to compute torsional backbone curve.

3.3. Spectral Capacity

To find the spectral capacity, S_c of a structure, one calculates the capacity of the surrogate structure using the equations in Figure 3.4 for the brittle (C_D=0) and ductile (C_D=1) forms, and then interpolates using the degradation ratio (C_D) of the structure. This capacity is then compared to the short period spectral acceleration demand that characterizes the seismic hazard under consideration, S_{MS}. If the capacity is greater than the demand (i.e. $S_c > S_{MS}$), then no retrofit is required. The equations in Figure 3.4 have embedded a probability of exceedance (POE) of 20%. If desired, a different POE may be selected, and the corresponding adjustment factor obtained from the *Guidelines.*

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

$$S_{c0,x} = \underset{\text{Modifier for } POE = 0.2}{0.60}\underbrace{(0.122 + 1.59A_{W,x})(1 - 0.5C_T)Q_s A_{U,x}^{0.60}}_{\text{Mean spectral capacity, } S_m} \qquad \mathrm{C_D = 0.0}$$

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

Figure 3.4 Evaluation equations

3.4. Optimal Retrofit

If the capacity is less than the demand, retrofit is required. We seek to find a retrofit that leads to acceptable seismic performance; namely, where $S_c > S_{MS}$. The Relative Strength Method suggests that the performance improvement is limited by the constraint of doing construction only in the ground floor. Conversely, there is some amount of retrofit that may lead to acceptable performance that is less than optimal. The equations in Figure 3.5 set the bounds on the retrofit strength. The upper limit yields a retrofit that gives the best performance for a ground story only retrofit. If the upper structure is very strong, then the lower limit may be used to provide a less costly ground floor retrofit that still meets the desired seismic performance.

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

Figure 3.5 Retrofit Equations

3.5. Retrofit

Once the added strength for the retrofit is determined, the new elements are placed in locations that are architecturally suitable and that minimize torsion. These elements need to be ductile, capable of at least 4% drift and able to maintain 80% of the peak strength at 3% drift. The new elements are then re-evaluated using the equations in Figure 3.4. Capacity design practices need to be rigorously applied to the foundations, collectors and diaphragm to ensure the system is capable of the high displacement demands. The equations also assume that diaphragms of the real structure are rigid enough to work with limited flexibility or yielding. The *Guidelines* have requirements for the placement of new retrofit elements to ensure that the diaphragms are suitable. For example, a diaphragm with a high aspect ratio, would need several retrofit elements placed along its length to minimize deformations and demands between new elements. Other irregularities can be mitigated in a similar way.

3.6. The Weak Story Tool

The backbone curves needed for characteristic equations are conceptually simple, but there is a significant amount of bookkeeping. The Weak Story Tool (WST) is software developed to simplify these tasks. The user graphically lays out the walls, and defines assemblies from drop down menus. The pushover curves and characteristic equations are automatically generated. The evaluation and retrofit requirements are also automatically provided by the WST.

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