Benchmarking Seismic Base Shear to Historical Practice

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Background

Changes to seismic design procedures for wood construction often lead designers and structural standards committees to ask the familiar question: "*How do all of these changes impact the design relative to historical practice?*" One approach to answering this question is to perform a design twice – once using the proposed version of the design standard, then again using the current or previous version – and compare the final results. This paper summarizes a comparison of seismic design loads (seismic base shear) and resistance values of wood structural panel shear walls over a period of approximately 50 years – beginning with the *1955 Uniform Building Code* (*UBC*) and concluding with the *2006 International Building Code* (*IBC*). The reference structure used in these design comparisons is a regular one-story wood-frame structure with wood structural panel shear walls.

Benchmark Design Format

Seismic load and wood-frame shear wall resistance are presented on an allowable stress design (ASD) basis as the benchmark design format because design loads and resistance provisions over the time period considered are predominantly based on ASD methods.

Benchmark Construction: Wood-Frame Shear Wall

The reference shear wall is assumed to be constructed as:

- Douglas-fir studs at 16 inches on center;
- 15/32-inch wood structural panel (sheathing grade);
- 10d common nails with 6-inch edge spacing and 12- inch field spacing; and
- Shear wall aspect ratio (wall height to wall width) h/w, = 2:1.

Changes to basic features of this reference shear wall are shown in **Table 1**.

Framing

From 1955 through to 1964, the *Uniform Building Code* (*UBC*) specified a minimum framing member thickness of 1-5/8 inches for horizontal roof and floor diaphragms and vertical wall diaphragms (i.e., shear walls). Framing thicknesses were later revised following the promulgation of lumber standards that specified a minimum nominal thickness and moisture content of framing members. In the 1967 *UBC*, reference to at least 2-inch nominal width framing replaced specific mention of 1-5/8 inch (actual) wide framing. By 1973, referenced *UBC* standards identified 2-inch nominal thickness as having minimum dressed thickness of 1-1/2 inches. This minimum actual thickness requirement continues to the present day. For shear walls having more closely spaced nails or greater shear resistance than the benchmark shear wall, modern codes may specify thicker framing such as at adjoining panel edges and bottom plates to minimize occurrence of splitting during fabrication or to delay onset of splitting failure under load.

Wood Structural Panel

The term "wood structural panel" reflects current terminology for panel products such as plywood and oriented strand board (OSB) meeting requirements of *Construction and Industrial Plywood, PS-1,* and *Performance Standards for Wood-Based Structural Use Panels, PS-2*, respectively. For the purposes of comparing shear wall resistance, the following panels and grade designations were considered to be equivalent:

- 1/2-inch Douglas-fir plywood (1955 through 1964 *UBC*);
- 1/2-inch Structural II (1967 through 1982 *UBC*);
- 15/32-inch Structural II (1985 through 1988 *UBC*); and
- 15/32-inch Sheathing Grade (1991 *UBC* through 2006 *IBC*).

Shear Wall Aspect Ratio: Ratio of Wall Height (h) to Wall Width (w)

- A maximum aspect ratio of 3.5:1 was permitted in all seismic zones from the 1955 *UBC* through to the 1994 *UBC*.
- Beginning with the 1997 *UBC*, aspect ratios greater than 2:1 were not permitted in high seismic zones. Similar limits were implemented in the 2000 *IBC*.
- In the 2003 and 2006 *IBC*, aspect ratios between 2:1 and 3.5:1 were permitted in all seismic zones provided the shear wall resistance was reduced by multiplying by 2w/h (e.g., for a shear wall with aspect ratio of 3.5:1, the shear wall resistance is multiplied by 2/3.5 or 0.57).

Table 1.—Changes in wood shear wall construction and shear resistance from 1955 to 2006.

	Year								
	1955	1958...1964	1967	1970	1973	1976...1994	1997	2000	2003...2006
Building code	*UBC*	→	→	→	→	→	*UBC*	*IBC*	*IBC*
Allowable unit shear, plf	319	→	→	→	→	→	→	→	310
Minimum framing thickness, in.	1-5/8	→	2-inch nominal		→	→	→	→	1-1/2
Aspect ratio, h/w	3.5:1	→	→	→	→	→	2:1	→	2:1[a]

[a] Aspect ratio up to 3.5:1 permitted, however, an adjustment factor is applied to the allowable unit shear capacity where aspect ratio is greater than 2:1 but not more than 3.5:1.

Nailing

- From 1955 through 1964, diaphragm tables for both horizontal diaphragms and shear walls specified the nail type as "common" with nail size designated by pennyweight.
- In the 1967 *UBC* and continuing to the present day, nail type is specified as "common or galvanized box" with the size continuing to be designated by pennyweight.

For purposes of comparison, nail type is assumed to be "common" and any differences in actual resistance of a shear wall fabricated with box nails having equivalent pennyweight designations (but smaller diameter) as common nails are not considered.

Shear Wall Resistance

Building code presentation of shear design values has changed over time (**Table 2**):

- From the 1955 *UBC* through to the 1964 *UBC*, allowable unit shear resistances for shear walls and diaphragms were provided in a single table. Adjustments to account for edge nail spacings were required (e.g., the allowable unit shear of 319 plf from 1955 *UBC* through 1964 *UBC* includes application of a 3/4 adjustment to tabulated unit shear values in accordance with table footnotes).
- In the 1961 *UBC*, tabulated unit shear values were based on "normal" load duration (i.e., 10-year basis)and therefore, a 1.33 load duration adjustment was applicable to adjust unit shear values for short-term wind or seismic loading. This "normal" load duration basis appeared for only one cycle as both earlier and later editions of the building code provided tabulated values for short-term wind or seismic loading and specified a reduction factor to convert values to a normal load duration basis.
- Basic presentation of allowable unit shear for the reference wood structural panel shear wall has remained essentially unchanged since the 1967 *UBC* where separate tables for shear wall and diaphragm resistances first appeared. Recent building codes continue to tabulate shear design values on a short-term load duration basis for wind and seismic loading (e.g., 10-minute loading) and account for different edge spacing directly in the tables.

Seismic Base Shear

The seismic base shear formula and values of seismic base shear are shown in **Table 3**. Base shear values are shown as a percentage of effective seismic weight, W, and are calculated for a regular one-story wood-frame structure with wood structural panel shear walls. For this reference structure, the effect of the following refinements are not considered in the calculation of seismic base shear:

1. revision of effective seismic weight, W, to include consideration for snow introduced in 1976 *UBC*;
2. increases to seismic base shear for presence of torsional irregularities; and
3. increases to seismic base shear for lack of redundancy.

In addition, because the reference structure is one story, revised provisions for vertical distribution of forces are not considered. Beginning in the 1985 *UBC*, where site coefficients are explicitly linked to soil profile in building code provisions, a stiff soil profile is assumed and taken as equivalent to site class D in the 2006 *IBC*.

Other refinements to seismic design criteria, including anchoring details for diaphragm attachment to concrete or masonry walls, more specific drift criteria, treatment of irregularities, determination of site specific seismic hazards, addition of seismic load combinations for additive and

Table 2.—Adjustment of tabulated shear wall design values from 1955 to 2006.

Building code	Building code tabulated shear wall value	Adjustment required to tabulated value	Allowable unit shear
	(plf)		(plf)
1955–1958 *UBC*	425	3/4 (boundary nail adjustment unless edge nail spacing is reduced)	319
1961 *UBC*	319	None	319
1964 *UBC*	239	1.33 (load duration adjustment to modify normal loading to short duration basis)	319
1967 *UBC*–2006 *IBC*	310	None	310

counteracting loads, and addition of strength design concepts and over-strength load combinations are not specifically addressed.

Allowable Stress Design Seismic Load

ASD seismic base shear is directly calculated from lateral force formulas appearing in the 1955 *UBC* through 1994 *UBC*. Strength based loads in the 1997 *UBC* through the 2006 *IBC* are converted to an ASD basis by multiplying by 1/1.4 for 1997 *UBC* and 0.7 for 2000–2006 *IBC*. The 0.7 factor is the current load factor on E in 2006 *IBC* basic load combinations for allowable stress design:

$$D + (W \text{ or } 0.7E) \quad [1]$$

Slightly larger ASD values result if strength-based loads in the *IBC* are converted to ASD by multiplying by 1/1.4 as given in the 1997 *UBC*-based load combinations and in the 2006 *IBC* alternative basic load combinations; however, the difference is considered to be minor.

Seismic Base Shear Range

The calculation of seismic base shear requires use of seismic hazard maps, site coefficients, and consideration of snow in determining the effective seismic weight for a particular location. As an alternative to assuming a fixed location for calculation of seismic base shear, the range of seismic base shear for a given time period is shown in **Table 3**. The range in base shear, rather than the value for a specific location, attempts to provide a more global view of changes in seismic base shear by capturing the low and high end of base shear for a given time period. These ranges are not directly applicable to any specific location as they represent a lower bound of base shear demand for areas of low seismic hazard and an upper bound of seismic base shear for areas of high seismic hazard.

Changes in the range of seismic base shear over time are shown in **Figure 1**. In general, these changes can be attributed to changes in seismic mapping and changes in coefficients used in the lateral force formula. For example, the slight decrease in seismic base shear between the 2000 *IBC* and the 2003 *IBC* directly relates to a change in the response modification coefficient, R (for light-frame walls with shear panels–wood structural panels) from 6.0 to 6.5. An alternative comparison is shown in **Figure 2** where the upper and lower bound values of base shear are presented as a ratio of the load determined in accordance with the 1988 *UBC* - where the R factor was first introduced in the lateral force formula. Ratios greater than 1.0 reveal increased seismic

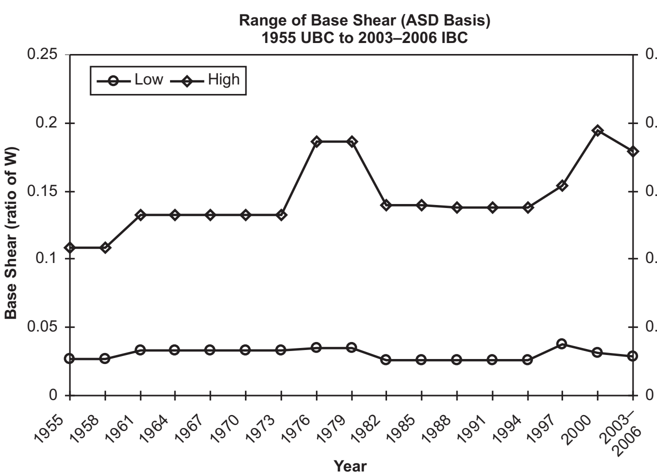

Figure 1.—Range of base shear, 1955 *UBC* to 2006 *IBC*.

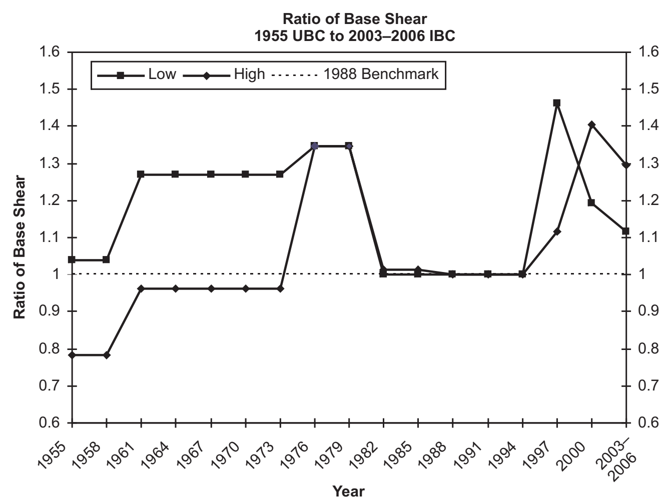

Figure 2.—Ratio of base shear to 1988 benchmark.

Table 3.—Seismic base shear (ASD basis).

Year	Map contour range (low – high)	Seismic base shear, V (low – high)	Lateral force formula	System design coefficient
1955–1958	Zone 1 – Zone 3	0.027W – 0.108W	F = CW	C[a]
1961–1973	Zone 1 – Zone 3	0.033W – 0.133W	V = ZKCW	K = 1.33
1976–1979	Zone 1 – Zone 4	0.035W – 0.186W	V = ZIKCSW	K =1.33
1982–1985	Zone 1 – Zone 4	0.026W – 0.14W	V = ZIKCSW	K =1
1988–1994	Zone 1 – Zone 4	0.026W – 0.138W	$V = ZICW/R_w$	$R_w = 8$
1997[b]	Zone 1 – Zone 4	0.039W – 0.157W	$V = 2.5C_aIW/R$	R = 5.5
2000	$S_s = 0.25 – 2.50$	0.031W – 0.194W	$V = C_sW = 2/3F_aS_sW/(R/I)$	R = 6.0
2003–2006	$S_s = 0.25 – 2.50$	0.029W – 0.179W	$V = C_sW = 2/3F_aS_sW/(R/I)$	R = 6.5

[a] Coefficient varies by zone and number of stories above story under consideration.
[b] Near source factor, N_a, equal to 1.1 in Zone 4.

base shear relative to the 1988 *UBC*. Ratios less than 1.0 reveal reduced seismic base shear relative to the 1988 *UBC*.

Seismic Map Contours

From the 1955 *UBC* through to the 1973 *UBC*, seismic map contours ranged from a low of Zone 0 to a high of Zone 3. However, in calculating the corresponding low-end base shear for this period of time, the Zone 1 coefficient was used because the lateral formula was not applicable for Zone 0. The high-end base shear was calculated using the Zone 3 coefficient. From 1976 through 1997, low and high-end of seismic base shear is based on coefficients from Zone 1 and Zone 4, respectively. In addition, the high-end of the seismic base shear range based on the 1997 *UBC*, includes the near source factor, N_a, equal to 1.1. For the 2000 and 2006 *IBC*, the range of S_s (mapped spectral accelerations for short period) is taken as 0.25 to 2.50 – to approximately correspond to a lower bound on Zone 1 and an upper bound on Zone 4 from prior building codes. An upper bound $S_s = 2.50$ represents the upper-bound S_s for the state of California. $S_s = 3.0$ is not used for the upper bound because this value applies only to a very limited number of geographic locations.

Ratio of Demand to Capacity

The combined effect of changes in seismic load in high seismic areas and shear wall resistance (demand-to-capacity) is shown in **Figure 3** for walls with aspect ratios of 3.5:1and 2:1 and less. The 1988 *UBC* is chosen as the benchmark because1998 represents the first year in which the R factor was introduced into the lateral force formula.

2:1 Aspect Ratio Walls

Figure 3 is very similar to the high seismic portion of **Figure 2** for shear walls having an aspect ratio of 2:1. **Figures 2 and 3** only differ slightly in the time frame from 1967 and earlier where the allowable unit shear was 319 plf versus 310 plf for the benchmark year. For 2:1 aspect ratio walls, both **Figures 2 and 3** show that the seismic load to shear wall resistance ratio is approximately 1.30 times greater than the benchmark for high seismic areas. This increase is largely attributed to new seismic hazard maps recognizing the increased hazard near faults.

3.5:1 Aspect Ratio Walls

The increase in ratio of seismic load to shear wall resistance beginning in 1997 reflects both increased seismic load near faults and strength reduction factors for narrow walls (i.e., aspect ratio greater than 2:1). It should be noted that increased ratios of seismic base shear to shear wall resistance would likely result even if the 2w/h aspect ratio (strength reduction factor) were not applied to walls with an aspect ratio of 3.5:1. This is because distribution of load based on relative stiffness would effectively reduce the load resisted by the narrow wall relative to longer walls in the same wall line. Therefore, **Figure 3** is more generally applicable to cases where all wall segments in the wall line have the same aspect ratio.

With revisions to seismic maps, a range of seismic base shear can result for a given geographic area where previously seismic base shear was based on a single seismic zone coefficient. **Table 4** shows seismic base shear for geographic areas surrounding Los Angeles, California, Seattle, Washington, and Memphis, Tennessee. Selection of "surrounding area" for each city is not based on specific radius for the city

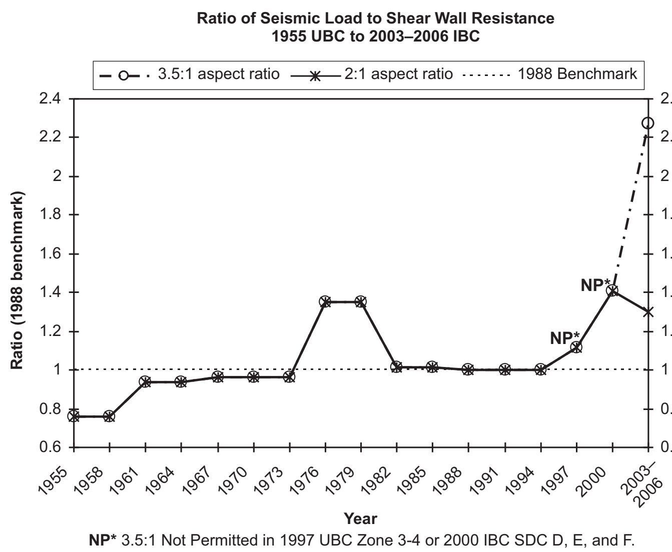

Figure 3.—Ratio of seismic load to shear wall resistance (demand to capactiy), 1988 benchmark.

Table 4.—Range of base shear for select metropolitan areas.

City and surrounding area	Year	Map contour	Base shear, V	Ratio of base shear (1988 benchmark)
Los Angeles, CA	1988	Zone 4	0.138W	1.0
	1997	Zone 4 – Zone 4 near source[a]	0.143 W – 0.157W[a]	1.04 – 1.14[a]
	2003–2006	S_s = 1.5 – 2.50	0.108W – 0.179W	0.78 – 1.30
Seattle, WA	1988	Zone 3	0.103W	1.0
	1997	Zone 3	0.117 W	1.14
	2003–2006	S_s = 1.0 – 1.50	0.079W – 0.108W	0.77 – 1.05
Memphis, TN	1988	Zone 3	0.103W	1.0
	1997	Zone 3	0.117 W	1.14
	2003–2006	S_s = 1.5 – 3.00	0.108W – 0.215W	1.05 – 2.09

[a] Near source factor, N_a, equal to 1.1.

center but rather an estimate based on visual inspection of mapped values of S_s and seismic zone coefficients for the same region. Ratios of base shear to the benchmarks are both higher and lower indicating both decreased and increased seismic load relative to the benchmark for the assumed geographic area. Similar to the procedure used for calculation base shear ranges, a stiff soil profile is assumed – equivalent to site class D in 2006 *IBC*.

Summary

The site- and structure-specific nature of seismic base shear makes it difficult to generally state whether the required length of shear walls has increased or decreased over time – without defining a specific geographic region. In some locations, loads have increased and in others locations loads have decreased. The range of base shear, however, provides a more stable reference. In general, seismic loads in modern codes have increased in areas with highest seismic risk (approx. 30% relative to the 1988 benchmark) while remaining comparable to seismic loads of past building codes in areas of relatively low seismic risk. For the reference shear wall, resistance has remained stable over time with reduced resistances attributed to narrow walls in modern building codes. Where narrow walls are used exclusively in areas of highest seismic risk, required wall length has increased significantly in recent codes due to a better understanding of increased loads for areas of high seismic risk and reduced capacities assigned to narrow walls.

References

References are available upon request.

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