Seismic Force-Resisting Systems

Part 2: Codified Systems

This is the second of a two-part series of articles discussing the SEAOC Seismology Committee's comments and recommendations on the current design considerations of Seismic Force-Resisting Systems. Part 1, published in the January 2009 issue, discussed Design Factors used for each system and Height Limitations. This article discusses System Attributes and recommendations to simplify Design Parameters for structural systems.

System Attributes

ASCE 7-05 groups the seismic force-resisting systems into broad categories. The four main categories include: bearing wall systems, building frame systems, moment-resisting frames, and dual systems, as well as their generic definitions, traced back to ATC 3-06 (Applied Technology Council, ATC 1978) and, with slight modification, to the first Blue Book (SEAOC Seismology Committee 1959).

In terms of resistance to lateral loads, the original categories distinguished primarily between moment-resisting frames and stiffer wall or braced frame systems. The stiffer systems were further divided according to whether gravity loads were supported by bearing walls or by the columns of a "complete" space frame. Indeed, the default system – a three-dimensional space frame – was defined in terms of how it supported gravity, not lateral, loads. Earthquake loads for other systems were prescribed relative to the default, either one-third higher (for bearing walls) or one-third lower (for the first modern SFRS, the ductile moment-resisting frame). Dual systems, combining moment-resisting frames with stiffer elements, comprised the fourth main category. Overall, these early design provisions expressed a strong preference for moment-resisting frames as the only system expected to provide ample energy absorption capacity over the elastic and plastic range.

Historically, each of the main system categories has been expected to provide a certain characteristic performance under earthquake loads. All modern systems, however, are premised on some measure of over-strength, inelastic capacity, and load redistribution (Building Seismic Safety Council, BSSC 2001). These expectations, implicit in building code design parameters and detailing provisions, have been based on assessments of:

- Past performance when subject to strong ground motion;
- Demonstrated inelastic deformation capacity;
- Relative vulnerability of gravity load carrying systems;
- Capacity for system over-strength and force redistribution after initial yielding; and
- Multiple modes of resistance, including redundant frame lines and backup systems.

ATC 3-06 subdivided the four main categories, principally by material, into 18 specific lateral force-resisting systems. Three inverted pendulum systems completed the list. ATC 3-06 also distinguished between "special" and "ordinary" moment frame systems, with the special systems required to incorporate the latest ductile detailing in order to qualify for the traditionally low design forces for moment frames.

Since ATC 3-06, the list of SFRS types in ASCE 7 has grown by the:

- Addition of new systems, such as Eccentrically Braced Frames and Special Truss Moment Frames;
- Addition of new materials, such as composite braced frames and steel sheet panels on light framing;
- Recognition of traditional systems, such as plain masonry, typically used in low seismic areas;
- Addition of new dual system combinations, including some with intermediate moment frames; and
- Further distinction of traditional systems by special, intermediate, and ordinary detailing.

Historically, it has been the position of the Seismology Committee that "exaggerated" forms of the defined systems should not necessarily qualify for tabulated *R* values (SEAOC Seismology Committee 1990). Special moment frames with isolated one-bay bents, shear walls with large openings, and strong beam/weak column frames were given as examples. More recently, however, provisions for redundancy, modeling, and detailing have tried to address some of those concerns. Still, it is the Committee's position that because the tabulated design parameters are largely based on judgmental notions of "typical" structures, any precedent-setting applications should be held to the requirements for undefined systems.

Bearing Wall Systems and Building Frame Systems

These two basic system types both use relatively stiff shear wall or braced frame elements to resist lateral earthquake loads. The principal difference is in how the SFRS interacts with the gravity load-carrying system of the building.

Historically, neither of these categories was expected to provide the highest level of inelastic deformation capacity. With the introduction of "special" reinforced concrete walls and braced frames, however, the characteristic performance within these categories has come to vary widely, depending on the mate-

Table 1: Comparison of R-values in selected Bearing Wall and Building Frame Systems.

SFRS type[1]	ASCE 7-05			1997 UBC[1]		
	Bearing Wall *R*	Building Frame *R*	R_{BW} / R_{BF}	Bearing Wall *R*	Building Frame *R*	R_{BW} / R_{BF}
Ordinary steel concentrically braced frame	NA	3.25	NA	4.4	5.6	0.79
Special reinforced concrete shear walls	5.0	6.0	0.83	4.5	5.5	0.82
Special reinforced masonry shear walls	5.0	5.5	0.91	4.5	5.5	0.82
Light-framed walls with rated wood structural panels	6.5	7	0.93	5.5	6.5	0.85

[1]SFRS types per ASCE 7- 05 Table 12.2-1. 1997 UBC SFRS type descriptions vary slightly from the ASCE 7-05 descriptions.

rial, detailing, and configuration of the system. Still, all of these systems are relatively stiff, and their design tends to be governed by strength requirements more than by drift limits.

A building frame system is said to have an "essentially complete space frame" if gravity loads are carried by columns, not by bearing walls (ATC 1978). Originally, this meant a three-dimensional grid of beams and columns independent of a discrete SFRS. By contrast, bearing wall systems (called box systems in the Unified Building Code, UBC and the Blue Book through 1985) had gravity load-carrying walls and partitions that interrupted or replaced columns in the overall building grid. The vertical load-bearing walls were allowed, but not required, to double as lateral load-resisting shear walls.

From the beginning, the presence of "a minor portion of bearing walls" was not intended to trigger the bearing wall provisions; stairwell and basement walls, for example, were not expected to affect "the action of a multi-storied building" (SEAOC Seismology Committee 1960). ASCE 7-05 Section 11.2 defines a bearing wall quantitatively in terms of the vertical load it resists, but does not say how many bearing walls create a bearing wall system. While the term "minor" is unclear, the 2000 NEHRP Commentary (BSSC 2001) suggests only that building frame systems should not have bearing walls that carry gravity load from more than "a few percent of the building area."

Given more recent design provisions for deformation compatibility and ductile detailing of gravity load-carrying elements, the question of whether significant gravity loads are supported by walls or frame columns is no longer meaningful. Still, for purposes of code compliance, the designer must make a selection and, in doing so, should judge whether the presence of bearing walls will influence the post-yield capacity of the gravity system.

The original distinction between bearing wall and building frame systems was based on a perceived need for a "second line of resistance," where shear walls carried the bulk of earthquake loads and a complete frame to carry the gravity loads. Walls and braced frames were considered to lack the ductility of moment frames. If they were also needed to carry significant gravity load, they were seen as potential collapse hazards. Code writers addressed this concern with a 33% increase in earthquake design loads for bearing wall systems (K of 1.33, as opposed to the default value of 1.00). The intent was to protect against collapse of the gravity system by encouraging robust gravity framing or, in its absence, by reducing the ductility demand on suspect bearing wall elements.

More recently, the distinction between bearing wall and building frame systems was somewhat reinterpreted. Although the code definitions of these two basic system types have scarcely changed since the earliest Blue Books, the distinction has been thought of as less about the completeness of the gravity system on its own than about the degree to which principal SFRS components carry both earthquake and gravity forces. Concentrically braced frames offer the most common example: If the diagonal braces carry gravity load in compression, the system has been deemed a "bearing wall" system (SEAOC Seismology Committee 1990). Future codes, however, will list steel braced frames only as building frame systems, acknowledging that the design needs only one set of parameters. The Seismology Committee concurs with this modification in that the braced frame need not be distinguished as bearing wall or building frame systems, and that past distinctions may be disregarded.

Indeed, the penalty in the code for bearing walls is no longer so great, nor is it the same for all systems. As *Table 1* indicates in its comparison of bearing wall R values (labeled here R_{BW}) with building frame R values (R_{BF}), the benefit of going to a building frame system is an increase in *R* and a subsequent decrease in the design base shear. Depending on the system, the decrease is between 7% and 17% in ASCE 7-05.

In practical terms, the original distinction between bearing wall and building frame systems has faded. Since good seismic performance at expected force levels is known to be a function of detailing and load path, the real effect of a small difference in the design base shear is negligible. Indeed, this difference in *R* is less than other potential code "penalties" for certain irregularities or low redundancy. Furthermore, current provisions for overstrength, deformation compatibility, capacity design of connections, and other factors account more directly for the likely ill effects of non-ductile failure in SFRS components that carry both earthquake and gravity forces.

Moment-Resisting Frame Systems

Moment-resisting frames were the first structural systems expressly designed for inelastic response under expected seismic loads. Since the first Blue Book editions, they have been exempted from height limits (indeed, they have been required for tall buildings), assigned the most optimistic design parameters, and prescribed as essential backup systems for less ductile walls and braced frames: "The ductility provided by this type of framing may well prove to be the difference between sustaining tolerable and, in many cases, repairable damage, instead of catastrophic failure" (SEAOC Seismology Committee 1967). Since then, some of the early high expectations have been shown to be premature, as poor performance led to substantial research and improved design provisions for concrete frames after the 1971 San Fernando earthquake and for steel frames after the Northridge earthquake in 1994. The latest of these provisions, while representing state of the art research, have not yet been tested in large numbers by real earthquakes.

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Nevertheless, current requirements for special moment-resisting frames are expected to provide as much or more ductility and energy dissipation capacity as any codified SFRS. Moment-resisting frame systems are generally more flexible than shear wall and braced frame systems, and their design is frequently governed by code drift limits.

As shown in ASCE 7-05 Table 12.2-1, the moment-resisting frames are further classified as special, intermediate, or ordinary. Each class, and each system, has specific height limits and detailing requirements. As discussed above, the quantitative height limits are largely arbitrary, and the prohibitions are judgmental, reflecting the limits of past experience. The ductile proportioning and detailing requirements for special moment-resisting frames are appropriate for their relatively high *R* values.

Since the first Blue Book, it has been accepted practice that not all bays of the space frame need to be moment-resisting (SEAOC Seismology Committee 1960). The engineer may designate selected portions of the space frame as the actual SFRS, as long as these portions satisfy the design requirements and provide the intended behavior. The purpose is to allow the engineer to select the most effective configuration. Still, the current design parameters were assigned at a time when the typical practice involved rather complete framing, usually around the full building perimeter and sometimes through the interior as well. Over time, architectural styles, construction economics, and optimization techniques gave rise to buildings with a minimal number of discrete frames, each only one or two bays wide. These optimized designs, unanticipated by early code development, are likely to require special attention to issues involving foundation uplift, load path elements (collectors), diaphragm connections, and the behavior of large or deep structural sections. The same potential concerns apply to narrow shear walls and braced frames.

Table 2: Conceptual SFRS table (see text for explanation).

System	*R*	Ω_o	C_d	Height limits [ft] SDC D and E[a]
Light frame walls				
With shear panels	7 [b]	3	4	65
With diagonal braces	4	2	3	65
Shear walls				
Special	6 [b]	2	5	160 [d]
Intermediate	5 [b]	2	4	NP
Ordinary	3 [b]	2	2	NP
Braced frames				
Special	6 [c]	2	5 [c]	160 [d]
Intermediate	5	2	4	35
Ordinary	3	2	2	NP
Moment-resisting frames				
Special	8	3	5	NL
Intermediate	5	3	4	NP
Ordinary	3	3	2	NP
Cantilevered columns				
Special	2	2	2	NL
Ordinary	1.5	2	1.5	NP

[a] NP = Not permitted. NL = No limit.

[b] Load increases (or reduced *R*-values) might be appropriate for wall elements carrying significant gravity load.

[c] Increased values might be appropriate for steel eccentrically braced frames.

[d] Height limits may be increased for some systems, similar to ASCE 7-05 section 12.2.5.4.

Undefined Systems

ASCE 7-05 section 12.2.1 permits use of systems that are not in Table 12.2-1 "if analytical and test data are submitted that establish the dynamic characteristics and demonstrate [acceptable] lateral force resistance and energy dissipation capacity." 1997 UBC makes a similar allowance and enumerates, in section 1629.9.2, seven specific characteristics that must be addressed.

In general, acceptance of a proposed system is left to the discretion of the code official. Between the ASCE 7-05 and the 1997 UBC provisions, however, the Seismology Committee supports and prefers the more specific UBC requirements. Further, it is the position of the Seismology Committee that the design of undefined or not-yet-codified systems should be peer reviewed with reference to the five broad criteria listed above under System Attributes.

Further, it is the position of the Seismology Committee that even a "defined" system should be held to the requirements for undefined systems when the application is precedent-setting in terms of building height, SFRS aspect ratio, member span or dimension, structural material, or other parameters.

New Thinking

Four structural system types listed in the 1960 Blue Book became 41 system types in the 1997 UBC, with 15 different *R*-values. ASCE 7-05 Table 12.2-1 lists 83 different systems with 17 different values of *R*.

As previously discussed, many code provisions and design parameters are holdovers from early Blue Book editions or from ATC-3-06. Most are based on judgment, somewhat outdated if not obsolete, and many of the early provisions are now irrelevant, contradictory, or incorrect. Considering the degree to which that judgment still influences system classification and design parameters, the number of codified structural systems has grown beyond reason.

Proposals for simplifying the SFRS tables and rationalizing the assigned design parameters were considered for the 2003 NEHRP Provisions, but not adopted by BSSC. It is the opinion of the Seismology Committee that the guiding principles for a new SFRS table should include:

- Fewer specific system types and fewer distinct values and combinations of numerical design parameters. Too much specificity gives an unwarranted impression of precision.
- Generic design parameters that clarify the expected performance of a proposed system. Instead of parameters being assigned to each new system, a proposed new system would need to qualify (by testing, for example) for the pre-defined generic parameters.
- Distinction of basic system types on the mode of seismic resistance, not the structural material or the gravity system. In particular, eliminate the distinction between "bearing wall" and "building frame" structures. Where additional conservatism is considered appropriate for SFRS walls that also support substantial gravity load, any modification of design load or wall capacity should be applied to the individual wall element, not to the whole structure.
- Distinction between specific systems based on expected reliability and ductility – special, intermediate, and ordinary, in current terms – not structural material or configuration.

  The generic design parameters would be used to align the various system groups so as to ensure roughly equivalent performance and reliability. Modifications to the generic design parameters (presented in footnotes, perhaps) could then be used to accommodate known attributes of specific systems. Material standards would give the necessary system-specific detailing provisions.
- Consistent classification of potential dual systems. Ideally, dual systems would be removed from the SFRS table. Almost any tabulated system that is permitted in the seismic design category (SDC) of interest could be combined with a special moment frame, and the dual system design parameters could be taken as the average of the parameters of the two component systems.

Table 2 shows what such a simplified SFRS table might look like, in principle, for seismic design categories D and E. Some systems listed as NP could be accepted in SDC B and C, and some additional prohibitions or height limits might be appropriate for SDC F. *Table 2* is conceptual only. For consistency with ASCE 7-05 Table 12.2-1, additional notes will be required for specific materials, systems, and configurations.▪

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