A Brief Guide to Seismic Design Factors

SEAOC Seismology Committee

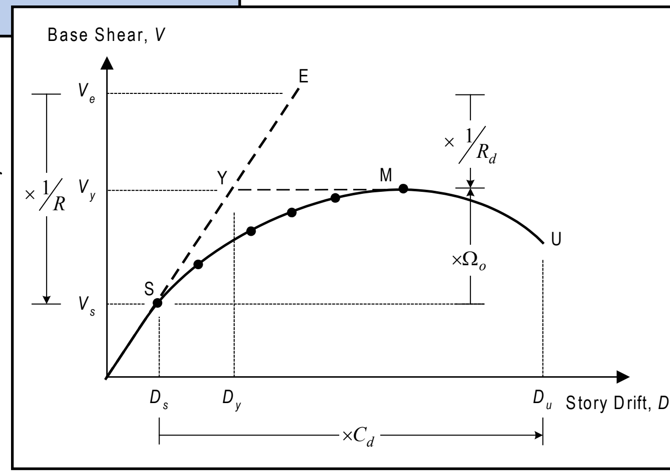

Figure 1: Inelastic Force-Deformation Curve.

Intent of Seismic Design Factors

Past experience and observation of building behavior following earthquakes has shown that a structure can be economically designed for a fraction of the estimated elastic seismic design forces, while maintaining the basic life safety performance objective. This design philosophy implies that structural inelastic behavior (and damage) is expected. This reduction in design seismic force is effected through the use of a Seismic Response Modification Factor, *R*. The intent of the *R* factor is to simplify the structural design process such that only linearly elastic static analysis (i.e., the equivalent lateral force procedure) is needed for most building design.

While some deformation-controlled members, detailed to provide ductility, are expected to deform inelastically, force-controlled members that are designed to remain elastic would experience a significantly higher seismic force level than that predicted based on actual design seismic forces. To account for this effect, the code uses a seismic force amplification factor, Ω_o, such that the realistic seismic force in these force-controlled members can be conveniently calculated from the elastic design seismic forces. Ω_o is termed the Structural Overstrength Factor in ASCE 7-02/05. To control drift or to check deformation capacity in some deformation-controlled members, a similar approach is also adopted. A Deflection Amplification Factor is introduced to predict expected maximum deformations from that produced by the design seismic forces. This factor is termed C_d in ASCE 7-02/05.

The typical response envelope relating force to deformation is shown in *Figure 1* and can be established from either testing or a pushover analysis (also known as a "backbone curve"). The structure first responds elastically, which is then followed by an inelastic response as the lateral forces are increased. A series of plastic hinges form throughout the structure, leading to a yielding mechanism at the strength level V_y.

The design method follows a simplified procedure. Based on the fundamental linear elastic period of the structure, a designer first calculates the elastic design base shear, V_e (see point E in *Figure 1*). V_e is then reduced by a factor, *R*, to establish a design seismic force level V_s (point S in *Figure 1*), beyond which elastic analysis is not valid:

$$V_s = \frac{V_e}{R}$$

To estimate internal forces that develop in force-controlled members for capacity design, the corresponding forces at the design seismic force level (V_s) are then amplified by a system overstrength factor, Ω_o. From an elastic analysis, the drift at the V_s level is determined via the amplification of displacement values by a deflection amplification factor, C_d to estimate the maximum (inelastic) drift; this calculated drift is limited by building code values.

Response Modification Factor

The *R* factor can be traced back to the *K* factor, which appeared in the first edition of the Blue Book (SEAOC *Recommended Lateral Force Requirements and Commentary*) in 1959. Although the format of design base shear has been changed over the past four decades, the design base shear, after some adjustment to account for the difference between working stress design and strength design, has not greatly varied. The purpose of any apparent change is to provide a rational relationship between response spectrum demand and the inelastic response reduction capabilities of a given structural system.

Deflection Amplification Factor

A deformation or story drift check in the force-based design procedure has been performed in either of two formats in the US: serviceability and ultimate limit state check. Prior to the 1997 SEAOC Blue Book and *Uniform Building Code* (UBC), the serviceability drift check was intended to minimize nonstructural damage caused by more frequent minor or moderate earthquakes. A drift limit of 0.005 of the story height is generally accepted as effective for this purpose. Originally developed by ATC 3-06, and later the NEHRP *Seismic Design Provisions*, a second format checks inelastic story drift expected from the design ground motion at a value several times larger than 0.005 of the story height. The expected inelastic drift, D_u, is computed by amplifying the story drift, D_s, by the deflection amplification factor, C_d (*see Figure 1*). The associated drift limit is in the range of 0.015 to 0.025 of the story height. In the 1985 UBC, the story drift limit for the design seismic forces, V_w, is 0.005*K*; note that it is dependent on the system factor *K*. To understand the implication of including *K* in the drift limit, consider the minimum required structural stiffness, which is represented by the initial slope of the response curve shown in *Figure 2*. As both the design base shear and the drift limit contain the *K* factor, the minimum stiffness, which is represented by the slope of segment OW, required to minimize nonstructural damage is independent of the ductility-related system factor *K* because this factor is cancelled out in the design process. This practice of including the *K* factor in the drift limit (0.005) is justified because the threshold for nonstructural damage is the same, which is irrelevant to the structure's ductility capacity. The serviceability drift check is performed in the elastic range because it is not expected that structural damage would occur in a minor or moderate earthquake.

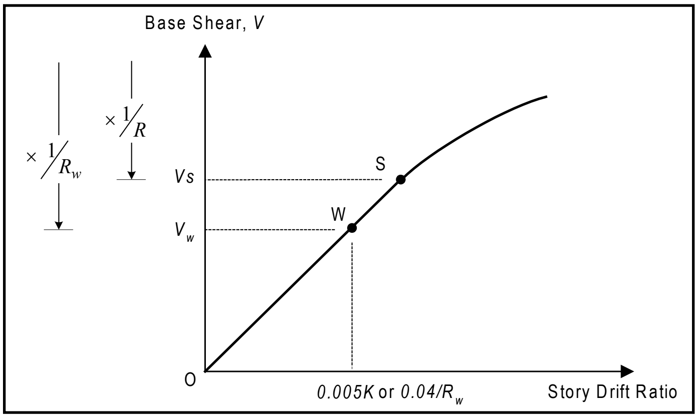

Figure 2: Story Drift Requirements.

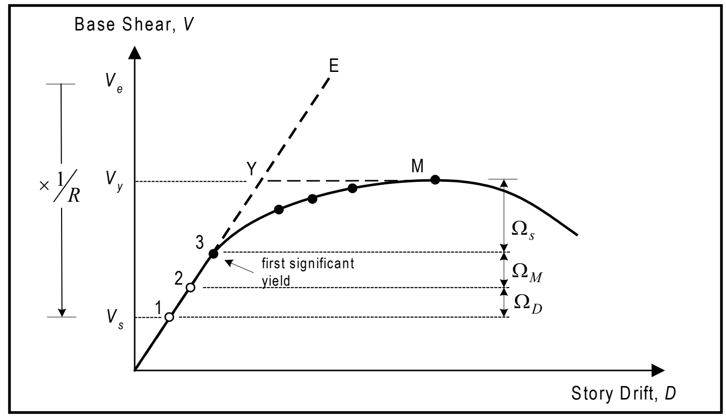

Figure 3: Components of System Overstrength.

System Overstrength Factor

To assist in the evaluation of the system overstrength factor, the 2001 NEHRP *Recommended Provisions* in its Commentary suggest that the factor be subdivided into three categories such that $\Omega_o = \Omega_D\Omega_M\Omega_S$ (see *Figure 3*). Ω_D represents the ratio in lateral strength between Points 2 and 1 in the figure, where Point 1 is the prescribed minimum design seismic force level, and Point 2 represents the point of "nominal" first significant yield (e.g., the formation of a plastic hinge in a moment frame) based on nominal material strengths. This portion of the overstrength varies considerably from one system to another, yet it is the one that can be quantified easily by elastic structural analysis tools. First, it is system dependent. For systems like braced frames and shear wall structures, Ω_D can be very low and close to unity; for other systems like steel special moment-resisting frames whose design is usually dictated by drift limitations, it is common that the Ω_D value varies between 2 and 3. Second, Ω_D is highly dependent on the seismic zone.

Ω_M represents material overstrength. This portion of the system overstrength, i.e., the ratio in lateral strength between Points 2 and 3 in the figure reflects the difference between the nominal and actual material strengths. Reinforced masonry, concrete, and steel provisions have historically used a factor of 1.25 to account for the ratio of mean to specified strengths. A survey of wide-flange shapes indicated that the ratios of mean to specified yield strengths were 1.37 and 1.15 for A36 and A572 Gr. 50 steels, respectively. Ω_S represents the system overstrength beyond the first significant yield point (Point 2 in the figure). It is dependent on the level of redundancy contained in the structure as well as the extent to which the designer has optimized the various elements that participate in lateral force resistance. See the NEHRP Provisions for further discussion on these components.

Deflection Amplification Factor

A comparison of deflection amplification factors in relation to response modification factors of several seismic provisions is summarized in *Table 1*.

Note that the C_d/R ratio as specified in ASCE 7-05, ranges from 0.5 to 1.0. The theoretical relationship of this ratio can be stated as:

$$\frac{C_d}{R} = \frac{\mu_s \Omega}{R_d \Omega_o} = \frac{\mu_s}{R_d}$$

For a single-degree-of-freedom system, Newmark and Hall in their 1982 EERI monograph, *Earthquake Spectra and Design*, suggested that that the C_d/R ratio should be equal to 1.0 in the equal displacement range, and larger than 1.0 in the shorter period range. *Table 1* shows that, except for the US seismic provisions, codes of other countries follow this rule.

Table 1: Comparison of Response Modification and Deflection Amplification Factors

Seismic Provisions	Response Modification Factor	Deflection Amplification Factor	Deflection Amplification Factor / Response Modification Factor
UBC 1994 1997	 R_w R	 (3/8) R_w 0.7R	 0.375 0.7
ASCE 7-05	R	C_d	0.5 – 1.0
Eurocode 8	q^{a}	q	1.0[c]
Mexico	Q^{a}	Q	1.0[c]
New Zealand	μ^{b}	μ	1.0[c]
NBC of Canada 1995 2005	 R/U R_dR_o	 R R_dR_o	U (=0.7) 1.0

[a]period-dependent in the short period range; reduces to 1.0 at T = 0 sec.
[b]period-dependent in the 0.45 (or 0.6) – 0.7 sec range; does not reduce to 1.0 at T = 0 sec.
[c]greater than 1.0 in the short period range.

Remaining Challenges

Currently, the Applied Technology Council is attempting to quantify certain aspects of seismic design factors. Considering the complexity of a building structure with components such as gravity load-carrying systems and "nonstructural" components that are not accounted for, and the limitations of the tools for analyzing idealized models, it is expected that in the foreseeable future engineering judgment and lessons learned from observed building performance in earthquakes will continue to play a vital role for adjusting the values of these system parameters.

Current seismic design codes still do not address the issue of permanent drift, which can be large, especially for near-fault ground motions. While no provisions for permanent drift currently exist, building codes have developed an indirect consideration of this issue through the provision of an incentive for better performance of the building after a major seismic event. This incentive is promulgated through the use of R factors in Building Frame Systems that are slightly higher than those for Bearing Systems. Additionally, values of R assigned to Dual Systems recognize the inherent redundancy of these designs.

One might consider the variation of system design factors across the continuum of structural systems. Two systems, one with a high ductility capacity and low overstrength and the other with a low ductility capacity and high overstrength, can have the same value of R. Nevertheless, numerous studies have shown that the largest source of uncertainty in predicting seismic response is contributed from the earthquake ground motion input. Therefore, increased ductility capacity attained through detailing for enhanced ductility is preferred over the use of higher system strength with little improved ductile detailing. On this basis, although two systems may have the same value of R, it may be appropriate to assign a higher reduction factor to a system with greater ductility.

The R-factor design approach was developed as a compromise to achieve an economical design by accepting inelastic action in the structure, yet allowing the structural engineer a greatly simplified elastic analysis method for use in routine design. It is critical to the progression of the profession to retain this vision in our future efforts to improve the accuracy of seismic design factors.▪

The Structural Engineers Association of California (SEAOC) is professional association of four member organizations representing the structural engineering community in California. Their stated mission is "to advance the structural engineering profession; to provide the public with structures of dependable performance through the application of state of the art structural engineering principles; to assist the public in obtaining professional structural engineering services; to promote natural hazard mitigation; to provide structural engineers with the most current information and tools to improve their practice; and to maintain the honor and dignity of the profession."

The SEAOC Blue Book, the new edition of SEAOC's signature publication, provides articles collected by the SEAOC Seismology Committee. New articles are added on an ongoing basis. For specifics on the Blue Book, or for additional information on Seismology Position Statements and other Seismology related articles, visit www.SEAOC.org.

Neither SEAOC, nor its members organizations, committees, authors, editors, or individuals who have contributed to this publication make any warranty, express or implied, or assume any legal liability or responsibility for the use, application of, and/or reference to opinions, findings, conclusions, or recommendations included in this publication.