STUDYING DIRECTION OF LOADING PROVISIONS IN MODERN CODES: RESEARCH MOTIVATION AND LITERATURE REVIEW

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Abstract

Direction of loading procedures intend to address the occurrence of earthquake shaking along two principal axes of a building simultaneously. Direction of loading provisions in several modern codes are reviewed, and a comprehensive literature review on the topic is presented. Research to date on direction of loading, based on both linear and nonlinear analysis, indicates potential underestimation of building seismic response. The motivation for an approach to assessing the direction of loading provisions in ASCE/SEI 7-10 using instrumented building data is outlined. Results of this approach will be reported in future publications.

Introduction

Direction of loading is known by many names between different codes, guidelines and published research. In addition to "direction of loading," it is sometimes referred to as orthogonal combination, directional combination, multidirectional effects, or concurrent effects. Regardless, the intent of its consideration is consistent throughout: To capture the occurrence of earthquake shaking along two or more axes of a building simultaneously. Although simplified design procedures often separate seismic shaking into two (or more) demands determined independently for each axis, it is known that earthquake ground motions induce simultaneous acceleration in all six degrees of freedom. Direction of loading provisions in modern codes attempt to approximate this reality through some combination of the demands determined independently for each axis.

The two most common orthogonal combination rules are the 100%+XX% rule and the square-root-sum-of-the-squares (SRSS) rule. The 100%+XX% rule is considerably more often used in modern codes than the SRSS rule and will therefore be the primary focus in this paper. Quantitative descriptions of both the 100%+XX% rule and the SRSS rule can be found in Equations 1 and 2, respectively. Note that when the SRSS and 100%+XX% rules are applied in design, it may be necessary to apply load factors on the individual responses before combination. Load factors can be found in modern codes (e.g. ASCE/SEI 7, ASCE/SEI 41). Some of the notation in Equations 1 and 2 is based on Rosenblueth and Contreras (1977).

$$R_{100\%+XX\%} = R_0 + max\begin{cases} R_1 + \alpha \sum_{i \neq 1} R_i \\ R_2 + \alpha \sum_{i \neq 2} R_i \\ \dots \\ R_n + \alpha \sum_{i \neq n} R_i \end{cases} \qquad \text{Equation 1}$$

$$R_{SRSS} = R_0 + \sqrt{\sum_{i=1}^{n} R_i^2} \qquad \text{Equation 2}$$

where

R_i = maximum value of the response quantity of interest (e.g., strong axis moment in a column) due to earthquake shaking in degree of freedom *i*

R_0 = maximum value of the response quantity of interest due to non-seismic loads

n = total number of degrees of freedom considered, less than or equal to 6

α = orthogonal combination factor for 100%+XX% rule that varies from 0 to 1 inclusive

In the further simplified form most often seen in modern codes, the 100%+XX% rule is reduced to only the two horizontal translational components of ground shaking and α is taken as 0.3. This is then referred to as the 100%+30% rule. When linear analysis is conducted (i.e., response quantities of interest are linearly related to the applied forces), the 100%+30% rule can be described by two load cases:

1. 100% of the seismic forces in the x-direction and 30% of the seismic forces in the y-direction
2. 100% of the seismic forces in the y-direction and 30% of the seismic forces in the x-direction

The x-direction and the y-direction must be orthogonal and are typically selected as the principal axes of the structure. Note that all combinations of positive and negative values must be considered in the above two load cases, thus expanding them to a total of eight. Further discussion on these cases is provided below under "Characterization of the ASCE/SEI 7-10 Provisions."

It is important to distinguish between directional combination rules and modal combination rules. Confusion concerning the difference between directional combination and modal combination as they appear in modern codes and especially computer software is not uncommon. This is partially owing to the fact that some rules, such as the SRSS procedure, can be applied for both modal and directional combination. Yet directional and modal combination procedures attempt to capture distinctly different phenomena. Modal combination rules approximately account for the total response of a structure due to ground shaking in one degree of freedom (e.g., translation along one horizontal axis) by combining in some way the response due to each mode. Typical modal combination rules include SRSS and Complete Quadratic Combination (CQC) (Menun and Der Kiureghian, 1998). Directional combination rules, on the other hand, are focused on capturing the total response of a structure due to ground shaking in multiple degrees of freedom (e.g., translation about two horizontal, orthogonal axes) by combining in some way the response due to ground shaking in each degree of freedom. Directional combination rules in modern codes, and their adequacy, are the focus of this paper.

Summary of Provisions in Modern Codes

Although many modern codes have adopted a form of the 100%+XX% orthogonal combination rules to approximate concurrent seismic effects, differences do exist in how they are applied and when they are required. This section summarizes direction of loading provisions in four current, nationally recognized codes and standards for seismic design or rehabilitation: ASCE/SEI 7-10 *Minimum Design Loads for Buildings and Other Structures* pertains to new building design; ASCE/SEI 41-13 *Seismic Evaluation and Retrofit of Existing Buildings* pertains to existing buildings; AASHTO *Guide Specifications for LRFD Seismic Bridge Design, 2nd Edition* pertains to new bridge design; and FHWA-HRT-06-032 *Seismic Retrofitting Manual for Highway Structures, Part 1 - Bridges* pertains to existing bridges.

ASCE/SEI 7-10 Provisions

ASCE/SEI 7-10 Section 12.5 contains the current provisions concerning direction of loading which are slightly different for each Seismic Design Category. Seismic Design Categories range from A to F in order of increasing earthquake demand and structural importance with Seismic Design Category A being exempt from ASCE/SEI 7 Chapter 12. For Seismic Design Category B, ASCE/SEI 7 only requires the seismic forces to be applied independently in each of two orthogonal directions and allows orthogonal interaction effects to be neglected. This essentially means that directional combination is not required for Seismic Design Category B. Neglecting directional combination in Seismic Design Category B stems from the fact that seismic forces rarely govern in this category.

Seismic Design Category C structures with lateral force-resisting systems which are not orthogonal must meet more stringent provisions than for Seismic Design Category B. If the equivalent lateral force or modal response spectrum procedures are used, ASCE/SEI 7 requires that the structural "members and their foundations [be] designed for 100 percent of the forces in one direction plus 30 percent of the forces for the perpendicular direction." This is the 100%+30% rule and is attributed to Rosenblueth and Contreras (1977) in the ASCE/SEI 7 commentary. If linear or nonlinear response history analysis is used in the structure's design, ASCE/SEI 7 instead requires that orthogonal pairs of ground motion records be applied simultaneously. It is also permissible to use the 100% + 30% rule with linear response history analysis. ASCE/SEI 7 Chapter 16 contains further guidance on response history analysis.

Seismic Design Category D through F buildings with either non-orthogonal lateral force-resisting systems or shared structural elements, such as corner columns, where the seismic axial demand exceeds 20% of the design strength are required to be "designed for the most critical load effect due to application of seismic forces in any direction." ASCE/SEI 7 further stipulates that this requirement can be met by using either the 100% + 30% combination rule for equivalent lateral force or modal response spectrum analysis, or simultaneous application of ground motion pairs for response history analysis. One could theoretically meet the provisions, however, by analyzing the building under all possible angles of seismic incidence and without using the orthogonal combination rule. This is achievable through application of the lateral forces at each angle with respect to the building axes for the equivalent lateral force or modal response spectrum procedures. Researchers studying the direction of loading provisions have also sometimes rotated ground motions in nonlinear response history analysis over all seismic incidence angles (MacRae and Mattheis, 2000; MacRae and Tagawa, 2001; Bisadi and Head 2011). The application of earthquake shaking at multiple angles with respect to the building in order to satisfy the direction of loading provisions is rarely, if ever, pursued in professional practice.

ASCE/SEI 41-13 Provisions

Provisions for multidirectional seismic effects appear in Section 7.2.5 of ASCE/SEI 41-13. In contrast with ASCE/SEI 7, ASCE/SEI 41 does not distinguish its direction of loading provisions by Seismic Design Category. It therefore only has one set of "triggers" for consideration of direction of loading. Buildings which have an irregularity either described by a discontinuous lateral force-resisting system (due to a shift either in-plane or out-of-plane from story to story), a lateral force-resisting system with a weak story, or a lateral force-resisting system with a torsional strength imbalance must be assessed per ASCE/SEI 41's multidirectional seismic effects provisions. Additionally, buildings that have one or more columns that form part of two or more intersecting frames must consider concurrent seismic effects.

Consideration of direction of loading, similar to ASCE/SEI 7, is dependent on the analysis procedure. When the linear static or linear dynamic procedures are selected, ASCE/SEI 41 permits the use of the 100%+30% combination rule to satisfy the requirement for considering concurrent seismic effects. This is consistent with provisions in ASCE/SEI 7. When the nonlinear static procedure is selected, ASCE/SEI 41 permits the use of the 100%+30% combination rule but clarifies that the 30% need only be the "forces (not deformations) associated with 30% of the displacements". This establishes consistency with the linear static and linear dynamic procedures which reduce the elastic forces by an *m*-factor to account for ductility and then take 30%. In the nonlinear static procedure, the inelasticity is modeled explicitly and thus directly reduces the elastic forces (i.e. no m-factor is required). The 30% is then taken on those reduced forces. Alternatively, ASCE/SEI 41 permits a nonlinear static analysis of the structure with "100% of the displacements in any single direction that generates maximum deformation and component demands" in place of the 100%+30% rule. The commentary clarifies that for the example of a corner column in a square, regular building, a nonlinear static analysis at a 45 degree angle with respect to the building's principal axes could be pursued.

In addition to the 100%+30% orthogonal combination rule, ASCE/SEI 41 includes language for the linear static, linear dynamic and nonlinear static procedures that states "other combination rules shall also be permitted where verified by experiment or analysis." This provides the engineer with an alternative path to demonstrate compliance with the intent of the concurrent seismic effects provisions. Finally, when the nonlinear dynamic procedure is performed on a 3-dimensional model, ASCE/SEI 41 simply requires that both components of ground acceleration be applied simultaneously.

AASHTO Guide Specifications for LRFD Seismic Bridge Design Provisions

The 2nd edition of the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* addresses the combination of orthogonal seismic displacement demands in Article 4.4. Similar to ASCE/SEI 7 and ASCE/SEI 41, the AASHTO Guide Specifications adopt the 100%+30% orthogonal combination rule. It is, however, applied slightly differently than in ASCE/SEI 7 and ASCE/SEI 41. Because the AASHTO Guide Specifications utilizes a displacement-based, rather than a force-based, design procedure, the 100%+30% rule is applied to displacements rather than forces. ASCE/SEI 41's nonlinear static procedure is similarly a displacement-based procedure. Unlike ASCE/SEI 41's nonlinear static procedure, though, the AASHTO Guide Specifications do not take 30% of the force demands but instead use 30% of the displacement demands. For a highly ductile system, 30% of the displacements could be 100% rather than 30% of the forces in individual structural members.

The AASHTO Guide Specifications does state that for design procedures that require the development of elastic seismic forces "the procedure for development of such forces is the same as that for displacements". Therefore, when a structural member action is required to remain elastic, and is not otherwise controlled by capacity-design requirements, only 100%+30% of the forces need be used. These structural members are therefore designed similarly to the procedures in ASCE/SEI 7 and ASCE/SEI 41.

FHWA-HRT-06-032 Provisions

The provisions for combination of seismic force effects occur in Section 7.4.2 of FHWA-HRT-06-032. It provides two alternatives to demonstrating compliance, the first being the square-root-sum-of-the-squares (SRSS) rule and the second being the 100%+40% rule. The 100%+40% rule is similar to the 100%+30% rule in ASCE/SEI 7 except that the 30% component is increased to 40%. The SRSS rule combines a response quantity of interest (e.g. moment about the strong axis of a column) in a different way than the 100%+XX% rules. In the example of column strong axis moment demand, defined as M_u, instead of taking 100% of M_u due to x-direction shaking and 30% of M_u due to y-direction shaking, the SRSS rule takes the square root of the sum of 100% of M_u due to x-direction shaking and 100% of M_u due to y-direction shaking. In contrast with ASCE/SEI 7, ASCE/SEI 41 and the AASHTO Guide Specifications, FHWA-HRT-06-032 also provides guidance on combination rules for when vertical seismic forces are considered. In the other documents, vertical seismic forces are considered through load combinations.

Literature Review and Background

Brief History of Procedures

Development of orthogonal combination rules for multi-component ground motions was first attempted by O'Hara and Cunnif (1963) while Chu et al. (1972) proposed the use of the SRSS procedure. A class of orthogonal combination procedures known as the 100%+XX% rules first appeared when Newmark (1975) suggested that 100% of response in one direction plus 40% in the other could conservatively capture bidirectional loading. Rosenblueth and Contreras

(1977), based on earlier work by A.S. Velestos and Newmark, proposed the 100% + 30% rule which has gained widespread use in modern codes. More recently, Menun and Der Kiureghian (1998) extended the well-known CQC modal combination rule to a modal and directional combination rule named CQC3 (Complete Quadratic Combination with three components). They also noted that both the SRSS and the percentage rules were simplified or special cases of the CQC3 rule. Hernandez and Lopez (2002) further developed the CQC3 method into the GCQC3 (Generalized Complete Quadratic Combination with three components). While analytically investigating other directional combination procedures, Fernandez-Davila et al. (2000) implemented a method which takes 120% of the demand from a unidirectional analysis and applies it in the most unfavorable direction for each element. Note that all the preceding rules were derived based on linear-elastic theory and often made assumptions about ground motion characteristics. Research since the development of the CQC3 and GCQC3 rules has therefore tended to focus on analysis of linear and nonlinear models under single and multi-component ground motions in assessing the suitability of directional combination procedures. For example, a nonlinear study by Zaghlool et al. (2001) motivated the proposal for a 100% + 45% combination rule while Cimellaro et al. (2014) recommend a 100%+60% combination rule for nonlinear static analysis.

Derivation of the 100%+30% Rule

As the most common orthogonal combination rule in modern codes, the 100%+30% rule is used in the design of most structures today. A derivation of the 100%+30% rule first appeared in Rosenblueth and Contreras (1977), an abbreviated form of which is included here for the case of considering only the two horizontal, translational components of ground shaking. For the complete derivation refer to Rosenblueth and Contreras (1977). Begin by first making several assumptions:

1. Linear behavior of the structure.
2. No non-seismic loads. This can be equivalently stated as $R_0 = 0$ (See Equation 1 for notation).
3. Equal earthquake spectra for both horizontal components and a doubly symmetric structure. This can be equivalently stated as $R = R_1 = R_2$ (See Equation 1 for notation).
4. Responses to earthquake spectra for each horizontal component are not correlated with each other. This permits the use of the SRSS rule to combine responses.
5. The structure has equal capacity along any axis (e.g., a structure composed of one cantilever, round column). This can be equivalently stated as the failure surface is circular.

Then consider two cases representing the maximum error on the safe and unsafe side, respectively, for the 100%+XX% rule. For each case, set the structure's capacity equal to the response predicted by the 100%+XX% rule. The demand is taken as the response due to simultaneous application of earthquake shaking in both directions. The error is defined as the capacity minus the demand divided by the demand.

1. Maximum error on the safe side occurs when the responses due to the ground motion components are perpendicular to each other. Because the responses are perpendicular, the maximum demand has magnitude equal to R. However, Equation 1 requires that

R_1 and αR_2 (and also R_2 and αR_1) be considered simultaneous and therefore the capacity is the vector sum with magnitude equal to $R\sqrt{1+\alpha^2}$.

2. Maximum error on the unsafe side occurs when the responses due to the ground motion components are collinear to each other. The maximum demand is then computed as the SRSS of the responses for each direction. It therefore has a magnitude equal to $R\sqrt{2}$. However, Equation 1 requires that R_1 and αR_2 (and also R_2 and αR_1) be considered simultaneous and therefore the capacity is the vector sum with magnitude equal to $R(1+\alpha)$.

Table 1 summarizes the calculations for the safe side and unsafe side cases as described above. The error is also shown in the far right column. The absolute value of the maximum errors on the safe and unsafe side are equated and α is computed. This results in α = 0.336 and maximum safe and unsafe errors of 5.5%. In Rosenblueth and Contreras (1977), α was then taken as a rounded value of 0.3.

Table 1. Safe and unsafe side cases for derivation of the 100%+30% rule

Case	Demand	Capacity	Error
Safe Side	R	$R\sqrt{1+\alpha^2}$	$\sqrt{1+\alpha^2}-1$
Unsafe Side	$R\sqrt{2}$	$R(1+\alpha)$	$\frac{1+\alpha-\sqrt{2}}{\sqrt{2}}$

An applied engineering analogy for the two cases considered in the derivation by Rosenblueth and Contreras (1977), as described above, is now made. For the case of maximum error on the safe side, consider the roof displacement of a square, one-story building. First calculate the roof displacement response due to simultaneous shaking in both horizontal directions. As stated in the assumptions for the safe side case of the Rosenblueth and Contreras derivation, shaking in the x-direction only produces roof displacement in the x-direction and vice versa for the y-direction. As a hypothetical example, the roof x-direction and y-direction displacements could each be equal to 2 inches. Now consider the simultaneous application of x-direction and y-direction shaking. Another assumption made is that the responses due to each direction are not correlated. This can be thought of more practically as that the maximum responses in each direction do not occur simultaneously. Therefore, the 2 inch roof displacement in the x-direction and 2 inch roof displacement in the y-direction will not occur at the same time even when both components of shaking are applied simultaneously. The roof displacement demand can then be considered as 2 inches in the x-direction or 2 inches in the y-direction but not both at the same time. However, the structure's capacity has been determined by the 100%+30% rule. The 100%+30% rule does not recognize that the x-direction and y-direction roof displacements occur at different points in time but instead requires that the structure be designed for the effects of 100% of the maximum response in one direction and 30% of the maximum response in the other concurrently. The vector roof displacement would then be, for the hypothetical numbers described previously, $\sqrt{(2\ inches)^2+(0.3*2\ inches)^2} \cong 2.1\ inches$. Both the demand and capacity are thus shown to be equal to the values represented in Table 1 for the safe side case after substituting R = 2 inches.

For the case of maximum error on the unsafe side, consider the same square, one-story building but designed to a different criteria. Instead of its capacity being set for a roof displacement from the 100%+30% rule, it has been designed for the axial load in a corner column from the 100%+30% rule. A corner column is one which receives axial force from frames in both the x-direction and the y-direction. For the example of a square building, the column would receive axial force due shaking in the x-direction and the same axial force due to shaking in the y-direction. As a hypothetical example, say this axial force is equal to 10 kips from each direction independently. When the ground shaking is applied simultaneously, the maximum of 10 kips from the x-direction and 10 kips from the y-direction will not occur at the same instant in time (just as before for the 2 inch roof displacement considered in the safe side case). However, because the response quantity of interest is now a scalar (i.e., axial force in the column) rather than a vector (i.e., roof displacement which has components both in the x-direction and the y-direction), the maximum demand is no longer limited to the maximum from each direction of shaking independently. Instead, the SRSS rule is used in the Rosenblueth and Contreras derivation. The SRSS rule is known to provide an accurate estimate of the combined response for this condition (Menun and Der Kiureghian, 1998). Thus the axial force demand in the corner column will be equal to $\sqrt{(10\ kips)^2 + (10\ kips)^2} \cong 14.1\ kips$. However, the 100%+30% rule requires instead that the corner column only be designed for $10\ kips + 0.3 * 10\ kips = 13\ kips$. Both the demand and capacity are thus shown to be equal to the values represented in Table 1 for the unsafe side case after substituting R = 10 kips.

Direction of Loading Assessment in the Literature

As mentioned previously, direction of loading has been referenced by many names, and evaluated using various methods. The following is a summary of how other researchers have approached the direction of loading issue.

Hisada et al. (1988) used the ratio of the response spectra computed using both horizontal components of ground motion to the response spectra computed using only one of the two components as a measure of the effect of concurrent seismic effects. The framework of maximum direction ground motions recently introduced in ASCE/SEI 7-10 is closely related to the work in Hisada et al. (1988).

MacRae and Mattheis (2000) assessed the SRSS, 100%+30%, and the Sum-of-Absolute-Values (SAV) rules for a steel moment frame building using nonlinear response history analysis with varying angle of ground motion incidence. The SAV rule takes the absolute value of the maximum response due to each earthquake shaking direction and adds them together. Drifts, rather than forces, were used in their evaluation "because forces do not always change significantly with displacement once the structure yields." This resulted in their reinterpretation of the 1997 UBC provisions as relating to "expected seismic drifts" rather than forces. Evaluation was conducted by first analyzing the model under each ground motion component independently to establish the SRSS, 100%+30% and SAV rules and then with both ground motion components simultaneously to predict the "true" response. They concluded that (1) the SRSS, 100%+XX% and SAV methods were dependent on the reference axes selected (i.e., at what rotation with respect to the principal axes of the building) and (2) all methods unconservatively estimated the frame inelastic story drifts.

Lopez et al. (2001) compared the SRSS, 100%+30% and 100%+40% rules to the CQC3 rule. They defined the critical response, r_{cr}, as that obtained from the CQC3 rule and found that the SRSS, 100%+30% and 100%+40% rules ranged between $1.00r_{cr}$ and $1.26r_{cr}$, $0.92r_{cr}$ and $1.16r_{cr}$, and $0.99r_{cr}$ and $1.25r_{cr}$, respectively. It was also noted that the critical response from the CQC3 method "increases when the vibration periods of the two modes that contribute most in the response to the x- and y-components of ground motion become close to each other. This effect is not taken into account by any of the multicomponent combination rules."

Zaghlool et al. (2001) assessed the 100%+XX% rules using linear and nonlinear response history analysis. Their approach took the response in the x-direction at the time of maximum response in the y-direction. This was then divided by the maximum response in the x-direction and was similarly computed for the y-direction. They describe this ratio as the "percentage activated of the maximum strong-axis response at the time of maximum weak-axis response" and can be interpreted as the XX% component of the 100%+XX% rule. From the results of their analysis, a 100%+45% rule was recommended.

MacRae and Tagawa (2001) considered linear and nonlinear response history analyses of a steel moment frame building with columns that were shared by the lateral force-resisting system in both directions. Similar to MacRae and Mattheis (2000), drifts rather than forces were used to assess the SRSS, 100%+30%, and SAV rules as shown in Figure 1. Linear response history analysis was utilized to define the combination rule envelopes. They found that the actual response for linear analysis was always within the SAV rule but often exceeded the SRSS and 100%+30% rules as seen in Figure 1a. For nonlinear analysis, all combination methods, including the SAV rule, were exceeded as seen in Figure 1b.

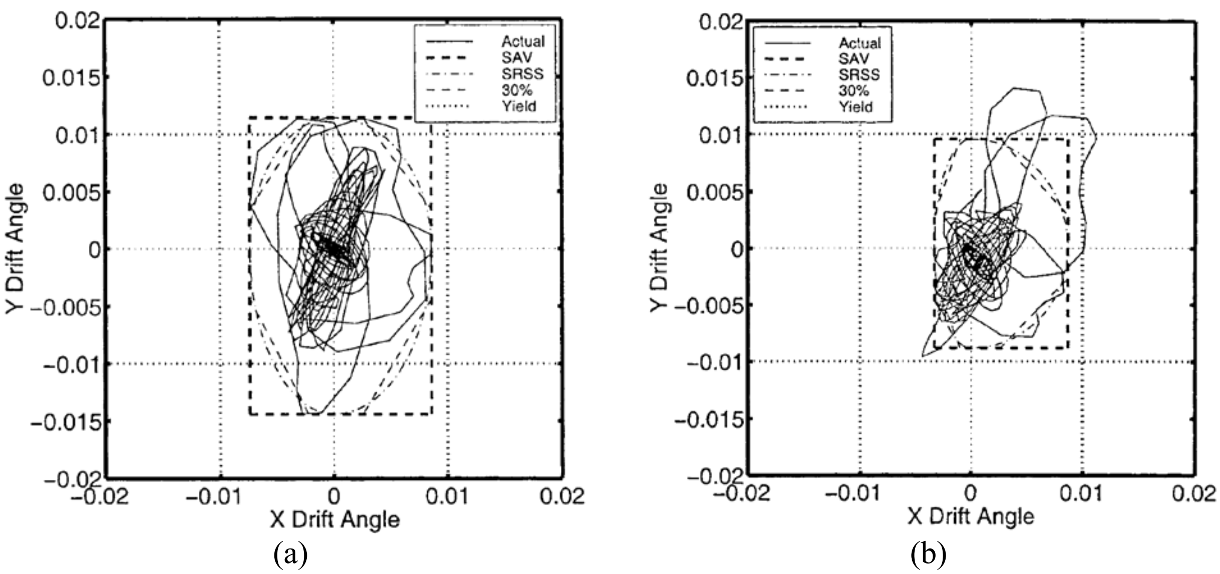

Figure 1. Results and combination rules for (a) linear and (b) nonlinear response history analysis. Note that (a) and (b) use a different angle of ground motion application to the building which explains why the combination rule envelopes differ. This figure is direct reproductions of Figure 4 and Figure 5, respectively, in MacRae and Tagawa (2001).

Sherman and Okazaki (2010) analyzed buckling-restrained brace frame (BRBF) buildings with columns that were shared by the BRBFs in both directions using nonlinear response history analysis. They used two criteria for designing the shared corner columns: (1) corner columns designed for 100% of the forces due to the capacity of the BRBs in one direction and 30% of the forces due to the capacity of the BRBs in the orthogonal direction, and (2) corner columns designed for 100% of the forces due to capacity of the BRBs in both directions. This is analogous to, but not exactly the same, as the 100%+30% rule in ASCE/SEI 7 because the column forces are based on system capacity rather than lateral design forces. They found that the first design criteria were unconservative in several cases and adequate in others. The second criterion was conservative for all cases, with the degree of conservatism increasing with height of the building due to the lower likelihood that all braces would be yielding simultaneously.

Bisadi and Head (2011) evaluated the 100%+30%, 100%+40% and SRSS rules using nonlinear response history analysis of bridges. They considered two cases: (1) apply only the major component of ground motion, defined as the component having the larger PGA, in each of the longitudinal and transverse directions of the bridge independently and combine responses using the combination rules, and (2) apply major and minor components simultaneously but run one analysis at an application angle of 0 degrees with respect to the bridge axes and another at 90 degrees. Combine the 0 and 90 degree analysis using the combination rules. They then determined the probability of underestimation for each combination rule for each of the two cases considered as shown in Figure 2. Note that the probability of underestimation changes depending on whether displacement demands or force demands are considered.

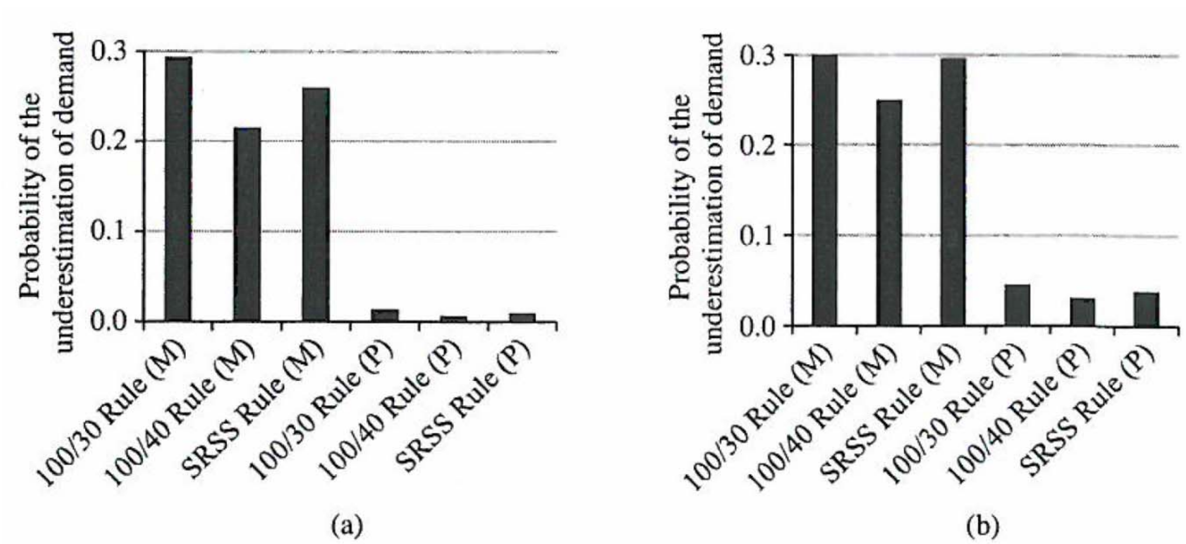

Figure 2. Probability of underestimation of (a) displacement and (b) force demands for SRSS, 100%+30% and 100%+40% combination rules. Letter M denotes only the major component of earthquake was used (Case 1) and letter P denotes that the paired record was used (Case 2). This figure is a direct reproduction of Figure 8 in Bisadi and Head (2011).

Cimellaro et al. (2014) proposed a modified nonlinear static analysis method that utilizes factors of 1.0 and 0.6 on the two orthogonal load patterns, respectively. The value of 0.6, which is different than the typical 100%+30% rule, was arrived at by calibration with nonlinear response history analysis of six highly irregular reinforced concrete frame buildings. They assert that the difference is a result of considering nonlinear rather than linear response, the latter of which formed the basis for the 100%+30% rule.

Approaches to Assessing Direction of Loading

With a history as long as that of the direction of loading provisions' development - dating back to the 1970s with Newmark (1975) and Rosenblueth and Contreras (1977) - a strong case must be made to effect change in modern codes. Such a case requires that the direction of loading provisions be evaluated in many independent ways using a variety of evaluation techniques. Some of the groundwork has been completed and is documented in the research literature. Stepping beyond that work, the authors are currently pursuing one approach using instrumented data from the Center for Engineering Strong Motion Data (CESMD). Other potential approaches would take advantage of the more explicit collapse safety criteria in modern codes, especially ASCE/SEI 7-10.

Characterization of the ASCE/SEI 7-10 Provisions

Although the direction of loading provisions in ASCE/SEI 7-10 are procedurally fairly straightforward, on further thought, they become quite challenging to interpret conceptually. In implementing the 100%+30% rule in ASCE/SEI 7, the engineer must check eight cases corresponding to all combinations of results for each direction considering positive and negative signs. For example, one case would be 100% of the positive x-direction forces in combination with 30% of the positive y-direction forces while another case would be 100% of the positive x-direction forces in combination with 30% of the negative y-direction forces. While these cases follow directly from implementation of the provisions, it is less clear how these "control points" assure adequate building performance for other regions in the response space. For example, how is the building design expected to perform for loading at a 45 degree angle with respect to the x- and y-direction axes?

Figure 3 illustrates several interpretations of how these control points could be interpolated to capture all regions of the response space. In Figure 3a, a fairly conservative interpretation is applied where only the regions enclosed by the eight control points are considered to be explicitly captured by the 100%+30% provisions. Any response point inside of the cross shape would be considered safe while any point outside may or may not be. A less conservative interpretation of the provisions is shown in Figure 3b. It assumes that satisfying the control points ensures building performance so long as the response stays within an octagon formed by those eight points. Some judgment is required in establishing the interpolation on the diagonal. Although a linear interpolation has been pursued in prior research (MacRae and Tagawa, 2001), the original derivation of the 100%+30% rule assumed a convex "failure surface." One might then conclude that an interpretation of the ASCE/SEI 7 provisions using an elliptical interpolation as presented in Figure 3c may be more appropriate. Note that elliptical interaction reduces to circular interaction under the special case when the response in the x-direction and that in the y-direction are equal.

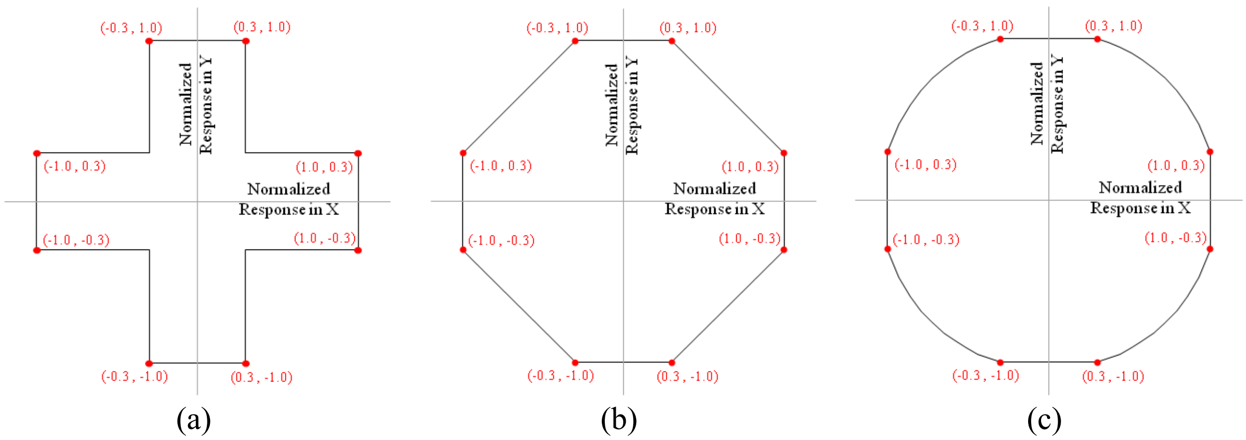

Figure 3. Interpolation of the eight control points in the ASCE/SEI 7-10 direction of loading provisions based on (a) no interpolation on the diagonal, (b) linear interpolation on the diagonal and (c) elliptical interpolation on the diagonal. Control points shown as red dots.

Assessment using Instrumented Building Data

As described in the previous section, all of the existing research on direction of loading appears to have focused on analytical studies. While these approaches are important and can add greatly to the understanding of direction of loading, they are limited by the profession's and academic community's ability to simulate the real response of structures. The existence of the Center for Engineering Strong Motion Data provides an opportunity to explore the response of real buildings during real earthquakes. The authors are currently pursuing a study which capitalizes on the advantage of access to seismically instrumented building data from the CESMD to evaluate the direction of loading provisions in ASCE/SEI 7-10.

The study takes the seismically instrumented building data from the CESMD and evaluates the relative displacement between instrumented levels, the relative displacement between an instrumented level and the ground, and the absolute acceleration of an instrumented level, all considering the simultaneous occurrence of these measures about both horizontal, principal axes of each station under each earthquake. Several metrics are defined to evaluate the 100%+XX% rule based on different evaluation techniques, some of which are conceptually described under "Characterization of the ASCE/SEI 7-10 Provisions," and the probability of exceeding each rule for the full CESMD database is calculated. This research is an ongoing effort by the authors, results of which will be reported in future publications.

The use of data from seismically instrumented buildings to assess the direction of loading procedures has the significant advantage of eliminating many sources of uncertainty by using the response of real buildings during real earthquakes. At the same time, it is also at a disadvantage compared with other, namely simulation-based, approaches. This is because a direct assessment of the direction of loading provisions requires a building to be designed by the provisions and then assessed against the collapse safety goals of the respective standard (e.g. ASCE/SEI 7) under extreme earthquake loading. The instrumented building data approach is limited on two major fronts in comparison against a direct assessment approach. Firstly, it tends to be sparse in the number of buildings which have experienced inelastic response, let alone extreme earthquake shaking. Secondly, the available data provide how a building responded to a specific earthquake but not what the design parameters would have been if that earthquake were specified for design. The latter would require analytical modeling of the structure and would therefore exist whether or not instrumented building data was available at or near extreme earthquake shaking levels.

Other Potential Approaches

Another approach to assessing direction of loading could be pursued using the FEMA P695 (FEMA, 2009) methodology. With the explicit definition of acceptable probability of collapse for new buildings now in the commentary to ASCE/SEI 7-10, the FEMA P695 procedure could be implemented for buildings designed using the current direction of loading provisions. This would amount to designing many buildings to the current provisions and then subjecting nonlinear analytical models of them to increasing levels of earthquake shaking. In combination with the approach taken by the authors, this further research could make a strong case for changes to the direction of loading provisions in modern codes.

Summary

Research motivations and a comprehensive literature review concerning the direction of loading provisions in modern codes have been enumerated. From a review of modern codes for seismic design and rehabilitation of bridges and buildings, it is observed that the 100%+30% orthogonal combination rule is the most prevalently referenced procedure. Its derivation appears in a 1977 paper by Rosenblueth and Contreras. Since that time, many other orthogonal combination procedures have been recommended by researchers including the SRSS, CQC3 and numerous 100%+XX% methods. In recent years, nonlinear response history analysis has generally demonstrated that the 100%+30% rule underestimates building seismic response. Several studies have emphasized the evaluation of structures thought to be especially susceptible to concurrent seismic effects such as buildings with shared corner columns.

In approaching a systematic evaluation of the direction of loading provisions in a modern code such as ASCE/SEI 7-10, it is discovered that some assumptions must be made as to how the provisions ensure acceptable building performance in all regions of the response space. The authors are currently pursuing a study which uses seismically instrumented building data from the Center for Engineering Strong Motion Data to evaluate the direction of loading provisions in ASCE/SEI 7-10. This research is an ongoing effort, results of which will be reported in future publications. Finally, other potential approaches for assessing the direction of loading provisions are suggested as future research.

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References

AASHTO (2011). *AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2nd Edition*. American Association of State Highway and Transportation Officials, Washington, DC.

ASCE (2010). *Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10*. American Society of Civil Engineers, Reston, Virginia.

ASCE (2013). *Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-13*. American Society of Civil Engineers, Reston, Virginia.

Bisadi, V., and Head, M., (2011). "Evaluation of Combination Rules for Orthogonal Seismic Demands in Nonlinear Time History Analysis of Bridges," *Journal of Bridge Engineering, Special Issue: AASHTO-LRFD Bridge Design and Guide Specifications: Recent, Ongoing, and Future Refinements*, p711-717.

Chu, S. L., Amin, M. and Singh, S., (1972). "Special Treatment of Actions of Three Earthquake Components on Structures," *Nuclear Engineering and Design*, Vol. 21, No. 1, p126-136.

Cimellaro, G., Giovine, T. and Lopez-Garcia, D. (2014). "Bidirectional Pushover Analysis of Irregular Structures," *Journal of Structural Engineering*, Vol. 140, No. 9, 04014059.

FEMA (2009). *Quantification of Building Seismic Performance Factors, FEMA P695*. Federal Emergency Management Agency, Washington, D.C.

Fernandez-Davila, I., Cominetti, S. and Cruz, E. F., (2000). "Considering the Bi-Directional Effects and the Seismic Angle Variations in Building Design," *Proceedings of 12th World Conference on Earthquake Engineering*, EQC, Auckland, New Zealand, Vol. 435.

FHWA (2006). *Seismic Retrofitting Manual for Highway Structures: Part 1 - Bridges*. Federal Highway Administration, McLean, Virginia.

Hernandez, J. J. and Lopez, O. A., (2002). "Response to Three-Component Seismic Motion of Arbitrary Direction," *Earthquake Engineering and Structural Dynamics*, Vol. 31, p55-77.

Hisada, T., Miyamura, M., Kan, S. and Hirao, Y., (1988). "Studies on the Orthogonal Effects in Seismic Analyses," *Proceedings of Ninth World Conference on Earthquake Engineering*, Tokyo, Japan.

ICBO (1997). *Uniform Building Code*. International Conference of Building Officials, Whittier, California.

Lopez, O. A., Chopra, A. K. and Hernandez, J. J., (2001). "Evaluation of Combination Rules for Maximum Response Calculation in Multicomponent Seismic Analysis," *Earthquake Engineering and Structural Dynamics*, Vol. 30, p1379-1398.

MacRae, G. and Mattheis, J., (2000). "Three-Dimensional Steel Building Response to Near-Fault Motions," *Journal of Structural Engineering*, Vol. 126, Issue 1, p117-126.

MacRae, G. A. and Tagawa, H., (2001). "Seismic Behavior of 3D Steel Moment Frame with Biaxial Columns," *Journal of Structural Engineering*, Vol. 127, No. 5, p490-497.

Menun, C. and Der Kiureghian, A., (1998). "A Replacement for the 30%, 40% and SRSS Rules for Multicomponent Seismic Analysis," *Earthquake Spectra*, Vol. 14, No. 1, p153-163.

Newmark, N.M., (1975). "Seismic Design Criteria for Structures and Facilities - Trans-Alaska Pipeline System," *Proceedings of the U.S. National Conference on Earthquake Engineering*, Ann Arbor, USA, p94-103.

O'Hara, G. J. and Cunnif, P. F., (1963). "Elements of Normal Mode Theory," Report 6002, Naval Research Laboratory, Washington, DC, USA.

Rosenblueth, E. and Contreras, H. (1977). "Approximate Design for Multicomponent Earthquakes," *Journal of the Engineering Mechanics Division*, Proceedings of ASCE, Vol. 103, No. EM5, p 881-893.

Sherman, J. and Okazaki, T., (2010). "Bidirectional Loading Behavior of Buckling-Restrained Braced Frames," *Proceedings of ASCE Structures Congress 2010*, Orlando, Florida.

Zaghlool, B. S., Carr, A. J. and Moss, P. J., (2001). "Inelastic Behavior of Three-Dimensional Structures under Concurrent Seismic Excitations," *Proceedings of 12th World Conference on Earthquake Engineering*, EQC, Auckland, New Zealand.