Engineering Structures 177 (2018) 234–243

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Probabilistic evaluation of combination rules for seismic force demands from orthogonal ground motion components

Henry V. Burton*, Nilofar Doorandish, Mehrdad Shokrabadi

Dept. of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

ARTICLE INFO

Keywords:
Orthogonal ground motion components
Seismic force demands
Probabilistic evaluation
Combination rules
Nonlinear response history analyses

ABSTRACT

A probabilistic approach to assessing the effectiveness of the rules used to combine demands from orthogonal ground motion components is developed. Full probability distributions of the ratio between the force demands obtained from nonlinear response history analyses using bidirectional loading, which are taken as the "true" demands, and rule-based combinations of the demands from unidirectional loading, are developed. For the percentage combination rules (*100-p*), a relationship is established between the value of *p* (e.g. *p* = *30%* for *100–30* rule) and the probability that the bidirectional loading demands exceed the rule-based combination of the unidirectional loading demands. Using this relationship, an appropriate value of *p* based on an acceptable exceedance probability is determined. The proposed framework is demonstrated using special concentric braced frames with biaxially loaded columns, which are shared by orthogonal braced frames. The combinatorial effect of the orthogonal responses is found to be influenced by several factors including the type of demand parameter (e.g. column axial forces versus stresses), demand level and building height.

1. Introduction

The lateral force resisting system (LFRS) in buildings is often oriented along two orthogonal directions. The force demands used to design these LFRS elements are obtained by analyzing the structure for the horizontal translational components of earthquake loads acting independently in each orthogonal direction and then combining them accordingly. The rules that govern the combination of orthogonal loading effects are intended to account for the simultaneous action of the translational components of earthquake ground motions, which is especially relevant to asymmetric structures and bi-directionally loaded LFRS elements. Examples of biaxially loaded LFRS elements include columns located at the intersection two orthogonal steel moment frames or special concentric braced frames (SCBF). Although not ideal, biaxially loaded LFRS columns are often used because of building architectural or programmatic constraints.

The current state of structural engineering practice for combining orthogonal earthquake load effects is to use either the square-root-sum-of-squares (SRSS) or a percentage combination rule. The percentage rule, which can be traced back to the works of Newmark [1] and Rosenblueth and Contreras [2], uses the larger of the responses obtained by combining 100% of the demand from loading in one direction with some percentage, *p*, that is associated with loading in the orthogonal direction. The "30%" rule, which was proposed by Rosenblueth and Contreras, has been adopted in Section 12.5 of ASCE 7-10 [3], which requires a LFRS to be designed for "100 percent of forces for loading in one direction plus 30 percent of forces for loading in the perpendicular direction". The rule is applicable to structures with a horizontal irregularity or columns or walls that form part of two intersecting LFRSs and have an axial load ratio greater than 20%. The "40%" rule proposed by Newmark has been used in the seismic analysis of nuclear facilities [4].

Smeby and Der Kiureghian [5] developed two alternative rules (denoted as CQC3 rules) for orthogonal seismic demands, which account for the effect of the excitation angle and correlations between the ground motion components and the modal responses of the structure. The first rule is based on prescribing an excitation angle that produces the largest response demand and the second considers the uncertainty in the excitation angle. Menun and Der Kiureghian [6] showed that the SRSS and percentage combination rules can be obtained from CQC3 using certain assumptions about the ground motion and response demand components. More specifically, they showed that the SRSS rule is a special case of CQC3, where the principal directions of the ground motions [7] coincide with the orthogonal axes of the structure or the intensity of the horizontal ground motion components are equal. They also showed that if the ratio between the horizontal principal-direction

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* Corresponding author.
E-mail address: hvburton@seas.ucla.edu (H.V. Burton).

https://doi.org/10.1016/j.engstruct.2018.09.061
Received 8 April 2018; Received in revised form 13 August 2018; Accepted 20 September 2018

ground motion components is about 0.85, the percentage rules (30% and 40%) provide conservative approximations to CQC3.

Several researchers have evaluated the adequacy of various rules that have been proposed for combining orthogonal load effects. Menun and Der Kiureghian compared the response demands obtained when the CQC3, 30%, 40% and SRSS rules are applied to a curved bridge. Heredia-Zavoni and Machicao-Barrionuevo [8] evaluated the ability of the percentage combination rules to adequately estimate the linear response of a generic one-story structural system with different torsional and translational stiffnesses on soft and firm soil conditions. The structures were analyzed in the frequency domain using principal-direction ground motion components from “large-intensity” Mexican earthquakes. The results showed that the percentage combination rules overestimated the force demands under certain conditions and underestimated the demands for others (e.g. torsionally stiff and translationally flexible structures). Lopez et al. [9] used 1-story symmetrical and asymmetrical plan buildings, a 9-story asymmetrical concrete frame building and a single 20-story symmetrical steel frame building to evaluate the SRSS and percentage combination rules using the CQC3 rule to benchmark the performance. The authors found that the 40% rule generally overestimated the demands in the one-story structures when the ratio between the horizontal ground motion components is about 0.65. For the same building cases, the SRSS rule underestimated the response. All three rules predicted response demands within 10% of CQC3 for the 20-story steel frame building. For the 9-story concrete frame building, the percentage and SRSS rules overestimated and underestimated the response demands, respectively.

The above-mentioned studies did not consider nonlinear structural response in their evaluation of combination rules for demands from orthogonal ground motion components. This is especially noteworthy since most structures are designed with the expectation that they will respond inelastically if subjected to the design basis loads. MacRae and Mattheis [10] conducted nonlinear response history analyses on a three-dimensional structural model of a 3-story steel frame building using bidirectional near-field ground motions applied at excitation angles ranging from zero to ninety degrees. The results were used to evaluate drift demands obtained from the 30%, SRSS and “sum-of-absolute-values” combination rules. All three rules underestimated the drift demands obtained when the ground motions are applied in the principal direction. Reyes-Salazar et al. [11] performed an extensive parametric study on 1-, 3-, 8- and 15-story steel moment frame structures with biaxially loaded columns. Response history analyses were performed on linear and nonlinear structure models of the four building cases using bi-direction ground motions oriented in the normal (aligned with building axes) and principal directions. The accuracy of the 30% and SRSS combination rules in estimating the total base shear and column axial loads was evaluated. Both rules were shown to underestimate the demands obtained from the principal-direction ground motions with the 30% rule performing slightly better. Both rules performed similarly for elastic and inelastic analyses.

The current study develops a probabilistic methodology for evaluating the adequacy of the existing rules for combining orthogonal earthquake load effects. The methodology uses engineering demand parameters generated from nonlinear response history analyses of building structures subjected to unidirectional and bidirectional loading. The performance of a combination rule is described in terms of the complete probability distribution of the ratio between the demands from bidirectional loading, which is taken as the “true” demands, and rule-based combinations of the demands from unidirectional loading. For the percentage combination rules (100-*p*), a relationship is developed between the value of *p* (e.g. p = 30% for 100–30 rule) and the probability that the bidirectional loading demands exceed the rule-based combination of the unidirectional loading demands. Using this relationship, an appropriate value of *p* based on an acceptable exceedance probability is determined. The methodology is demonstrated through application to a set of symmetric SCBF systems with biaxially loaded columns. However, it is presented in a generalized manner such that it can be applied to other types of LFRS configurations (e.g. biaxially loaded moment frame columns or structures with plan irregularities).

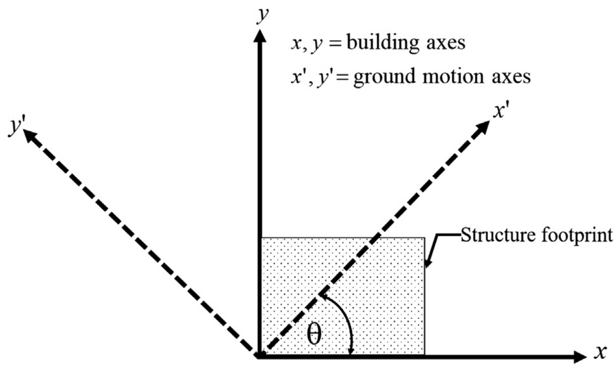

Fig. 1. Axes defining the location of the building structure and horizontal ground motion components.

2. Generalized description of combination rules

The combination rules can be described in terms of the peak response demands in the directions of the building axes and parameters related to the LFRS and ground motion components. This general formulation, which has been developed in prior works (e.g. [9]), is presented to provide context for the probabilistic assessment methodology. Fig. 1 shows a schematic plan view with the horizontal axes of the building (x and y) and principal directions of the ground motion (x' and y'). The relative orientation of the building and principal ground motion axes is described in terms of the angle θ, which is measured counterclockwise from x and x'. The response demands in the x and y directions are denoted as D_x and D_y, respectively. To facilitate describing the combination rules in terms of dimensionless parameters, the ratio between the response demands D_y and D_x is defined as β and γ and taken as the ratio between the response spectra of the principal direction ground motion components, which is assumed to be the same at all periods. The combined response demand can be estimated using the CQC3 rule [5,9].

$$D_{CQC3} = \left[D_x^2(1+\beta^2) - D_x^2(1-\gamma^2)\left(1-\frac{\beta^2}{\gamma^2}\right)sin^2\theta + 2\left(\frac{1-\gamma^2}{\gamma}\right)D_{xy}sin\theta cos\theta\right]^{\frac{1}{2}} \tag{1}$$

where D_{xy} is a cross term that accounts for the correlation between modal responses. Given that θ is typically unknown during the design process, the maximum combined response demand considering all values of θ can be computed using Eq. (2) [5,9].

$$D_{cr,CQC3} = D_x\left[(1+\gamma^2)\left(\frac{1+\beta^2}{2}\right) + (1-\gamma^2)\sqrt{\left(\frac{1-\beta^2}{2}\right) + (\alpha\beta)^2}\right]^{\frac{1}{2}} \tag{2}$$

where α is the correlation coefficient for the response demands D_x and D_y, which is taken as the ratio between D_{xy} and D_xD_y. The SRSS combination rule can be obtained from Eq. (1) by assuming that the principal directions of the ground motion are aligned with the building axes or $\theta = 0$.

$$D_{SRSS} = max\left[D_x\sqrt{1+(\gamma\beta)^2},\ D_x\sqrt{\gamma^2+\beta^2}\right] \tag{3}$$

Note that Eq. (3) reduces to the square-root-sum-of-squares of D_x and D_y if the orthogonal ground motion components are assumed equal ($\gamma = 1$). The percentage rules attempt to account for the differences in the spectral intensities of the ground motion components ($\gamma < 1$).

$$D_p = max\left[D_x(1+p\beta),\ D_x(p+\beta)\right] \tag{4}$$