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Simplified relations for the application of rotational components to seismic design codes

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ABSTRACT

In this paper, after reviewing the characteristics of earthquake rotational components, the acceleration response spectra of rocking and torsional components are presented. In addition, the proposed relations in the author's previously published paper on the rotational loading of structures are extended, and application of the new relations is examined. The numerical results of this study show that the contribution of earthquake rocking components to the rotational loading of multistory buildings is strongly sensitive to structural irregularity, structural height and seismic excitation. The rocking component contribution to story shear can be one-third of the horizontal component contribution, and should be included in seismic design codes. Further, the value of the eccentricity of 0.05 plan dimension, which is prescribed in the most current seismic design codes for accidental torsional effects, is not a conservative approximation for the accidental eccentricity caused just by the influences of the torsional component, particularly in symmetric, torsionally stiff, multistory buildings.

1. Introduction

The definition of reliable and accurate earthquake loading patterns is one of challenges in structural engineering. In spite of the fact six components – three translational and three rotational – are needed to describe the Strong Ground Motions (SGMs), in the past four decades there has been little research on the effects of rotational components on the seismic behavior of structures. However, the theoretical studies on the failure of engineering structures during the past SGMs have shown that parts of earthquake damage or even the collapse of structures cannot be solely attributed to translational components. In fact, unexpected failures of structures such as tall, asymmetric buildings or irregular frames [1], bridge piers [2], slender tower-shaped structures [3], nuclear reactors [4], vertically irregular buildings [5], and even ordinary multistory buildings near earthquake faults [6] may be due to the influence of seismic loading of the rotational motions [7–19]. Because of the limited recorded data on the rotational components, the earthquake resistant structures are mainly designed to consider only the influences of the translational components, and the seismic loading due to rotational components is ignored or underestimated by most seismic design codes. This paper seeks to determine the effects of earthquake rotational components on structural loading.

The effects of the rocking components on the seismic loading of structures are only considered by Eurocode 8, part 6 (EC8.6, 2005) [20]. The code recommends that rocking excitation should be considered for tall structures (higher than 80 m) designed in regions of high seismicity. This code also presents a formula in the form of a torsional response spectrum to consider seismic loading due to the torsional component. However, the effect of the torsional component is usually considered by introducing the accidental eccentricity in most seismic design codes and is included in the seismic loading by applying equivalent lateral forces at a distance from the Center of Rigidity (CR). Some codes also specify this eccentricity with respect to the shear center. The concept of CR arises from single-story structures with rigid floor diaphragm where there is always a point on the floor (CR) which if a static load (of arbitrary magnitude and direction) applied through this point, will translate the floor without rotation. This concept cannot always be extended to multistory structures in terms of a set of points at floor levels that possess the same property. However, there is only a special class of multistory buildings, namely buildings having vertical resisting elements with proportional stiffness matrices, in which a set of CRs can be defined in the aforementioned strict sense and lie on a common vertical line [21,22]. Because seismic provisions are based on studies concerning the torsional response of single-story systems and the dynamic response of plane frames [23–26], these provisions rigorously apply to the uniform multistory shear or flexural type structures (proportionate buildings).

The code provision for the design eccentricity at the fth floor, e_{df}, can be expressed in a general form as $e_{df} = \delta_1 e_f + \beta b_f$ and $\delta_2 e_f + \beta b_f$

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where e_f is the static eccentricity at the *f*th floor defined between the floor Center of Mass (CM) and the CR, b_f is the plan dimension of the *f*th floor normal to the considered direction of ground motion, and coefficients δ_1, δ_2, and β are the code specified constants. The accidental eccentricity is assumed to be a fraction of the plan dimension and the term βb_f is introduced in seismic codes to account for eccentricities because of two main reasons: differences between the analytical and actual location of centers of mass, shear, and resistance in structures during an SGM, and the torsional vibration induced by spatial variation of ground motions at the base of structures. The coefficient β based on the finding of the elastic analysis of rigidity supported structures and on engineering judgment is proposed to be in the range of 0.05–0.1 in most seismic design codes. The results of past researches on current code provisions related to rotational components have shown that for a seismic design, none can safely estimate the influence of seismic loading due to the rotational components on the structural behavior, and the current provisions of the seismic code need extensive modification [27,28].

In this study, the characteristics of rotational components and their relation to corresponding translational components are reviewed and the effects of rocking and torsional loading in the seismic loading patterns of structures are discussed. To achieve this, the formulation given in the previously published paper of the author [19] for the rotational loading of single-story buildings is extended, and the applicability of the new relation is studied for multistory buildings. In addition, it is shown that the behavior of a single-story building is not similar to its equivalent proportionate multistory building subjected to the combined action of three earthquake components (horizontal, rocking, and torsional components).

2. Characteristics of rotational components

The characteristics of rotational components are studied in three parts: (1) mathematical background; (2) simplified forms of rotational motions; and (3) spectral density function of rotational components along principal axes.

2.1. Mathematical background

The displacement SGM components always accompany the rotational components induced by spatial variation of seismic waves. From an engineering aspect, a common method to estimate the rotational components is the evaluation of the gradient of the corresponding translational components. In this case, it is required to assume an appropriate wave propagation system. Fig. 1(a) shows a schematic diagram of the wave propagation mechanism of a seismic event from the hypocenter to the site. Herein, by assuming the translational displacements at point O at the site (see Fig. 1(a)) as:

$$\vec{u}(t) = u_x(t)\vec{i} + u_y(t)\vec{j} + u_z(t)\vec{k} \tag{1}$$

the corresponding rotational components are estimated. By defining a Cartesian coordinate system on the ground surface ($z = 0$) as shown in Fig. 1(a), displacement gradient, $\nabla\vec{u}(t)$, which is a second order tensor, can be written as:

$$\nabla\vec{u}(t) = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right) & 0 \\ \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right) & \frac{\partial u_y}{\partial y} & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & -\frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right) & -\frac{\partial u_z}{\partial x} \\ \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right) & 0 & -\frac{\partial u_z}{\partial y} \\ \frac{\partial u_z}{\partial x} & \frac{\partial u_z}{\partial y} & 0 \end{bmatrix} \tag{2}$$

where the symmetric matrix corresponds to the strain tensor in small deformation and the anti-symmetric matrix is the rotation tensor. From this relation, the rotational components vector, $\vec{\theta}(t)$, may be expressed as:

$$\vec{\theta}(t) = \frac{\partial u_z(t)}{\partial y}\vec{i} - \frac{\partial u_z(t)}{\partial x}\vec{j} + \frac{1}{2}\left[\frac{\partial u_y(t)}{\partial x} - \frac{\partial u_x(t)}{\partial y}\right]\vec{k} \tag{3}$$

To simplify Eq. (3), it is necessary to determine the contribution of the different seismic waves to the translational components. In this case, the translational components corresponding to Eq. (1) are expressed in the frequency domain as:

$$\vec{U} = U_x(\kappa_x x + \kappa_y y + \kappa_z z - i\omega t)\vec{i} + U_y(\kappa_x x + \kappa_y y + \kappa_z z - i\omega t)\vec{j} + U_z(\kappa_x x + \kappa_y y + \kappa_z z - i\omega t)\vec{k} \tag{4}$$

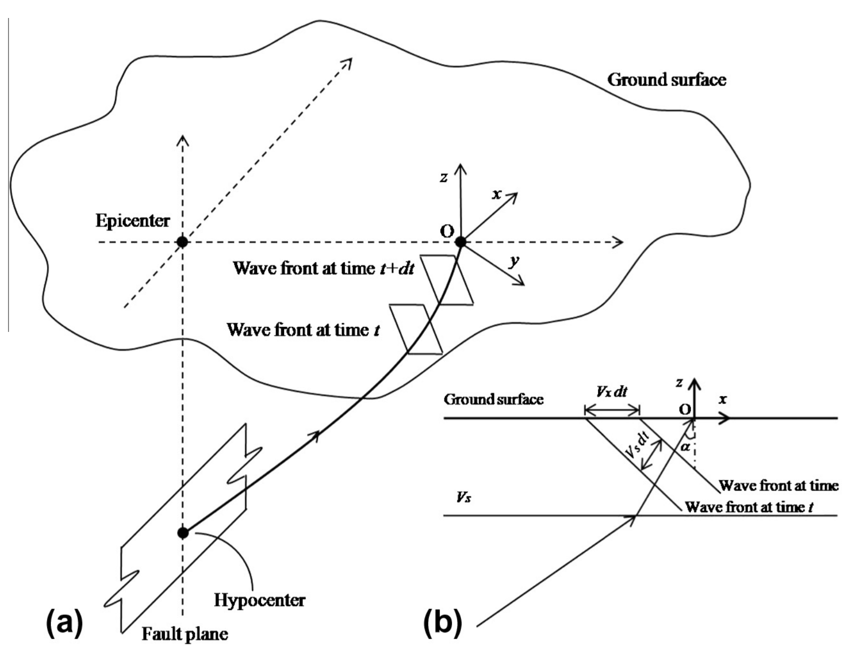

Fig. 1. Schematic diagram of the considered wave propagation system: (a) seismic wave propagation from the hypocenter to the site; (b) geometric interpretation of a plane wave incident on the ground surface.