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Accidental eccentricities, frame shear forces and ductility demands of buildings with uncertainties of stiffness and live load

Jaime De-la-Colina, Carlos A. González-Pérez, Jesús Valdés-González *

Facultad de Ingeniería, Universidad Autónoma del Estado de México, Cerro de Coatepec S/N, Ciudad Universitaria, Toluca, México C.P. 50130, Mexico

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ABSTRACT

Monte Carlo simulations of 3D structural models with 4, 6 and 15 stories, subjected to bidirectional seismic excitation, were generated to study the accidental torsional response of frame buildings. Variations of accidental eccentricities, story shear forces and story-drift ductility demands were studied. The probabilities of exceeding typical accidental-eccentricity recommendations of building codes were analyzed. Simulations assumed the following variables as random: (1) live-load magnitude, (2) live-load spatial distribution, and (3) flexural stiffness of columns and beams. The other structural variables, as well as the excitation, were considered as deterministic. Results show that, although the plan aspect ratio seems important for the selection of a design accidental eccentricity, this ratio does not have a significant influence on frame shear forces. Results indicate that maximum accidental eccentricities decrease as the building height decreases and that a normalized accidental eccentricity $e_a/b = 0.05$ seems acceptable for the tallest models studied, whereas a normalized eccentricity of $e_a/b = 0.10$ seems acceptable for shorter buildings. When an exceedance probability of 2% of frame shear forces is considered, results indicate that, for the unsymmetrical case, the frame shear force results roughly 20% larger than the computed force of the corresponding symmetrical case. Results also suggest that the design of regular frame buildings can be simplified by providing formulas to increase frame shear forces directly, instead of estimating and distributing building torsional moments among frames. The variations of both live loads and stiffness used in this study led to frame shear-force increments that varied between 10% and 40%, as compared with the nominally symmetrical case. The dispersion of the computed ductility demands caused by accidental eccentricity resulted small.

1. Introduction

Traditionally, the purpose of building codes [1,2] was to provide the minimum requirements of structures to get safe buildings; however, current codes provide design requirements to attain specific performance levels. Ideally, recommendations for building earthquake design should optimize the total cost of these constructions, taking into account their initial cost, maintenance cost and the cost of plausible reparations or failures [3]. It is also assumed that the uncertainties of structural parameters are smaller than those of seismic processes. Therefore, large efforts have been directed to define suitable seismic probabilistic models and to formulate criteria for estimating parameters involved in such processes [4,5].

The study of the effects of structural uncertainties on the response of buildings cannot be discarded because it is an important part for the calibration of specific design recommendations. Thus, Esteva and Ruiz [6] studied the influences of several structural parameters on the computed failure probabilities of systems designed for a given seismic intensity. Liel et al. [7] also studied the uncertainties associated to the simulation of the structural response of frames. This response is related to the analysis method and the extent to which the idealized model accurately represents real behavior. Such study involved the probabilistic assessment of the collapse risk through nonlinear response simulations, which incorporates the uncertainty associated with ground motions and structural modeling. These two previously described studies used plane frames. Therefore, the effects of the variations of both location and magnitude of inertial masses (dead and live loads) on the floors were not incorporated.

The assessment of specific building code recommendations related to seismic building torsion is also important, particularly for buildings susceptible to rotation during earthquakes. Accidental eccentricity (e_a), which is the *distance* used by several building codes in design to account for the uncertainties of both masses and

* Corresponding author.
E-mail address: jvaldes@uaemex.mx (J. Valdés-González).

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stiffness, takes different values in some codes. For instance, both the International Building Code [1,8] and the European code [9] recommend for this distance e_a a value equal to 0.05*b*, where *b* is the building maximum plan dimension perpendicular to the direction of the applied seismic forces. On the other hand, the Mexico City building code specifies e_a = 0.10b. These differences among codes reveal that design recommendations related to accidental eccentricity require additional scrutiny.

Building codes recommend accidental eccentricities that are invariant with respect to the building height. Some authors [10,11], however, present arguments suggesting that accidental eccentricity should vary with building height. Such studies also reveal that design recommendations obtained from studies based on one-story models (*e.g.*, [12]) cannot be directly applied to multistory buildings. These arguments indicate that further studies on accidental eccentricity of multistory buildings are required.

For a building subjected to an earthquake, the distributions of mass and stiffness, which are the main variables that affect accidental eccentricity, are different to those distributions assumed in design. This paper studies, through Monte Carlo simulations, the effect of these two quantities on the linear and nonlinear response of buildings. The purposes of this study are: (1) to study the variations of (peak) accidental eccentricities of some building models; (2) to study the variation of exceedance probabilities of the frame story shear of the building models; and (3) assess the building code recommendations that suggest equal values of the accidental eccentricity (0.05*b* or 0.10*b*), disregarding the influence of the studied variables. The study is focused on low-rise frame office buildings.

2. Methodology

The basic elements of the methodology used in this paper are: the Monte Carlo method, a bidirectional earthquake record, and a set of three-dimensional frames with some random properties and loads. By varying the main variables that affect accidental eccentricity, such as mass and stiffness, a sample of response parameters is generated. This response sample is used to study variations of accidental eccentricities and frame shear forces.

As for the Monte Carlo method, the only variables of the structural analyses that were assumed to vary according to selected probability functions were: (1) the intensity of the live load (offices), (2) the position in plan of the live-load resultant, and (3) the flexural stiffness of both beams and columns. The probable soil rotation is neglected because its contribution to accidental eccentricity is small for typical-size buildings.

No statistical correlation was introduced in the generation of *variates* (random variables generated from a desired probability density function, according to Law and Kelton [13]). For instance, for two columns with equal cross section, the only relationship between their stiffness *variates* is given by the same *nominal* moment of inertia used to define the mean of the probability density functions. However, once these functions are defined, no correlation among stiffness values is introduced between both variates. They are generated independently.

For each *realization* of the simulation process, the deterministic structural variables such as plan geometry, story heights, number of stories, etc. were assumed constant for each *case*. A *case* was defined for a particular building model and ground motion. In this study, six different cases were considered, as summarized in Table 1. Details of the building models, as well as a brief description of the earthquake records, are presented in Section 3.

For all nominal cases, the theoretical distribution of both stiffness and mass was doubly symmetrical with respect to the plan principal axes so that the natural building eccentricities e_d were equal to zero. Natural eccentricity (e_d) is the computed distance between the nominal stiffness center and the nominal shear center for a story. Notice that if these cases were designed with a typical code using dynamic analyses, the design recommendation to account for accidental eccentricity would be to move all floor masses a given distance (0.05*b* or 0.10*b*, respectively), with respect to the plan geometric center. For each case, 10,000 realizations were carried out in order to generate a large sample, which can be used to estimate the exceedance probabilities of the response parameters with respect to the accidental-eccentricity code recommendations. This number of simulations was selected on an analysis described in Section 4. As for the structural analysis, first-order, linear-elastic analyses were used [14]. For the structural analysis, the beta Newmark method was used with an integration time step equal to 0.004 s.

Table 1
List of studied *cases*.

Case	Identifier	Number of stories	Plan aspect ratio
1	M4-S	4	1:1
2	M4-R	4	2:1
3	M6-S	6	1:1
4	M6-R	6	2:1
5	M15-S	15	1:1
6	M15-R	15	2:1

3. Building models and earthquake records

In this study six 3D frame-building models were analyzed. Building model plans are shown in Fig. 1. As indicated in Table 1, model heights ranged from four to fifteen stories. For each building height, two plan aspect ratios were considered. For models of 4 and 6 stories, the separation between columns (along both horizontal directions) was equal to 6.0 m. For models of 15 stories, the separation was equal to 8.0 m. Table 2 summarizes story heights, nominal dimensions of column cross sections, and distributed dead loads applied on slabs. Dead loads include the weight of slabs, beams, covers, ceilings and installations only. The weight of columns was additional. All beams were assumed with a width = 0.20 m and a depth = 0.50 m. These cross sections were used to estimate the moment of inertia of the sections, which were taken as the mean values to generate the *variates* [13]. The nominal stiffness values of columns and beams were based on their nominal cross section without consideration of the reinforcement or cracking. In all cases, in-plane rigid diaphragms were considered, the columns were assumed axially rigid, and a damping ratio ζ equal to 0.05 was used for all modes.

Table 3 summarizes the main dynamic properties of the models computed from the sample of generated models. In all cases, the first two modal shapes are associated to translation movements, while the third one is associated to rotation along the vertical axis. For each model, the coefficients of variations (c.o.v.) of the modal frequencies resulted smaller than 2% and they decreased with the model height. These frequency changes are smaller than those reported by other authors [15–17]. Since the accidental eccentricity is the only source of change considered in this study, the frequency changes are small. Other sources of change such as soil conditions (*e.g.* consolidation), long-term time effects on concrete, occupancy changes, vibration amplitudes, etc. were not considered.

The concrete elasticity modulus was equal to E = 252,671 kg/cm^2 [25,756 MPa], which corresponds to a value of f′c = 280 kg/cm^2 [28.54 MPa], according to the American Concrete Institute [18]. These modal properties were computed for a live-load intensity equal to 122 kg/m^2 [1.20 kPa] (Table 4). A justification of the