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Probabilistic capacity and seismic demand models and fragility estimates for reinforced concrete buildings based on three-dimensional analyses

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ABSTRACT

This paper presents bivariate fragility estimates for reinforced concrete (RC) buildings accounting for their three-dimensional (3D) response to earthquake ground motions conditioning on spectral accelerations in the two horizontal directions. The fragility estimates are conducted using the demand and capacity models typically for the 3D responses. The demand models expressed in terms of drift are developed as functions of the spectral accelerations in the two horizontal directions. The demand prediction is compared in a probabilistic framework with the capacity estimates. The proposed capacity models for five performance levels consider the strength and stiffness degradation under the bi-axial loading. The proposed approach for the fragility estimates considers the uncertainties involved in the spectral acceleration components and capacity variation. The proposed approach is illustrated considering a typical 3-story RC building and results are compared with those from a traditional two-dimensional approach. The results indicate that the two-dimensional approach tends to significantly underestimate the fragility.

1. Introduction

Most existing studies on the seismic reliability of buildings are based on two-dimensional (2D) analyses. Examples include, Hwang and Low [1], Erberik and Elnashai [2], Ramamoorthy et al. [3,4], Ellingwood et al. [5], Celik and Ellingwood [6], and Bai et al. [7]. Hwang et al. [1] developed estimates of the reliability of planar frame structures subject to the in-plane earthquake excitation. Erberik and Elnashai [2] studies the seismic reliability of the flat-slab structure. Ramamoorthy et al. [3,4], Ellingwood et al. [5], Celik and Ellingwood [6], and Bai et al. [7] studied the reliability of non-seismic designed reinforced concrete (RC) buildings. This paper shows that reliability estimates based on 2D analysis tend to be inaccurate even for the symmetric buildings.

More recently a few studies have started to look at the reliability of buildings based on three-dimensional (3D) analysis. For example, Schotanus et al. [8] developed a response surface to consider the different failure modes of the structure under bi-axial loadings. Jeong and Elnashai [9] proposed a spatial index to evaluate the 3D structural response. Aziminejad and Moghadam [10] studied the effect of different types of eccentricities on the reliability estimates. However, while they carried out 3D time-history analysis, the reliability was only expressed in terms of a single intensity measure. This paper finds that it is important to compute the reliability of buildings considering the intensity measures in both horizontal directions.

This paper develops probabilistic seismic demand and capacity models based on the 3D response of a typical three-story RC building. The demand models are functions of two horizontal spectral accelerations, which consider the effects of both two horizontal ground motion components on the structural response. Capacity models proposed for five performance levels take into account the strength and stiffness degradation due to bi-axial loadings. Then bivariate fragility estimates are developed for the considered RC building, based on the proposed demand and capacity models. Fragility is defined as the conditional probability of attaining or exceeding a specified performance level, for given measures of the seismic intensity. Finally, this paper compares the results from the proposed 3D fragility analysis with those from the traditional 2D fragility analysis.

2. Proposed formulation of drift demand model for 3D response of RC buildings

This paper uses the definition of seismic demand given by Wen et al. [11] as the maximum inter-story drift (δ_D) of a building subject to an earthquake ground motion. Ramamoorthy et al. [3]

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defined the following linear model that relates the natural logarithm of δ_D with the natural logarithm of the spectral acceleration at the building fundamental period S_a:

$$\ln(\delta_D) = \theta_0 + \theta_1 \ln(S_a) + \sigma\varepsilon \tag{1}$$

where $\boldsymbol{\theta} = (\theta_0, \theta_1)$ and $\boldsymbol{\Theta} = (\boldsymbol{\theta}, \sigma)$ are the unknown model parameters; $\sigma\varepsilon$ is the model error [12]; σ is the unknown standard deviation of the model error; ε is a normal random variable with zero mean and unit standard deviation. The unknown parameters were estimated using virtual data so that the model is overall unbiased. However, Ramamoorthy et al. [3] showed that the linear model form in Eq. (1) tends to underestimate δ_D for small and large values of S_a, and to overestimate δ_D for intermediate values of S_a.

To overcome this local bias, Ramamoorthy et al. [3] proposed a bilinear model that can be written as

$$\begin{aligned} &\ln(\delta_D) = \theta_0 + \theta_1 \ln(S_a) + \sigma_1\varepsilon_1, \text{ when } \ln(S_a) \leqslant \theta_{S_a} \\ &\ln(\delta_D) = \theta_0 + \theta_1\theta_{S_a} + \theta_2[\ln(S_a) - \theta_{S_a}] + \sigma_2\varepsilon_2, \text{ when } \ln(S_a) > \theta_{S_a} \end{aligned} \tag{2}$$

where $\boldsymbol{\theta} = (\theta_0, \theta_1, \theta_2, \theta_{S_a})$ and $\boldsymbol{\Theta} = (\boldsymbol{\theta}, \sigma_1, \sigma_2)$ are the unknown model parameters; $\sigma_1\varepsilon_1$ and $\sigma_2\varepsilon_2$ are the model errors for the two portions of the model; σ_1 and σ_2 are the corresponding unknown standard deviations; ε_1 and ε_2 are corresponding normal random variables with zero mean and unit standard deviation. Comparing Eqs. (1) and (2) we see that θ_2 is the slope of the second part of the bilinear model. The models in Eqs. (1) and (2) are functions of only one spectral acceleration and can only be used for two-dimensional (2D) analysis. However, they do not account for the bi-axial loading in a three-dimensional (3D) analysis.

To account for the bi-axial loading in 3D analysis, we use a model form proposed by Simon et al. [13] for 3D analysis. Simon et al. [13] generalized Eq. (1) as

$$\ln(\delta_{Dk}) = \theta_{0k} + \theta_{1k} \ln(S_{ak}) + \sigma_k\varepsilon \tag{3}$$

where $k = [x, y]$; δ_{Dk} is the maximum inter-story drift in the direction k from a 3D analysis; S_{ak} is the spectral acceleration at the fundamental period in the direction k; $\boldsymbol{\theta} = (\theta_{0k}, \theta_{1k})$ and $\boldsymbol{\Theta} = (\boldsymbol{\theta}, \sigma_k)$ are the unknown model parameters; $\sigma_k\varepsilon$ is the model error; σ_k is the unknown standard deviation of the model error. Similarly, they generalized Eq. (2) as

$$\begin{aligned} &\ln(\delta_{Dk}) = \theta_{0k} + \theta_{1k}\ln(S_{ak}) + \sigma_{1k}\varepsilon_1, \text{ when } \ln(S_{ak}) \leqslant \theta_{S_ak} \\ &\ln(\delta_{Dk}) = \theta_{0k} + \theta_{1k}\theta_{S_ak} + \theta_{2k}[\ln(S_{ak}) - \theta_{S_ak}] + \sigma_{2k}\varepsilon_2, \text{ when } \ln(S_{ak}) > \theta_{S_ak} \end{aligned} \tag{4}$$

where $\boldsymbol{\theta} = (\theta_{0k}, \theta_{1k}, \theta_{2k}, \theta_{S_ak})$ and $\boldsymbol{\Theta} = (\boldsymbol{\theta}, \sigma_{1k}, \sigma_{2k})$ are the unknown model parameters; $\sigma_{1k}\varepsilon_1$ and $\sigma_{2k}\varepsilon_2$ are the model errors for the two portions of the model; σ_{1k} and σ_{2k} are the corresponding unknown standard deviations.

Based on the relationship between δ_{Dk} and S_{ak} given above, the following total demand model is used to predict the logarithm of the maximum inter-story drift $\ln(\delta_D)$:

$$\begin{aligned} &\delta_{SRSS} = \sqrt{\delta_{Dx}^2 + \delta_{Dy}^2} \\ &\ln(\delta_D) = \theta_{0D} + \theta_{1D} \ln(\hat{\delta}_{SRSS}) + \sigma_D\varepsilon \end{aligned} \tag{5}$$

where $\boldsymbol{\theta} = (\theta_{0D}, \theta_{1D})$ and $\boldsymbol{\Theta} = (\boldsymbol{\theta}, \sigma_D)$ are the unknown model parameters; $\hat{\delta}_{SRSS}$ is the point estimate of δ_{SRSS} following $\hat{\delta}_{SRSS} = \sqrt{\hat{\delta}_{Dx}^2 + \hat{\delta}_{Dy}^2}$; $\hat{\delta}_{Dx}$ and $\hat{\delta}_{Dy}$ are the medians of δ_{Dx} and δ_{Dy} obtained from Eq. (3) or (4); $\sigma_D\varepsilon$ is the model error; σ_D is the unknown standard deviation of the model error. In this paper, we develop a probabilistic drift demand model for the 3D response of RC buildings using the model form in Eqs. (4) and (5).

3. Drift demand model for typical three-story RC building

3.1. Building configuration and design

This paper considers a typical three-story RC building designed according to the non-seismic provisions of ACI-318 [14] shown in Fig. 1. The structural configuration is the same as the one considered in Ramamoorthy et al. [4], which is a typical configuration

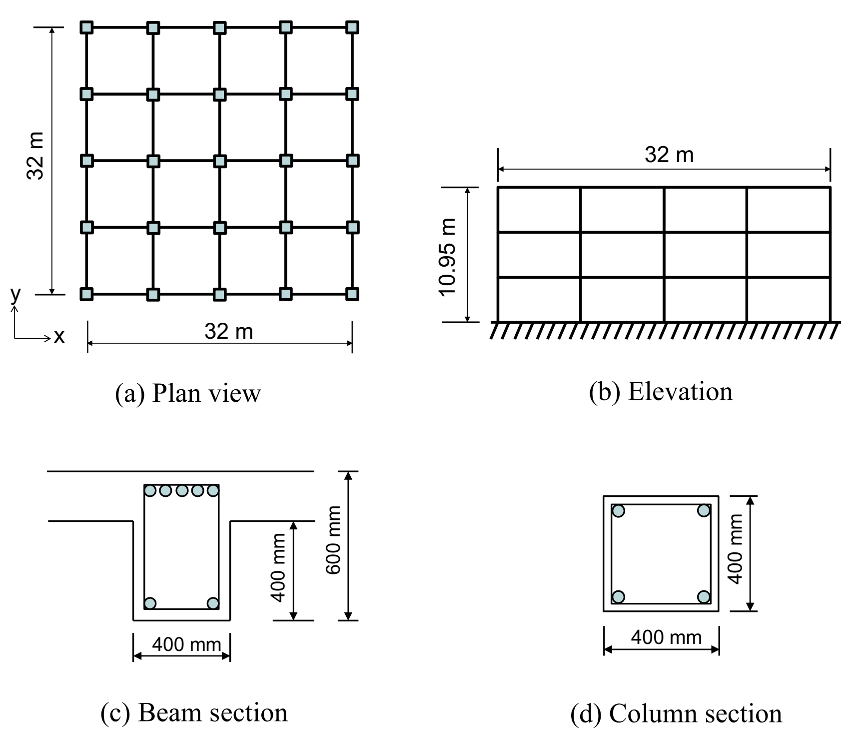

Fig. 1. Building configuration.