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ON THE PRACTICAL ESTIMATION OF THE DISTRIBUTION OF PEAK FOOR ACCELERATION DEMANDS

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ABSTRACT

The present contribution addresses the prediction of the record-to-record dispersion of peak floor acceleration (PFA) demands on elastic spatial structures. The distribution of PFA demands is approximated by an extended Complete-Quadratic-Combination (CQC) modal combination rule, based on a dispersion pseudo-acceleration response spectrum rather than the common median pseudo-acceleration response spectrum. Therefore, the selected ground motions must comply not only with target mean and but also with target dispersion spectral accelerations. Application on elastic spatial steel benchmark structures shows that the proposed methodology yields cumulative distribution functions of the PFA demand that approximate well the corresponding cumulative distributions derived in computationally expensive response history analyses.

Keywords: Peak Floor Acceleration Demands; Response Spectrum Method; Response Dispersion

1. INTRODUCTION AND MOTIVATION

Seismic risk assessment can be conducted within the well-known framework of performance based earthquake engineering (PBEE), which can be traced back to the pioneering work of Cornell and Krawinkler (2000) among others. PBEE represents a rigorous approach, mathematically expressed in terms of the PEER-triple-integral (Moehle and Deierlein 2004), which allows estimating probability distributions of decision variables (DVs) by means of successive integration of probabilistic functions of damage measures (DMs), engineering demand parameters (EDPs), and seismic intensity measures (IMs) (Krawinkler and Miranda 2004).
Peak floor acceleration (PFA) demands are well correlated with damage of acceleration-sensitive nonstructural and content components, and thus, they need to be predicted to capture the global risk and loss. The first integral of the previously described procedure represents the probability of EDP given IM, which can be extracted accurately by nonlinear time history analysis under multiple ground motions, e.g., via Incremental Dynamic Analysis (Vamvatsikos and Cornell 2002). However, in engineering practice simplified methods are preferable because of the low modeling effort, simple application, and low computational costs. FEMA P-58-1 (2012), for instance, provides simplified procedures for the assessment of mean and dispersion of PFA demands for different broad classes of structural systems. The applicability of this procedure for PFA demand prediction is restricted because of limits on the maximum number of stories, the level of inelasticity, and the irregularity of the considered building. Thus, more robust methods are desirable that can be applied to a larger class of structures, and simultaneously reduce the error relative to the benchmark solution obtained from nonlinear dynamic analysis.
Herein, the estimation of the conditional distribution of PFA given IM is based on response spectrum methods. More recently, several extended Complete-Quadratic-Combination (CQC) modal combination rules have been developed focusing on the elastic mean PFA demand (Taghavi and Miranda 2009, Pozzi and Der Kiureghian 2015, Moschen et al. 2016, Moschen and Adam 2016).

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However, all of these methods have in common that the dispersion of PFA demand has not been addressed, and thus, the full distribution of demands cannot be easily predicted. To close this gap, the present paper aims at predicting also the dispersion of the PFA demand by means of an extended CQC rule. The idea is based on FEMA P-58-1 (2012), where dispersions of spectral accelerations are defined for different regions in the United States of America (USA). Thus, dispersions of PFA demands will be approximated by the extended CQC rule using a dispersion pseudo-acceleration response spectrum rather than the common median pseudo-acceleration response spectrum. Therefore, a ground motion record selection procedure is required, which addresses target mean and target dispersion spectral accelerations. Recently, Kohrangi et al. (2017) and Moschen et al. (2017) developed independently such methods representing extended conditional mean spectrum (CMS) methods (Baker 2011, Jarayam et al. 2011) satisfying these needs. The proposed methodology to estimate the distribution of PFA demands is tested on elastic spatial steel structures actually developed for the benchmark test of the closed form CQC rule (Moschen et al. 2016).

2. METHODOLOGY

The proposed procedure is based on the assumption that the seismic structural response can be sufficiently accurately described by the normal stationary random vibration theory with zero mean (Crandall and Mark 1963, Newland 2005), although in reality earthquake excitation is a non-stationary stochastic process (Shinozuka and Wu 1988). However, in general, the structural assessment of earthquake excited buildings is governed by the peak response that is related to the strong motion phase of an accelerogram, which is considered to be stationary (Der Kiureghian 1981).
At first, it is repeated how the central tendency (median) of PFA demands of elastic structures can be predicted by means of an extended CQC rule presented in Taghavi and Miranda (2009), Pozzi and Der Kiureghian (2015), and Moschen et al. (2016). On this foundation, it is discussed how the dispersion of the PFA demands can be assessed utilizing the extended CQC rule.

2.1 Estimation of the Central Tendency of PFA Demands

Consider the equations of motion of an elastic multi-degree-of-freedom (MDOF) structure subjected to uniform base acceleration in one principal direction (Chopra 2016),

$$\mathbf{M}\ddot{\mathbf{u}}^{(\mathrm{rel})}(t) + \mathbf{C}\dot{\mathbf{u}}^{(\mathrm{rel})}(t) + \mathbf{K}\mathbf{u}^{(\mathrm{rel})}(t) = -\mathbf{M}\mathbf{e}\ddot{u}_{\mathrm{g}}(t) \tag{1}$$

in which vector $\mathbf{u}^{(\mathrm{rel})}(t)$ contains the deformations of the *N* nodes relative to the displacement of the ground, $u_{\mathrm{g}}(t)$, and $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ denote the mass-, stiffness-, and damping matrix associated with the *N* dynamic degrees-of-freedom (DOFs). Inertia forces as a result of the ground acceleration are spatially redistributed by the quasi-static influence vector, $\mathbf{e}$. Modal expansion of Equation 1 yields the *N* modal oscillator equations,

$$\ddot{d}_i^{(\mathrm{rel})}(t) + 2\zeta_i\omega_i\dot{d}_i^{(\mathrm{rel})} + \omega_i^2 d_i^{(\mathrm{rel})} = -\ddot{u}_{\mathrm{g}}(t), \quad i = 1, \ldots, N \tag{2}$$

with ω_i denoting the *i*th natural frequency and ζ_i the *i*th modal damping ratio. Defining the total modal accelerations, $\ddot{d}_i(t) = \ddot{d}_i^{(\mathrm{rel})}(t) + \ddot{u}_{\mathrm{g}}(t)$, and utilizing static correction (Chopra 2016), the total acceleration of the *k*th degree of freedom can be expressed as

$$\ddot{u}_k(t) \approx \sum_{i=1}^{n} \phi_{i,k}\Gamma_i\ddot{d}_i(t) + \left(1 - \sum_{i=1}^{n} \phi_{i,k}\Gamma_i\right)\ddot{u}_{\mathrm{g}}(t) = \ddot{u}_k^{(n)}(t) + r_k^{(n)}\ddot{u}_{\mathrm{g}}(t) \tag{3}$$

where the modal series are approximated by the first few $n < N$ modes only. Variable $\phi_{i,k}$ represents the *k*th component of the *i*th mode shape, and $\Gamma_i = (\boldsymbol{\phi}_i^{\mathrm{T}}\mathbf{M}\mathbf{e})/(\boldsymbol{\phi}_i^{\mathrm{T}}\mathbf{M}\boldsymbol{\phi}_i)$ is the generalized participation factor. Application of the static correction method (which is equivalent to the mode

acceleration method, Chopra 2016) accelerates the rate of convergence of the modal series, because the quasi-static contributions of the truncated n+1 to N modes are included exactly in the residual $r_k^{(n)}$, compare with the second term of Equation 3. In the high frequency domain (in this context the spectral domain associated with the n+1 to N modes) the modal oscillator Equation 2 can be approximated by $\omega_i^2 d_i^{(\text{rel})} \approx -\ddot{u}_\text{g}(t)$, capturing the quasi-static response only, and thus referred to as *static approximation method* (Chopra 2016). Consequently, the residual $r_k^{(n)}$ governs the spatial redistribution of the base acceleration to the kth DOF of the MDOF structure.
Now, it is assumed that Equation 3 describes a stationary random process. Hence, evaluation of the stochastic process at any instant of time yields random variables independent of time (denoted by capital letters), i.e., $\ddot{u}_k(t) = \ddot{U}_k$, $\ddot{u}_k^{(n)}(t) = \ddot{U}_k^{(n)}$ and $\ddot{u}_\text{g}(t) = \ddot{U}_\text{g}$. Subsequently, the multi-modal variance of the kth total acceleration reads (Moschen et al. 2016):

$$Var\left[\ddot{U}_k\right] = Var\left[\ddot{U}_k^{(n)}\right] + \left(r_k^{(n)}\right)^2 Var\left[\ddot{U}_\text{g}\right] + 2r_k^{(n)} Cov\left[\ddot{U}_k^{(n)}, \ddot{U}_\text{g}\right] \tag{4}$$

Based on Equation 4 Taghavi and Miranda (2009) derived the extended CQC rule to estimate the mean PFA demand of the kth DOF, m_{PFA_k},

$$E\left[\max\left(\left|\ddot{U}_k\right|\right)\right] \equiv m_{PFA_k} \approx \left[\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{p_k}{p_i}\frac{p_k}{p_j} \phi_{i,k}\phi_{j,k}\Gamma_i\Gamma_j S_{\text{a},i} S_{\text{a},j}\rho_{i,j} + \left(\frac{p_k}{p_\text{g}} m_{PGA} r_k^{(n)}\right)^2 + 2m_{PGA} r_k^{(n)} \frac{p_k}{p_\text{g}} \sum_{j=1}^{n} \frac{p_k}{p_i} \phi_{i,k}\Gamma_i S_{\text{a},i}\rho_{i,\text{g}}\right]^{\frac{1}{2}} \tag{5}$$

in analogy to the original CQC rule (Der Kiureghian 1981) for relative response quantities. In Equation 5, p_i, p_j, p_k and p_g denote mean peak factors for modal and physical coordinates. Variable $S_{\text{a},i} = E\left[\max\left(\left|\ddot{D}_i\right|\right)\right] = E\left[S_{A,i}\right]$ denotes the mean pseudo-spectral acceleration related to the ith mode, and $m_{PGA} = E\left[\max\left(\left|\ddot{U}_\text{g}\right|\right)\right] = E[PGA]$ the mean peak ground acceleration (PGA). Correlation coefficients between modal total accelerations, and modal total acceleration and the ground acceleration are represented by $\rho_{i,j}$, and $\rho_{i,\text{g}}$, respectively. Closed form solutions of these quantities are found in Moschen et al. (2016). As discussed in Shome et al. (1998), the dispersion of seismic peak response quantities can be reasonably described by a lognormal distribution. Hence, Equation 5 is used to estimate the median PFA demand, $\tilde{m}_{PFA_k}$, rather than the corresponding mean, m_{PFA_k} utilizing median pseudo-spectral accelerations and median peak factors instead of the mean values. For a more comprehensive discussion refer to Moschen et al. (2016).

2.2 Estimation of the Dispersion of PFA Demands

Starting point for estimation of PFA demand dispersion of the kth degree of freedom is Equation 4 and the acceptance of the lognormal assumption of the seismic peak response distribution. Substituting the random variables (e.g. $\ddot{U}_k$) of this equation by the logarithm of the peak value of these variables (e.g. $\ln\left(\max\left(\left|\ddot{U}_k\right|\right)\right)$) yields the expression for estimating the PFA dispersion based on the CQC approach,

$$\sqrt{Var\left[\ln\left(\max\left(\left|\ddot{U}_k\right|\right)\right)\right]} \equiv \sigma_{\ln(PFA_k)} \approx \left[\sum_{i=1}^{n}\sum_{j=1}^{n} \phi_{i,k}\phi_{j,k}\Gamma_i\Gamma_j \sigma_{\ln(S_{A,i})}\sigma_{\ln(S_{A,j})}\rho_{i,j}^{(\sigma)} + \left(\sigma_{\ln(PGA)} r_k^{(n)}\right)^2 + 2\sigma_{\ln(PGA)} r_k^{(n)} \sum_{j=1}^{n} \phi_{i,k}\Gamma_i \sigma_{\ln(S_{A,i})}\rho_{i,g}^{(\sigma)}\right]^{\frac{1}{2}} \tag{6}$$

In Equation 6, the unbiased estimator of dispersion of the logarithm of the pseudo-spectral acceleration of a record set (which consists of m individual records) at the period/frequency of the ith mode, $\sigma_{\ln(S_{A,i})}$, reads (Benjamin and Cornell 1970)

$$\sigma_{\ln(S_{A,i})} = \sqrt{Var[\ln(S_{A,i})]} = \sqrt{\frac{1}{m-1}\sum_{j=1}^{m}\left(\ln(S_{a,i,j}) - E[\ln(S_{A,i})]\right)^2} \quad (7)$$

The dispersion of the PGA, $\sigma_{\ln(PGA)}$, is computed in analogy to Equation 7.
In Equation 6, all factors are defined except the correlation coefficients between the modal pseudo-spectral accelerations, $\rho_{i,j}^{(\sigma)}$, and between pseudo-spectral acceleration and the peak ground acceleration, $\rho_{i,g}^{(\sigma)}$. A correlation coefficient is defined as the ratio of the covariance of two random variables and the square root of the product of their variances (Benjamin and Cornell 1970). Consequently, based on the lognormal approximation of the probabilistic distribution of pseudo-spectral accelerations, and utilizing both the ith and the jth spectral value of the median response spectrum and dispersion spectrum, yields the following estimate of the desired modal correlation coefficients,

$$\rho_{i,j}^{(\sigma)} = \frac{Cov[\ln(S_{A,i}), \ln(S_{A,j})]}{\sqrt{Var[\ln(S_{A,i})]Var[\ln(S_{A,j})]}} \quad (8)$$

Correlation coefficient $\rho_{i,g}^{(\sigma)}$ is computed in analogy to Equation 8, replacing the jth modal random variable by the random PGA variable.

2.3 Estimation of the Distribution of PFA Demands

The multi-modal variance of the PFA demand is evaluated in accordance to Equation 6, and the multi-modal median PFA demand according to Equation 5. Additionally, the probabilistic distribution of the multi-modal PFA demand needs to be approximated. The multi-modal random variable represents a sum of uni-modal random variables. Consequently, if the logarithm of any uni-modal random variable is assumed to be normally distributed, the multi-modal random variable is lognormal distributed as well. A lognormal distribution is fully defined by the mean and the dispersion of the logarithm of the random variable under consideration (Benjamin and Cornell 1970). Thus, the cumulative distribution function (CDF) that estimates the probabilistic distribution of PFA demands of the kth DOF reads

$$F_{PFA_k}(pfa_k) = F_U\left(\frac{\ln(pfa_k) - \ln(\breve{m}_{PFA_k})}{\sigma_{\ln(PFA_k)}}\right) = F_U(u) \quad (9)$$

where $F_U(u)$ represents the CDF of the standardized normal distribution (Benjamin and Cornell 1970).

3. GROUND MOTION RECORDS AND STRUCTURAL MODELS

3.1 Ground Motion Records

In this study for the site under consideration (Century City in Los Angeles (34.05366°N, 118.41339°W)), the multi-objective ground selection procedure developed by Moschen et al. (2017) is used to select the acceleration records because it addresses the needs of a target mean and a target dispersion spectrum, as required for the proposed PFA demand prediction procedure. More specific, a global optimization procedure is applied to select the ground motion records from the PEER Ground

Motion Database (2015) matching the following criteria (Moschen et al. 2017) :

- Moment magnitude: $5.5 \leq M_W \leq 7.9$.
- NEHRP Site Classification D (stiff soil, shear wave velocity: 180 m/s $\leq v_s$ 30 $\leq$ 360 m/s).
- Fault mechanism (FM): strike-slip (SS), reverse (RV), reverse-oblique (RVO).
- Joyner and Boore distance (1981): 0 km $\leq r_{jb} \leq$ 80 km.
- Constant scale factor for all ground motions in the range of $1/5 \leq \alpha \leq 5$.
- Constant lognormal target dispersion spectrum of 0.80.
- Period range of interest 0.05 s $\leq T \leq$ 3.00 s.

This procedure yields 92 ground motions, whose response spectra are shown in the upper plot of Figure 1 by grey lines. The bold black line represents the corresponding median spectrum, which closely matches the target median spectrum also shown in this figure. The dashed lines refer to 16th and 84th percentile spectra. In the lower plot of Figure 1 the target normal dispersion spectrum indicated by a constant line and the normal dispersion spectrum of this ground motion set are shown. Alternatively, any ground motion selection procedure can be used that are based on target median and target dispersion spectra (e.g., Kohrangi et al. 2017, Baker 2011, and Jarayam et al. 2011).

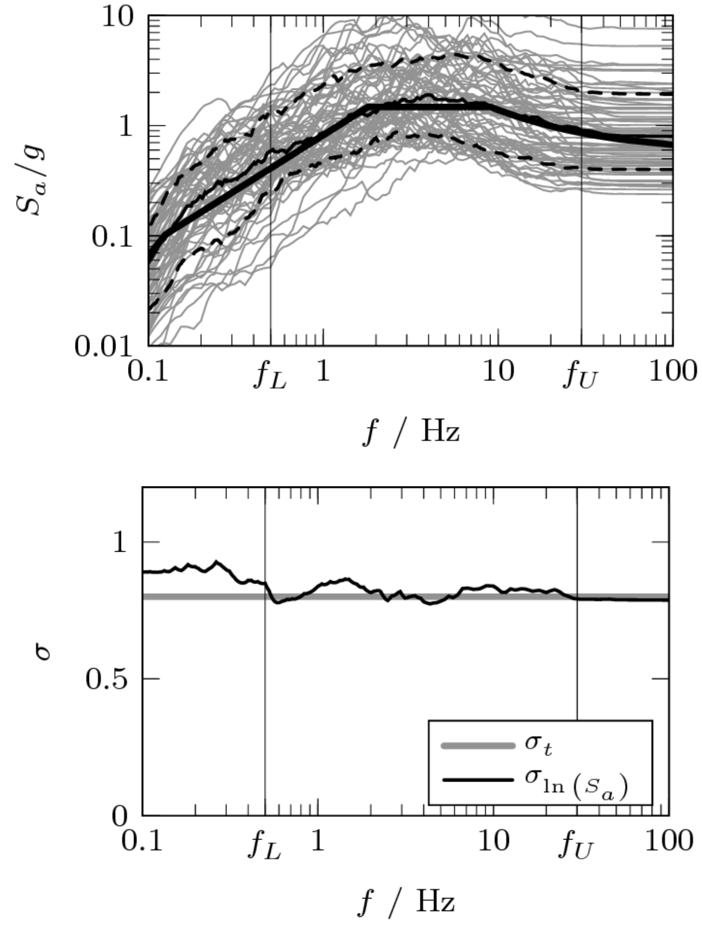


Figure 1. Upper plot: Response spectra of individual records (gray lines) of the record set, corresponding median and dispersion spectra (solid and dashed black lines), and target median response spectrum (bold black line). Lower plot: Target normal dispersion spectrum (horizontal line constant at 0.80), and corresponding sample normal dispersion (Moschen et al. 2017).

3.2 Structural Models

The proposed methodology for predicting the dispersion of PFA demands is evaluated on generic spatial steel-moment-resisting-frames (SMRF) tuned to fundamental periods defined in ASCE 7-16 (2016). Figure 2 depicts the top view of the *k*th floor and an isometric view of the first two stories of those structures. Each story is composed of a rigid quadratic massless plate with an attached lumped mass, supported at the corners by elastic massless columns with symmetric cross-section. The lumped mass is slightly eccentric vis-à-vis the center of stiffness as shown in Figure 2 (left), and as such the first three natural frequencies of the coupled bending-torsional modes are closely spaced. In Table 1 these frequencies are listed for the considered 6-, 12- and 12-story frames. Consequently, consideration of correlation of modal total accelerations is of major importance for realistic prediction of the PFA demands (Moschen et al. 2016, Moschen and Adam 2016). Rayleigh-type damping is considered with a modal damping ratio of $\zeta = 0.05$ assigned to the fundamental mode and to the 95% cumulative mass participating mode. It should be noted that the fundamental mode shape is linear with respect to the structural height when the lumped masses are located in the center of stiffness. Further details for these structures are found in Moschen (2016).

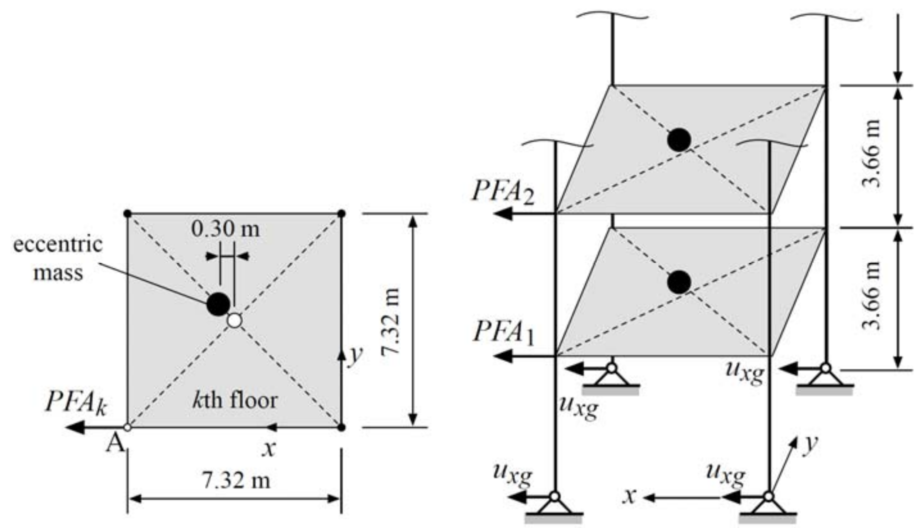


Figure 2. Top view of the *k*th floor (left), and isometric view of the first two stories (right) of the considered generic spatial structures (Moschen et al. 2016).

Table 1. First three natural frequencies of the considered generic spatial structures.

Structure	ω_1 [rad/s]	ω_2 [rad/s]	ω_3 [rad/s]
6-story	7.22	7.33	7.96
12-story	4.14	4.21	4.59
24-story	2.38	2.42	2.64

4. BENCHMARK TEST

The base of the considered SMRF structures is uniformly excited in horizontal *x*-direction by the set of ground motions introduced in Section 3.1 (indicated by coordinate u_{xg} in Figure 2). Since in Moschen et al. (2016) and Moschen and Adam (2016) the *median* PFA demands in *x*-direction at the column line "A" of these structures has been assessed, subsequently the *distribution* of these PFA demands is evaluated by the proposed procedure. In particular, Figures 3 to 5 show the probabilistic distribution of this response quantity at mid height (upper subplots) and at the roof (lower subplots) for different

numbers of considered modes when utilizing the discussed CQC methodology. Dashed CDFs correspond to first mode approximations, Dash-dot-dotted curves refer to CDF estimates based on the first and second mode, and the solution displayed by a solid black line includes all modes up to the 95% cumulative seismic active mass. The corresponding reference solution based on response history analysis (RHA) conducted in OpenSees (McKenna et al. 2014) is displayed in gray. The red curve represents the fitted lognormal distribution, referred hereinafter as reference CDF. Visual inspection reveals that the lognormal probabilistic model captures reasonably the dispersion of the PFA demand, which is consistent with findings reported by Shome et al. (1998).
Inspection of Figures 3 to 5 shows that both the one mode and the two modes approximations of the CDF are inaccurate. However, the multi-modal solution of the proposed CQC approach yields in general a distribution that closely matches the reference solution. It should be noted that the median PFA demand of this structure is approximated accurately regardless of the considered story (Moschen et al. 2016, Moschen and Adam 2016). The median, the 16^{th} and 84^{th} percentile of the PFA predictions are highlighted by thin horizontal solid lines.
Table 2 summarizes the response statistics (median and dispersion) for the considered structures at the locations discussed above. The third and the fourth column represent the statistics of the reference solution (from RHA), the fifth and sixth column the corresponding statistics of the lognormal approximation. Additionally, the relative errors of the lognormal approximation with respect to the reference solution are listed in the last two columns. In the respect, the relative error percentage of the median, $\varepsilon(\breve{m}_{PFA_k})$, and the dispersion of the logarithm, $\varepsilon\big(\sigma_{\ln(PFA_k)}\big)$, are defined as

$$\varepsilon(\breve{m}_{PFA_k}) = \frac{\breve{m}_{PFA_k}^{(\mathrm{RHA})} - \breve{m}_{PFA_k}^{(\mathrm{CQC})}}{\breve{m}_{PFA_k}^{(\mathrm{RHA})}} \cdot 100 \tag{10}$$

$$\varepsilon\big(\sigma_{\ln(PFA_k)}\big) = \frac{\sigma_{\ln(PFA_k)}^{(\mathrm{RHA})} - \sigma_{\ln(PFA_k)}^{(\mathrm{CQC})}}{\sigma_{\ln(PFA_k)}^{(\mathrm{RHA})}} \cdot 100 \tag{11}$$

The largest relative error of the median is 6,48% (mid height of the 12-story structure) and of the dispersion -9,24% (roof of the 6-story structure). It is observed that all relative errors of the median are positive, that is the CQC approximation underestimates slightly the median PFA demand. In contrast, the relative errors of the dispersions are negative, indicating that the CQC method over-predicts the dispersion.

Table 2. Comparison of statistics based on the reference solution and the approximation.

Structure	**Location**	**Reference CDF**		**Approximation**		**Relative Error**	
		$\breve{m}_{PFA_k}^{(\mathrm{RHA})}$ [m/s²]	$\sigma_{\ln(PFA_k)}^{(\mathrm{RHA})}$ [-]	$\breve{m}_{PFA_k}^{(\mathrm{CQC})}$ [m/s²]	$\sigma_{\ln(PFA_k)}^{(\mathrm{CQC})}$ [-]	$\varepsilon(\breve{m}_{PFA_k})$ [%]	$\varepsilon\big(\sigma_{\ln(PFA_k)}\big)$ [%]
6-story	Mid height	14,45	0,72	14,32	0,77	0,89	-3,85
	Roof	30,72	0,72	29,10	0,85	5,26	-9,24
12-story	Mid height	13,32	0,66	12,47	0,72	6,48	-3,92
	Roof	31,88	0,70	29,92	0,76	6,16	-4,41
24-story	Mid height	10,62	0,78	11,30	0,67	5,99	-7,63
	Roof	32,17	0,69	30,67	0,80	4,66	-7,62

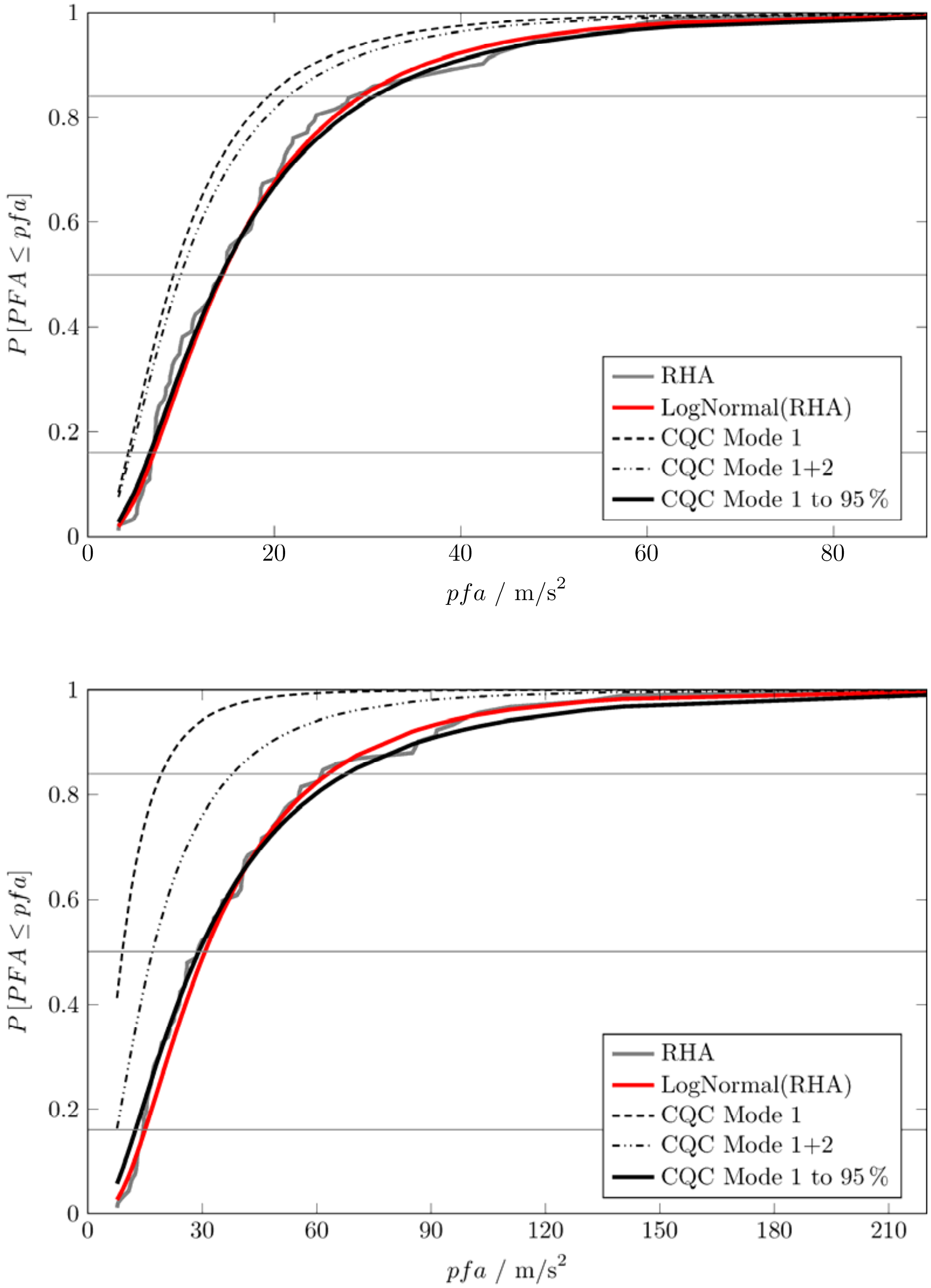
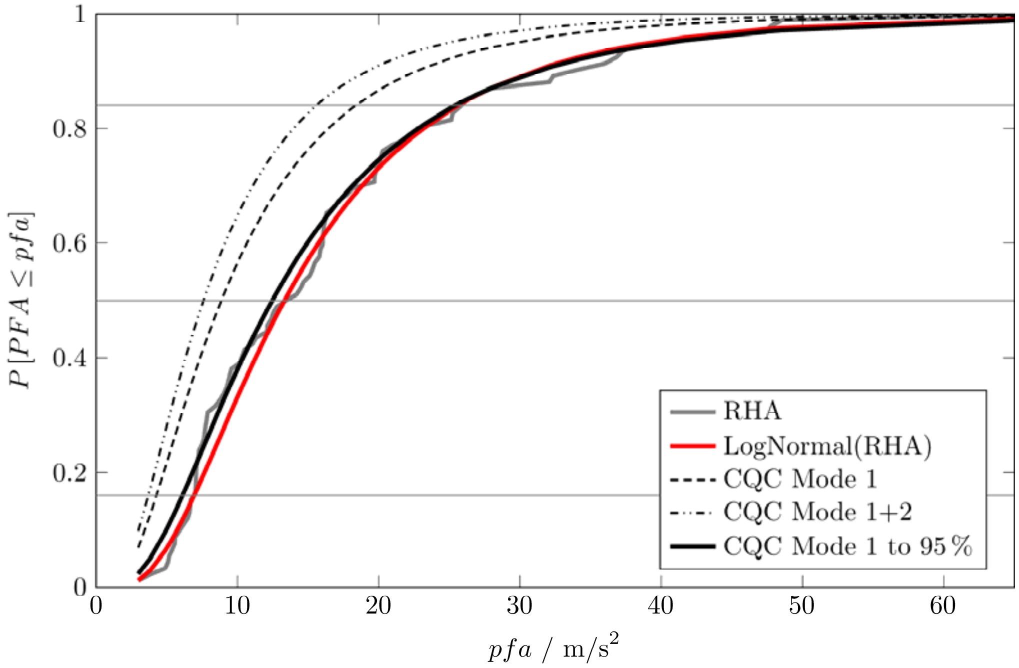


Figure 3. CDFs of PFA demands of the 6-story frame at (upper plot) mid height, and (lower plot) at the roof.



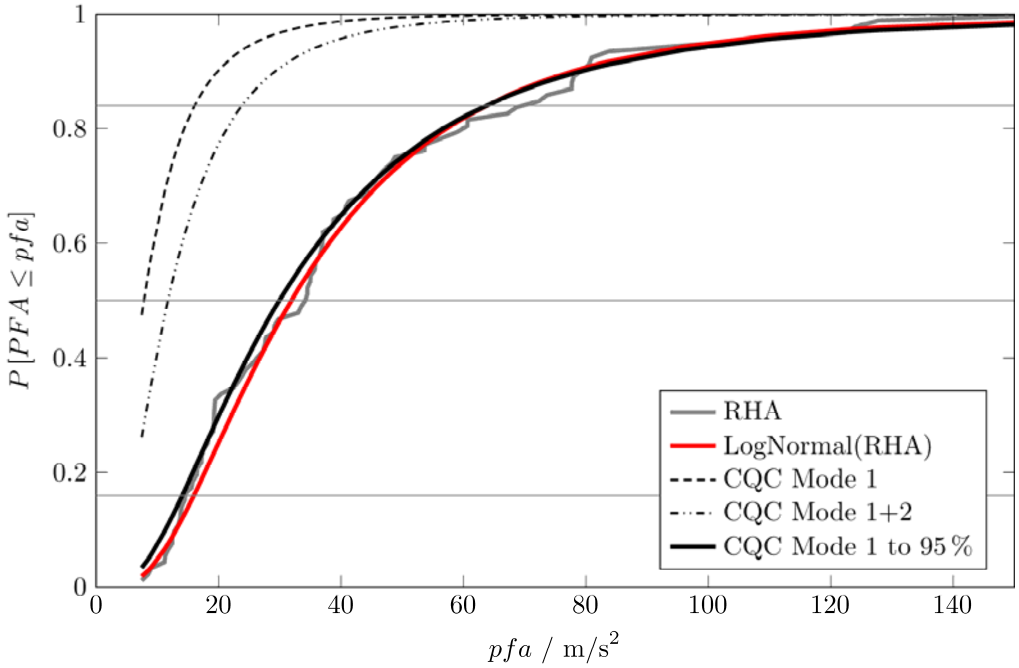
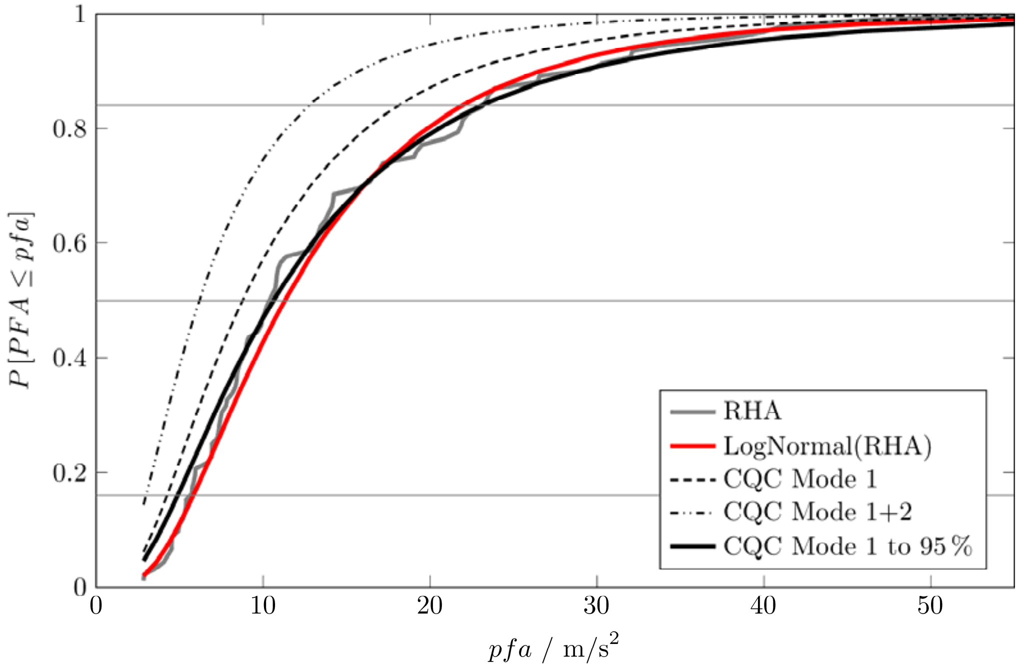


Figure 4. CDFs of PFA demands of the 12-story frame at (upper plot) mid height, and (lower plot) at the roof.



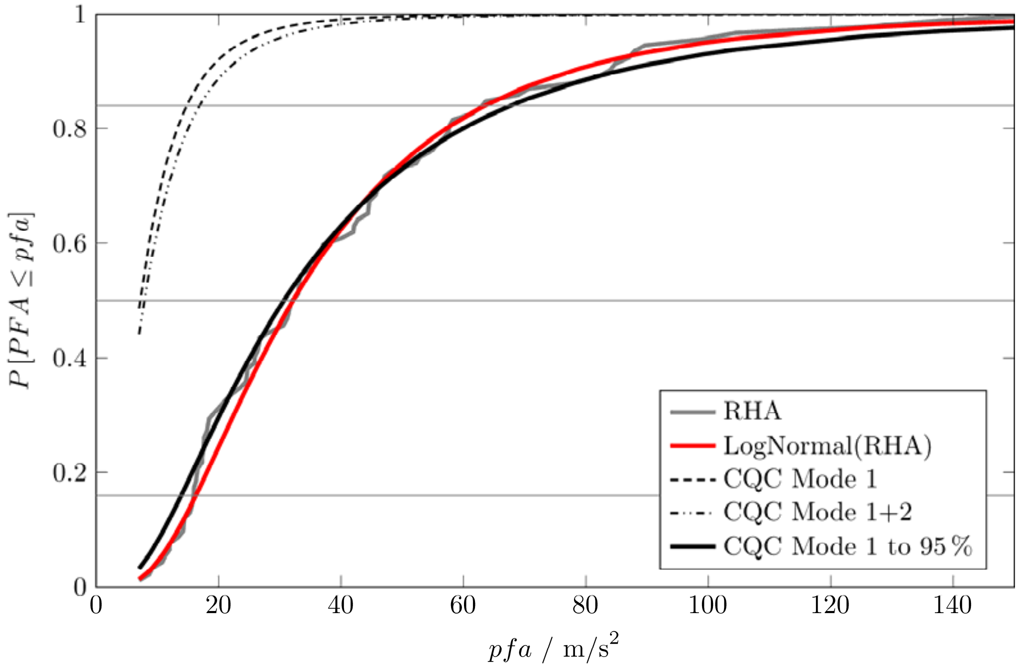


Figure 5. CDFs of PFA demands of the 24-story frame at (upper plot) mid height, and (lower plot) at the roof.

5. SUMMARY, CONCLUSION, AND OUTLOOK

A simple but still sufficiently accurate method has been presented to estimate the probabilistic distribution of peak floor acceleration (PFA) demands of seismically excited spatial elastic frame structures. The fundamental ingredients of this method are (*i*) the complete-quadratic-combination rule, and (*ii*) a ground motion selection procedure, where the selected ground motions match a pseudo-spectral target mean and variance over a large range of periods. The proposed procedure has been tested on 6-, 12-, and 24-story elastic spatial steel-moment-resisting-frame structures. As a result, in

general the cumulative distribution functions of the PFA of these structures based on this approximate lognormal probabilistic model are in excellent agreement with the corresponding probabilistic distributions obtained from response history analyses, which serve as reference solution. Subsequently, goodness-of-fit tests will be conducted to quantify the error of the PFA demand distributions derived by the proposed probabilistic model.
Further research activities will be devoted to the extension of the proposed methodology to predict the PFA distributions of *inelastic* structures. In this respect it should be noted that the underlying procedure for assessing the median PFA demand of inelastic structures is readily available (Moschen et al. 2017).

6. ACKNOWLEDGMENTS

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