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Seismic Fragility Analysis of Precast RC Shear Wall-Frame Structures with Connection Defects

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ABSTRACT: As observed in many evidences during past earthquakes, the quality of precast concrete (PC) connections is one of the main factors that affect the seismic reliability of PC structures. In the context of China's rapid development of PC structures in high seismic regions, it is important to assess the effect of connection deficiency on their seismic performance. This paper proposes a framework for seismic fragility analysis of PC shear wall-frame structures whose wall panels are assembled through grout sleeve connections that are susceptible to insufficient grouting. The uncertainties associated with the defected sleeve connections are taken into account, and then the probabilistic response of shear wall model is estimated through Point Estimate (PE) method. Then, a generic shear wall-frame building is modeled on platform of OpenSees. Seismic fragility analysis is performed to the structures with different degrees of connection deficiency, showing that the seismic performance is significantly affected by connection deficiencies, and great effort should be taken for the quality control of grout sleeve connections in construction site.

KEYWORDS: seismic fragility, precast concrete, shear wall-frame structure, connection defect, reliability

Precast concrete (PC) structures are in the stage of rapid development now in China due to advantages of higher construction speed, fewer construction site operations and less environmental pollution (Wang et al. 2016). When PC structures are constructed in high seismic intensity area, their seismic reliability becomes a major concern. Many evidences about the behavior of precast structures during past earthquakes have been reported, such as the 2008 Wenchuan Earthquake (Xu 2009), the 2010 Chile Earthquake (Franco et al. 2010) and the 2012 Emilia Earthquake (Bournas et al. 2013). In these earthquakes, failure of connections was observed as a main factor leading to the collapse of PC structures.

Concrete shear wall-frame structure is widely used in multi-story buildings because of its effectiveness in providing lateral strength and stiffness to limit structural drift. For PC shear walls, the grout sleeve connections are typical for installation. The mechanical behaviors of sleeve connections have been tested by lots of experimental studies, and the results have shown that grout sleeves could ensure sufficient strength ductility and energy dissipation capacity of structural members (Adajar et al. 1993; Belleri and Riva 2012; Peng et al. 2016). However, their loading performances at real construction site are not as good as their laboratory counterparts. The grout sleeve connections at construction site are susceptible to defects such as insufficient grouting and deviation of reinforcement from the center of sleeve. The situation becomes even worse recognizing that effective methodology is lacking currently to detect those defects.

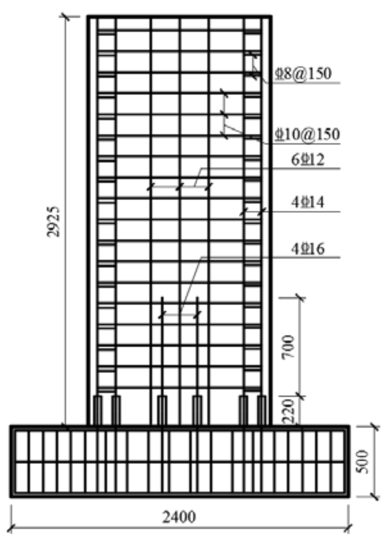
Considering the possible deficiencies in shear wall connections, this paper presents the seismic reliability analysis of a generic PC shear wall-frame structure in high seismic region of

China. The probabilistic PC shear wall-frame model is established firstly. Then the seismic fragility analyses are performed to investigate the influence of connection defects on reliability of structures under earthquake ground motions.

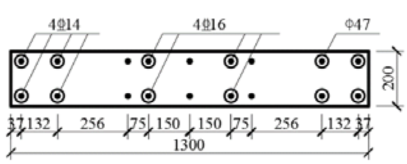
1. PROBABILISTIC MODEL OF DEFECTED CONNECTIONS IN PC SHEAR WALL

Due to the large lateral stiffness and strength, the behavior of PC shear wall often dominates the seismic response of shear wall-frame structures, so this research focuses on the defects in grout sleeve connections in shear walls.

The PC shear wall considered in this research is 2.925m high and 1.3m wide, whose dimensions and locations of gout sleeve connections are shown in Figure 1. The loading behavior of this PC shear wall specimen with fully grouted sleeves had been investigated experimentally (Peng 2010).



(a) Dimensions of PC shear wall (mm)



(b) Locations of sleeve connections (mm)

Figure 1: Dimensions of PC shear wall and locations of grout sleeve connections.

To develop the probabilistic model of this shear wall with defected connections, three aspects of uncertainty should be taken into consideration: (1) the number of defected connections; (2) the locations of defected connections; (3) the loading behavior of defected connections.

1.1. Probabilistic model for occurrence of defected connections

Suppose that a PC shear wall panel is installed in the structure through m grout sleeve connections, and the mean occurrence rate of defected sleeve connections is λ, then the occurrence probability of i (i=0,1,…,m) defected connections is

$$P_i = C_m^i \lambda^i \left(1-\lambda\right)^{m-i} \tag{1}$$

in which C_m^i is the number of combinations to select i samples from the pool of totally m samples.

The i defected connections may occur at several combinations of possible locations. The probability of a specific location case j conditioned on the occurrence of i defected connections is denoted as $p_{(i,j)}$. Then the occurring probability of a specific case of defected connections (i,j) can be calculated by:

$$P_{(i,j)} = P_i \cdot p_{(i,j)} \tag{2}$$

1.2. Probabilistic model for the behavior of defected connections

Various grouting defects could take place in sleeve connections, such as deviation of reinforcement from the center of sleeve and insufficient grouting, which affect the behavior of connections significantly (Zhu and Ye 2007). Experiment studies had been carried out to investigate the loading response of defected grout sleeve connections (Xu et al. 2018). As the defective degree that defined in terms of volume-ratio of insufficient grouting increases from 0 to 50%, the loading behaviors of defected connections are presented in Figure 2.

In this study, the volume-ratio of insufficient grouting of defected connection is assumed as uniformly distributed between 0 and 50%. The behavior of defected connection is characterized by the dropping of strength at smaller slip, so the uncertainty associated with the loading behavior is reflected in the probabilistic distribution of the slip at ultimate stress. The probabilistic model was obtained through Monte Carlo (MC) simulation with 10,000 samples, which is shown in Figure 3.

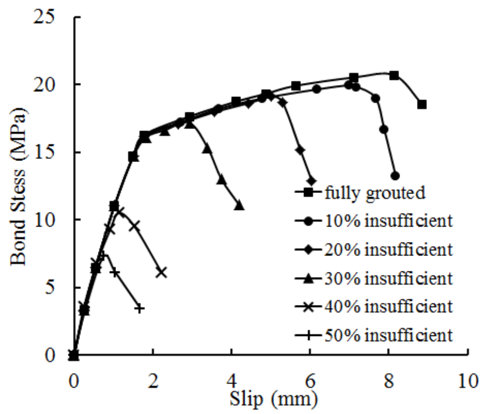


Figure 2: Bond behavior of defected grout sleeve connections.

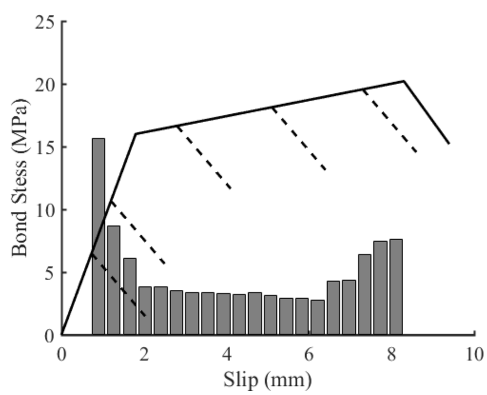


Figure 3: Probabilistic model of defected grout sleeve connection.

2. PROBABILISTIC MODELING OF GENERIC PC SHEAR WALL-FRAME STRUCTURE WITH CONNECTION DEFICIENCIES

2.1. Probabilistic modeling of PC shear wall behavior

Numerical simulations based on Finite Element (FE) analysis were performed at the platform of ABAQUS (HKS 2014), as depicted in Figure 4. The 8-node solid elements with reduced integration (C3D8R) were used for the simulation of concrete, and the Concrete Damaged Plasticity (CDP) model was used to present the constitutive relationship. Steel bars were modeled by two-node truss elements (T3D2), and a bilinear model was adapted for the stress-strain relationship. The loading behavior of grout sleeve connections is also simulated by T3D2 elements with material properties specifically defined to be consistent with the bond behavior shown in Figure 3.

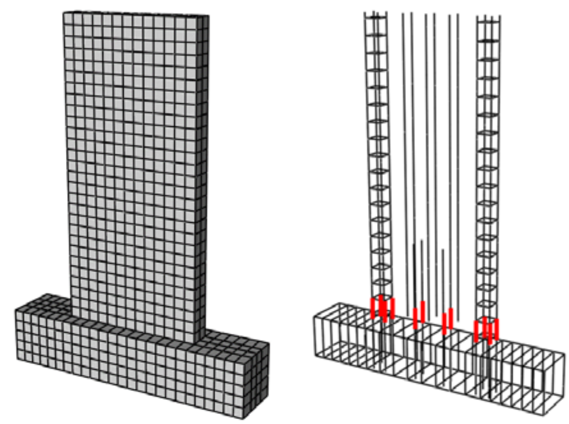


Figure 4: FE model of PC shear wall.

The FE analysis of the nonlinear model in Fig.4 is time-consuming, and the MC simulation to investigate its loading behavior statistically imposes a significant computation burden to computer. To solve this problem, Point Estimate (PE) method, first proposed by Rosenblueth (1981), was adopted to analyze the response of PC shear wall in the following.

PE method basically replaces the original (continuous) probability density function of each random variable (X_a) by a set of sampled values and their probability masses (concentrations) determined from the moments of random variables. The sampled values and their denoted probability concentrations are obtained by solving a set of nonlinear equations. These equations are written as:

$$\sum_{j=1}^{n} w_{a,b} x_{a,b}^{A} = E\left[X_{a}^{A} \right] \quad A = 0,1,......,(2n-1) \quad (3)$$

in which $x_{a,b}$ is the b^{th} sampled value of X_a, $w_{a,b}$ is the probability concentration of $x_{a,b}$, $E[\cdot]$ is the expected value of the random variable in the bracket. Eq. (3) shows that by using n samples and their denoted probability concentrations, the first (2n - 1) order moments of X_a are satisfied.

For probabilistic modeling of PC shear wall with defected connections, suppose the failure slip of each defected connection is represented by a random variable, X_a. In this study, for any specific case (i,j) for locations of defected connections, the probability distribution of each X_a was replaced by 3 sampled values, ($x_{a,1}$, $x_{a,2}$, $x_{a,3}$), with their probability concentrations, ($w_{a,1}$, $w_{a,2}$, $w_{a,3}$), i.e. n=3. Then, according to PE method, the mean value of a structural response measurement, Θ, of the PC shear wall is given by:

$$E\left[\Theta\right]_{(i,j)}=\sum_{b1=1}^{3}\sum_{b2=1}^{3}\cdots\sum_{bi=1}^{3}(w_{1,b1}\cdot w_{2,b2}\cdot\ldots\cdot w_{i,bi})\cdot\Theta\left[x_{1,b1},x_{2,b2},\ldots,x_{i,bi}\right] \quad (4)$$

in which $\Theta\left[x_{1,b1},x_{2,b2},\ldots,x_{i,bi}\right]$ is obtained through FE analysis of the PC shear wall model.

With $E[X_a^0]$ = 1, $E[X_a]$ = 4.18, $E[X_a^2]$ = 24.35, $E[X_a^3]$ = 161.80, $E[X_a^4]$ = 1139.4 and $E[X_a^5]$ = 8278.6, which were determined according to Figure 3, sampled values ($x_{a,1}$, $x_{a,2}$, $x_{a,3}$) and probability concentrations ($w_{a,1}$, $w_{a,2}$, $w_{a,3}$) could be calculated by solving Eq. (3):

$$\begin{cases} x_{a,1}=1.22 & w_{a,1}=0.377 \\ x_{a,2}=4.38 & w_{a,2}=0.318 \\ x_{a,3}=7.61 & w_{a,3}=0.305 \end{cases} \quad (5)$$

Similarly, the mean value of θ^2 is given by:

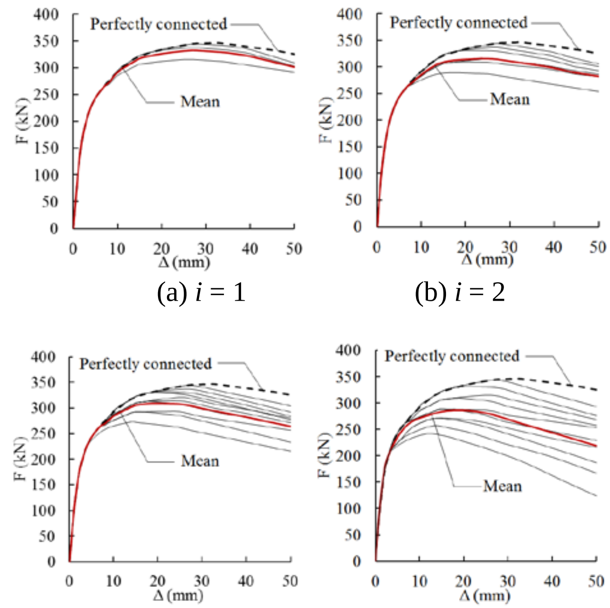
$$E\left[\Theta^2\right]_{(i,j)}=\sum_{b1=1}^{3}\sum_{b2=1}^{3}\cdots\sum_{bi=1}^{3}(w_{1,b1}\cdot w_{2,b2}\cdot\ldots\cdot w_{i,bi})\cdot\Theta^2\left[x_{1,b1},x_{2,b2},\ldots,x_{i,bi}\right] \quad (6)$$

Considering the uncertainty associated with the number and the locations of defected connections, for a given occurrence rate of defected grout sleeve connection (λ), the mean values of θ and θ^2 are calculated by

$$E\left[\Theta\right]=\sum_{i=1}^{m}P_i\cdot\sum_{j}p_{(i,j)}E\left[\Theta\right]_{(i,j)}$$
$$E\left[\Theta^2\right]=\sum_{i=1}^{m}P_i\cdot\sum_{j}p_{(i,j)}E\left[\Theta^2\right]_{(i,j)} \quad (7)$$

in which P_i can be calculated by Eq. (1). And the variance of θ is obtained by

$$Var\left[\Theta\right]=E\left[\Theta^2\right]-E^2\left[\Theta\right] \quad (8)$$



(a) i = 1 (b) i = 2
(c) i = 3 (d) i = 4

Figure 5: Sample force-displacement curves using PE method.

Some typical sampled force-displacement curves are shown in Figure 5 for cases of i=1, i=2, i=3 and i=4. The influence of connection deficiency on the response of PC shear wall was reflected in the decrease of the ultimate strength and the slop of descending section in force-displacement curves. So the displacement increment from yielding point to ultimate point ($\Delta'=(\Delta_u-\Delta_y)$) and the slope of descending section (K') were adopted as response measurement (Θ), and were treated as lognormally distributed random variables to reflect the uncertainty in loading behavior of PC shear wall in the following analysis. The mean values and the variance of Δ' and K' for different occurrence rates of defected sleeve connection, e.g., λ = 0, 25%, 50%, 75% and 100%, are presented in Table 1.

Table 1: Statistical properties of parameters for loading behavior of PC shear wall.

λ		0	25%	50%	75%	100%
Δ' (mm)	Mean	28.2	23.0	18.9	15.8	13.2
	Variance	0	20.8	21.5	17.9	15.6
K' (kN/mm)	Mean	-1.10	-1.41	-1.69	-1.97	-2.25
	Variance	0	0.17	0.24	0.27	0.25

2.2. Probabilistic modeling of PC shear wall-frame structure

A generic eight-story PC shear wall-frame structure based on a prototype building was considered in this study, which was designed according to Chinese Code for Seismic Design of Buildings (GB50011-2010) for intensity of 8 with site condition of Group 1 and Class IV. The elevation view is shown in Figure 6. The beams have cross-section of 250mm×550mm, the columns have cross-section of 550mm×550mm, and the dimensions and reinforcements of PC shear wall can be seen in Figure 1. The fundamental period of vibration is 0.48 seconds, and the axial compression ratios of column and shear wall are both 0.2. The generic building has a rigidity characteristic coefficient of 1.75, which is representative for shear wall-frame structure according to Chinese code for seismic design (GB50011-2010).

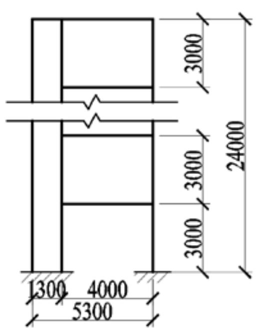


Figure 6: Elevation view of the generic building (mm).

The influence of insufficiently grout sleeves on seismic performance of PC shear wall-frame structures was investigated by means of nonlinear time history analysis, which was performed on the platform of OpenSees (McKenna and Fenves 2009). The plasticity-distributed fiber beam-column element (Spacone et al. 1996) was used to model the beams and columns in the structure. The shear wall was discretized into eight macro-elements, and each was representative of one floor of the structure, as shown in Figure 7. The macro-element for shear wall had two uniaxial sub-elements at the two sides of the wall which were used to model the flexural behavior, and one spring sub-element at the center which was used to model the shifting of neutral axis. The material properties of the uniaxial sub-elements (k_1 and k_2) and the spring element (k_H) were treated as random variables, with values determined according to the sampled response of PC shear wall with defected grout sleeve connections.

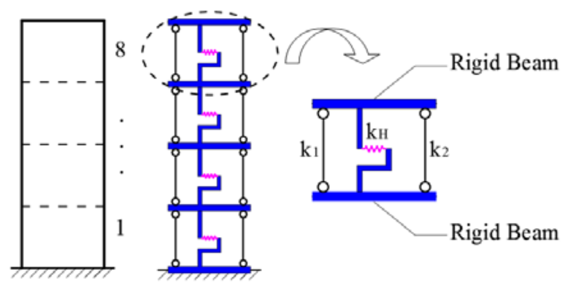


Figure 7: Macro-element modeling of shear wall.

3. SEIMEIC FRAGILITY ANALYSIS BY NONLINEAR TIME HISTORY ANALYSIS

Probabilistic seismic demand analysis was conducted for the PC shear wall-frame structure with different degrees of connection deficiency. 20 natural earthquake ground motion records were selected according to the design acceleration spectrum specified in the seismic design code (GB50011-2010), whose spectral accelerations are shown in Figure 8. Nonlinear time history analyses of PC shear wall-frame structures were performed using the selected ground motions in OpenSees.

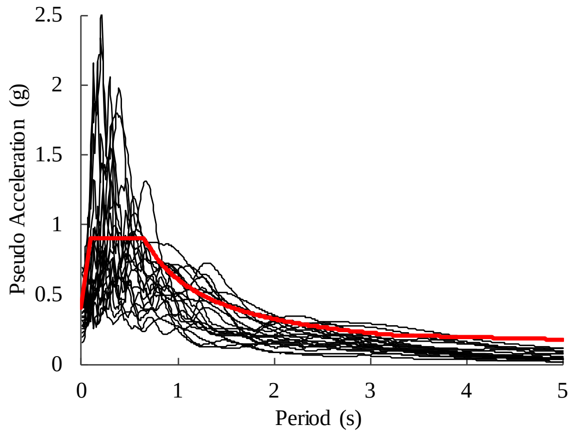


Figure 8: Acceleration spectra of earthquake ground motions.

Peak ground acceleration (PGA) was adopted as the seismic intensity measure (IM) for earthquake ground motions since the ground motion intensity for design in Chinese code is given in terms of PGA (GB50011-2010), and the peak inter-story drift ratio (θ_m), that is the maximum among all the stories of the structure, was taken as the structural response parameter (θ). The relationship between structural response (θ) and seismic intensity (IM) can be established by performing nonlinear dynamic analyses of the structural system model under a suite of ground motions at different levels of intensity. In view of the nonlinear nature of the problem and large scattering of the response due to record-to-record variation, a power-law form was recommended to be used (Cornell et al., 2002):

$$\theta = a \cdot \mathrm{IM}^b \cdot \varepsilon \tag{9}$$

where a and b are parameters determined by regression analysis and ε is the one-median random error associated with the power-law form.

The Latin Hypercube Sampling (LHS) technique (Iman and Conover 1980) was used to consider the uncertainty associated with the behavior of PC shear wall due to the uncertain grout sleeve connection quality. For a given occurrence rate of defected grout sleeve connection (λ), the mean value and the variance of the peak inter-story drift ratio (θ_m) were obtained by 100 structural model samples that were generated by LHS simulation for each earthquake ground motion. The mean values of θ_m under the excitation of 20 selected earthquake ground motions are presented in Figure 9 for different occurrence rates of defected sleeve connection, e.g., $\lambda = 0$, 25%, 50%, 75% and 100%, which are functions of PGA:

$$\begin{aligned}
\theta_m &= 0.0232\mathrm{PGA}^{1.14}, \quad \sigma_{\ln\varepsilon} = 0.312 \quad \text{for } \lambda = 0 \\
\theta_m &= 0.0265\mathrm{PGA}^{1.20}, \quad \sigma_{\ln\varepsilon} = 0.329 \quad \text{for } \lambda = 25\% \\
\theta_m &= 0.0294\mathrm{PGA}^{1.22}, \quad \sigma_{\ln\varepsilon} = 0.342 \quad \text{for } \lambda = 50\% \\
\theta_m &= 0.0323\mathrm{PGA}^{1.24}, \quad \sigma_{\ln\varepsilon} = 0.347 \quad \text{for } \lambda = 75\% \\
\theta_m &= 0.0361\mathrm{PGA}^{1.23}, \quad \sigma_{\ln\varepsilon} = 0.338 \quad \text{for } \lambda = 100\%
\end{aligned} \tag{10}$$

where $\sigma_{\ln\varepsilon}$ represents the aleatory uncertainty in seismic demand given an earthquake ground motion characterized by PGA.

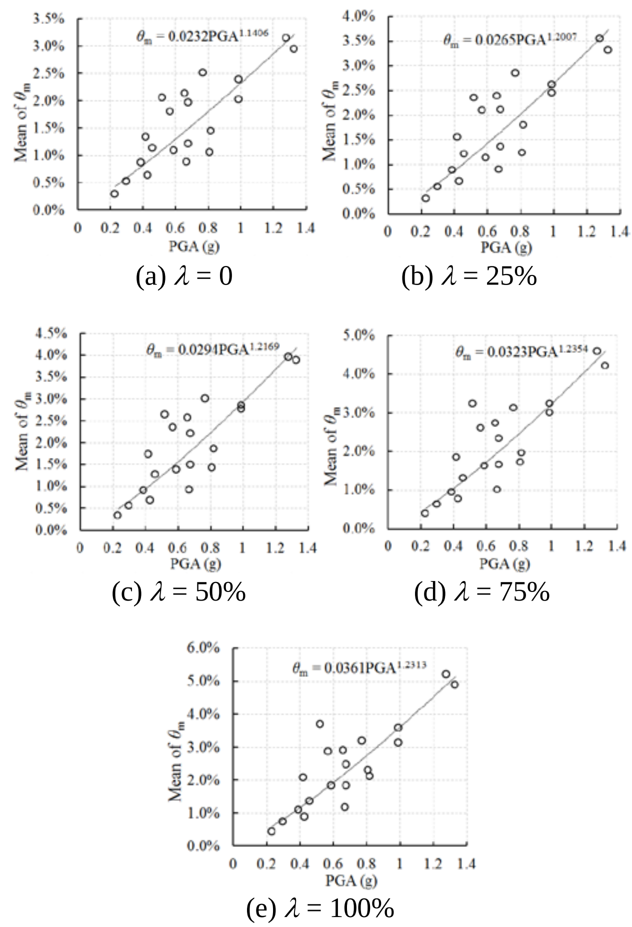


Figure 9: means of peak inter-story drift ratio for different occurrence rates of defected grout sleeve connection.

The seismic fragility is defined as the probability of exceeding a prescribed damage state (D_i) conditioned on IM (PGA is adopted in this study). In NEHRP Guidelines for the seismic rehabilitation of buildings (FEMA 1997), four performance/damage levels are identified: immediate occupancy (IO), life safety (LS), collapse prevention (CP) and incipient collapse (IC). Each performance level is related to a structural response level described by drift limit. Since the structural response is uncertain and is often assumed to follow lognormal distribution, the seismic fragility (F_R) could be written as:

$$F_R\left(D_i \mid \mathrm{PGA}=y\right)=\Phi\left(\frac{\mu_{\theta|y}-\ln\left(\theta_{cr,i}\right)}{\xi_\theta}\right) \quad (11)$$

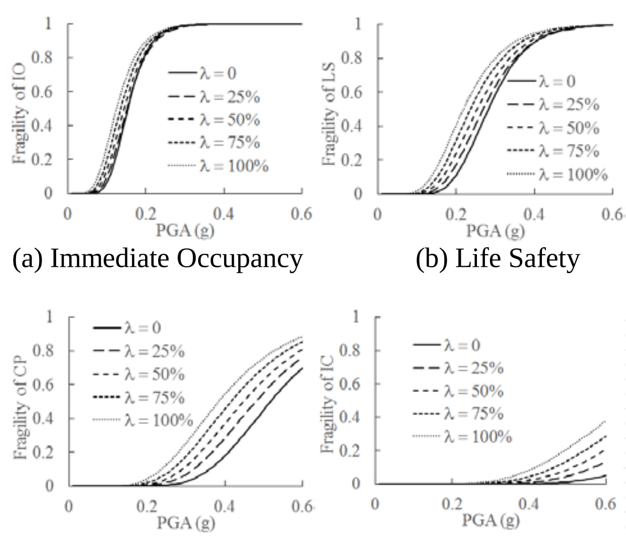
in which $\Phi(\cdot)$ is the cumulative probability function of standard normal distribution, $\theta_{cr,i}$ is the structural performance limit of interest, which is 0.25%, 0.5%, 1% and 2%, respectively for damage state (D_i) of IO, LS, CP and IC; $\mu_{\theta|y}$ and ξ_θ are the logarithmic mean and logarithmic standard deviation of structural response (θ) when PGA = y. $\mu_{\theta|y}$ can be calculated according to Eq. (10). The uncertainty term, ξ_θ, includes two parts, one is $\sigma_{\ln\varepsilon}$ which reflects the uncertainty in seismic demand due to earthquake ground motions, the other is $\sigma_{\ln\theta}$ which is due to the uncertainty associated with loading response of shear wall with defected connections. So ξ_θ is calculated by

$$\xi_\theta=\sqrt{{\sigma_{\ln\varepsilon}}^2+{\sigma_{\ln\theta}}^2} \quad (12)$$

where $\sigma_{\ln\theta}$ was obtained by LHS simulation, and was 0, 0.082, 0.145, 0.164 and 0.171, respectively for λ = 0, 25%, 50%, 75% and 100%.

The seismic fragilities of PC shear wall-frame structures with different occurrence rates of defected connections for four performance levels are presented in Figure 10. It is observed that the connection deficiency generally affect the seismic performance of PC shear wall-frame structures, in terms of increasing the probability of exceeding a certain damage state, especially for severe damage states. However, the influence of construction deficiency on seismic fragility is negligible for slight damage state.

As the building was design for seismic intensity of 8, the probability of reaching damage state of LS subjected to the earthquake with design intensity (0.2g) should be sufficiently small (e.g. less than 10%), and the probability of reaching CP should be almost 0 (e.g. less than 0.1%). The structure without construction deficiency meets this requirement with probability of LS being 9.2% and probability of CP being 0.04%; however, the two probabilities increase to 17.5% and 0.31%, 24.2% and 0.88%, 33.6% and 1.92%, and 42.7% and 4.17% respectively as the defection occurrence rate increases to 25%, 50%, 75% and 100%, indicating that the seismic performance may no longer meet the requirement of seismic design as the defection occurrence rate exceeds 25%. These comparisons demonstrate the importance of construction quality inspection and quality control of grout sleeve connections for PC shear wall-frame structures.



(a) Immediate Occupancy (b) Life Safety

(c) Collapse Prevention (d) Instantaneous Collapse

Figure 10: Seismic fragilities for IO, LS, CP and IC of PC shear wall-frame structure with different occurrence rates of defected connections.

4. SUMMARY AND CONCLUSIONS

This paper presents a comprehensive framework for seismic fragility assessment of PC shear wall-frame structures, which are susceptible to insufficient grouting of sleeve connections for the installation of shear wall panels. To establish the probabilistic model for behavior of PC shear wall, Point Estimate method is employed to account for three aspects of uncertainty, including number, locations and loading behavior of defected connections. The results of seismic fragility analysis shows that, the insufficient grouting of sleeve connections of PC shear wall significantly increases the probability of structure suffering severe damage under rare earthquake, but its effect on the probability of minor damage is slight. The occurrence rate of insufficient grouting is a key parameter for the seismic performance of the structure, and it should be controlled carefully in construction site.

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