Fragility Analysis of Space Reinforced Concrete Frame Structures with Structural Irregularity in Plan

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Abstract: Because significant damages to structures having structural irregularity in their plans were repeatedly observed during many past earthquakes, there have been great research efforts to evaluate their seismic vulnerability. Although most of the previous studies used simplified structural representations such as one-dimensional or two-dimensional models in the fragility analysis of plan-irregular structures, simple analytical models could not represent true seismic behavior from the complicated nonlinear coupling between lateral and torsional responses as the degree of irregularity increased. For space structures with high irregularity, more realistic representations such as three-dimensional models are needed for proper seismic assessment. However, the use of computationally expensive models is not practically feasible with existing approaches of fragility analysis. Thus, in this study, a different approach is adopted that can produce vulnerability curves efficiently, even with a three-dimensional model. In this approach, an integrated computational framework is established that combines reliability analysis and structural analysis. This enables evaluation of the limit-state faction without constructing its explicit formula, and the failure probability is calculated with the first-order reliability method (FORM) to deal with the computational challenge. Under the integrated framework, this study investigates the seismic vulnerability of space reinforced concrete frame structures with varying plan irregularity. Material uncertainty is considered, and more representative seismic fragility curves are derived with their three-dimensional analytical models. The effectiveness of the adopted approach is discussed, and the significant effect of structural irregularity on seismic vulnerability is highlighted. **DOI: 10.1061/(ASCE)ST.1943-541X.0002092.**

Author keywords: Seismic vulnerability; Fragility curve; Space structure; Plan irregularity; First-order reliability method; Reliability analysis.

Introduction

With significant structural damages and losses observed during past destructive earthquakes (Anderson 1987; Ellingwood 1980; DesRoches et al. 2011; Elnashai et al. 2010a; Motosaka and Mitsuji 2012; Rosenblueth 1986; Rossetto and Peiris 2009), many researchers have made great efforts to evaluate the seismic vulnerability of various structures so that the extent of structural damage can be predicted in advance and further minimized (Calvi et al. 2006). In this regard, a seismic fragility curve has been widely used as a probabilistic indicator of structural safety against earthquake hazards (Moon et al. 2016). A seismic fragility curve, or seismic vulnerability curve, is expressed as conditional failure probabilities meeting a predefined damage state criteria for different levels of ground motion intensity (Ellingwood 2001); it shows how well a structure performs during earthquake events as a graphical representation of seismic risk (Rossetto and Elnashai 2003). Deriving appropriate and accurate fragility curves is one of the most critical tasks in seismic vulnerability assessment of structures because they significantly affect the overall assessment outcomes.

To derive analytical fragility curves, most previous research studies have used simplified structural representations, such as one-dimensional or two-dimensional models. When simplified analytical models can properly represent seismic behavior of target structures, they give valid seismic fragility curves with a substantial reduction in simulation time. In case of plan-regular space structures, two-dimensional analytical models can be used in deriving effective and efficient seismic vulnerability curves (Moon et al. 2016). However, in many cases, simplified models may be inadequate to assess seismic performance of structures and their seismic vulnerability. Especially for a space structures having a high degree of plan irregularity, it is not desirable to use a simple model in the analysis because it could not properly capture highly nonlinear structural behavior due to the lateral-torsional coupling effect; it is reported that overall structural performance with detailed or sophisticated models can be very different, both qualitatively and quantitatively, from that with simplified models (Anagnostopoulos et al. 2009, 2010; De Stefano and Pintucchi 2008). Thus, for such structures, more representative analytical models should be used in deriving their seismic fragility curves; otherwise, overall vulnerability assessments would be questionable.

In this study, three-dimensional representations are used to evaluate appropriate and accurate seismic performance of space reinforced concrete (RC) frame structures with structural irregularity in their plans. However, using a three-dimensional model in fragility analysis is very challenging because it inevitably causes a significant increase in computational time and cost. From a practical point of view, the use of a computationally expensive model is not feasible with existing approaches to seismic vulnerability analysis. In order to

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overcome the great challenge in using computationally demanding models, this study provides a novel approach that can derive seismic fragility curves efficiently even with three-dimensional analytical models for space structures. In the adopted approach, computational platforms of reliability and structural analysis are coupled with the development of a linking interface. This integrated computational framework enables quick calculation of structural failure probabilities, using the first order reliability method (FORM), by not evaluating the limit-state function explicitly. In deriving fragility curves, the adopted method is computationally very efficient when compared with the most widely-used Monte Carlo simulation method (Lee and Moon 2014), which makes possible to use a more realistic structural representation or a computational expensive model for vulnerability analysis of space structures. Unlike previous studies, this study investigates the seismic vulnerability of space RC frame structures having different degrees of plan irregularity by deriving more accurate fragility curves with the use of three-dimensional models. The uncertainty in concrete and steel strength is considered, and the influence of plan irregularity on seismic vulnerability is discussed.

Space Structures with Plan Irregularity

In plan-irregular structures, center of mass does not coincide with center of stiffness. Earthquake-induced inertia forces act through center of mass, and reaction forces generated by lateral load-resisting members act through center of stiffness. The distance between the centers of mass and stiffness is defined as eccentricity, and it causes an additional torsional moment. The torsional response is coupled with the lateral response, leading to a considerable increase in deformation demand (Chandler and Hutchinson 1986). In general, plan-irregular structures are much more vulnerable to earthquake damage (Moon 2013). Evidently, considerable damages to such structures due to torsional vibration have been repeatedly observed during many past earthquakes (Anderson 1987; Ellingwood 1980; Durrani et al. 2005; Elnashai et al. 2010a; Rosenblueth 1986). Accordingly, there have been continuous research efforts to assess seismic vulnerability of plan-irregular structures.

In deriving seismic fragility curves for vulnerability assessment, it is very important to use an appropriate representation for a target structure that can reflect important characteristics of structural behavior. This is because final assessment outcomes would be unreliable and misleading if a selected analytical model could not represent real seismic behavior. For space structures with high irregularity, three-dimensional analytical models are more proper structural representations than one-dimensional or two-dimensional models to estimate the complex dynamic behavior from the coupled lateral-torsional responses. However, there is an actual challenge associated with the simulation of a three-dimensional model in vulnerability analysis. Each structural analysis with a three-dimensional model will take much more time, and correspondingly, overall computational time of the fragility analysis will increase drastically with many iterations of the time-consuming earthquake simulation. Unfortunately, the use of such a computationally expansive model is not readily available with existing methods of seismic fragility curve derivation. This study provides a novel way to derive fragility curves very efficiently even with a three-dimensional analytical model.

Seismic Fragility Curve Derivation Method

The seismic fragility curve is defined as the relationship between ground motion intensity and failure probability when a structure reaches or exceeds a certain response level (Jeong and Elnashai 2007). The failure probability can be calculated either by simulation or analytically. Accordingly, existing methods can be grouped into two categories: a simulation-based method and an analytical function–based method. The simulation-based method, such as Monte Carlo simulation, is conceptually straightforward. The failure probability is determined by conducting a series of numerical simulations and counting failure cases out of total cases (Melchers 1999). This method can easily handle any type of structural analysis technique and can give good accuracy with enough samples. However, a simulation-based method can be extremely time-consuming when each structural analysis is pricey or an expected level of failure probability is relatively low. In the analytical function–based method, the probability of failure is expressed as a conditional probability of reaching a specified limit-state condition given a certain level of hazard intensity, where the limit-state function is defined as the difference between structural capacity (supply) and seismic response (demand). This method is viable only when the structural capacity and seismic response can be expressed as analytical functions of selected random variables, so that the limit-state function has a closed-form or explicit expression. Although this method requires extensive statistical knowledge and mathematical techniques, it can give an exact solution for the failure likelihood. However, the use of an analytical function–based method is limited to very simple structures.

This study provides a different method to derive seismic fragility curves for plan-irregular space structures. The reason is that existing methods are not practically applicable when considering the fact that more realistic and complicated models are wanted for space structures with high structural irregularities. This new method can handle computational demanding models in fragility analysis, and it lies between the simulation-based method and analytical function–based method. In the adapted method, the failure probability is analytically computed without constructing a closed-form expression of the limit-state function. The seismic supply and demand are separately estimated through the structural analysis, and the limit-state function is numerically calculated as supply minus demand. This method necessitates the coupling of reliability analysis and structural analysis so as to evaluate the limit-state function implicitly and to obtain the failure probability numerically. This method does not involve complicated or cumbersome calculations of analytical functions, and it can be generally applied to any structural system.

To tackle the computational challenge, the adopted method uses the first-order reliability method. FORM is known to be an efficient, yet reliable, method to estimate the failure probability. In FORM, an event, often called "failure," is initially defined with selected random variables, and the limit state of the failure is expressed by a function of $\mathbf{x}$ in the original space, where $\mathbf{x}$ is the column vector of random variables. Then, the random variables in the original space are transformed into corresponding standard normal space using a one-to-one mapping transformation matrix, and the limit-state function is redefined by a function of $\mathbf{u}$, where $\mathbf{u}$ is the column vector of standard normal variables. Afterward, failure surface defined by the limit-state function is linearly approximated with the first-order Taylor series expansion, and a reliability index β is computed as the minimum distance from the origin to the approximated limit-state function in the standard normal space. Finally, the failure probability is calculated as

$$P_f = \Phi(-\beta) \tag{1}$$

where $\Phi(\cdot)$ = cumulative distribution function of the standard normal distribution. Fig. 1 shows the linearized limit-state function for the failure domain in the two-dimensional standard normal space

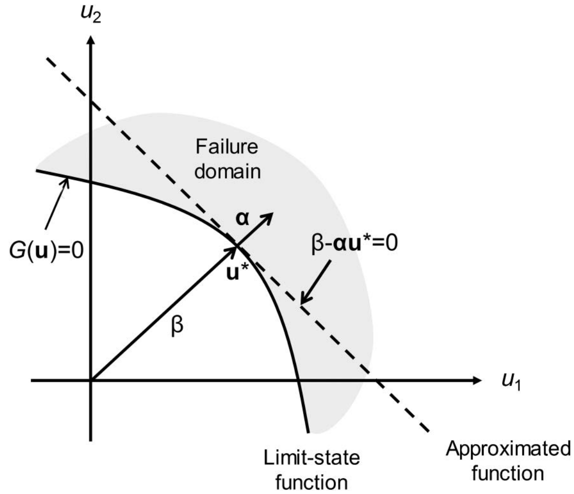

Fig. 1. Linear approximation in FORM.

and the minimum distance from the origin to the approximated linear function. In FORM, linearization of the failure surface makes it possible to deliver an estimate of the failure probability cost effectively. Further details about FORM are available elsewhere (Der Kiureghian 2005; Rackwitz and Flessler 1978).

Integrated Computational Framework

The adopted method requires the coupling of reliability analysis and structural analysis. For this, finite-element reliability using MATLAB (FERUM) and ZEUS-NL are selected as computational tools for the reliability and structural analysis. FERUM, provided by the University of California at Berkeley, is one of the popular reliability analysis software packages. It offers various reliability analysis methods, including FORM (Haukaas 2003). FERUM has been widely used in solving a variety of structural reliability problems. ZEUS-NL is an advanced structural analysis software package that is specially developed for earthquake engineering applications by the Mid-America Earthquake (MAE) Center (Elnashai et al. 2010b). This software adopts a fiber-based element modeling approach so that it can consider the material inelasticity spread within the member cross-section as well as along the member length. ZEUS-NL has been extensively used for nonlinear static and dynamic analysis of various structural systems (Jeong et al. 2012). Because source codes for both software packages are open to the public, necessary modifications can be made to develop an integrated platform of FERUM and ZEUS-NL.

The integrated computational platform, referred to as FERUM-ZEUS, is established with the development of linking interface between the FERUM and ZEUS-NL. The linking interface makes possible the automatic exchange of information between two different analysis tools during fragility analysis, and it enables implicit calculation of failure probability and efficient derivation of fragility curves. Fig. 2 presents the computational platform of FERUM-ZEUS. In this platform, FERUM provides ZEUS-NL with deterministic input values for selected random variables based on their distribution types, and ZEUS-NL generates an analytical model with the determined input parameters. Then, ZEUS-NL determines the structural capacity (supply) from a push-over analysis and estimates the seismic response (demand) from an inelastic response-history analysis. The analysis outcomes are sent back to FERUM, and FERUM evaluates the limits-state function numerically as supply minus demand. FERUM repeatedly calls ZEUS-NL until the failure probability is found with FORM. The integrated platform is developed in MATLAB, and the process of fragility curve derivation is automated. This platform can handle computationally expensive models in seismic vulnerability analysis, and it can derive fragility curves very efficiently with FORM. Additionally, in order to save computational time for the cases when an expected failure probability is too low or high, an algorithm is added to assign a probability zero or one depending on the calculated limit-state function value.

Seismic Vulnerability Analysis

Analytical Models

Three-dimensional regular and irregular three-story moment-resisting RC structures were investigated. The three-dimensional analytical models were developed based on the two-dimensional model (Lee and Moon 2014) benchmarked from a previous study by Kwon and Elnashai (2006). The selected structure was designed mainly for gravity loads, and it can serve as a typical low-rise RC structure with limited ductility and no seismic details in many regions, including the central United States and Central and Northern Europe. The studied structures had three bays in the longitudinal and transverse direction. The length of each bay was 5.486 m (216 in.), and the total height was 10.744 m (423 in.). Fig. 3 shows the plan and elevation view of the studied RC frame structures. For detailed design information, refer to Bracci et al. (1992).

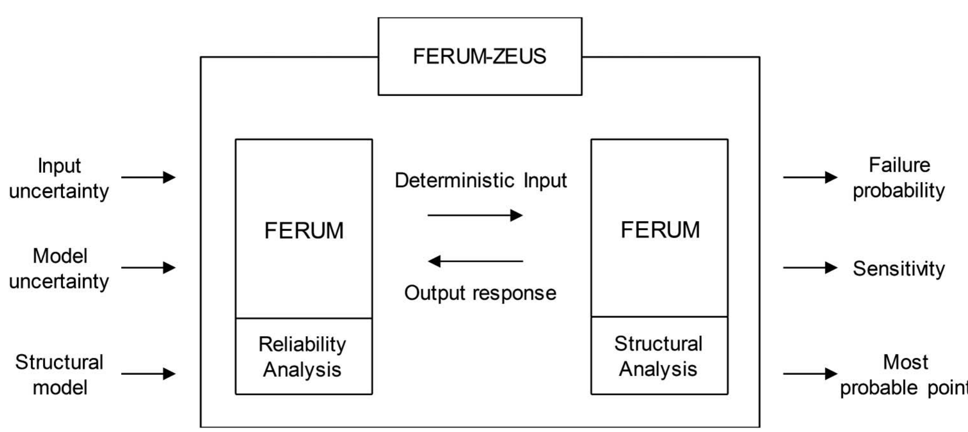

Fig. 2. Computational platform of FERUM-ZEUS.

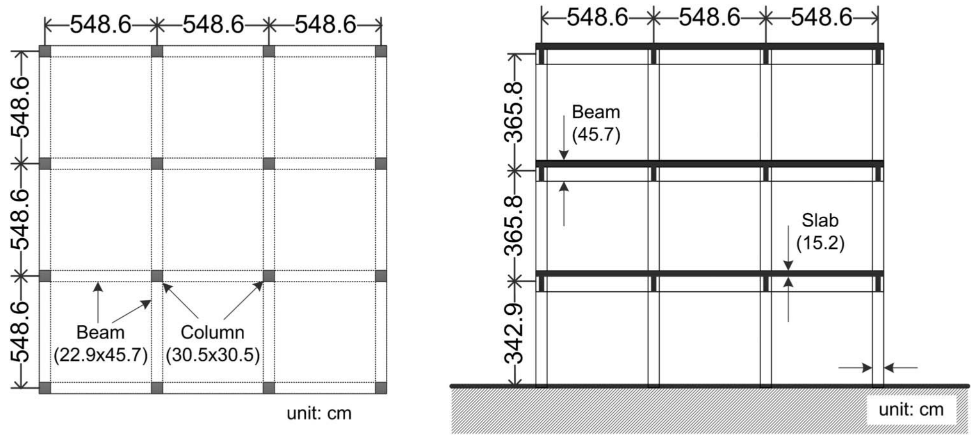

Fig. 3. Plan and elevation view of studied RC frame structures.

Table 1. Eccentricities and fundamental periods of analytical models

	Regular	Irregular			
Model property	ME000	ME025	ME050	ME075	ME100
Eccentricity (mm)	0	137.15	274.3	411.45	548.6
Dimensionless eccentricity (%)	0	2.5	5	7.5	10
First period (s)	0.8982	0.9148	0.9349	0.9549	0.9745
Second period (s)	0.8978	0.8979	0.8978	0.8978	0.8978
Third period (s)	0.8879	0.8712	0.8494	0.8271	0.8042

Five different types of analytical models were explored; one of them was for a regular structure, and four were for irregular structures. The regular structure model had coincident centers of mass and stiffness, whereas the irregular ones had varying eccentricity from the noncoincident centers. Eccentricity is defined as the distance between center of stiffness and center of mass, and dimensionless eccentricity is defined as the ratio of the eccentricity to the floor dimension. Irregular models have eccentricities that vary from 2.5 to 10% of the floor dimension in the transverse direction. In the irregular models, stiffness is distributed symmetrically, but mass has a nonsymmetric distribution under the assumption that live loads are asymmetrically distributed along the slabs. To generate various degrees of structural irregularity, different values of live loads are applied to each half of the slabs. Table 1 summarizes the eccentricities, fundamental periods, and reference names of the five analytical models. Fig. 4 shows first three mode shapes of the regular model and 10% irregular mode. The first and second modes correspond to the translational response in the longitudinal and transverse direction, and the third mode corresponds to the torsional response.

The numerical models were created in the nonlinear finite-element analysis program ZEUS-NL. They consisted of 48 columns and 72 beams, and each column and beam member had six and seven elements, respectively. The reinforced concrete columns had a square cross-section with 30.5 cm (12 in.) side width. The thickness of the slab was 15.2 cm (6 in.), and beams had a reinforced concrete T section with total depth of 45.7 cm (18 in.). Lumped masses corresponding to the calculated gravity loads were placed only at the beam–column connections in order to reduce the size of the mass matrix. Nonlinear material behaviors based on a bilinear elasto-plastic model with a kinematic hardening and modified Mander's model (Martínez-Rueda and Elnashai 1997) were used for steel and concrete, respectively, and hysteretic damping was considered. Fig. 5 shows a three-dimensional numerical model created in ZEUS-NL and the schematic locations of the centers of mass and stiffness in regular and irregular models.

Input Ground Motions

The ground motions were selected based on the ratio of the peak ground acceleration (PGA) to the peak ground velocity (PGV). The PGA/PGV ratio is known to correlate well with the frequency characteristics of the ground motion and to account for many seismo-tectonic features and seismic site effects (Pavel and Lungu 2013). A total of 15 ground motion records were chosen to have different PGA/PGV ratios, and the selected records fell into three categories depending on the PGA/PGV ratio (Zhu et al. 1988): low (less than 0.8 g/m/s), medium (between 0.8 and 1.2 g/m/s), and high (greater than 1.2 g/m/s). Each group included five ground motions. For non-region-specific applications, selecting ground motion records from each PGA/PGV ratio range is necessary to impose possible seismic demands on structures from various earthquake scenarios (Elnashai and Di Sarno 2008). The PGA of selected motions was scaled from 0.02 to 1 g; the increment was 0.02 g up to 0.08 g and is 0.04 g afterward. The acceleration time-history records of the selected ground motions in each group and the averaged response spectra for three distinct groups are shown in Fig. 6. Details on selected ground motions are provided in Table 2, and the statistical summary of PGA/PGV ratios for earthquake records in each group is presented in Table 3.

Definition of Uncertainty and Limit State

Uncertainties in structural capacity and earthquake hazard were considered in deriving the seismic vulnerability curves of space RC frame structures. Uncertainty in structural capacity, or supply, was taken into account by considering concrete ultimate strength

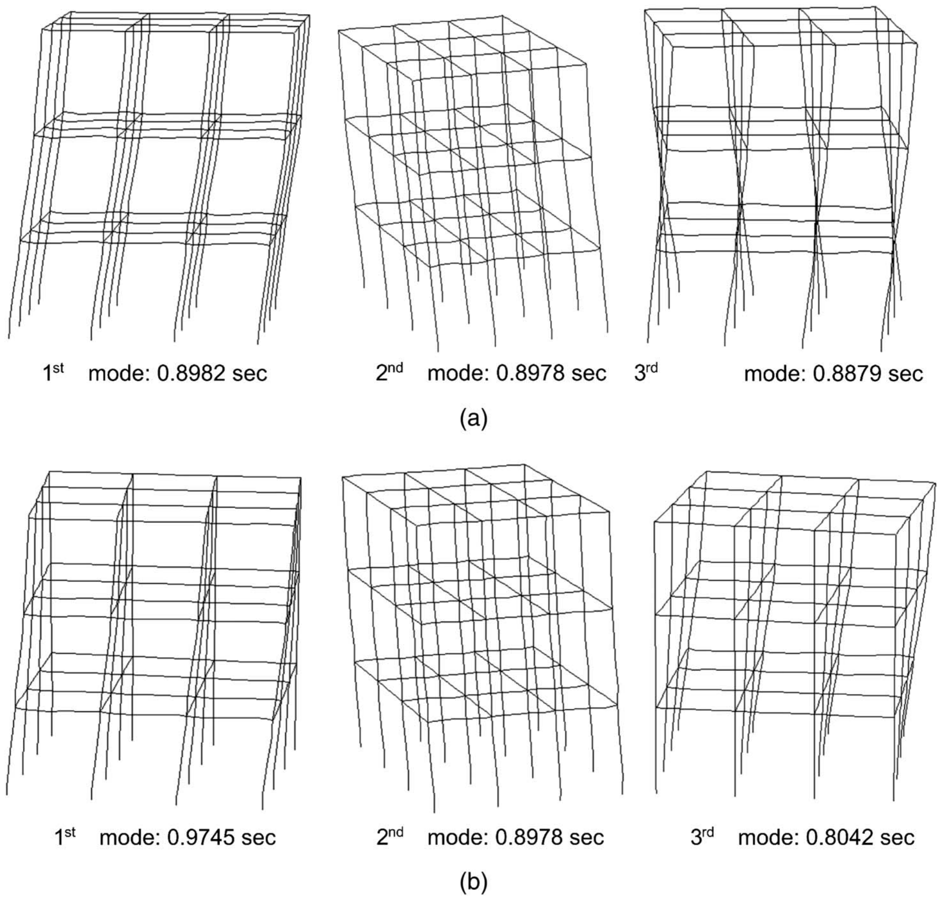

Fig. 4. First three mode shapes of selected analytical models: (a) regular model (ME000); and (b) 10% irregular model (ME100).

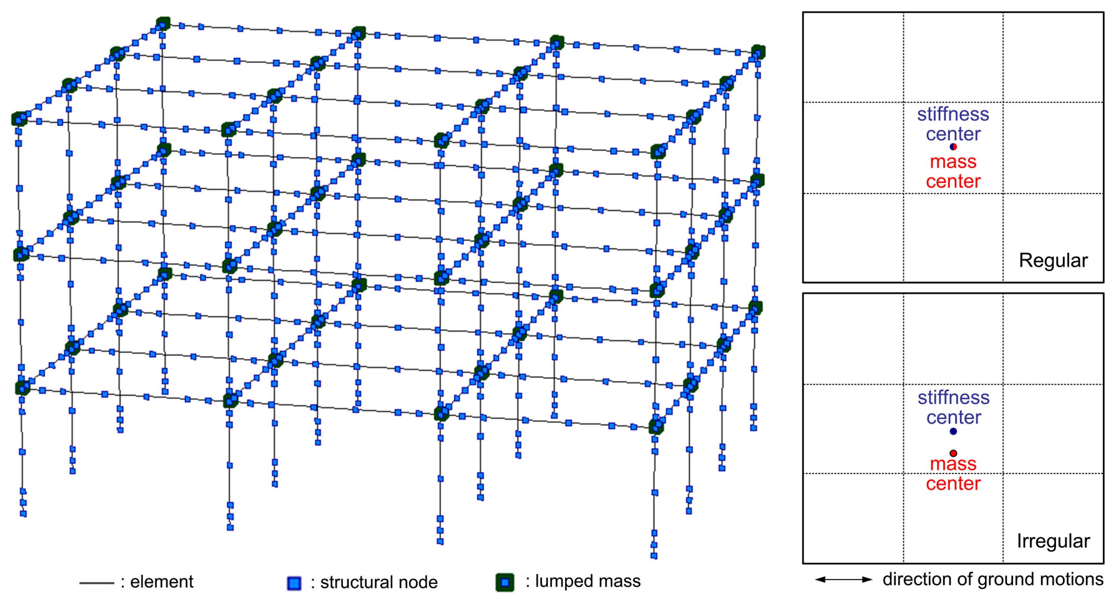

Fig. 5. Three-dimensional numerical model and schematic locations of mass and stiffness centers.

and steel yield strength as random variables. The design concrete ultimate strength was 24 MPa, and the in-place strength of concrete was assumed to have a normal distribution of a mean of 33.6 MPa and a coefficient of variation of 18.6% based on the findings of Bartlett and MacGregor (1996). The reinforcement was designed with grade 40 steel, and the yield strength of reinforcing steel was assumed to follow a normal distribution with a mean of 337 MPa and a coefficient of variation of 10.7%, as suggested from the strength test results of steel bars performed by Mirza and MacGregor (1979) and adopted in several studies (Lu et al. 2005; Kwon and Elnashai 2006; Moon et al. 2016). Table 4 summarizes the statistical properties of the random variables considered in the

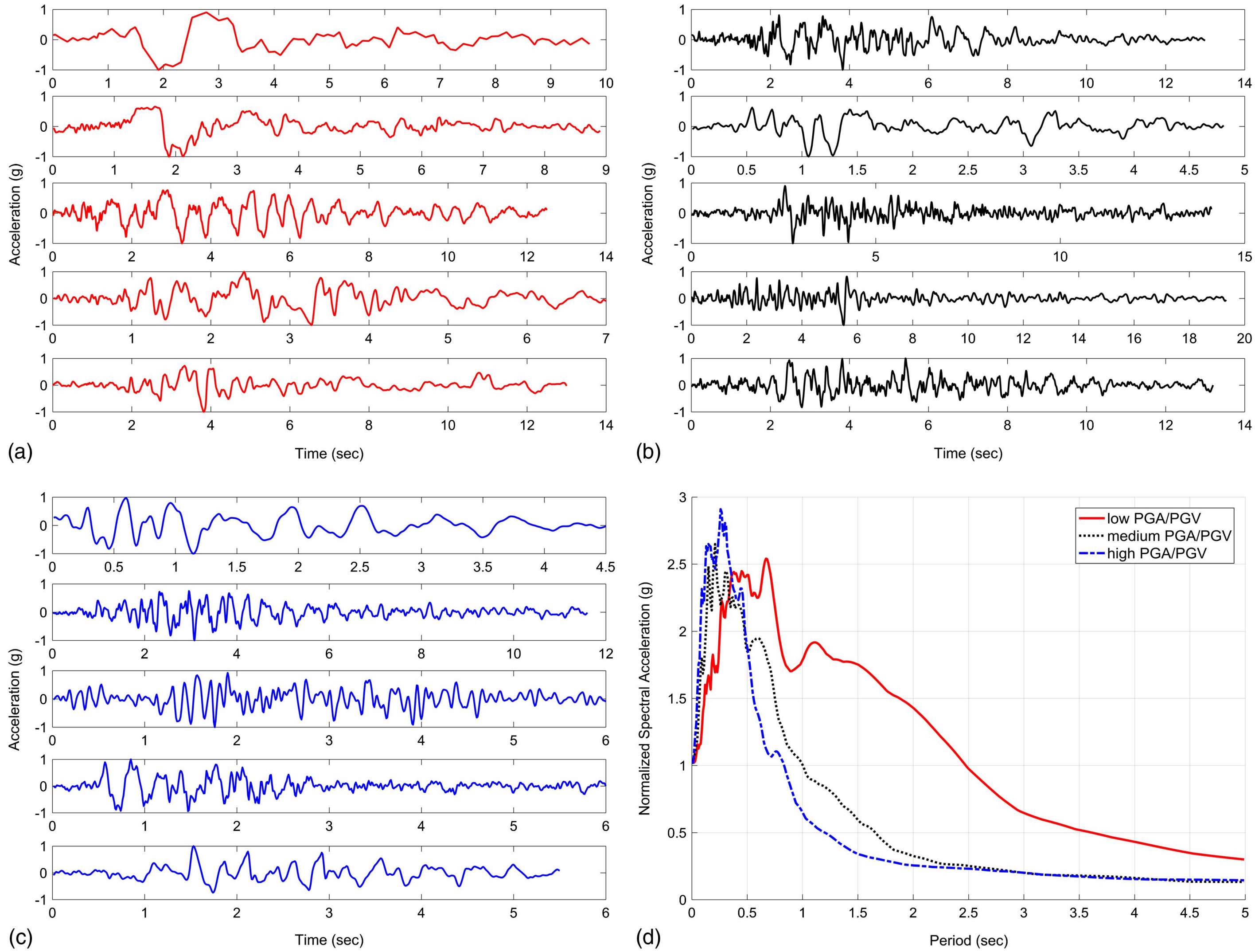

Fig. 6. Selected ground motion records: (a) low PGA/PGV; (b) medium PGA/PGV; (c) high PGA/PGV; and (d) average response spectrum.

Table 2. Properties of selected ground motions

Earthquake	Date	Magnitude	PGA (g)	PGA/PGV (g/m/s)	PGA/PGV category	Reference name
Bucharest	03/04/1977	6.4	0.19	0.28	Low	1-1
Erzincan	03/13/1992	Unknown	0.39	0.38	Low	1-2
Montenegro	05/24/1979	6.2	0.12	0.63	Low	1-3
Kalamata	09/13/1986	5.5	0.22	0.66	Low	1-4
Kocaeli	08/17/1999	Unknown	0.31	0.75	Low	1-5
Friuli	09/15/1976	6.1	0.08	1.04	Medium	2-1
Athens	09/07/1999	Unknown	0.11	1.09	Medium	2-2
Umbro-Marchigiano	09/26/1997	5.8	0.10	1.11	Medium	2-3
Lazio Abruzzo	05/07/1984	5.7	0.06	1.14	Medium	2-4
Basso Tirreno	04/15/1978	5.6	0.07	1.18	Medium	2-5
Gulf of Corinth	11/04/1993	4.7	0.07	1.43	High	3-1
Montenegro	05/24/1979	6.2	0.07	1.53	High	3-2
Montenegro	05/24/1979	6.2	0.17	1.56	High	3-3
Friuli	05/06/1976	6.3	0.36	1.73	High	3-4
Umbro-Marchigiana	11/09/1997	5.0	0.04	1.90	High	3-5

study. The uncertainty in earthquake loads, or demand, was taken into account by using various ground motion records in the analysis.

This study used three levels of limit state: serviceability, damage control, and collapse prevention. The serviceability limit state was defined at the first yielding of reinforcing steel in column members. The damage control and collapse prevention states were defined at the maximum element strength and maximum confined concrete strain in column members, respectively. The interstory drift (ISD) was used to determine if a structure failed based on the limit-state definition. To determine threshold values of ISDs corresponding to each limit-state condition, a series of adaptive pushover analyses was conducted with five different prototype structures. Fig. 7 compares total base shear force versus maximum top drift ratio from the adaptive pushover analysis using inverted-triangle (code defined), and uniform lateral-load distribution, and it graphically shows that structures with more irregularity have less seismic capacity.

The studied analytical models had 48 columns (i.e., 16 columns on each story), and a limit-state condition was assumed to be achieved when the ISD of any column reached the specified drift criteria. Although the failure of one column may not necessarily correspond to the failure of the structure as a whole, this more conservative definition of failure limit-state condition is used in the study. The limit-state function $g(x)$ is defined as follows:

$$g(\mathbf{x}) = \mathrm{ISL}_{\mathrm{LS}} - \max[\mathrm{ISD}_{C01}(\mathbf{x}), \mathrm{ISD}_{C02}(\mathbf{x}), \ldots, \mathrm{ISD}_{C48}(\mathbf{x})] \leq 0 \tag{2}$$

where $\mathrm{ISD}_{\mathrm{LS}}$ = threshold ISD value of the limit state; and $\mathrm{ISD}_{C01}, \mathrm{ISD}_{C02}, \ldots, \mathrm{ISD}_{C48}$ denote the ISDs of the 48 columns (C01–C48). In this equation, $\mathrm{ISD}_{\mathrm{LS}}$ represents the seismic capacity provided by a structure, and the maximum ISD of columns represents the seismic demand imposed by the earthquake. Table 5 shows the threshold ISD ratio values of three limit states for all analytical models. The threshold value decreases with the increase of eccentricity.

Table 3. Statistical summary of PGA/PGV ratios of earthquake records

Statistical property	Low PGA/PGV	Medium PGA/PGV	High PGA/PGV
Range	0.275–0.750	1.040–1.183	1.432–1.902
Mean	0.540	1.111	1.631
Coefficient of variation	0.373	0.048	0.114

Table 4. Statistical properties of random variables

Random variable	Distribution type	Mean (MPa)	Coefficient of variation
Concrete ultimate strength	Normal	33.6	0.186
Steel yield strength	Normal	336.5	0.107

Seismic Vulnerability Curves

Seismic vulnerability curves of space RC frames with different degrees of structural irregularity were successfully derived with their three-dimensional analytical models. With the help of the

Table 5. Threshold ISD ratio values of limit states

	ISD ratio (%)				
Limit state	ME000	ME025	ME050	ME075	ME100
Serviceability	0.58	0.56	0.55	0.53	0.51
Damage control	1.09	1.07	1.00	0.96	0.93
Collapse prevention	2.26	2.04	1.83	1.73	1.62

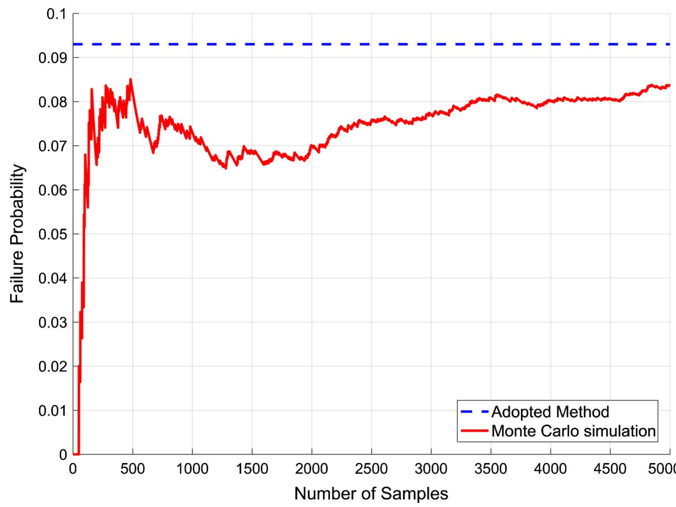

Fig. 8. Failure probability estimation with Monte Carlo simulation and the adopted method.

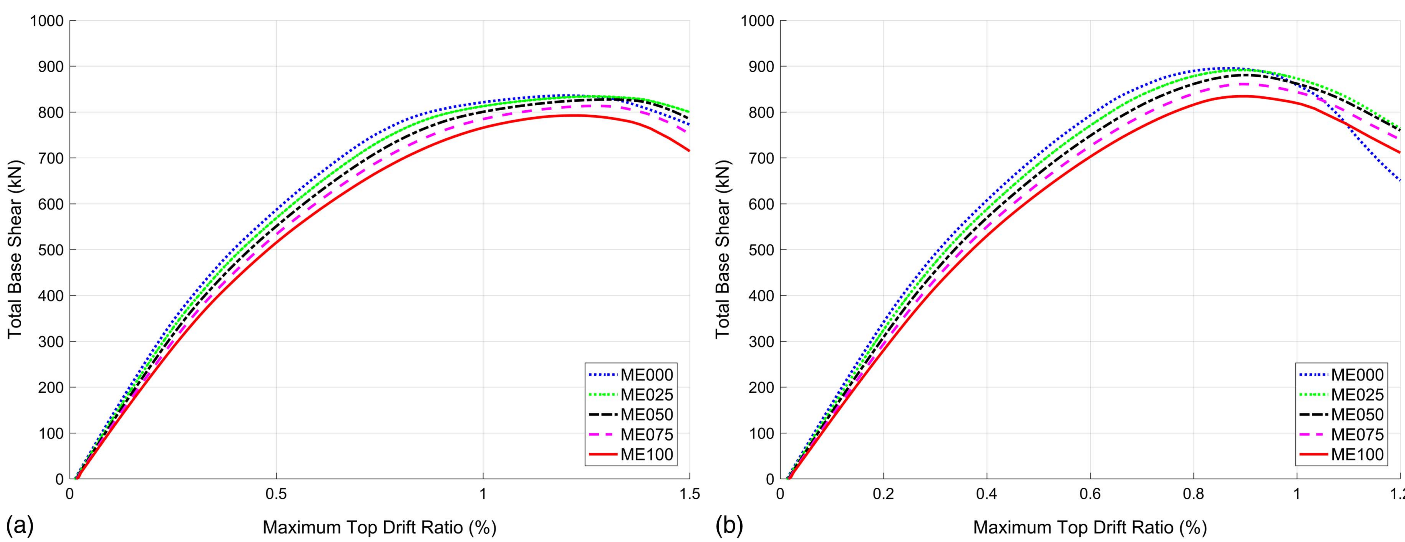

Fig. 7. Total base shear versus maximum top drift ratio curves from adaptive pushover analyses: (a) inverted triangle lateral load distribution; and (b) uniform lateral load distribution.

computational platform described in the previous section, the use of more computationally demanding models becomes practically feasible. Consequently, fragility curves of space structures can be obtained on a standard personal computer (IntelCore i7-870, 2.93 GHz CPU, 12 GB RAM). If the same numerical problem were solved with the most widely used Monte Carlo simulation, obtaining fragility curves would be extremely time consuming because the computational cost of each structural analysis becomes much expensive with the use of three-dimensional models. The use of a high-performance computer such as a supercomputer would be inevitable to handle heavy computing; however, even with such a computer, it would still take a considerable amount of time and effort to derive fragility curves.

In deriving seismic fragility curves with three-dimensional models under the adopted framework, the required simulation analyses were 4,295, 3,865, 3,904, 3,847, and 3,649 for ME000, ME025, ME050, ME075, and ME100 models, respectively. For the ME000 model, 4,295 dynamic response-history analyses were conducted, and it took about 36 h with four parallel processes. In the previous study, Kwon and Elnashai (2006) derived seismic fragile curves of a similar structure with two-dimensional models using Monte Carlo simulation; they reported that a total of 23,000 simulation analyses were performed with the PGA increment of 0.05 g, and it took 456 h with a Pentium IV-2.65 GHz PC. When comparing the required amount of structural analysis and overall computational time, the adopted approach is proven to be very efficient in deriving fragility curves even with three-dimensional models. Fig. 8 demonstrates the failure probability convergence with the number of samples in Monte Carlo simulation. The adopted method estimated the failure probability of the ME500 model to be 0.093 after

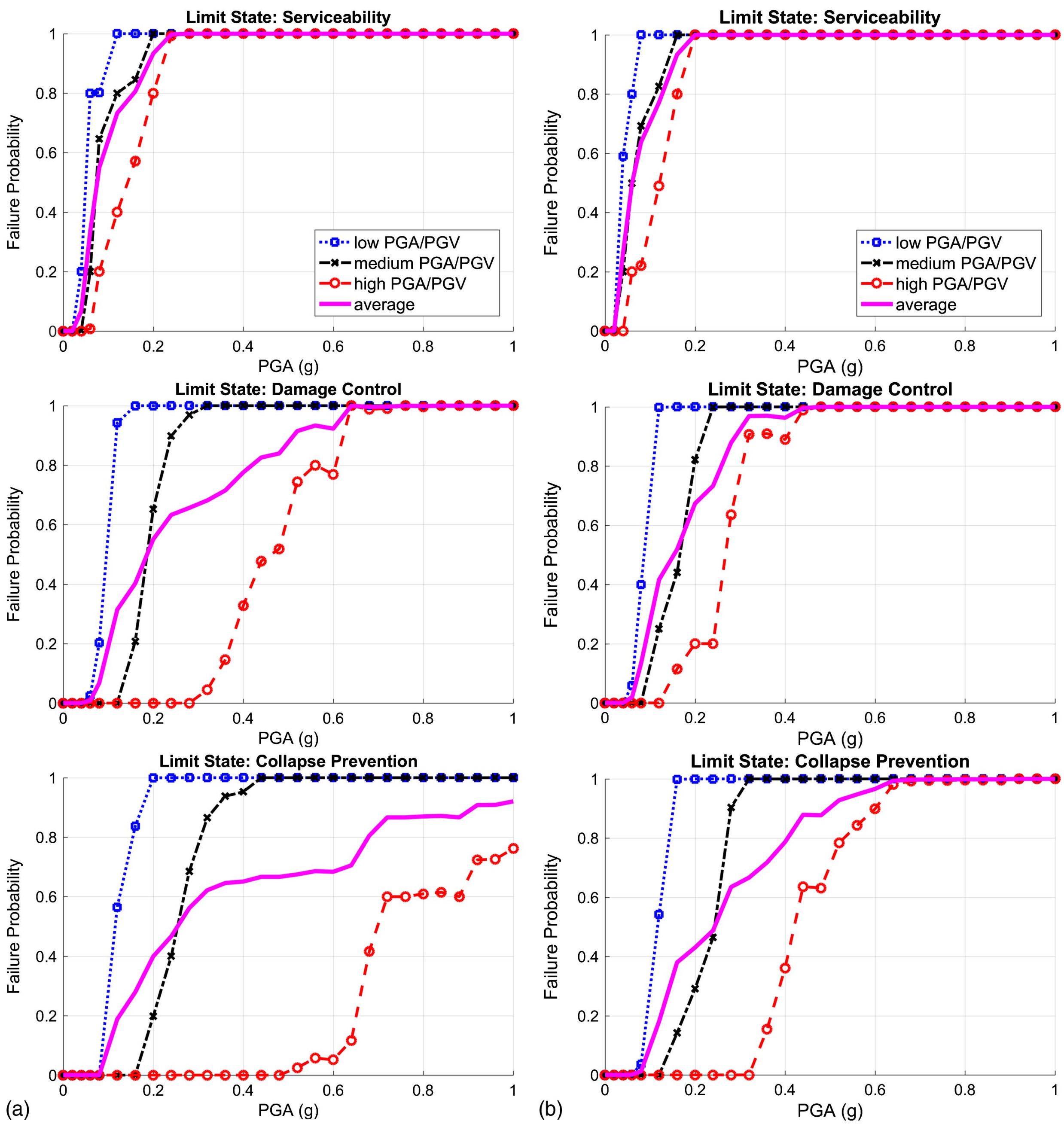

Fig. 9. Seismic fragility curves derived with three-dimensional analytical models: (a) without structural irregularity (ME000); and (b) with structural irregularity (ME100).

Table 6. Lognormal mean and variance values for seismic fragility curves with three distinct groups of ground motions

		Serviceability		Damage control		Collapse prevention	
Model	PGA/PGV	Mean	Variance	Mean	Variance	Mean	Variance
ME000	Low	0.053	0.00030	0.086	0.00146	0.148	0.00471
	medium	0.093	0.00026	0.190	0.00134	0.474	0.01457
	High	0.122	0.00092	0.268	0.00259	0.790	0.04310
ME025	Low	0.052	0.00027	0.088	0.00160	0.137	0.00459
	medium	0.092	0.00039	0.179	0.00077	0.401	0.01047
	High	0.114	0.00075	0.250	0.00208	0.623	0.02322
ME050	Low	0.050	0.00031	0.077	0.00126	0.130	0.00372
	medium	0.085	0.00054	0.162	0.00178	0.343	0.01220
	High	0.115	0.00038	0.244	0.00205	0.521	0.01668
ME075	Low	0.045	0.00030	0.072	0.00181	0.126	0.00306
	medium	0.083	0.00007	0.162	0.00190	0.325	0.00896
	High	0.121	0.00015	0.239	0.00223	0.485	0.01300
ME100	Low	0.041	0.00030	0.072	0.00179	0.122	0.00318
	medium	0.085	0.00025	0.163	0.00227	0.271	0.00375
	High	0.119	0.00023	0.234	0.00286	0.451	0.00946

12 simulations under the earthquake scenario 3-2 with a PGA of 0.20 g with the damage control limit-state definition. As shown in the figure, unlike the adopted method, the failure probability could not be accurately estimated with Monte Carlo simulation after 5,000 simulations.

Fig. 9 illustrates seismic fragility curves of space RC frame structures without irregularity and with 10% irregularity for the given three limit states. In each graph, fragility curves derived with three distinct groups of ground motions are compared, and the averaged fragility curve over all ground motions are depicted. It is evident that different ground motion sets and structural irregularities produce considerable differences in seismic fragility curves. As expected, the failure likelihood decreases with a stricter definition of the damage state. The fragility curves in the figure are drawn by connecting data points where each point is a failure probability calculated from a series of structural and reliability analyses. Material uncertainty is considered, and an analytical model in each simulation has different steel and concrete strengths.

For general application, a series of regression analyses was performed to get a functional form for each fragility curve. The

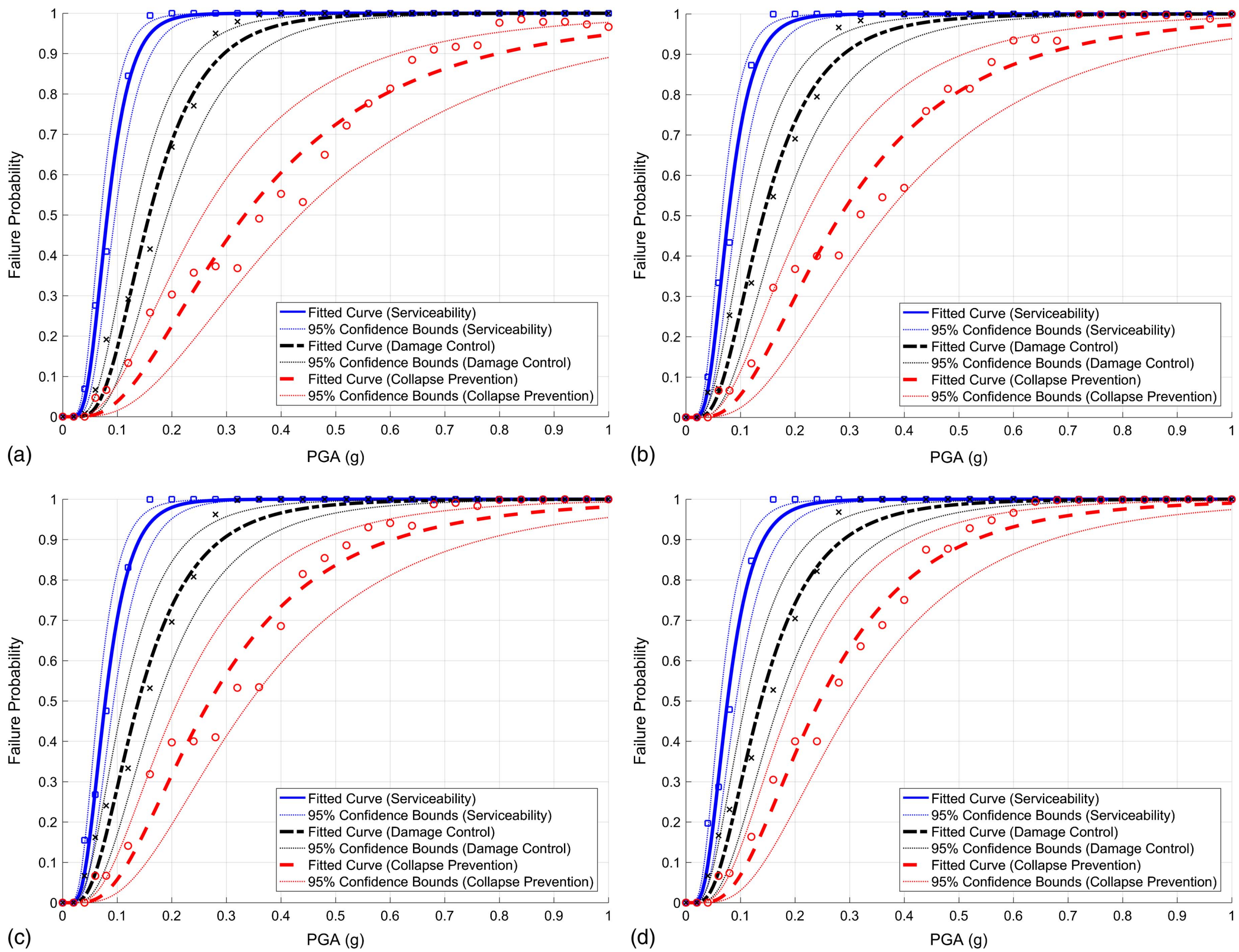

Fig. 10. Seismic fragility curves of space RC frame structures with different degrees of plan irregularity: (a) 2.5% eccentricity (ME025); (b) 5% eccentricity (ME050); (c) 7.5% eccentricity (ME075); and (d) 10% eccentricity (ME100).

Table 7. Lognormal parameters for seismic fragility curves of studied structures

	Serviceability		Damage control		Collapse prevention	
Model	Mean	Variance	Mean	Variance	Mean	Variance
ME000	0.0934	0.0017	0.1893	0.0099	0.5416	0.2463
ME025	0.0889	0.0015	0.1785	0.0085	0.4204	0.1034
ME050	0.0857	0.0016	0.1653	0.0099	0.3506	0.0656
ME075	0.0870	0.0018	0.1645	0.0108	0.3291	0.0527
ME100	0.0858	0.0020	0.1625	0.0105	0.2938	0.0378

lognormal cumulative distributions were assumed to represent the curves, and the mean and variance were obtained after fitting the data in a least-squares sense. Table 6 tabulates lognormal means and variances for seismic fragility curves of all studied structures with three distinct groups of ground motions.

Fig. 10 plots seismic fragility curves of space RC frames with four different structural irregularities. In the figure, each graph has fragility curves for three limit states. The fitted lognormal curves are plotted, and the 95% confidence bounds are depicted. The fragility curve of the serviceability limit-state is located to the left of that of the collapse prevention limit-state. Seismic fragility curves are noticeably affected by the structural irregularity.

Effect of Structural Irregularity on Seismic Vulnerability

The effect of structural irregularity on seismic vulnerability is investigated by comparing fragility curves and their statistical parameters. Table 7 summarizes lognormal parameters for seismic fragility curves of space RC frame structures. The ratios of the ME100 (10% irregular model) mean to ME000 (regular model) mean were 91.9, 85.8, and 54.2% for serviceability, damage control, and collapse prevention limit states, respectively. Fig. 11 shows how the lognormal mean values are affected by the eccentricity and depicts fitted curves with second-degree polynomials. It is clearly shown that the space RC frame structures with high irregularity are much more vulnerable than the regular structure.

Fig. 12 compares fragility curves for different structural models with the given three limit states. The fragility curve shifts toward the left as the degree of irregularity increases; in other words, the likelihood of failure increases with the increase of structural irregularity. As seen in the figure, plan irregularity has a great impact on the structural performance during earthquakes or seismic vulnerability. This agrees well with the fact that plan-irregular structures are highly vulnerable to earthquake damage, as evidenced by structural damages and losses to such structures during past earthquakes.

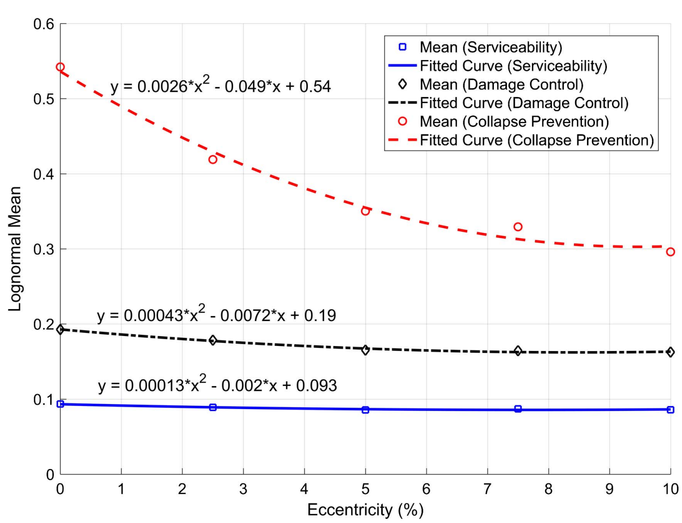

Fig. 11. Variation of lognormal mean with the structural irregularity.

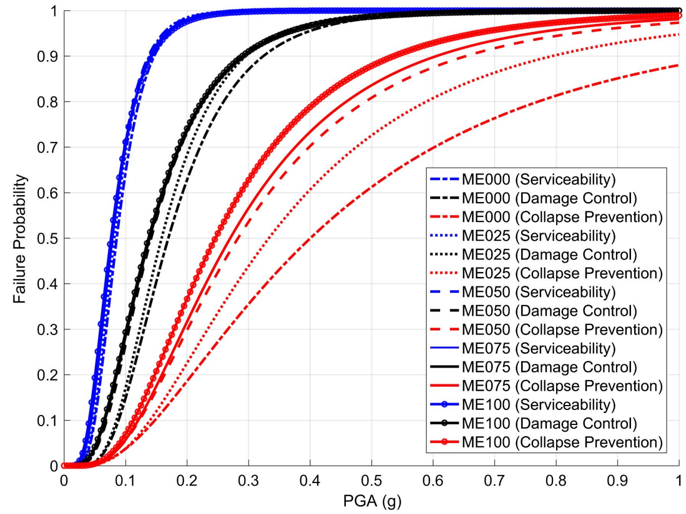

Fig. 12. Effect of structural irregularity on seismic fragility curves.

Summary and Conclusion

This study aims to derive more accurate and appropriate seismic fragility curves for space RC frame structures with different degrees of plan irregularity with their three-dimensional models and investigate the effect of structural irregularity on their seismic vulnerability. Instead of simplified models, three-dimensional analytical models are adopted to take into account true nonlinear coupled lateral-torsional responses. To address the significant computational challenge associated with the use of three-dimensional models, this study establishes a computational framework that integrates structural and reliability analysis. FERUM and ZEUS-NL are selected as the reliability and structural analysis tools, and a linking interface is provided that enables automatic interchange of the necessary data between two analysis tools. FORM is used to estimate the failure probabilities. With the adopted framework, seismic vulnerability of various space RC frame structures, with and without plan irregularity, is investigated. Five different models of RC frame structure are studied, with varying plan irregularities from 0 to 10% with a 2.5% increment. A total of 15 ground motions are used, and they are categorized into three groups based on the ratio of PGA to PGV. Uncertainties in structural capacity and earthquake demand are both considered. Three limit states are defined, serviceability, damage control, and collapse prevention. The corresponding values of interstory drift ratio for each limit state are obtained from a series of adaptive pushover analyses. Under the integrated framework, seismic fragility curves of space RC fame structures with different degrees of plan irregularity are successfully derived with their three-dimensional models on a standard personal computer. The lognormal cumulative probability distribution is assumed for the fragility curves, and statistical parameters are provided after conducting extensive regression analysis.

The proposed approach of deriving seismic fragility curves makes it practically possible to use computationally expensive models in the analysis, and it produces fragility curves very efficiently.

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From the derived fragility curves, it is observed that seismic vulnerability is considerably affected by the structural irregularity, and the PGA/PGV ratio of ground motions has a noteworthy effect on the fragility curves. The numerical results clearly indicate that space RC frame structures become much vulnerable to earthquake damage as the plan irregularity increases. This agrees well with many of the previous research results and the actual damage observed in past earthquakes. Structural irregularity is the one of the major causes of the failure or collapse of structures, so considerable attention should be paid when conducting seismic vulnerability analysis. The main contributions of this study are as follows: (1) it establishes an integrated computational framework for efficient fragility analysis, (2) it derives more representative fragility curves with the use of three-dimensional analytical models, (3) it provides functional forms of seismic fragility curves for space RC frame structures with varying plan irregularity, and (4) it investigates the effect of plan irregularity on seismic vulnerability with more realistic fragility curves. The proposed approach is expected to be very useful when more accurate seismic vulnerability for complex structures is required. This study delivers seismic fragility curves for typical low-rise space RC frame structures with varying plan irregularity, but the general application may be limited because seismic performance could be very different depending on the structural configuration and the damage state definition.

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