Analytical fragility research on RC frame-core tube structures with an optimum intensity measure

Shansuo Zheng[(1)], Yixin Zhang[(2)], Jinchuan He[(3)], Qing Qin[(4)]

[(1)] Professor. Xi'an University of Architecture and Technology, China. zhengshansuo@263.net

[(2)] PhD. Xi'an University of Architecture and Technology, China. zyx19910619@126.com

[(3)] Associate Professor. Xi'an University of Architecture and Technology, China.

[(4)] PhD. Xi'an University of Architecture and Technology, China. 495680791@qq.com

Abstract: In this paper, the analytical seismic fragility relations of RC high-rise frame-core tube structures is derived with an improved intensity measure (IM). As reference buildings, nine typical RC frame-core tube structures with varying height, width of building plan and seismic fortification levels (SFL) are designed and numerically modeled for conducting nonlinear dynamic time history analysis. To ensure sufficiency and efficiency for IM, which is the geometric mean of spectral acceleration over a certain period range in the study, an optimization algorithm is developed to select the period range. Consequently, the comparison of this optimal spectral value with traditional IMs exhibits a substantial reduction in correlation with seismic parameters (sufficiency) and in dispersion with respect to structural response (efficiency). Then the fragility curves are obtained based on the defined damage states that are consistent with current seismic design code. The impact of aspect ratio and seismic fortification levels on the fragility relationships are also investigated. As expect, no significant trends were observed between structural seismic fragility and aspect ratio including both height and width of building plan, while seismic fortification level has a great impact on fragility assessment.

Key words: high-rise RC frame-core tube structures; intensity measure; fragility assessment

1. Introduction

The high-rise building inventories, in which frame-core tube structures have a certain proportion, have increased rapidly to meet the exploding population and land shortage in the urban areas of China. Hence the reliable estimation of seismic risk aimed at this class of buildings is in need especially in Chinese active seismic zone, whereas the relevant domestic literatures are limited to the author's knowledge [1-2]. Within the framework of Performance-Based Earthquake Engineering (PBEE), the seismic risk assessment involves three interrelated parts, which are seismic hazard, fragility and loss analysis. Thereof the fragility is the exceeding probability of multiple damage states under the certain ground motion excitation described with intensity measure (IM). Thus, the key points for assessing seismic fragility are to obtain the relationship of structural response described by engineering demand parameters (EDP) and IM, as well as the discrete limit states (LS) concerning the structural damage. Both empirical and analytical methods (e.g. [3-4]) can be used to the process and the latter is adopted in this paper due to the lack of field data in the past earthquakes.

As the representation of ground motion and parameters of fragility functions, the choice of IM undoubtedly influenced the accuracy of final estimation. Since an optimal IM needs to satisfy both efficiency and sufficiency condition and the nature of structures varies greatly, there is no consensus regarding selection IM despite amount of studies were focused on it (e.g. [5-9]). Efficiency gauges the degree of variability in the EDP-IM relationships. A more efficient IM can reduce this variability and thus the same confidence level can be achieved via imputing fewer seismic records, which is especially meaningful for assessing the fragility for several reference buildings. Sufficiency, proposed by Luco and Conell [8], renders structural response statistically independent with ground motion characteristics like earthquake magnitude (M) and source-to-site distant (R). When IM is insufficient, the estimation of exceeding probability varies with the set of selected ground motions. Recently, the studies of geometric mean spectral acceleration [10-12] serving as the IM has been arisen due to its good performance and simpler than vector IMs. Nevertheless, the selection of period range still remains an open research.

On account of above, this paper will investigate the fragility curves of high-rise RC frame-core wall structures through Incremental Dynamic Analyses (IDA) with a geometric mean spectral acceleration over the period range as an IM. The criteria of efficiency and sufficiency with respect to drift response is used to select the optimum period range adaptive to reference buildings, which is designed with varying aspect ratio and seismic fortification level (SFL). The influence of these variables on the fragility is also discussed.

2. Reference structures and ground motions

2.1 Design parameters and nonlinear modelling

Twelve reference buildings with different storey (20 storey and 30 storey), plan width and SFL were designed representing the state of construction practice through PKPM (a general design software in China [13]) and numerically modelled using Perform-3D [14-15]. The layouts of them, considered architectonic reasons, are similar and shown in Fig.1 as well as the Perform-3D model. The height of ground storey is

3.9m, larger than the upper ones which is 3.3m. The site class is Ⅱ and the seismic group belongs to the first. Basic wind load is 0.385kN/mm^2 and exposure category is C. Other basic information of reference structures are shown in the Table 1. All reinforcement steel adopted is HRB400 grade.

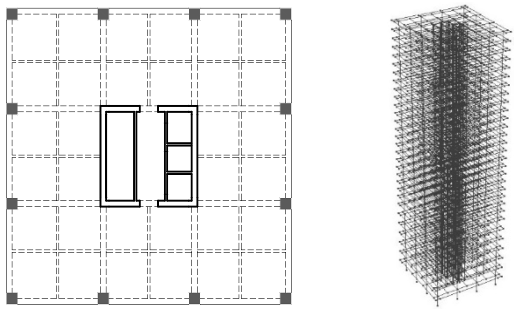


Fig.1 Layout of structures and 30-storey reference building model in Perform-3D

A spatial model consists of both frames and core wall was created in the Perform-3D analysis platform. Inelastic fiber section is utilized to model RC beams, column and walls based on the material properties, of which strength is employed mean value. Stress-strain relationship adopted is in accordance with the design code [16-17]. The lumped-plasticity elements is used for beam and column while the distributed- plasticity elements is used for core-wall. Rayleigh damping is chosen and set as 5% to simulate equivalent viscous damping according to the recommendation of Powell [14]. The slabs are assumed to be rigid. *P-delta* effects is also taken into consideration.

Table1 Main features of reference buildings

Index	**SFL**	**Width**	**Period(1st)**	**Concrete strength grade**		**Cross section/ mm**						
						Square Column				**Wall**	**Beam**	
				1-20	21-30	1-4	5-10	11-20	21-30		1-20	21-30
S1		18	3.455	C40	C30	900	800	600	450	350	350*550	350*450
S2	6	24	3.501	C40	C30	900	800	700	700	350	350*600	350*500
S3		24	2.440	C40	/	800	600	450	/	300	300*500	300*400
M1		18	3.265	C40	C30	900	800	600	450	400	400*600	400*500
M2	7	24	3.228	C40	C30	1200	1100	900	800	500	500*600	500*500
M3		24	2.235	C40	/	850	650	450	/	300	350*550	350*450
L1		18	2.571	C40	C30	1000	800	600	500	400	500*900	400*700
L2	8	24	2.544	C45	C40	1200	1100	900	800	500	500*950	500*750
L3		24	1.863	C40	/	900	750	900	/	350	400*750	400*600

Note: 1.Concrete strength grade and cross section are divided according to story.

2. The cross section dimensions are in unit of mm.

2.2 Ground motions selection

The variability of ground motions are accounted through the employing and scaling 22 far-field records recommended by FEMA P695 [18], which actually contains two components and one of them are selected randomly. Magnitude ranges from 6.5 to 7.6 and distance to source covers 8.7~98.2km. The response spectra is illustrated in Fig.2.

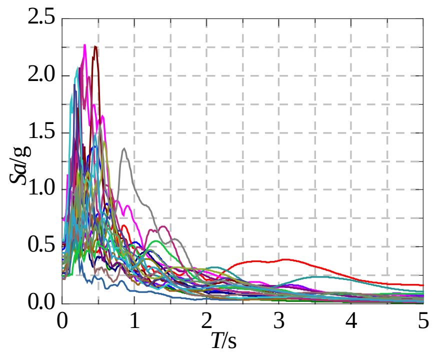


Fig.2 (Pseudo-) Acceleration response spectra of ground motions (5% damping)

3 Intensity measure selection

3.1 Analysis method

To evaluate efficiency and sufficiency of IMs, a log linear regression model is adopted to assess the relationship between EDPs and IMs in Eq. (1), where a and b are coefficients obtained through linear least square method and ε_i is the residual between observation value and computation value. In this paper, the maximum peak inter-story drift over the height of building, denoted $\ln\theta_{\max}$, is chosen as EDP to represent structural response and damage in accordance with domestic seismic codes [17].

$$\ln EDP_i = a + b\ln(IM_i) + \varepsilon_i \tag{1}$$

For the purpose of quantifying efficiency, which exhibit the dispersion of EDPs under the specific IM, the impact of scaling factor on the EDPs has to be excluded. Expressed another way, efficiency is an unbiased estimation of standard error, which has the number of $N-2$ degrees of freedom since one degree of freedom from independent variables is eliminated. The lower this standard error is, expressed as $\beta_{D/IM}$, the higher efficiency is.

In addition, the sufficiency is quantified by the statistical significance between ε_i and earthquake magnitude (M) or source-to-site distance (R). Thus a linear regression analysis between them is performed and followed with the hypothesis test whose result is determined by p-value. A small p-value (usually less than 0.05) indicates the linear relation is significant and therefore the IM is insufficient, and vice versa.

On account of the above prerequisites, this study will explore the optimal period range to maximize sufficiency and minimize dispersion at the same time. The adopted $Sa_{opt,avg}$ is computed in Eq.(2) with the 0.01 second increment which is almost continuous in the ground motion spectral acceleration. MATLAB [19] codes was developed to hunt for the period range and accordingly any period range of which the length is a multiple of 0.01s is in the hunting zone. The output is k_1T_m and k_nT_m where T_m is the median first-mode of reference structures.

$$Sa_{opt,avg} = \sqrt[n]{\prod_{i=1}^{n} Sa(k_i T_m)} \tag{2}$$

3.2 efficiency and sufficiency test

The performance of selected $Sa_{opt,avg}$ was compared with the more common IMs, i.e. Peak Ground Acceleration (*PGA*) and the 5% damped spectral acceleration at the median or mean first-mode of reference buildings ($Sa(T_m)$). Despite the operation results of MATLAB indicates that single spectral accelerations aren't appropriate for the whole reference buildings which include a certain period range, their efficiency and sufficiency on account of single buildings need to be considered and thus illustrated in the Fig.3 with an exemplar of reference buildings. Evidently, for the tested building, *PGA* and $Sa(T_m)$ are both insufficient concerning seismological parameters of M and R whilst $Sa_{opt,avg}$ are most efficient.

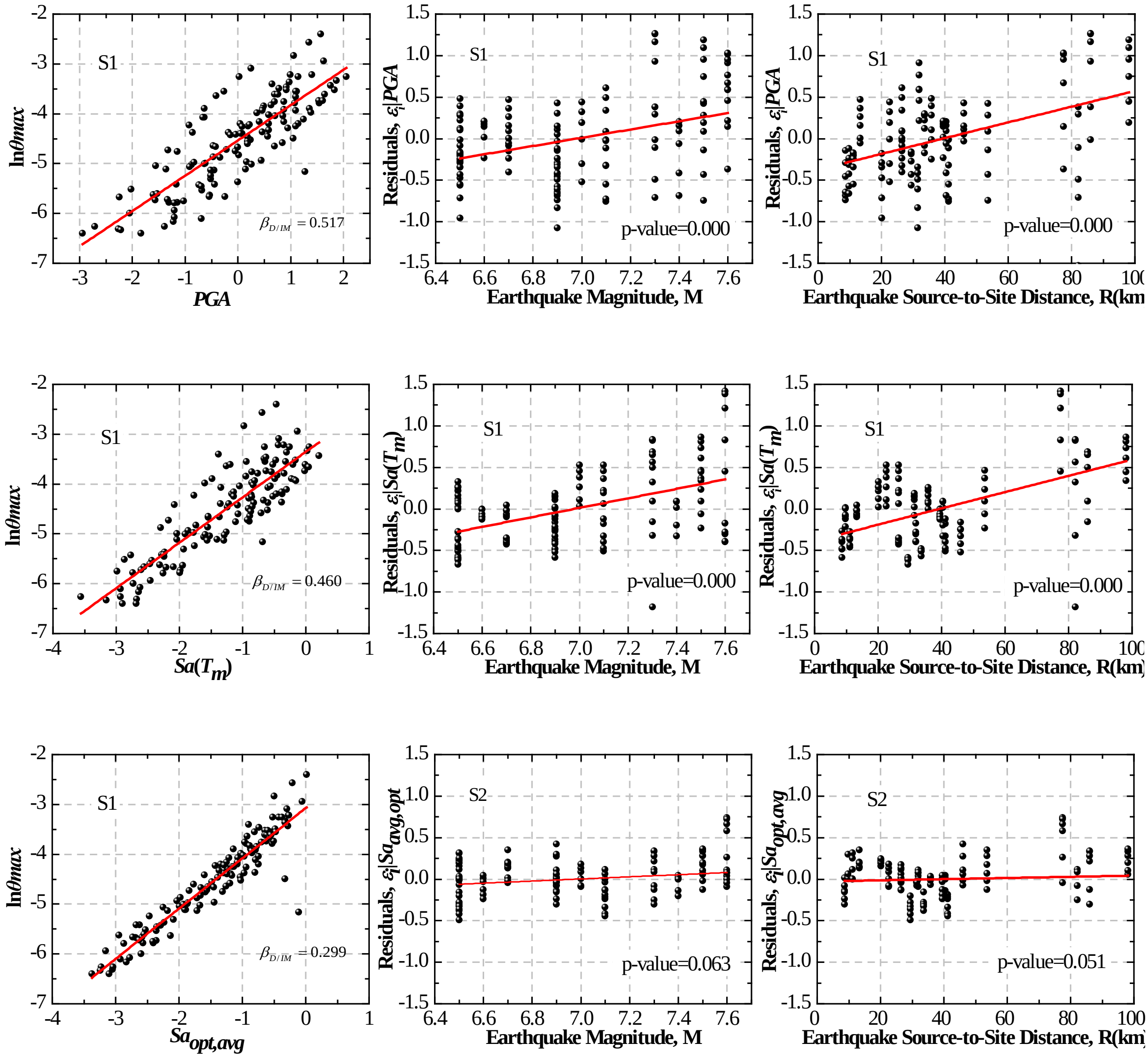


Fig.3 Efficiency and sufficiency property considering different IMs of the building S1

4 Seismic fragility assessment

4.1 Fragility function and performance criteria

The general function of fragility is as follow [20]:

$$F(x) = \Phi\left[\frac{\ln(x/m_R)}{\beta_R}\right] = \Phi\left[\frac{\ln(x) - \ln(m_R)}{\beta_R}\right] \tag{3}$$

where $\Phi[\cdot]$ is the standard normal cumulative distribution function; m_R and β_R are respectively median and logarithmic standard deviation, which can be calculated with Eq.(4).

$$m_R = \left(\frac{m_C}{e^a}\right)^{1/b}, \quad \beta_R == \sqrt{\frac{\beta_C^2 + \beta_{D|IM}^2}{b^2}} \tag{4}$$

Thereof a, b and $\beta_{D/IM}$ are derived from the log linear regression analysis (Eq.(4)) as discussed previously; m_C is the median of capacity for a given limit state while β_C is the corresponding uncertainty.

In this paper, three quantitative limit states except collapse which are divided the structural damage degree into four parts are defined according to Chinese seismic code [17] since it has the statistical significance for the performance evaluation of a class of buildings. However, the collapse threshold accepted is 2.5% in compliance with the recommendation of Ghobarah [21]. Above quantification damage states are summarized in Table2.

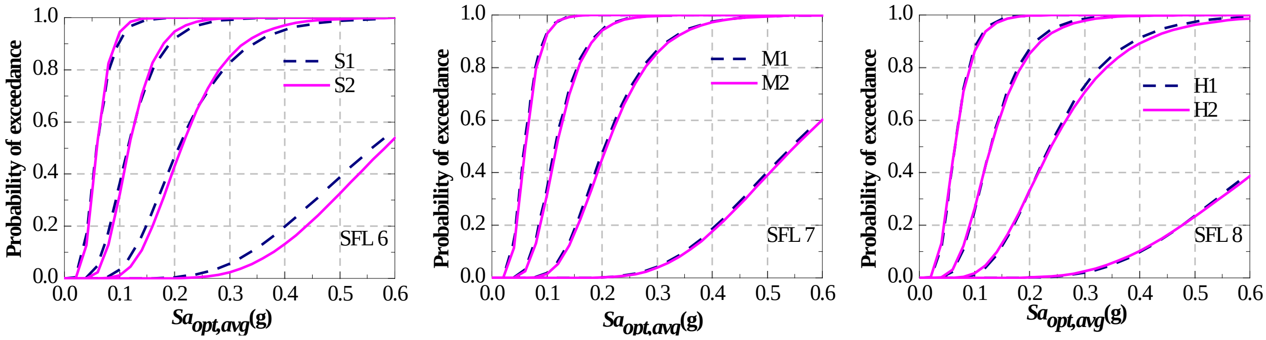
Table2 Quantitive values of damage states in terms of maximum inter-story drift

Damage States	Slight	Moderate	Severe	Collapse
$\theta_{\max}$	1/400	1/200	1/110	1/40

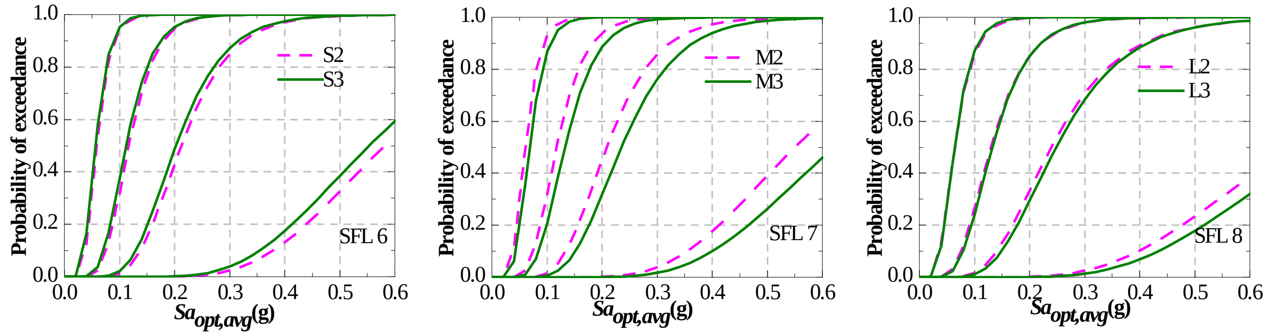
4.2 Impact of aspect ratio on the fragility curves

Fragility curves with respect to aspect ratio was compared and plotted in Fig.4 because the aspect ratio, determined based on height and width of buildings, is considered to be the macro control of structural stiffness, stable, bearing capacity and economic rationality [16].

As evident from Fig.4, there is no apparent variance in fragility among the buildings either with different height or width under the same SFL. This similarity can be explained since all the reference buildings are designed in accordance with Chinese seismic code [17] and then resulted in the close maximum inter-story drift under the frequent earthquake excitation of specific seismic fortification level. However, the impact of span seems to be more subtle than the impact of height on the fragility as we can see from the comparison of Fig.4 (a) and Fig.4. (b) Furthermore, the slopes are slightly steeper and the probability of exceeding certain limit state is higher with the increase of building height.



(a) Seismic fragility curves of reference structures with varying plan width (18m and 24m)



(b) Seismic fragility curves of reference structures with varying story (20 story and 30 story)

Fig.4 Seismic fragility curves of reference structures with varying aspect ratio

4.3 Impact of SFL on the fragility curves

Seismic intensity fortification is the prime determinant of design response spectra and details of seismic design. The derived fragility curves composed of varying SFL is shown in Fig.5. As expect, the seismic fragility curves tend to be flat with the increasing SFL, that is, a decreasing exceedance probability of certain damage states, illustrating the improvement of structural seismic resistance. For the structures with SFL 6 and 7, the fragility estimates are close, while the gap between the seismic fragility curves of structures with SFL 8 and 7 is large. The reason behind this difference is that under the condition of SFL 6, the structures reinforcement is more dependent on the bearing capacity and other than design seismic force, thus resulting in a safer margin during earthquake excitations.

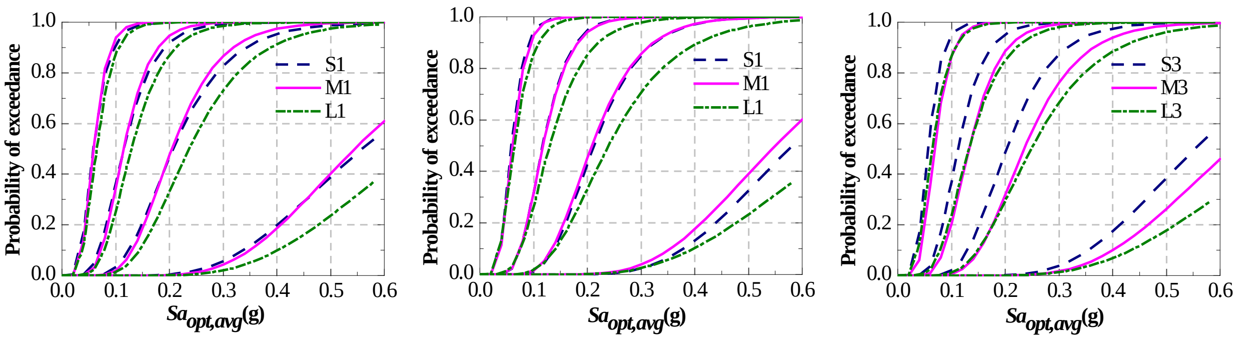


Fig.5 Seismic fragility curves of structures under different seismic fortification level

As evident from Fig.6, for the same damage states of structures with SFL 8 and 7, the curves are almost coincident at low value of $Sa_{opt,avg}$, and then they becomes apart, indicating the increase level of seismic fortification doesn't work on the seismic performance at elastic stage of structures until elastic-plastic stage. Moreover, it can be observed that the difference between structural fragility curves becomes more significant from slight LS to collapse LS. Expressed another way, for the reference buildings, the fragility estimates of slight LS is similar whereas the estimates of collapse LS varies greatly. This is because the ductility, which is often quantified by the ratio of ultimate deformation to yield deformation, increases with a higher level of seismic fortification.

5. Conclusions

This paper focused on the fragility assessment of RC frame-core tube structures based on a new proposed intensity measure ($Sa_{opt,avg}$), which is the geometric mean of certain period range. The efficiency and sufficiency is adopted as the performance criteria for IMs and thus an optimization algorithm is developed in MATLAB to calculate the period range for the purpose of maximizing the efficiency and sufficiency. The design and numerical modeling of the reference building with varying height, plan width and seismic fortification level is also included in the study. The running results of algorithm demonstrated that an optimum period range appropriate to these high-rise buildings covers both above and below of T_m, thus taking consideration of soft effects on period and higher modes. The disparities of fragility curves among structures with different aspect ratio are small while seismic fortification level has significance influence on the fragility.

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