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Evaluation of the Robustness of Tall Buildings with Bundled Tube Resistant Skeleton using Fragility Curves

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ABSTRACT: This research assesses the seismic resilience of structures with a lateral load-resisting system including moment frames and internal simple frames using statistical methods and probabilistic functions. For this purpose, two structures of 24 and 48 stories with bundled tube resistant system were considered. The structural system of the studied models consists of nine integrated rigid cells. The studied bundled tube structures have been designed based on the sixth and tenth issues of the Iranian National Building Code (INBC) and the fourth edition of the Iranian Seismic Code (Standard No. 2800). The seismic behavior of the studied bundled tube structural systems is investigated in this paper by performing incremental dynamic analyses (IDA) and seismic fragility assessments under near-field ground motions with various directivity effects. The fragility curves of the studied structures have been plotted according to the FEMA provisions to calculate the probability of the resistant skeleton exceeding six seismic performance levels, namely the post-linear (PL), the immediate occupancy (IO), the damage control (DC), the life safety (LS), the collapse prevention (CP) and the probabilistic global instability (GI). Then, by determining the damage coefficients according to the HAZUS 2005 guidelines and applying the proposed formulation of the loss function by the MCEER-09-0009 report, the seismic resilience indexes of the studied structures were obtained.Based on the obtained results of the conducted nonlinear dynamic analyses, it was concluded that the 24 and 48-story studied bundled tube structures have a relatively sufficient safety margin against the probable collapse mode under near-field records containing velocity pulses. Moreover, the evaluation of the probabilistic values of occurrence of the various limit states for the studied structures shows that the bundled tube structural system can control the gradual process of stiffness deterioration and strength degradation with a more comprehensive formation of the geometric nonlinear behavior.The results of the performed fragility analyses indicate that the application of bundled tube resistant skeleton in high-rise buildings can provide a high capability of dynamic stability against the process of damage expansion. The robustness indexes of the 24 and 48-story studied bundled tube structures were also obtained as 83.6% and 84.8%, respectively. Based on the seismic resilience calculations, it was found that the 48-story studied structure loses a lower amount of strength and efficiency after strong earthquake tremors.

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1- Introduction

Moment frames are widely used as lateral resisting systems in structures. It is important to evaluate the seismic performance and vulnerability of the flexural frames under near-field earthquakes with various directivity effects. Kim et al. studied the progressive collapse in structures with a resistant system containing multiple rigid cells [1].

By performing incremental dynamic analysis, the seismic capacity of the lateral load-resisting system can be checked based on the intensity measure (IM) and structural demand measure (DM) [2]. Also, the approximate ranges of elastic behavior, yielding mechanism, the process of entering the structure into the non-linear performance, and the probability of the occurrence of dynamic instability in a structure can be determined from the IDA curve [3,4]. Using nonlinear dynamic analysis, Haji-Kazemi et al. (2020) investigated the effects of the number of floors on the progressive collapse of two-dimensional flexural frames based on the bending strength of the columns [5].

Resilience is defined as the essential ability to reduce the probability of damage associated with the occurrence of an event as well as to reduce the related effects or to rapidly rebuild after an intensive tremor [6]. The four concepts of seismic resilience are robustness, redundancy, resourcefulness, and rapidity. The robustness index as the main parameter of seismic resilience expresses the resistance

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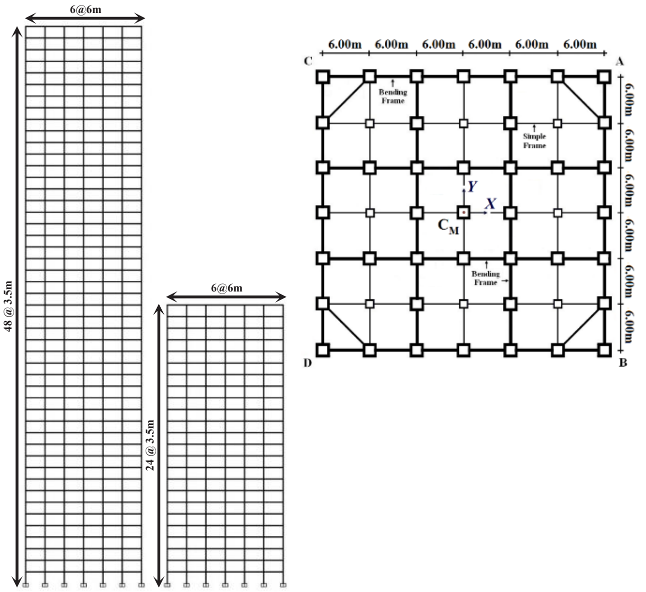

Fig. 1. Plan and elevation of the 24 and 48-story studied bundled tube structures

of the structural system to the damage caused by the occurrence of an unpredictable hazard and risk. Gerasimidis et al. (2017) evaluated the seismic resilience of a 15-story steel frame by simultaneously considering the approach of fire and progressive collapse based on the effects of member removal [7]. Lu and Feng (2020) calculated the robustness of a diagrid structure by considering the damage coefficients and seismic importance factor for the structural elements [8]. In the present research, the vulnerability of high-rise buildings with bundled tube systems has been investigated by the robustness component of seismic resilience. Firstly, incremental dynamic analyses and fragility evaluations have been performed on the studied structures under the selected near-field records.

2- Design of the studied structures

In this paper, two structures of 24 and 48 stories with bundled tube systems (Figure. 1) were designed according to the Iranian National Building Code (INBC) Issues 6 and 10, and the Iranian Seismic Code (Standard no. 2800). The detailed information and data are available in main research [9,10,11,12]. The arrangement of the moment frames in the resistant structure creates nine rigid cells at the height of the building. The studied structures were modeled in Sap 2000 software [13]. The nonlinear behavior characteristics of members of the studied structures were defined based on FEMA 440 and ASCE/SEI 41-17 [14,15]. The structural elements were made of steel grade 37 with Fy = 2400 kgf/cm^2 and Fu = 3700 kgf/cm^2.

3- IDA curves assessment

The seismic performance of the studied structural models under near-field three-component records was evaluated in Perform-3D software using incremental dynamic analysis [16,17]. In the nonlinear analysis, the peak ground acceleration parameter (PGA) and the maximum story drift ratio are considered structural demand (DM) and seismic intensity (IM) factors. The results of the IDA analyses are illustrated in Figure. 2. It is demonstrated that bundled tube frames provided a safety margin against collapse, especially for high-rise buildings.

4- Fragility analysis of the studied structures

The failure curve shows the probability of exceeding a seismic performance level for the structures at different seismic intensity levels [18]. The fragility function for the collapse state of the structures is defined according to the following equation:

$$P\left[C\left|IM=im_i\right.\right]=P\left[IM_C\geq IM=im_i\right] \tag{1}$$

The values exceeding the range of limit states for the response of the structures in different levels of earthquake acceleration are determined through conditional probability ($P\left[C\left|IM=im_i\right.\right]$). The fragility curve of the structures is calculated based on the log-normal statistical distribution as represented in Figure. 3. The limit of the performance levels of the structures for the story drift parameter is assumed according to FEMA 356 recommendations [19]. Six symbolic levels of seismic performance including post-linear (PL), immediate occupancy (IO), damage control (DC), life safety (LS), collapse prevention (CP), and global instability (GI) point of the structure have been considered.

5- Calculation of loss function

According to the MCEER-09-0009 report, the loss function is defined based on the building repair costs ($C_{S,j}$), replacement building costs (I_S), and annual discount rate (r) as follows [20]:

$$L_{S_{total}}(I)=\sum_{j=1}^{n}\left[\frac{C_{S,j}}{I_S}\cdot\prod_{i=1}^{T_i}\frac{(1+\delta_i)}{(1+r_i)}\right]\cdot P_j\left\{\bigcup_{i=1}^{n}(R_i\geq r_{\lim i})/I\right\}j \tag{2}$$

Where δ_i is the annual depreciation rate; P_j is the probability of exceeding a performance limit state j conditional an extreme event of intensity I occur; t_i is the time range in years between the initial investments and the occurrence time of the extreme event. In this paper, the loss function calculations are related to the design control and seismic resilience assessment of tall buildings with the bundled tube system.

The damage ratio for structural and non-structural components in various limit states are determined based on the HAZUS 2005 guidelines in the loss function [21]. Also, the control limit of the structures was obtained from the Iranian seismic design code based on the soil type of the region and the modal characteristics of the buildings.

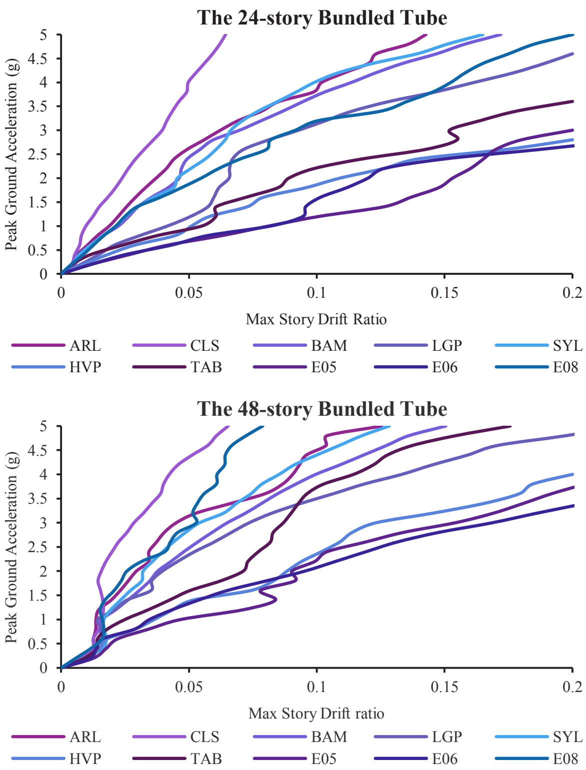

Fig. 2. IDA results for the studied structures

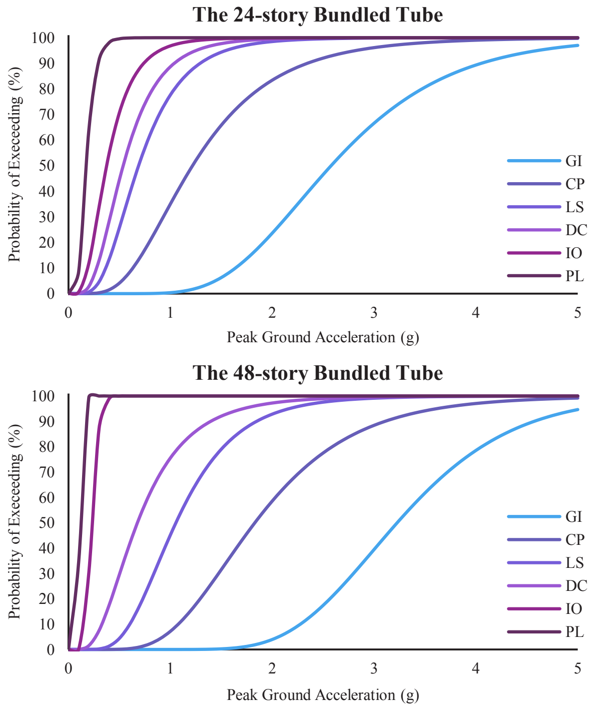

Fig. 3. Fragility curves of the studied bundled tube structures in various limit states

6- Seismic resilience

The ability of the structural system to stabilize against the uncertainties in the seismic design and earthquake records is determined based on the robustness index as the most important resilience criterion [22]. According to the MCEER-09-0009 report, the robustness of the structures is calculated using the following equation:

$$Robustness = 1 - L_{S_{total}} \tag{3}$$

In Table 1, the value of the quality function and the resilience index for the 24 and 48-story studied structures are presented.

Table 1. The seismic resilience parameter of the studied bundled tube structures

Resilience parameter	Structure	
	24-story model	48-story model
Loss function	0.164	0.152
Quality function	0.836	0.848
Robustness index	83.6%	84.8%

7- Conclusions

In the present research, the seismic resilience parameters of two 24 and 48-story studied bundled tube structures were evaluated under near-field earthquakes. Incremental dynamic analyses (IDA) were performed on the studied structures and then the fragility functions were calculated based on log-normal statistical distribution. The damage ratios for different limit states were considered according to HAZUS 2005 guidelines. Finally, the robustness of structures was obtained based on the proposed formulation of the loss function by the MCEER-09-0009 report.

The results of the fragility analysis showed that the bundled tube system creates a high level of reliability to prevent the occurrence of global dynamic instability in high-rise buildings. The total loss function values for the 24 and 48-story studied structures are equal to 0.164 and 0.152, respectively. It is determined that the reduction in strength and efficiency of the 48-story studied structure under near-field earthquakes is lower. Also, the robustness index of the 24-story studied structure was calculated as 83.6% and for the 48-story studied structure as 84.8%. Based on the obtained results, it can be concluded that the combination of bending and simple frames in bundled tube systems with the form of symmetrical rigid panels, creates suitable stability for tall buildings; especially the ones with long spans.

References

[1] J. Kim & Y.H. Lee, Progressive collapse resisting capacity of tube-type structures, The Structural Design of Tall and Special Buildings, 19(7) (2010) 761-777.

[2] D. Vamvatsikos & M. Fragiadakis, Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty, Earthquake Engineering and Structural Dynamics, 39(2) (2010) 141-163.

[3] D. Vamvatsikos & C.A. Cornell, Applied incremental dynamic analysis, Earthquake Spectra, 20(2) (2004) 523-553.

[4] D. Vamvatsikos & C.A. Cornell, Direct estimation of seismic demand and capacity of multi-degree of freedom systems through incremental dynamic analysis of single degree of freedom approximation, Structural Engineering, 131(4) (2005) 589-599.

[5] M. Hajikazemi, B. Mohebi & M. Montazeri-Pour, Analysis of steel special moment frames including damaged column subjected to far and near-field ground motions, Australian Journal of Structural Engineering, 21(3) (2020) 193-207.

[6] M. Bruneau, S.E. Chang & R.T. Eguchi, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthquake Spectra, 19(4) (2003) 733-752.

[7] S. Gerasimidis, N.E. Khorasani, M. Garlock, P. Pantidis & J. Glassman, Resilience of tall steel moment resisting frame buildings with multi-hazard post-event fire, Constructional Steel Research, 139 (2017) 202-219.

[8] C. Liu & D. Fang, Robustness analysis of vertical resistance to progressive collapse of diagrid structures in tall buildings, The Structural Design of Tall and Special Buildings, 29(13) (2020).

[9] Iranian National Building Code (INBC), 2014. “Steel Structures”. Issue 10, Tehran, Iran (in Persian).

[10] Iranian National Building Code (INBC), 2014. “Design Loads for Buildings”. Issue 6, Tehran, Iran (in Persian).

[11] Iranian Code of Practice for Seismic Resistant Design of Buildings, 2014. Standard No. 2800, 4th edition, Building and Housing Research Center (BHRC), Tehran, Iran (in Persian).

[12] M. Roshani, Study on effect of vertical irregularity on nonlinear behavior of high-rise bundled tube frames through dynamic stability criteria, MSc. Thesis, Kharazmi University, Tehran, Iran, 2021 (in Persian).

[13] CSI, Analysis Reference Manual for SAP2000, 2010. Berkeley, California, USA.

[14] FEMA 440A, 2009. “Effects of strength and stiffness degradation on seismic response”. Federal Energy Management Agency (FEMA), Redwood City, California.

[15] ASCE/SEI 41-17, 2017. “Seismic evaluation and retrofit of existing buildings”. American Society of Civil Engineers, Reston, Virginia.

[16] Pacific Earthquake Engineering Research Center (PEER). Ground Motion Database, University of California, Berkeley, USA.

[17] CSI, User Guide PERFORM 3D, 2011. Nonlinear Analysis and Performance Assessment for 3D Structures. Berkeley, California, USA.

[18] D. Lallemant, A. Kiremidjian & H. Burton, Statistical procedures for developing earthquake damage fragility curves. Earthquake Engineering and Structural Dynamics, 44(9) (2015) 1373-1389.

[19] FEMA 356. Prestandard and commentary for the seismic rehabilitation of buildings. Federal Energy Management Agency (FEMA), Reston, Virginia, 2000.

[20] G.P. Cimellaro, C. Fumo, A.M. Reinhorn & M. Bruneau, Quantification of Disaster Resilience of Health Care Facilities. Technical Report MCEER-09-0009, University of Buffalo, New York, 2009.

[21] Multi-Hazard Loss Estimation Methodology (HAZUS), Technical Manual, Federal Emergency Management Agency & Department of Homeland Security, Washington, D.C., 2005.

[22] G.P. Cimellaro, A.M. Reinhorn & M. Bruneau, Framework for analytical quantification of disaster resilience. Engineering Structures, 32(11) (2010) 3639-3649.

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