Seismic Performance of Buckling-Restrained Braces in Irregular Reinforced Concrete Buildings under Successive Earthquakes

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ABSTRACT

This study evaluates the seismic performance of irregular reinforced concrete (RC) structures equipped with buckling-restrained braces (BRBs) under successive earthquakes involved foreshock-mainshock and mainshock-aftershock. Seismic sequence phenomenon refers to the occurrence of multiple shocks in a short time interval, whose cumulative effects can significantly change the structural response compared to a single shock. In this regards, three RC frames with 3, 6, and 9 stories were designed based on the Iranian Code 2800. Nonlinear dynamic analyses were performed in OpenSees after verification of the studied frames based on reference model. Comparison of the response of frames under single and successive shocks indicate that BRBs improve lateral force distribution, increased ductility in the upper stories (up to 32%), and reduced beam and column cross-section dimensions. Also, residual displacements and inelastic strains have been increased about 47% in frames with fewer BRBs. Moreover, increased damage has been observed up to two times. Generally, the results indicate that buckling braces are a reliable option for improving the seismic performance of irregular reinforced concrete structures under successive earthquakes due to providing high energy absorption capacity and stable hysteresis behavior.

KEYWORDS

Buckling Restrained Brace, Reinforced Concrete Structures, Seismic Sequence Phenomenon, Irregularity, Nonlinear Dynamic Analysis.

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1. Introduction

Successive earthquakes with short time intervals can significantly affect the seismic performance of structures. In these scenarios include foreshock-mainshock or mainshock-aftershock, first shocks usually have medium to high intensity and next shocks occur with approximately similar intensity. This succession can increase material fatigue, decrease effective strength and disrupt the safe eviction. Furthermore, structural irregularity (in plan or height) can lead to diminish the seismic performance of buildings because of torsion and stress concentration in earthquake. Recently, buckling restrained braces (BRBs) have been known as one of the most efficient methodology in energy dissipation systems in new and existing structures. These braces can absorb considerable energy and improve the seismic response of irregular structures through symmetric behavior in pressure and tension [1-4]. This paper tries to evaluate the seismic performance of buckling-restrained braces in irregular reinforced concrete buildings under successive earthquakes. In this regards, key parameters such as ductility, residual drift and damage index have been investigated for regular/irregular RC frames under single and consecutive shocks.

2. Research Methodology

Despite the high potential of successive shocks in increasing the structural/nonstructural damages, single earthquake has been considered as “Design earthquake” by seismic design cods. This theory becomes more critical when buildings have irregularity in plan or height. Therefore, three irregular RC buildings with BRB and 3, 6 and 9 story have been designed based on Standard 2800 with medium importance, official and commercial landuse in very high seismicity zone. Figure (1) shows plan and the schematic view of 6-story model. Section properties of the studied models are reported in Table (1). Period of models are 0.336, 0.56 and 0.843 (s). In the following, one frame has been implemented in Opensees. For this purpose, *Force-Based Beam-Column* element have been used for modeling of beams and columns. Also, BRBs are modeled using *Truss Element*. Nonlinear behavior of concrete has been considered by *Concrete01* material (with zero tension strength). Moreover, *Steel02* based on *Menegotto-Pinto* and *Isotropic Strain Hardening* formulations has been used for yielding behavior of steel in braces and bars. It should be noted that modeling procedure of the studied frames in Opensees is verified based on [5-6] with comparing period and pushover curve (Figure 2). In order to examine the seismic response of the studied models, critical successive shocks are selected based on [7].

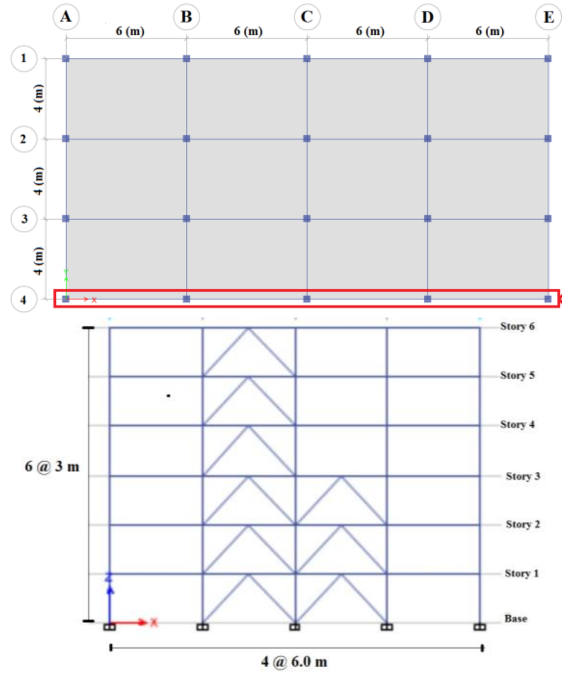

Figure 1. Plan and the schematic view of 6-story model

Table 1. Section properties of the studied models

Model	Story No.	Column	Beam	BRB
3-story	3	C35x35-8T18	B35x45-2T16-3T16	PL12x100
	1-2			PL 20x100
6-story	6	C40x40-12T16	B35x50-3T16-3T18	PL10x100
	5			PL20x75
	4			PL20x150
	3	C50x50-16T18	B40x50-3T18-4T16	PL20x150
	1-2			PL20x100
9-story	9	C60x60-16T18	B40x50-3T16-4T14	PL10x100
	8			PL20x125
	7			PL20x175
	6		B40x45-3T16-3T16	PL20x175
	4-5			PL20x200
	1-3	C40x40-12T18		PL20x175

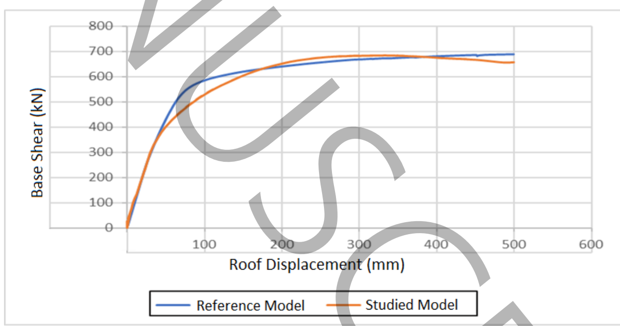

Figure 2. Pushover curve of the reference and studied model

3. Results and Discussion

After gravity loads, nonlinear dynamic analysis has been performed for all RC frames. Then, key parameters such as ductility, residual drifts, drift ratio and damage index have been evaluated caused by single and successive shocks. Seismic sequence phenomenon increases drift ratio for all frames based on Figure (3) so that average of the increased response is 34, 25 and 24% for 3, 6 and 9 story models. Moreover, successive shocks lead to more residual drifts than single scenarios according to Figure (4). Maximum increased residual drifts because of successive shocks are 30, 22 and 28%.

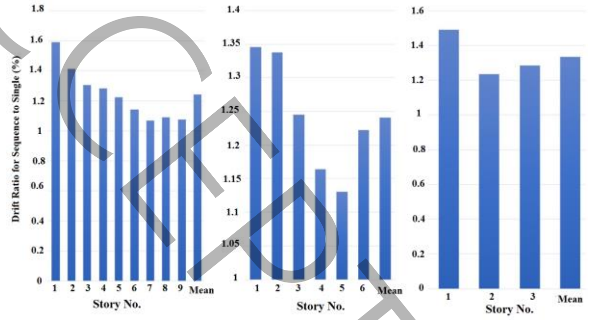

Figure 3. Ratio of drift (successive/single) for 3-story (Right), 6-story (Middle) and 9-story (Left)

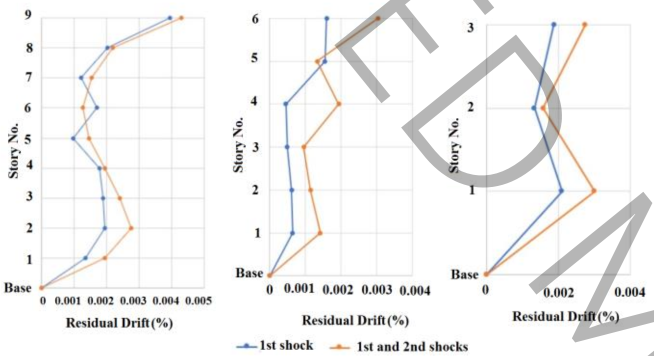

Figure 4. Residual drift ratio for 3-story (Right), 6-story (Middle) and 9-story (Left)

For ductility, effect of the successive shocks is ascendant for all frames and average of the increased responses is 24, 20 and 51%. Park-Ang damage index [8] is also calculated for the studied models and reported in Figure (5). Maximum increase is observed for 6-story frame approximately more than double value.

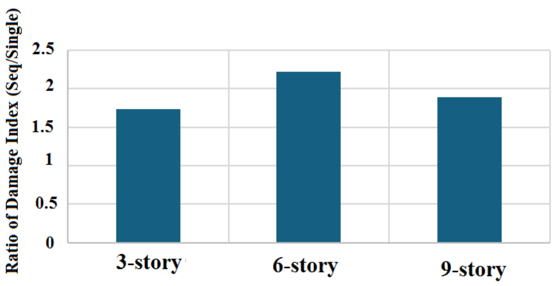

Figure 5. Ratio of increased damage index

4. Conclusions

This paper reveals that single shocks cannot be suitable representative of successive scenarios especially for irregular structures. However, decreasing the damage index in taller models is demonstrative of improvement of distribution of lateral forces and more effective participation of braces in energy absorption. Hence, it can be said that optimum design of BRBs has notable effects on residual drifts, increased ductility, and damage concentration prevention in special stories in irregular structures. Therefore, BRBs are proposed to control the instability and improve the progressive damages pattern.

5. References

[1] Niyonyungu, F., and Noroozinejad Farsangi, E., 2020. "Application of buckling restrained braces to upgrade vertical stiffness of existing RC frames". Civil and Environmental Engineering Reports, pp. 68-93. https://doi.org/10.2478/ceer-2020-0034.

[2] Orellana, G. M., Ramos, B. C., Velásquez, F., Casas Rius, J. R., and Delgadillo, R. M., 2024. "Spectral Dynamic Analysis of Buckling Restrained Brace (BRB) Configurations in an Irregular Building". In Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024), pp. 1-6. University of Toronto Press.

[3] Vaziri, S. J., Vahdani, R., and Souri, O., 2024. "Seismic evaluation of BRBF steel structures with L-shaped irregular plan considering soil-structure interaction". Bulletin of Earthquake Engineering, 22: pp. 5347–5377. https://doi.org/10.1007/s10518-024-01963-4

[4] Kong, S., Shi, F., Zhou, Y., Ma, Y., and Xie, L., 2022. "Influence of BRBs deformation capacity on the seismic performance of RC building frames". Soil Dynamics and Earthquake Engineering, 161:107442. https:// doi.org/ 10.1016/ j.soildyn. 2022.107442.

[5] Chen, H., and Bai, J., 2022. "Loading protocols for seismic performance evaluation of buckling-restrained braces in RC frames". Journal of Building Engineering, 45: 103522. https://doi.org/10.1016/j.jobe.2021.103522

[6] Bai, J., Chen, H., and Jin, S., 2021. "Investigation on the interaction between BRBs and the RC frame in BRB-RCF systems". Engineering Structures, 243: 112685. https:// doi.org/ 10.1016/j.engstruct. 2021.112685.

[7] Rajabi, E., and Ghodrati Amiri, G., 2020. "Generation of critical aftershocks using stochastic neural networks and wavelet packet transform". Journal of Vibration and Control, 26(5-6): pp. 331-351. https://doi.org/10.1177/1077546319879536

[8] Park, Y. J., Ang, A. H. S., and Wen, Y. K., 1985. "Seismic damage analysis of reinforced concrete buildings". Journal of Structural Engineering, 111(4):pp.740-757. https:// doi.org/ 10.1061/(ASCE)0733-9445(1985)111:4(740)