Damage Evaluation of Steel Moment and Buckling Restrained Braces Frames under Critical Successive Earthquakes

Haniehsadat Banijamali[a], Elham Rajabi[b], Gholamreza Ghodrati Amiri[c*]

[a] MSc, Student, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[b] Assistant Professor, Department of Civil Engineering, Tafresh University, 39518-79611 Tafresh, Iran
[c] Professor, Natural Disasters Prevention Research Center, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

ACCEPTED MANUSCRIPT

ABSTRACT

In the seismic active zones, structures are often exposed to successive earthquakes. Seismic sequence phenomenon refers to the occurrence of repeated earthquakes with significant PGA shortly after the first earthquake. Vulnerability of steel structures with buckling restrained brace (BRB) subjected to successive earthquakes consist of main-shock and critical aftershocks indicates that the effect of consecutive earthquakes, depending on their intensity, has significant effects on structural failure. For this purpose, 2D steel moment and buckling restrained brace frames with 3, 7 and 11-story are designed based on Iranian Standard 2800 (Fourth Edition). In the following, studied frames are implemented in OPENSEES software and analyzed under single and critical successive earthquakes after verification. Based on the results of nonlinear dynamic analysis, the Park-Ang damage index was calculated for all frames and after processing the output results in MATLAB software, the final results were reported. The results show that in all frames, successive earthquakes increased the damage index due to the accumulation of damage in the elements due to stiffness and strength degradation. It has also been observed that the ratio of increased damage in the steel moment frame caused by consecutive compared to single case was higher rather than the BRB frames. That is, considering the BRB has reduced the ratio of this failure under consecutive earthquakes.

KEYWORDS

Critical Successive Earthquakes, Park-Ang Damage Index, Steel Moment Frame, Buckling Restrained Brace Frame, Nonlinear Dynamic Analysis

* Corresponding Author: Email: ghodrati@iust.ac.ir

1. Introduction

Earthquakes occur due to the storage of large amounts of energy inside the earth and their sudden release due to the rapid rupture of faults in the earth's crust in a short period of time. Minor earthquakes usually occur before the main earthquake, releasing some of this stored energy. The set of these earthquakes is called pre-shocks. Also, large earthquakes are usually accompanied by a number of shocks with less intensity called aftershocks. Aftershocks may occur within a few minutes to several months after the main earthquake and sometimes have a magnitude close to the magnitude of the main earthquake [1]. The occurrence of several consecutive earthquakes with a short time interval in an area is called seismic sequence phenomenon. The mentioned successive earthquakes have a significant maximum acceleration and often include foreshock, main shock and aftershock. Due to the short time interval between the occurrences of two earthquakes, there is often no opportunity to improve and repair the structure, and the damaged structure exposed to the main earthquake suffers more severe damages when faced with a strong aftershock. In such a way, there is even a possibility of the structure collapsing. Since Iran is located on the Alpine-Himalayan seismic belt, it has many faults and is exposed to earthquakes containing seismic sequences. Moreover, statistics evidence of the past earthquakes also shows that many shocks have occurred in this region. For this reason, despite what is often assumed in the Seismic Design Codes such as Iran Standard 2800, it is necessary to investigate the seismic performance of structures under this phenomenon. Unfortunately, structures are still designed according to the modern seismic codes which only apply a single earthquake. On the other hands, the design earthquake is defined as a single event while ignoring the occurrence of successive earthquakes causes an increase in casualties, injuries and damage to the structure. This paper evaluates the damage in steel moment and buckling restrained braces frames under critical successive earthquakes

2. Critical Successive Scenarios

In general, choosing appropriate scenarios to apply structures is always one of the most important problems and challenges faced by researchers and engineers in seismic evaluations. In this regard, many factors affect the selection of appropriate accelerograms; As an example, we can mention the magnitude of the earthquake, intensity, distance or proximity to the fault, duration of the earthquake, frequency content, etc. In 2005 [2], during a study, Gohdra Amiri and Manochehri Dana introduced the maximum effective acceleration (EPA) parameter as a suitable criterion for selecting critical seismic scenarios. Therefore, in this paper, the successive shocks are selected based on EPA parameter. For this purpose, reported consecutive earthquakes in PEER database with a time interval of less than 10 days have been considered. For each earthquake, different accelerograms have been recorded at different stations. First, the first shock with the most EPA is determined, and if the second shock occurred at the same station and similar direction with the largest EPA compared to the rest of the recorded accelerograms in other stations, the set of the first and second shocks is selected as a critical consecutive earthquake. Since in this study, the sequence of earthquakes has been taken into consideration, no distinction has been made between for-shock and after-shock in successive earthquakes.

3. Steel Frames

In the first step, all the studied steel moment and BRB frames were modeled in the ETABS software and the structural sections was designed using the spectral analysis method (pseudo-dynamic) based on the standard 2800, fourth edition, for soil type 3 (dense to moderate soil) and high seismicity area. Then, according to the regulations of AISC360-05/IBC2006 [3], seismic design was done and sections of beams and Columns have been obtained by checking the ratio of demand to capacity in beams and columns and applying the same range for the ratios in all sections of the moment and BRB frames.

4. Park-Ang Damage Index

The seismic performance of structures can be quantified by determining the extent of the damage using the damage index. Among the most widely used types of damage indices, we can mention the Park-Ang damage index which has been presented in 1985 [4]. This index shows the amount of damage to a member or the whole structure using several variables. The damage index is a normalized quantity whose value is equal to zero for the elastic state (without damage) and equal to one for the state in which rupture has occurred, and the damage potential of structural members is a linear combination of damages caused by maximum deformations and provides absorbed cycle energy. For example, we can refer to the study of Hoidai and Radpour in 2020 [5] and the study of Kazemi and Behnamfar [6], which used this index. Equation (1) is used to calculate the Park-Ang damage index:

$$DI_{PA} = \frac{\delta m}{\delta u} + \beta_{PA} \frac{\int dE}{Q_y \times \delta u} \quad (1)$$

In this regard, δ_m and δ_u represents the maximum and

ACCEPTED MANUSCRIPT

ultimate deformation of the member, β_{PA} is the constant factor related to cyclic loading, Q_y is the yield strength and $\int dE$ represents the energy absorbed by the member during the analysis of the time history of the response and is equivalent to the area under the curve of hysteresis cycles of the member.

5. Park-Ang damage index for steel moment and BRB frames under critical single and consecutive earthquakes

In order to calculate the Park-Ang damage index, it is necessary to determine the maximum deformation of the member and the energy absorbed by the member during the time history analysis. For this purpose, by performing nonlinear dynamic analysis, these parameters have been extracted. Also, dynamic time history analysis has been performed assuming linear behavior of elements for all frames under single and consecutive earthquakes, and finally the Park-Ang damage index has been calculated based on Equation (1) and compared for seismic scenarios with/without seismic sequence. It should be noted that all the frames were subjected to gravity loading before analysis.

Table 1. Physical interpretation of damage index

Intensity of injury	Damage index	Situation	No.
Collapse	>1	Destruction	1
Intense	0.4-1	Beyond Repair	2
Medium	>0.4	Repairable	3
Minor	0.2<		4

6. Comparison of The average ratio of the damage index for steel frames under consecutive to single earthquakes

In this section, in order to more comprehensively examine the damageability of steel frames under critical successive earthquakes, the average ratio of the damage index under consecutive to single earthquakes is shown in Figure1.

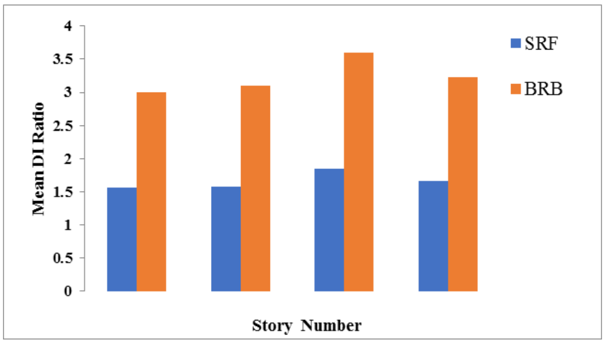

Figure 1. The average ratio of the damage index for steel frames under consecutive to single earthquakes

7. Results

Despite the importance of the seismic sequence phenomenon, successive earthquakes have not been considered in the structural design process of seismic design codes such as Standard 2800. If only a single earthquake is considered in the design of the structure, there will be no difference between the performance of the structure under a single and successive earthquakes and consequently the structure may not be able to meet the successive earthquakes and suffer more damage and even collapse.
Based on the comparison of the Park-Ang damage index, the structural collapse capacity of the studied frames decreases due to (1) the increased damage caused by the first shock, (2) the accumulation of damage in the elements because of the deterioration of stiffness and strength. Therefore, the structure collapses under consecutive earthquakes much earlier than what the design regulations have been assumed considering the single design earthquake, and the value of the damage index has increased.

8. Conclusions

The seismic sequence has increased the damage ratio in the moment frames compared to the BRB frames.

9. References

[1] Jafari, A. (1991). Gitashenasi Novin Geographical & Cartographic, No (5), Tehran. Iran. (In Persian).
[2] Amiri, G.G. and Dana, F. M. (2005). Introduction of the most suitable parameter for selection of critical earthquake. Computers & structures. 83(8-9): 613-626.
[3] Morfuni, F., Freddi, F., and Galasso, C. (2019). Seismic Performance of Dual Systems with BRBs under Mainshock-Aftershock Sequences.13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13 Seoul, South Korea, May 26-30, 2019.
[4] Park, Y.J and Ang, A.H.S. (1985). Mechanistic seismic damage model for reinforced concrete. Journal of structural engineering, 1985. 111(4): 722-739.
[5] Hoveidae, N., and Radpour, S. (2020). Performance evaluation of buckling-restrained braced frames under repeated earthquakes. Bulletin of Earthquake Engineering, 19: 241–262 (2021).
[6] Kazemi.M., and Behnamfar, F. (2020). Active control of structures based on an arbitrary damage index distribution .2020. AUT Journal of Civil Engineering.

ACCEPTED MANUSCRIPT