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EFFECT OF LIFETIME CUMULATIVE DAMAGE OF MULTIPLE LOW INTENSITY EARTHQUAKES IN REINFORCED CONCRETE BUILDINGS

Ali NASIRI[1], Abdolreza SARVGHAD MOGHADAM[2], Pasha JAVADI[3]

ABSTRACT

This paper presents evaluation of reinforced concrete structures subjected to multiple low intensity earthquakes (earthquakes in the range of $3 \leq M_w \leq 5$) effects in their lifetime. Small repeated earthquakes are common in earthquake prone regions.Because of the low possibility of collapse or significant damages in the structures under the influence of small earthquakes, this phenomena is disregarded in earthquake engineering researches. Looking at the history of the ground motions in earthquake prone regions shows the large number of these types of earthquakes. So far, many investigation of seismic response of Reinforced Concrete (RC) structure only consider maximum earthquakes action and the cumulative damage effect of the small earthquakes to structure is neglected. This study focused on the effect of accumulated damage of repeating low intensity earthquakes on moment resisting reinforced concrete structures, using OpenSees software. All records were selected from Fin1 station, near Bandar Abbas, Iran. In order to examine the effect of the cumulative damage from low intensity earthquakes, multiple earthquakes with different number of sequences (20, 40 and 60 records) were considered. Between two consecutive seismic events, a time gap is applied. On the other hand, In order to examine the effect of multiple low intensity earthquakes on the performance of RC structures, we employed some kind of concrete and steel reinforcement models, used in OpenSees program, to consider which concrete and steel reinforcement models can represent more realistic performance of structure in these types of earthquakes.

Keywords: Low intensity Earthquakes; Reinforced Concrete Building; Stiffness and Strength Degradation; Structural Demand; Cumulative Damage

1. INTRODUCTION

The basic approach for seismic design of structures utilizes a single loading scenario and a single performance criterion; usually life-safety (DiSarno 2013); while structures built in seismic areas are often affected by earthquakes with various frequency and magnitude during their lifetime. Current seismic codes specify design earthquake loads as single events and assume that all of the structures in earthquake prone regions are able to withstand frequent low intensity earthquakes that is likely to occur at their location; However the structure may experience multiple ground accelerations including small multiple earthquakes in their lifetime. Looking at the history of the ground motions in earthquake prone regions shows the large number of these types of earthquakes. Despite the fact that low intensity earthquakes do not cause remarkable damage to the structures singly, high occurrence probability and inducing accumulated damage to the structures during their lifetime, make this types of earthquakes important. In this types of earthquakes, the structure can maintain its stability and has no problem in bearing the non-seismic loads, but it can quickly lose load-carrying capacity due to the next major earthquakes.

[1]MSc Student, Science and Research Branch Of Islamic Azad university, Tehran , Iran, nasiri3289@yahoo.com
[2]Associate Professor, Structural Engineering Research Center, IIEES International Institute of Earthquake Engineering and Seismology, Tehran, Iran, moghdam@iiees.ac.ir
[3]Assistant Professor, Department of Engineering, Science and Research Branch Of Islamic Azad university, Tehran, Iran, pasha_javadi@yahoo.com

There is an urgent need to understand the response of structures subjected to multiple low intensity earthquakes. Because of the low possibility of collapse or significant damages in the structures under the influence of small earthquakes, this phenomena is disregarded in earthquake engineering researches. But separately, there have been several investigations aimed at studying the effect of seismic sequences and low intensity earthquakes on the response of civil engineering structures. Numerous research studies can be mentioned here examining the effects of repeated earthquake phenomena on single-degree-of-Freedom (SDOF) systems (Hatzivassiliou et al. 2015). Due to their simplicity, SDOF systems incorporating inelastic hysteretic force-displacement relationships have been extensively used by many researchers such as Amadio et al. (2003) where the effects of repeated earthquakes on nonlinear SDOF systems were examined and quantified. Furthermore, Hatzigeorgiou and Beskos (2009) proposed appropriate inelastic Displacement ratios for the case of seismic sequences. Additionally, Moustafa and Takewaki (2011) examined simple stochastic models representing repeated seismic sequences .In addition, MDOF systems such as moment resisting steel and concrete frames were also studied. One can mention here the works of Fragiacomo et al. (2004), Li and Ellingwood (2007) and Ruiz-Garcia and Negrete-Manriquez (2011) which have examined steel framed structures and Loulelis et al. (2012) Faisal et al. (2012) DiSarno (2013) and Abdelnaby and Elnashai (2014) which have focused on multi-story reinforced concrete frames. It is worth noticing that there is not research work that has examined the effects of multiple low intensity earthquakes on three-dimensional reinforced concrete (RC) structures. Thus, the need for the development of an efficient methodology for the inelastic analysis of three-dimensional RC buildings under these types of earthquakes is apparent.

The present study investigated the nonlinear behavior of concrete structures under real multiple low intensity earthquakes and their effects on structure's performance level. Small repeated shaking induces accumulated damage to structures that can affects their stiffness and strength. This study focused on the effect of accumulated damage of repeating low intensity earthquakes on moment resisting reinforced concrete structures. For this purpose, a regular three-bay 8 story moment resisting RC building, having standard occupancy was modeled, considering non-degrading and degrading features of both concrete and steel reinforcements, using OpenSees software. All records were selected from Fin1 station, near Bandar Abbas, Iran. In order to examine the effect of the cumulative damage from low intensity earthquakes, multiple earthquakes with different number of sequences (20, 40 and 60 records) were considered. Between two consecutive seismic events, a time gap is applied, which is equal to 40 seconds. This gap is enough to cease the vibration of structure by damping.

2. DESCRIPTION OF SEISMIC INPUT AND MODEL

2.1 Seismic Input

For this research, data from the Fin 1 station has been used. The Fin 1 station located in Hormozgan province, south of Iran. On the basis of geological divisions of Iran, Hormozgan is located between the Zagros and Makran structural zones. In this area, the boundaries of these two zones are characterized by a system of faults. The important and remarkable faults of the region have a general view of the North-South, NorthWest-SouthEast and East-West trends. Since 2004, 536 earthquakes with a magnitude more than 3 have occurred in the province. This data includes earthquakes with low magnitudes (range of 3 to 5 degrees on the Richter scale) recorded since the establishment of the station in 1994 which are collected from Iran Strong Motion Network (ISMN). As I mentioned before, the present study investigated the nonlinear behavior of reinforced concrete structures under real multiple low intensity earthquakes and their effects on structure's performance level. In order to examine the effect of the cumulative damage from low intensity earthquakes, multiple earthquakes with different number of sequences (20, 40 and 60 records) were considered to determine the effect of the number of small earthquakes on the structure's performance.

Figure 1. Locality and major faults map of Hormozgan (IRSC, 2015)

It is necessary to say that low intensity earthquakes that affect the structures in their lifetime, can be considered as a sequential earthquakes (like mainshock–aftershock sequence-type ground motions), because after the occurrence of each earthquake, the probable damage impacts on the structure are not considered.

2.2 Buildings Description

The studied structure in this study consist of an 8 story reinforced concrete frame building that you can see the plan's details and structural features in figure 2. The above building was first used in research by Tran-Gilmour (2004) and then used in Ruiz-Garcia (2014). The dead loads (excluding self-weight) and live loads are equal to 20 and 10 KN/m, respectively, and are directly applied on the beams. All floors are assumed to be rigid in plan to account for the diaphragm action of concrete slabs. Material properties are assumed to be 22 MPa for the concrete compressive strength and 480 MPa for the yield strength of both longitudinal and transverse reinforcements. In order to accurately capture the degrading behavior of the RC buildings on the concrete and steel material level, a distributed plasticity model is developed using fiber-based finite element analysis tool, OpenSees. For this purpose the cross section of the elements are divided into different segments based on the material types. Models and relationships considering degrading in steel and concrete are employed and assembled to demonstrate the behavior of the cross section and member. P-Δ effects were considered through a geometric stiffness matrix, and the base of the columns on the ground story were assumed to be rotationally fixed. In the case of the dynamic non-linear analyses, the non-linear model of the frames considered 5% of critical damping through a Rayleigh matrix that assigned the indicated damping to the first two modes of vibration.

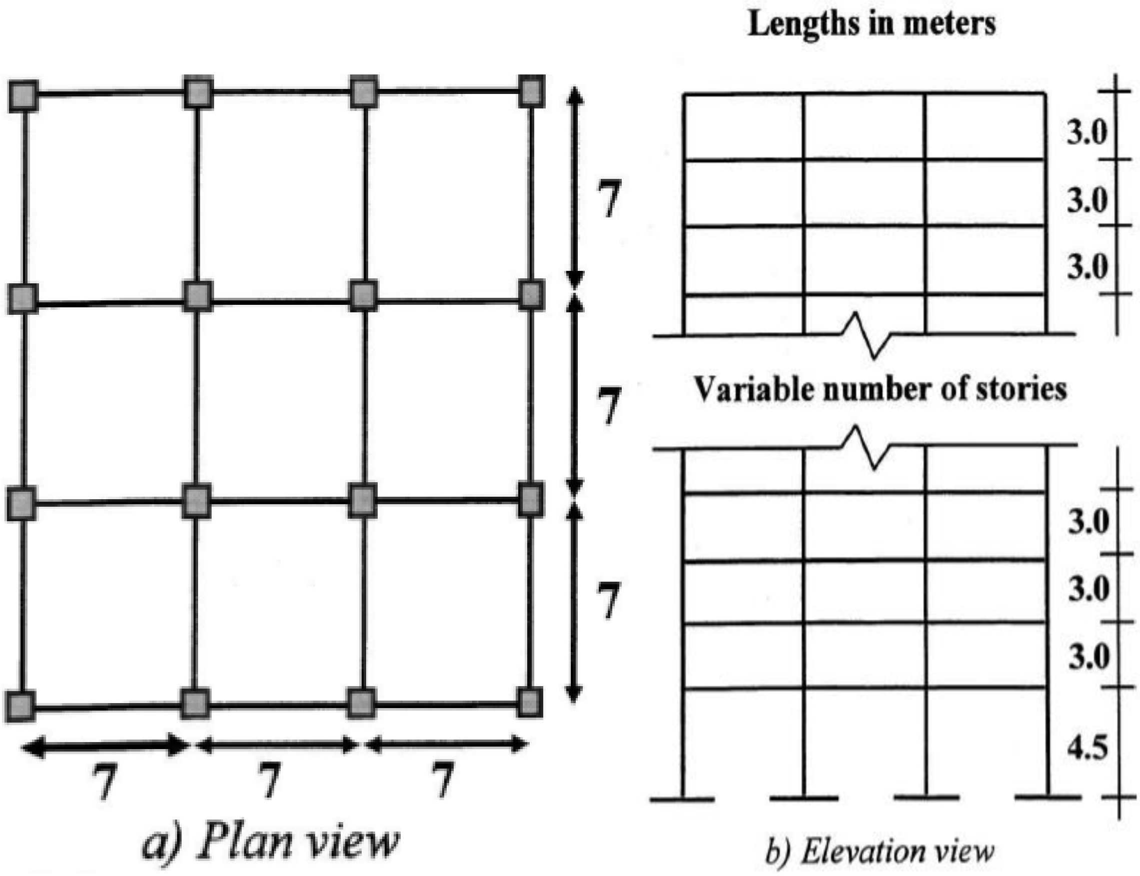


Figure 2. Plan's details and structural features (Tran-Gilmour, 2004)

2.3 Model Development

In order to examine the effect of multiple low intensity earthquakes on the performance of RC structures, we employed some kind of concrete and steel reinforcement models, used in OpenSees program, to consider which concrete and steel reinforcement models can represent more realistic performance of structure. For this purpose, we have used a variety of materials, such as Concrete 01 and Concrete 02 for concrete and Steel 01 and Reinforcing Steel for steel materials. The models used in this study are shown in Table 1.

Table 1. Models Description.

FRAME NO.	STEEL MATERIAL	CONCRETE MATERIAL
1	REINFORCING STEEL	CONCRETE 01
2	STEEL 01	CONCRETE 01
3	REINFORCING STEEL	CONCRETE 02

3. SELECTED RESULTS

The inelastic behavior of the examined RC framed structures, which are subjected to the abovementioned seismic sequences, is investigated in this section. This study focuses on the following basic design parameters: Maximum Top Displacements, Roof Displacement and interstorey drift ratios. Also, by using the obtained data and comparing with the drift values given in ASCE 41-06, values that provided to illustrate the overall structural response associated with various structural performance levels. (Table 2) Then, we will obtain the level of performance of our structures after the successive earthquakes, and we will examine different states of it.

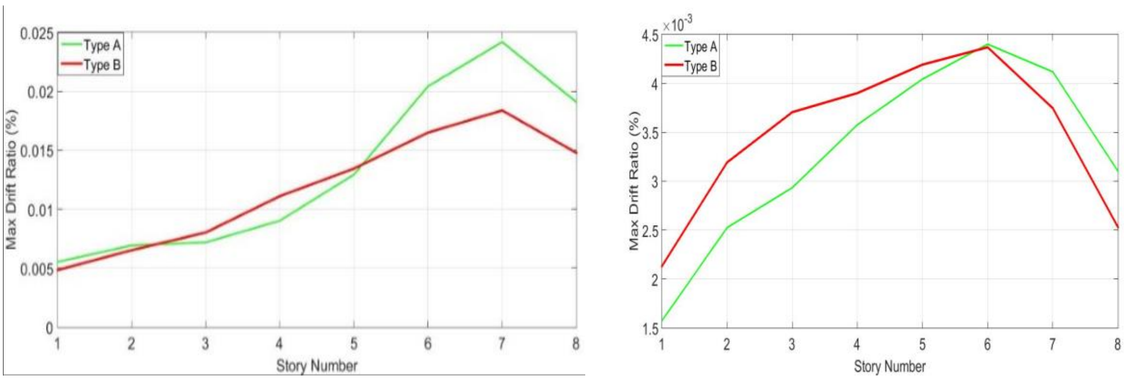
Table 2. The limit states defined in this study based on the value of drift.

Element	Type	Structural Performance Levels		
		Collapse Prevention	**Life Safety**	**Immediate Occupancy**
Concrete frames	Drift	4% transient or permanent	2% transient 1% permanent	1% transient Negligible permanent

In the following, we will review the results obtained by considering the number of input earthquakes as well as the structural models defined, separately.

3.1 Maximum Interstory Drift Ratio

To help understand the effect of the low intensity Earthquakes on the response of the framed building under consideration, two sets of seismic sequences were defined. Figure 3 shows Maximum Interstory Drift Ratio along height for the building in 2 different ground motion scenarios. It can be observed that the frame is able to adequately control its Maximum Interstory Drift Ratio within its design threshold when it is subjected to the set of low intensity Earthquakes (20 and 40 earthquakes). Noteworthy is also the fact that Maximum Interstory Drift value varies in frames designed by two different materials, and this difference reaches 0.05% in the 7th story in 40 earthquakes scenario.



a) b)

Figure 3. Maximum Interstory Drift Ratio along height for the building, comparing No. 2 (Type A) Frame with No. 3 (Type B) a) 40 earthquakes scenario b) 20 earthquake scenario

3.2 Interstory drift ratio (IDR)

The Interstory drift ratio is the maximum relative displacement between two stories normalized to the story height. It should be mentioned that from the analysis of test data on components and small-scale structures, it was found that an Interstory drift ratio value smaller than 1% corresponds to damage of non-structural components, while values of IDR larger than 4% may result in irreparable structural damage or collapse (Sozen MA., 1981). Examples of IDR values appear in Figure 1 and Figure 2, for 20 and 60 sequential ground motions. Additionally, despite the limitation of damage into non-structural elements in the case of 20 low intensity earthquakes (IDR<1%), the sequential 60 ground motions lead to structural damage, i.e. IDR>1%.

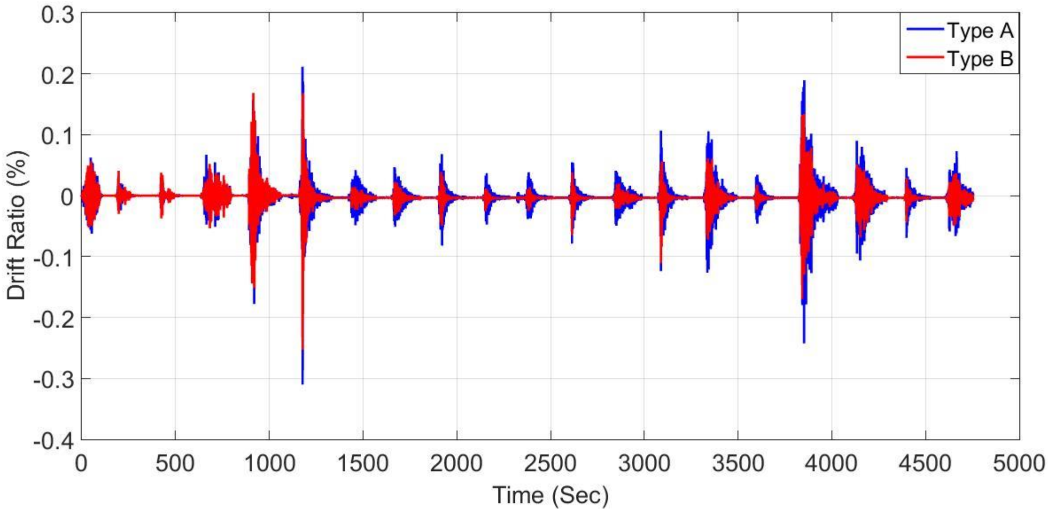


Figure 4. Interstory Drift Ratio (IDR), comparing No. 2 (Type A) Frame with No. 1 (Type B) in the case of 20 earthquakes

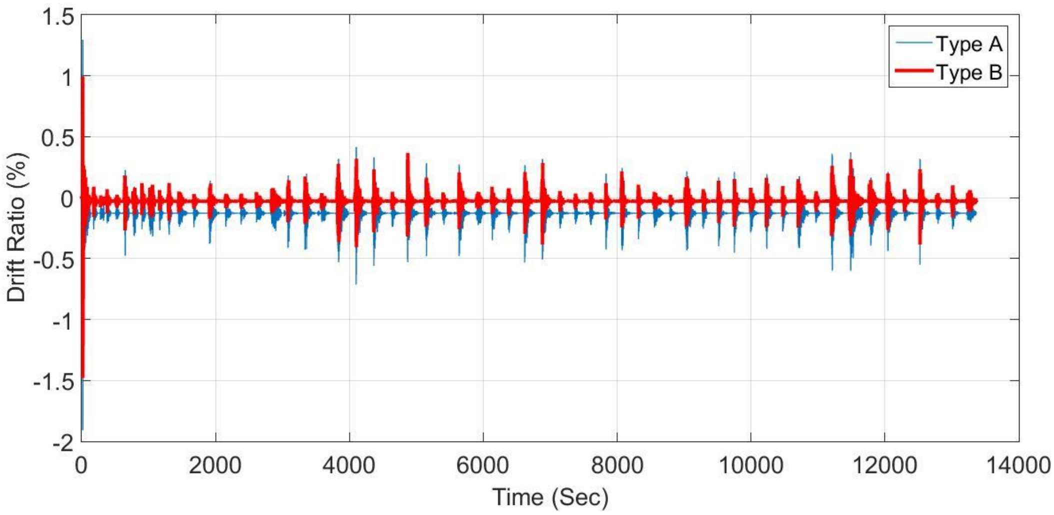


Figure 5. Interstory Drift Ratio (IDR), comparing No. 2 (Type A) Frame with No. 1 (Type B) in the case of 60 earthquakes

It is also observed that the response of structures, constructed with simpler structural models is more in both scenarios than the more advanced models that display the behavior of the structure more accurately.

3.3 Maximum Top Displacement

The maximum top displacements, for all selected sequential ground motions, are shown in Figure 6 for various characteristic cases of structures and various number of earthquakes. Finally, it can be easily concluded examining Figure 6 that, for the most of the cases, higher number of seismic sequences generally lead to higher and more intense response of the structure. Also, structures constructed with simpler models often have larger responses due to earthquakes. As you can see in the figure below, the structural response developed by concrete 01 and steel 01 is larger in all seismic scenarios, but the responses for the other cases are close in all cases.

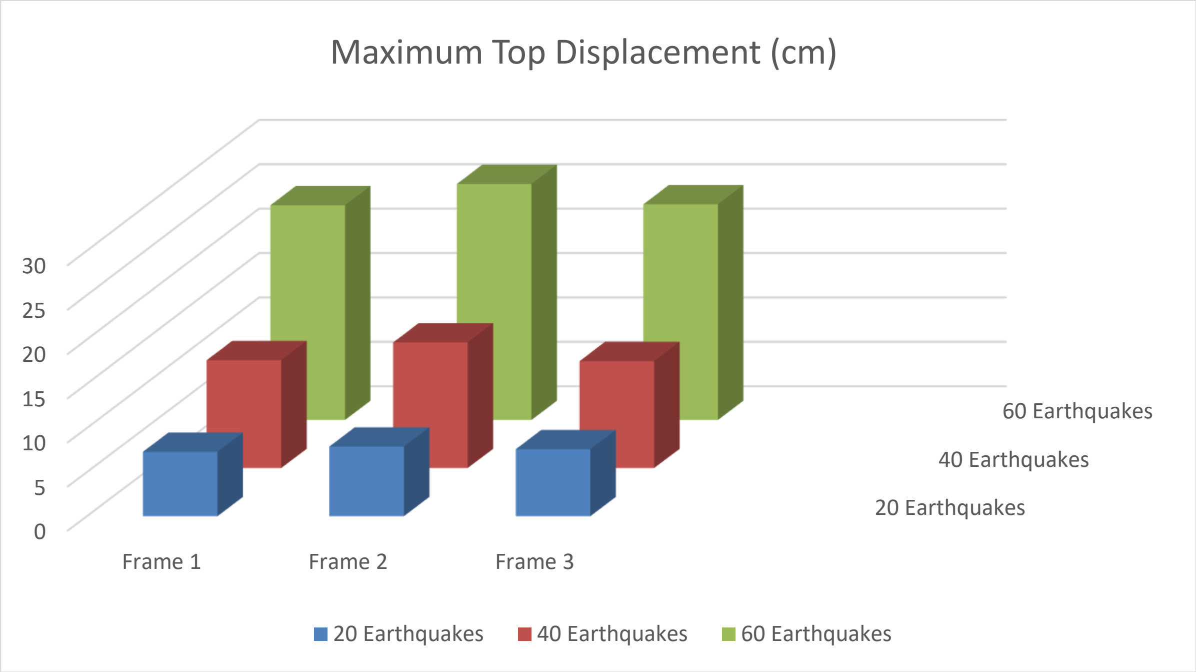


Figure 6. Maximum Top Displacement, comparing All Frames with all earthquake cases

4. CONCLUSIONS

This manuscript investigates effects of lifetime cumulative damage of multiple low intensity earthquakes in RC structures. The response of the structure compared by using different steel and concrete models of degrading features, and multiple earthquakes with different number of sequences (20, 40 and 60 records) were considered. Based on the analysis results, it is shown that multiple low earthquake effects have no significant impact on the behavior of reinforced concrete structures in a lower number of sequences, but have a considerable effect in higher number of earthquakes. Also, this research confirms that the degrading response is not accurately captured in simple models. Finally, it is recommended that future research should focus on providing detailed guidelines for assessing of the existing structures, especially the old ones, located in earthquake prone regions and affected from low intensity Earthquakes.

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