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by Ade Faisal

Effect of Repeated Earthquake on Inelastic Moment Resisting Concrete Frame

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Abstract. This paper investigates the response of inelastic moment resisting concrete building under repeated earthquakes. 2D models consist of 3-storey, 6-storey and 9-storey representing low to medium rise building frame were designed using seismic load and ductility class medium (DCM) according to the requirements set by Euro Code 8. Behaviour factor and stiffness degradation were also taken into consideration. Seven sets of real repeated earthquakes as opposed to artificial earthquakes data were used. The response of the frame was measured in terms of the inter-storey drift and maximum displacement. By adopting repeated earthquake, the recorded mean IDR increased in the range of 3% - 21%. Similarly, in the case of maximum displacement, the values also increased from 20 mm to 40 mm. The findings concluded that the effect of using repeated earthquake in seismic analysis considerably influenced the inter-storey drift and the maximum displacement.

INTRODUCTION

The impact of main-shock from devastating earthquake events (Kobe, Chile and Tohoku) towards man-made structures had caused casualties and losses estimated at millions of dollars. In reality, earthquake events occurred in sequences namely fore-shock, main-shock and after-shock. These sequences, commonly known as repeated earthquake can be activated from nearby or far ruptures. The existences of repeated earthquakes were shown in many ground motion database such as Mexico (1985) and Northridge (1994). Repeated earthquakes are gaining attention from researches around the world although single earthquake is still presumed by the design codes and practices till nowadays. However, Hatzigeorgiou and Liolios [6] reported that the effect of repeated earthquake was apparent compared to single earthquake. Code of Practice such as Eurocode 8 was developed for allowing seismic load in the analysis and design. In terms of ground motion record, EC8 allows the use of artificial and real earthquake. However, difficulty in assembling repeated earthquake due to lack of real seismic sequences (i.e 2 to 5 events) have lead some researches on switching to artificial earthquake [7].

Hatzigergiou and Beskos [7] introduced the technique on assembling artificial earthquake in order to overcome the complex behaviour of real repeated earthquakes. Previous researchers used single degree of freedom (SDOF) or multiple-degree of freedom (MDOF) frames under repeated earthquakes. These frames were simplified into 2D or 3D model, incorporating hyteresis and strength degradation of the materials [1, 3, 7, 10, 12, 16].The findings revealed that the response of frames under artificial repeated earthquake increased the maximum floor displacement and inter-storey drift compared to single earthquake event. Using source site real repeated earthquake, Hatzigeorgiou and Liolios [6] showed that the use of real repeated earthquake on 2D moment resisting reinforced concrete frame (MRCF) lead to the increase in the inter-storey drift and maximum displacement. However, Ruiz-

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Garcia and Negrete-Manrique [8] used near and far field repeated earthquake for MDOF steel frames and reported that the inter-storey drift was not significantly affected compared to the single earthquake event.

Thus, the study on building response is essential especially on multi-storey buildings subjected to real repeated earthquake. A comprehensive study is required to classify the effect of real repeated earthquake as the finding is to enhance better understanding of seismic excitation on MDOF frames. This paper investigates the effect of repeated earthquake phenomenon using nonlinear dynamic analysis of MRCF. Three types of 2D frames consist of 3, 6 and 9-storey, representing low to medium rise building were examined. Nonlinear time history analysis (NTHA) was performed to the frames using single and repeated earthquake events from source to site ground motion. Results in terms of inter-storey (IDR) and maximum displacement are presented and discussed accordingly.

Description of 2D Frames Modelling

This study focuses on low to medium rise 2D regular RC frames consist of 3, 6 and 9-storey and designed according to European Codes [5]. This study is based on the concept and generic frames produced by Hatzigergiou and Liolis [6] and extended by varying the height of the frames. The site was assumed to be located in the European region with high seismicity activities where the elastic response spectra Type 1 were selected. Peak ground acceleration of 0.2g was selected with soil type B and the load combination was adopted according to Hatzigergiou and Liolis [6]. Figure 1shows the moment resisting concrete frames in 2D view. The fundamental period of the buildings were calculated to be T = 0.39s, 0.68s and 0.91s for 3, 6 and 9 storey, respectively. The dead and live load were 25 kN/m² and 10 kN/m², respectively. These loads were applied directly to the beams. Concrete compressive strength and the yield strength for reinforcement were taken as C35 and 500 MPa, respectively. For the 3 storey model, the frame was regular in horizontal and vertical arrangement where floor to floor height was set to be 3m. In the case of 6 and 9-storey, an opening with the height of 4 m was located at the first storey. The rest of the floor to floor height remained at 3m. The total span length was 15m for all frames. The beams and columns of each storey have non-uniform stiffness distribution. Horizontal force, Fi was calculated using $F_i = F_b . [z_i . n_i)/ \Sigma j. n_j]$ and the forces were distributed along the height of the frames.

Capacity design theory was adopted by implementing strong column weak beam to satisfy the requirement of EC 8 [5] where $\sum M_{RC} \geq \sum 1.3 M_{RB}$. The frames were considered as rigid due to the incorporation of rigid slab, floor and diaphragm. In order to satisfy EC 8, behaviour factor q = 3.9 was included in the analysis. Maximum moments and maximum axial load were obtained from linear analysis with the aid of SAP 2000 software [4].These values were used as the parameters in designing the beams and columns. Reinforcement details for each beam and column are shown in Table 1.The size of the beams and columns were 300 mm × 500 mm and 500 mm × 500 mm, respectively. The 2D frames were analysed under nonlinear dynamic condition using Ruaumoko software [2]. The foundation was assumed to be fixed hence neglecting the effect from the soil-structure interaction. Beams and columns were modelled as nonlinear frame elements and plastic hinges were adopted at the ends of each frame. Strength and stiffness of the flexural moments were considered for beams meanwhile moment and axial forces were considered for columns. These values were obtained from CUMBIA software [9].

In order to accommodate the stiffness-degrading effect, Modified Takeda hysteresis model was adopted in this study where the unloading and reloading parameter α=0.5, β=0.6 were used as suggested by [11]. This approach ensured the RC beams and columns members to undergo hysteretic behaviour under cyclic loading. For rotation purposes, plastic hinge length, I_{ph}=0.5H was applied as suggested by [14]. For each member, the plastic hinge was set to be half of the section height. As this study focuses on multi-degree of freedom (MDOF) frames, 5% damping ratio was also applied to the first and second mode for all frames. Similarly, P-delta (i.e larger displacement) effect was also considered in the analysis.

a) 3 storey b) 6 storey c) 9 storey

FIGURE 1: 2D MRCF frames

TABLE 1. Reinforcement details of moment resisting concrete frames

Storey	**3 storey**		**6 storey**		**9storey**	
Section (mm)	**Beam 300 x 500**	**Column 500 x 500**	**Beam 300 x 500**	**Column 500 x 500**	**Beam 300 x 500**	**Column 500 x 500**
Steel Bar (1-3 storey)	3H20-T 2H20-B	2H16 2H16	3H25-T 3H20-B	2H16 2H16	4H25-T 3H20-B	2H16 2H16
Steel Bar (4-6 storey)	-		3H25-T 2H20-B	2H16 2H16	4H25-T 3H20-B	2H16 2H16
Steel Bar (7-9 storey)	-		-		3H25-T 2H20-B	2H16 2H16
Link (mm)	H10@100		H10@100		H10@100	

Earthquake Input

Previous studies utilised artificial repeated earthquake in the analysis. As a results, large displacement and increased of inter-storey drifts were observed. Therefore, it is interesting to examine frames under real recorded earthquakes in order to provide good understanding on the effect of single and repeated earthquake to the frames. Seven set of strong individual ground motions consist of real recorded earthquake within a short period of time and under the same station were used in the analysis. The earthquake sequences are Chalfant Valley (2 events), Chi-Chi (2 events), Coalinga (2 events), Imperial Valley (2 events), Livermore (2 events), Mammoth Lakes (2 events) and Whittier Narrows (2 events) as shown in Figure 2. Details of seismic input are listed in Table 2. It is worth mentioning that some of these ground motions were used by [6], [8] in their study. The earthquake databases were downloaded from Pacific Earthquake Engineering Research (PEER) [13]. These databases matched with soil type B and compatible with design criteria.

The following criteria of the ground motion were employed where each individual real earthquake data with magnitude greater than 5.0 were applied. For the single event (main-shock), earthquake data with maximum peak ground acceleration were assembled as main-shock. This approach was adopted due to the fact that the main-shock of real repeated earthquake exhibited higher peak ground acceleration (PGA) compared to aftershock. Each earthquake database was assembled in sequences with an interval of 100s buffer time between two consecutive earthquakes [15]. This gap ensures the achievement of zero acceleration as the frames are in the state of rest after shaking due to the damping effect. To meet the design criteria the seismic sequences were scaled with maximum PGA of 0.2g as implemented by [6].

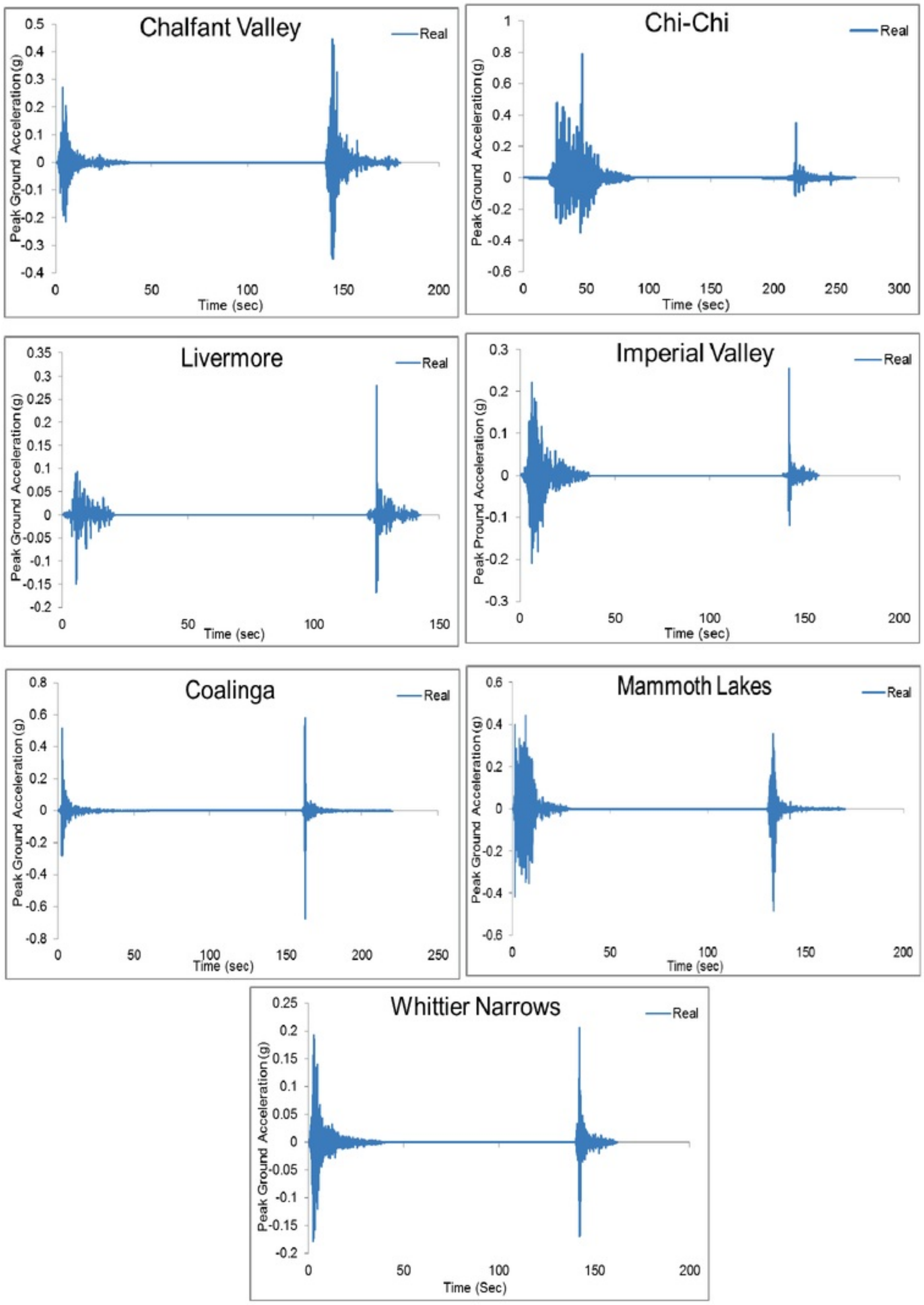

FIGURE 2: Seismic sequences of selected ground motion

TABLE 2. Ground motion details

Seismic Sequence	Station	Date	Magnitude	PGA (g)
Chalfant Valley	Zack Brothers Ranch	[illegible]	5.9	0.272
		21/07/1986	6.3	**0.447**
Chi-Chi	TCU 065E	[illegible]	7.6	**0.790**
		20/09/1999	5.9	0.348
Coalinga	Coaling (Old CHP)	[illegible]	6.0	0.519
		25/07/1983	5.3	**0.677**
Imperial Valley	Holtville P. Office	[illegible]	6.6	0.221
		15/10/1979	5.2	**0.254**
Livermore	San Ramon Eastman	[illegible]	5.8	0.150
		29/01/1980	5.4	**0.280**
Mammoth Lakes	Convict Creek	[illegible]	6.1	0.442
		25/05/1980	5.7	**0.485**
Whittier Narrows	San Marino-SW	01/10/1987	5.9	0.194
	Academy	04/10/1987	5.3	**0.206**

**bold= main-shock*

RESULT AND DISCUSSION

Three RC frames representing low to medium rise building subjected to seven set of real ground motions were carried out in this study. Figure 3 shows the results in terms of IDR and maximum displacement for 3, 6 and 9-storey both under single (S) and repeated (R) earthquakes. It can be seen that, the lower storey for all frames suffered the most IDR due to the potential occurring of soft storey level and presence of high column loading compared to the upper storey. This finding is similar to Ruiz-Garcia and Negrete-Manrique [8] when analysing existing steel frames under main and after-shock. The same pattern of high IDR was also observed at the lowest floor level.

In the case of 3-storey frame subjected to single earthquake, the mean inter-storey (IDR) at lower storey is 0.0023. The mean IDR for the 6-storey frame is recorded to be 0.0033 at the lower storey. As for the 9-storey frame, the mean IDR at the lower storey is 0.0034. On the other hand, the results for repeated earthquake of 3-storey frame showed that the mean IDR for the lower storey is 0.0026. Meanwhile, for 6-storey frame, the mean IDR for the lower storey is 0.0038. The mean IDR for 9-storey frame of the lower storey is 0.0043.

Figure 3 shows the overall results of the IDR for the 2D frames subjected to single and repeated earthquake. It can be seen all frames indicated insignificant difference. This finding is particularly true for 3-storey and 6-storey frames. However, the 9 storey model showed an increase of IDR under repeated event especially at the lower storey. It can be observed that all frames experienced low IDR values due to the design rules imposed in EC 8 [5] that have resulted increase in strength with regards to the behaviour factor, especially under ductility class medium (DCM).

In the case of the maximum floor displacement for 9-storey frame, the results for repeated earthquake increased the displacement compared to single earthquake as shown in Figure 4. The same scenarios were also observed for 3 and 6-storey frames under repeated earthquake.

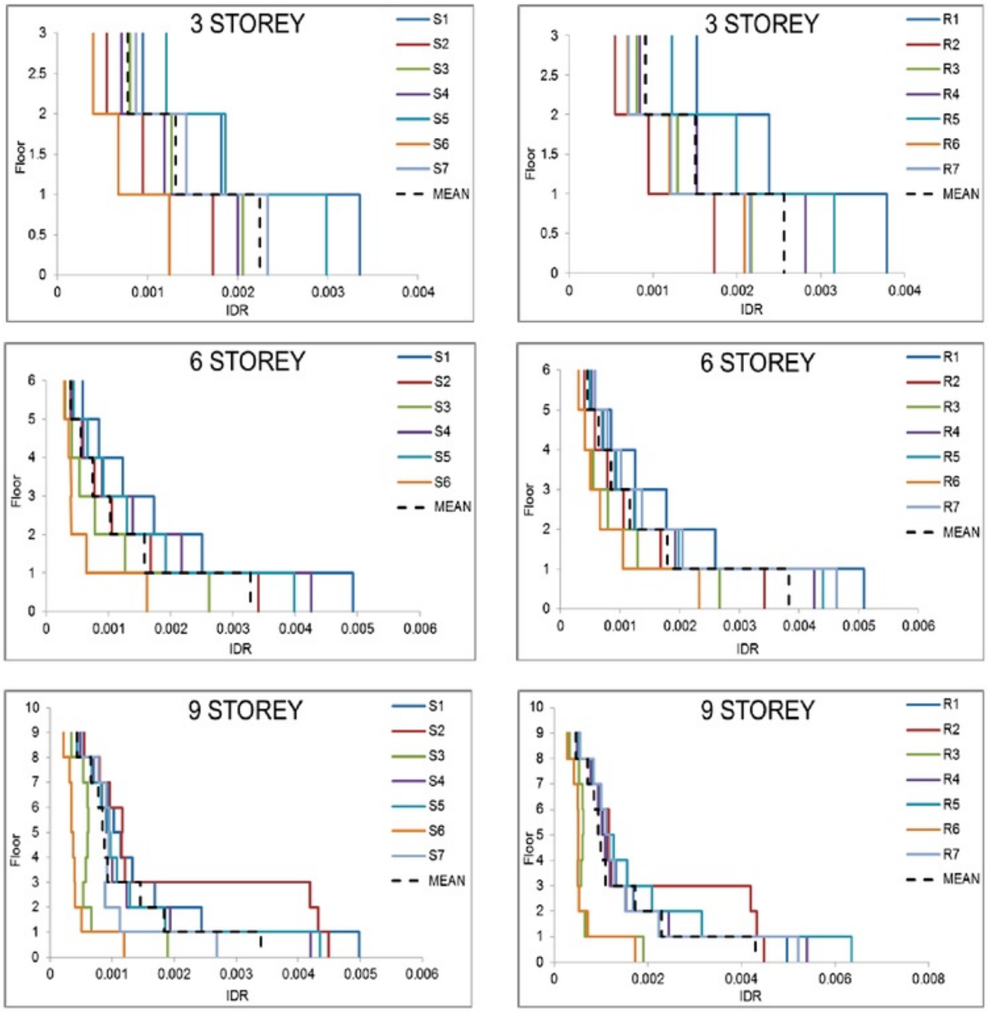

FIGURE 3: Mean inter-storey drift for 2D frames under single and repeated earthquake.

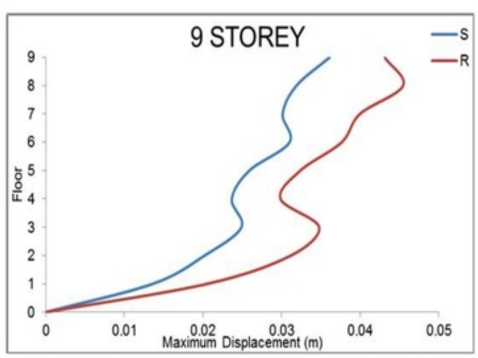

FIGURE 4: Maximum floor displacement of single and repeated event.

CONCLUSION

This paper presents the results of 3, 6 and 9-storey RC frames subjected to single and repeated earthquakes. The study focuses on investigating whether as-recorded repeated earthquake has the potential to increase the IDR and maximum displacement compared to single earthquake as reported by previous researchers. Hence, a set of 7 recorded repeated earthquakes were used. The pattern developed from the IDR results at the lower storey showed the tendency of soft storey occurrence. It was found out that the 3 and 6-storey frames showed insignificant difference in terms of IDR between single and repeated earthquakes. However, 9-storey showed an increase of IDR under repeated earthquake especially at the lowest storey. The findings concluded that the effect of using repeated earthquake in seismic analysis considerably influenced the inter-storey drift and the maximum displacement.

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