

Reducing The Seismic Failure Potential Of Reinforced Concrete Frames

Neda Asgarkhani ^{1*}, Farzin Kazemi ¹, Ahmed Manguri ², and Robert Jankowski ¹

¹ Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, ul. Narutowicza 11/12, 80-233 Gdansk, Poland.

² Civil Engineering Department University of Raparin Rania, Kurdistan Region, Iraq.

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*Email address:

neda.asgarkhani@pg.edu.pl

*Corresponding Author



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Abstract:

Nowadays, there is an extreme need for buildings with seismic resistance capability in rural areas, in which, it is possible to increase the floor number of buildings. In this study, the effects of number of bays and story levels on the seismic performance level of Reinforced Concrete (RC) frames were investigated. The 3-, 5-, 7-, and 9-story RC frames were modeled using ETABS software. In order to collapse state analysis, Incremental Dynamic Analyses (IDAs) were performed on the verified 2D models in Opensees subjected to near field records with and without pulse like (i.e., PL and NL) effects. The results of analysis showed that the number of bays had considerable effects on the seismic performance levels of RC frames and it should be considered in seismic design process. For this process, a specific procedure can be implemented to connect the beams of lateral bays to the main moment-resisting frame. It should be noted that the beam connection should be further designed to resist axial and bending deformations of seismic load. In addition, it is recommended to use the result of this study for retrofitting purposes.

Keywords: Reinforced Concrete, Seismic Performance Levels, Incremental Dynamic Analyses, Potential Seismic Failure.

1. Introduction

Investigating the seismic behavior of Reinforced Concrete (RC) buildings can be known as important topic due to increasing number of buildings in rural area. Requena-Garcia-Cruz et al. [1] employed a 5-story RC building. They performed Incremental Dynamic Analysis (IDA) and nonlinear static analysis to evaluate the seismic behavior of buildings. Their computational results demonstrated the significant impact of the soil on the performance of the building. Firoj et al. [2] analyzed the seismic performance of a mid-rise building with proportionate lateral stiffness of columns of RC buildings in the orthogonal direction. They showed that, lateral stiffness has a considerable impact on seismic performance. Huang, W. et al. [3] implemented lead viscoelastic damper with the purpose of enhancing the seismic performance of the RC frames, which have low strength subjected to sequence earthquakes. They created a six-story RC frame having lead viscoelastic damper; then, modeled this structure in Opensees [4] to conduct IDA. They concluded that due to using this damper, the weaker RC frame had better performance compare to the original one. Asgarkhani et al. [5] investigated the procedure for retrofitting the RC buildings with adjacent steel buildings using viscous dampers. They improved the performance of RC building with connecting them to steel building. Mohebi et al. [6] proposed a procedure for estimating the damage in the steel braced frames and tried to propose a procedure to resist them. To enhance the seismic resistance of RC frames, one approach is to connect additional bays of frames to the primary structure. This strategy aims to increase both the lateral stiffness and strength of the structure, thereby reducing the potential for seismic failure. Several studies in the field of structural engineering have investigated the effectiveness of this approach and comprehensively investigated the procedure for enhancing seismic performances [7-9].

Connecting additional bays of frames effectively increases the lateral stiffness of the structure. This means that during seismic events, the structure is better able to resist lateral forces, reducing deformations and preventing excessive drift. By connecting more bays to the primary structure, the overall strength of the system is improved. This is particularly beneficial in seismic regions where structures need to withstand significant lateral loads. Additional bays help redistribute seismic forces more uniformly throughout the structure. This prevents localized overstressing of individual members and reduces the likelihood of structural failure at specific weak points. This research has shown that connecting extra bays to the primary structure can lead to improved seismic performance, as evidenced by reduced damage and increased resilience during earthquake events. By increasing both lateral stiffness and strength, this approach enhances the overall structural resilience and contributes to a safer built environment in seismically active regions.

2. Modeling of Buildings

The 3-, 5-, 7-, and 9-story RC frames were modeled using ETABS software. In order to investigate the seismic failure potential of RC frames, all frames with one to five bays were designed having bay length of 5.0 m, 6.5 m, and 7.5 m. For brevity, only the results the bay length of 6.5 m were discussed. To model RC frames, the seismic parameters of special moment-resisting frame were selected as $R=8$, $C_d=5.5$, and $\Omega=3$ according to ASCE/SEI 7-16 [10] for a site with soil class D. Therefore, in the 3D models, only the selected bays have the special behavior; thus, other columns can be assumed as gravity columns [11-14]. Figures 1 and 2 present the three-dimensional view of three and five story RC buildings having five and three bays with special behavior (red color), respectively.

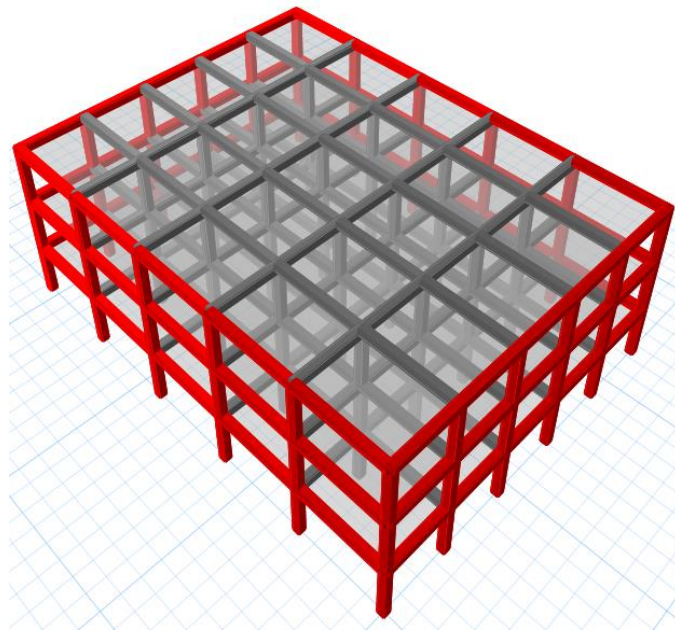


Figure 1: Three story RC building having three bays with special behavior designed in ETABS software.

In order to perform collapse state analysis, the procedure used by and Haselton and Deierlein [15] Kazemi et al. [16, 17] were employed to define 2D structures in Opensees [4] software with seismic behavior of 3D buildings. To do this, the red color frame was selected as special frame, and other columns were modeled with gravity column to consider the P-delta effect [18-20]. Using gravity column knows as leaning column provide a simplified model with acceptable accuracy that reduces the analytical efforts yet reliable results provided [21-23]. To model RC frames, the assumptions to uniform dead and live loads with regular plan were selected to avoid torsion effects; then, the 3D

buildings can be modeled as 2D frames. It should be noted that the RC frames were verified with their fundamental periods of 3D buildings. The modelling process and the results of analysis were validated based on the investigations of authors (for more detail see [5, 6, 24-26]).

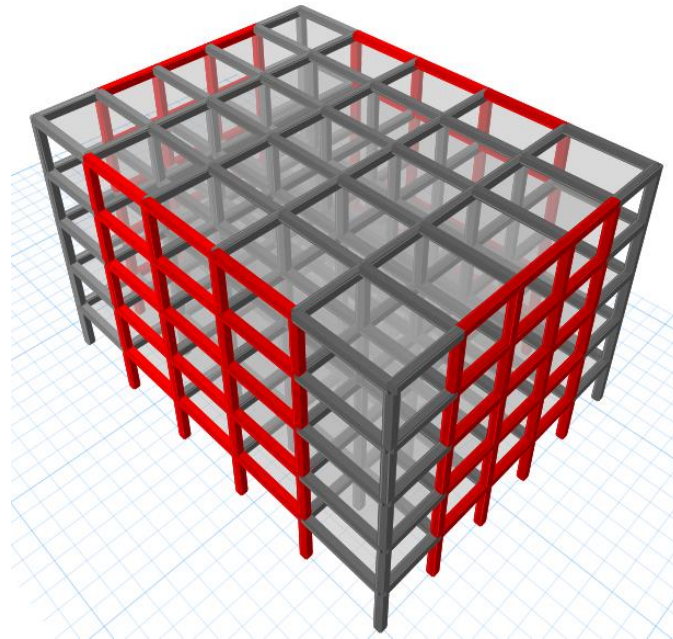


Figure 2: Five story RC building having three bays with special behavior designed in ETABS software.

3. Incremental Dynamic Analysis

To perform collapse analysis, IDA was selected assuming the near-field pulse-like and near-field no-pulse ground motions. For more details of ground motions see Table 1 [12-14]. The main difference between the ground motions is the pulse-like effects that can play a crucial role in seismic performance and failure potential of RC structures. In addition, the correct selection of intensity measure can affect the results [27-29].

Table 1: Summary of record characteristics [12-14].

RSN	M	Year	Name	Fault Type	PGA _{max} (g)	PGV _{max} (cm/s.)
near-field pulse like record subset						
181	6.5	1979	Imperial Valley-06	Strike-slip	0.44	111.9
182	6.5	1979	Imperial Valley-06	Strike-slip	0.46	108.9
292	6.9	1980	Irpinia, Italy-01	Normal	0.31	45.5
723	6.5	1987	Superstition Hills-02	Strike-slip	0.42	106.8
802	6.9	1989	Loma Prieta	Strike-slip	0.38	55.6
821	6.7	1992	Erzican, Turkey	Strike-slip	0.49	95.5
828	7.0	1992	Cape Mendocino	Thrust	0.63	82.1
879	7.3	1992	Landers	Strike-slip	0.79	140.3
1063	6.7	1994	Northridge-01	Thrust	0.87	167.3
1086	6.7	1994	Northridge-01	Thrust	0.73	122.8
1165	7.5	1999	Kocaeli, Turkey	Strike-slip	0.22	29.8
1503	7.6	1999	Chi-Chi, Taiwan	Thrust	0.82	127.7
1529	7.6	1999	Chi-Chi, Taiwan	Thrust	0.29	106.6
1605	7.1	1999	Duzce, Turkey	Strike-slip	0.52	79.3

near-field no-pulse record subset						
126	6.8	6.8	Gazli, USSR	Thrust	0.71	71.2
160	6.5	1979	Imperial Valley-06	Strike-slip	0.76	44.3
165	6.5	1979	Imperial Valley-06	Strike-slip	0.28	30.5
495	6.8	1985	Nahanni, Canada	Thrust	1.18	43.9
496	6.8	1985	Nahanni, Canada	Thrust	0.45	34.7
741	6.9	1989	Loma Prieta	Strike-slip	0.64	55.9
753	6.9	1989	Loma Prieta	Strike-slip	0.51	45.5
825	7.0	1992	Cape Mendocino	Thrust	1.43	119.5
1004	6.7	1994	Northridge-01	Thrust	0.73	70.1
1048	6.7	1994	Northridge-01	Thrust	0.42	53.2
1176	7.5	1999	Kocaeli, Turkey	Strike-slip	0.31	73
1504	7.6	1999	Chi-Chi, Taiwan	Thrust	0.56	91.8
1517	7.6	1999	Chi-Chi, Taiwan	Thrust	1.16	115.1
2114	7.9	2002	Denali, Alaska	Strike-slip	0.33	126.4

Figures 3 and 4 present the IDA curves of the 3-story and 5-story RC frames having three bays including near-field pulse-like records, respectively. Figures 5 and 6 present the IDA curves of the 7-story and 9-story RC frames having four bays including near-field no-pulse records, respectively. Comparing the IDA curves demonstrate that in most of the records the RC frames have been collapsed after interstory drift ratio of 7%. Therefore, using interstory drift ratio of 10% is a good limitation of interstory drift ratio for collapse state assessment

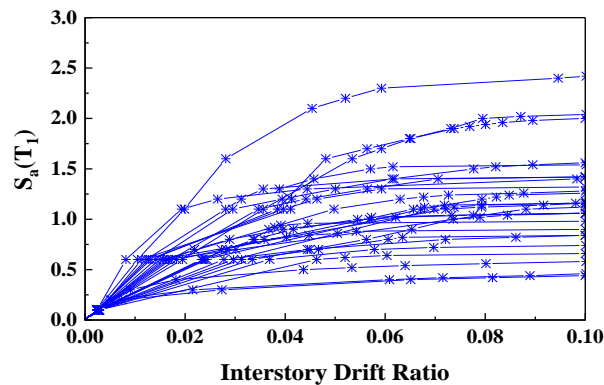


Figure 3: IDA curve of the 3-story RC frame having three bays including near-field pulse-like records.

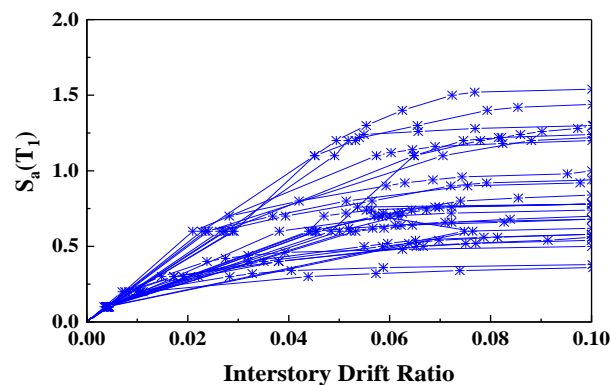


Figure 4: IDA curve of the 5-story RC frame having three bays including near-field pulse-like records.

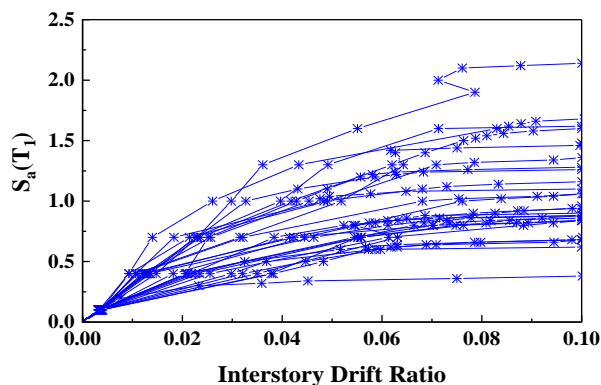


Figure 5: IDA curve of the 7-story RC frame having four bays including near-field no-pulse records.

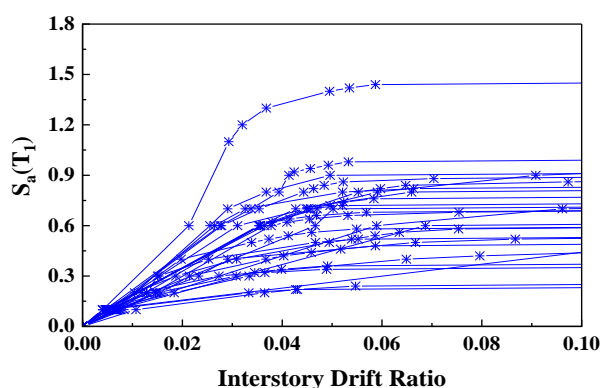


Figure 6: IDA curve of the 9-story RC frame having four bays including near-field no-pulse records.

4. Results and Discussions

In this section, the results of analysis for investigating the potential failure of RC frames are discussed. To evaluate the seismic performance levels of RC frames, life safety and total collapse performances are assumed by the interstory drift ratio of 2.0% and 10%, respectively [30-32]. According to IDA curves presented in Figures 3 to 6, the median of IDA curves (MIDA) were determined. Figure 7 illustrates the MIDA of the 3-story and 5-story RC frame having three bays including near-field no-pulse and near-field pulse-like records.

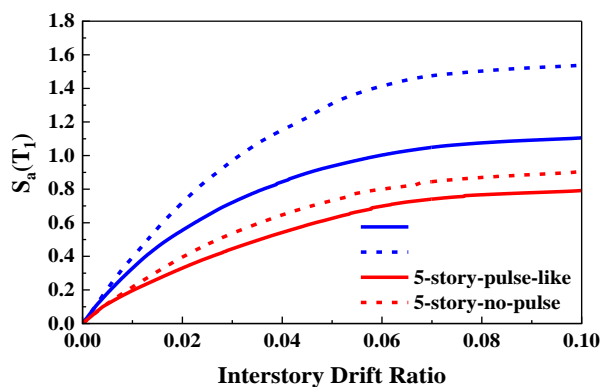


Figure 7: MIDA of the 3-story and 5-story RC frames having three bays including near-field no-pulse and near-field pulse-like records.

It can be observed that the pulse-like effects increased the vulnerability of the 3-story and 5-story RC frames. For life safety and collapse performances of the 3-story RC frames, the performance levels decreased by 22.91% (from 0.720 to 0.555) and 28.2% (from 1.538 to 1.105), respectively, and for the 5-story RC frames, decreased by 16.7% (from 0.395 to 0.329) and 12.59% (from 0.905 to 0.791), respectively. Therefore, the pulse like effect of near field records have significant influence on the failure of RC frames.

To investigate the effects of number of bays, one to five bays for each of the RC frames were analyzed. Due to importance of near-field pulse-like records, results of this records were plotted. Figure 8 presents the MIDA of the 7-story RC frame having one to five bays including near-field pulse-like records. According to Figure 8, it can be seen that the one-bay RC frame has the lowest values of $S_a(T_1)$ compared to other structures. In addition, by increasing the number of bays, values of $S_a(T_1)$ increased, which shows the effects of bays on the failure potential of RC frames. For instance, in life safety performance, the $S_a(T_1)$ values of 0.261, 0.301, 0.311, 0.329, and 0.347 were determined for one to five bays RC frames, respectively, which confirms the increasing percentages of 15.32%, 19.15%, 26.05%, and 32.95%, for adding two to five bays, respectively. In total collapse performance, the $S_a(T_1)$ values of 0.402, 0.616, 0.654, 0.786, and 0.845 were determined, respectively, which shows the increasing percentages of 53.23%, 62.68%, 95.52%, and 110.19%, for adding two to five bays, respectively. Therefore, adding bays can considerably increase the life safety and total collapse performances by 1.329 and 2.1 times of the one bay, respectively.

Figure 9 presents the MIDA of the 9-story RC frame having one to five bays including near-field pulse-like records. According to Figure 9, it can be observed that the one-bay RC frame has the lowest values of $S_a(T_1)$. In life safety performance, the $S_a(T_1)$ values of 0.210, 0.297, 0.301, 0.311, and 0.326 were determined for one to five bays RC frames, respectively. In total collapse performance, the $S_a(T_1)$ values of 0.269, 0.476, 0.544, 0.625, and 0.785 were determined, respectively. Therefore, adding bays can considerably increase the life safety and total collapse performances by 1.55 and 2.918 times of the one bay, respectively. Therefore, to decrease the vulnerability of RC frames, it is recommended to add bays of frames to improve the potential of failure as retrofitting strategy. To do this, it can be possible to check the seismic performance of current RC frame; then, provide the additional bays to check the amount of improvements in the seismic performance levels. This procedure can also help civil engineers to enhance performance of the existing RC buildings.

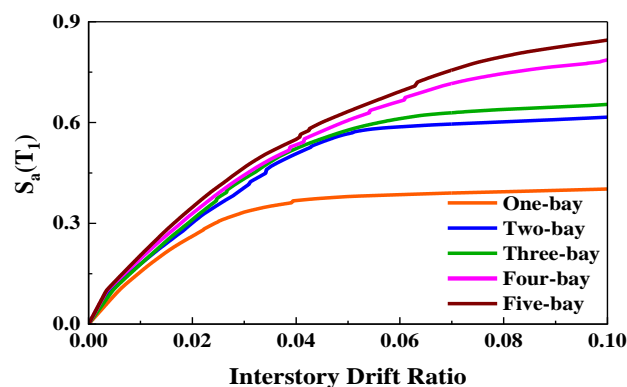


Figure 8: Med_{IDA} of the 6-story structure having soil B including three record subsets.

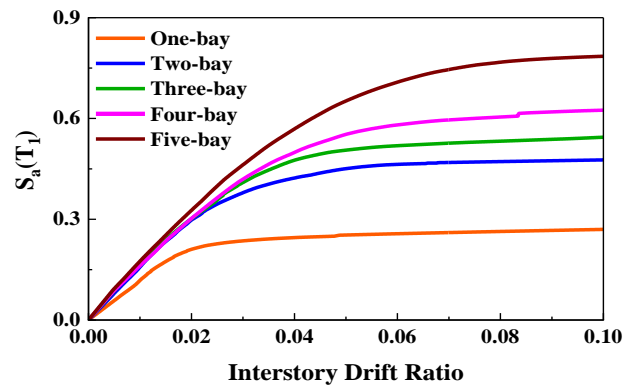


Figure 9: Med_{IDA} of the 4-story structure having all soil types including near field no pulse records.

5. Conclusions

In this study, the failure potential of the 3-, 5-, 7-, and 9-story RC frames having one to five bays including near-field pulse-like and near-field no-pulse records were investigated. For brevity, only the results for the bay length of 6.5 m were presented, while similar trends were observed for other bay length. To evaluate the performance levels of RC frames, MIDA of structures were plotted based on the IDA curves achieved from the near-field pulse-like and near-field no-pulse records. To improve the failure potential of the RC frames, it is recommended to connect the lateral bays to the main special resisting system to increase the number of bays. Doing this, it would be possible to enhance the seismic performance levels. For instance, improving the one bay to five bay RC frames, increased the life safety performance by 1.329 and 1.55 times, respectively, and the total collapse performance increased by 2.1 and 2.918 times, for the 7-story and 9-story RC frames respectively. In addition, more increase happened in the total collapse performance compared to other performance levels. For instance, in life safety performance of the 7-story RC frame, the $S_a(T_1)$ values increased by percentages of 15.32%, 19.15%, 26.05%, and 32.95%, for adding two to five bays, respectively. While, in total collapse performance, the increasing percentages of 53.23%, 62.68%, 95.52%, and 110.19%, for adding two to five bays were experienced, respectively.

6. Author's Contribution

We confirm that all named authors have read and approved the manuscript. We also confirm that each author has the same contribution to the paper. We further confirm that all authors have approved the order of authors listed in the manuscript.

7. Conflict of Interest

There is no conflict of interest for this paper.

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