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A Study of Nonlinear Behavior of Multistoried Structure for Repeated Earthquake

Sachin P. Patil[1*], Jagadish G. Kori[2]

1. Assistant Professor, Civil Engineering Department, Sanjay Ghodawat University, Kolhapur, India
2. Professor and Head of the Department of Civil Engineering, Government Engineering College, Haveri-581101, Karnataka, India

Corresponding author: *shravanisachin1771980@gmail.com*

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ABSTRACT

According to current practices in earthquake engineering, and as per guidelines of codes the multistoried structures are analyzed and designed only for a single, rare design earthquake. In reality, most of the locations are affected by multiple earthquakes within short time intervals, also the repeated earthquake effect is ignored. The repeated earthquake affects the strength and stiffness degradation of the structure. In this paper4-, 8-, 12-, 16-storey structures are investigated under repeated earthquakes. The Time history analysis is performed with single, double, and triple earthquake events for calculating drift, displacement, and ductility. The result shows that the drift, displacement, and ductility demand increase with compared to a single earthquake. This research focuses on the study of the effect of a single and repeated earthquake on the multistoried structure and damage identification can be found using deformation in building frame or in frame element with the formation of plastic hinges. The default hinge properties are assigned to elements of structure and the study is carried out to find the location, formation of plastic hinges, and plastic hinge rotation due to repeated earthquake and this study is used to strengthening the element strength. This paper studies the interstory drift ratio and displacement under aftershocks of an earthquake and remedial measures are suggested to strengthen the structure capacity.

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1. Introduction

Most multistoried structures are subjected to infrequent sequential earthquake loading, due to this loading the structure behaves as inelastic. To capture this inelastic behavior of structure nonlinear analysis is essential. The current practice of the Design of RCC structure considers the only single effect of the earthquake, also the design codes such as EUROCODE 8 [1], FEMA368 [2], IS1893 [3] considers only a single earthquake not the effect of a repeated earthquake. These codes are explaining the analysis and design procedure for a single earthquake effect on the structure Due to single earthquake effect the horizontal displacement, drift has small values compared to actual effect of multiple earthquakes. In the case of repeated earthquakes generally, the mainshock is followed by aftershock or vice versa. Therefore, if the structure is subjected to repeated earthquake i.e. Main shock followed by an aftershock. it is impossible to repair the structural damage induced due to the mainshock before the next earthquake, due to a short interval of time. In this case, the aftershock increases the level of damage to the structure due to the accumulation of damage. Accumulation of damage is depending on the strength capacity of the structure, stiffness of the structure, and seismic event characteristics. therefore, there is a requirement to investigate the effect of a repeated earthquake.

A few researchers have studied the effect of a sequential earthquake on the structures. Amedio et al (2003) [4] shows that sequential earthquake cusses increase the damage level and Effect of reduction of Behaviour factor. George Hatzigeorgiou et al (2009) [5] study the effect of the repeated earthquake and shows that the increase of force reduction factor leads to an increase of the inelastic displacement ratio and vice versa. mohdZulhamAffandi bin Mohd Zahid et al (2012) [6] study the effect of a repeated earthquake on the near field high Rise structures and shows that structural response quantities i.e. displacement ductility, storey ductility displacement ductility demand increases. . George Hatzigeorgiou et al (2010) [7] shows that repeated earthquake increases displacement demand in comparison with single earthquake and seismic damage is higher in case of a repeated earthquake than single effect.

This paper focuses on the study of the repeated earthquake on low, medium, and high-rise structures to investigate the response in terms of storey ductility, storey displacement, and storey drift. The response of 4^{th},8^{th},12^{th} 16^{th}storey structures under repeated earthquake and single earthquake will be compared and demand parameters are evaluated.

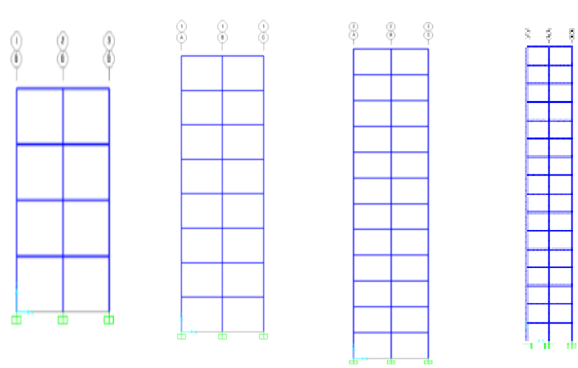

Fig. 1. 2D framed structure.

2. Description of model, seismic input, and scaling of ground motion

2.1. Description of structure and assumption for modeling

In this paper, four different types of structures are considered to represent low to high rise RC buildings for analysis purposes. The structure consisting of 4-storied, 8- storied, 12- storied, 16 - storied building with beam-column RC frame i.e. moment-resisting frame without a shear wall. The proposed structures are designed using IS code. In IS code and EUROCODE, the effect of a repeated earthquake is not deliberated. For analysis &design of multistoried structure the load combination is taken from IS1893:2002 CODE & the building is designed for modal analysis.

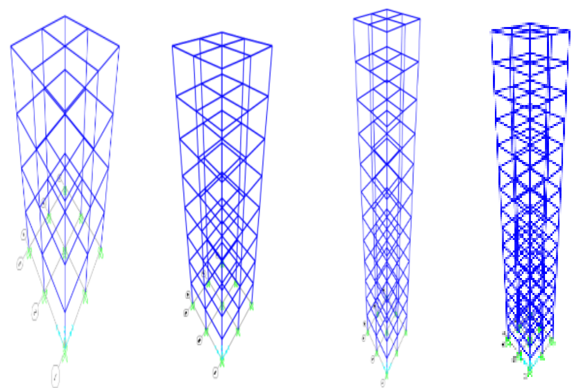

Fig. 2. 3D framed structure.

To perform nonlinear dynamic analysis, the model of 4-, 8-, 12-,16- storied building structure is taken and described as- bay size 5m X 5m with the same height of each floor 3.5 m, as per IS code Zone - V, with zone factor = 0.36, importance factor =1.5, response reduction factor R= 5, are followed with M40 grade of concrete and grade of steel is Fe500. The type of building is a hospital commercial building, located in Delhi, India with a high seismic region is taken for design and analysis. Fig.1 & Fig. 2 shows a 2D and 3D model of 4 types of structure.

The proposed model is 3D regular model, the irregularities in plan, mass, vertical geometry are not taken in reflection. In his study strong column – weak beam concept is adopted therefore the design of the structure should satisfy the Eurocode 8 ductility condition at joint of beam and column $4.4.2.3

$$\sum MRc \geq 1.3 \sum MRb \tag{1}$$

Where ∑MRc and ∑MRb are the sums of the design values of the moments of resistance of the columns and beam framing the joint. Over strength factor of (αu/α1) = 1.3 for multibay and multistory structures as per Eurocode 8. The stiffness decreases by increasing the height of the structure (F.Dorri et.al 2019) [8] The reduction of stiffness along the height of the building is followed by the method by E. Mirinda and Reyes (2002) [9]. For accurate distribution of lateral stiffness, a decreasing stepwise distribution of lateral stiffness which followed parabolic stiffness distribution is used in the current study. The lateral stiffness of the structure changes for every three stories.

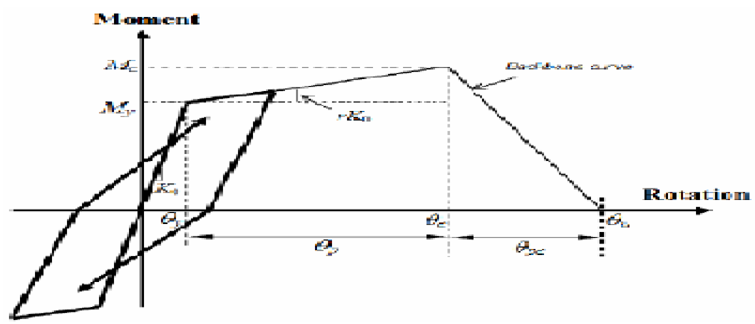

Fig. 3. Modified Takeda Hysteresis and backbone curve [10].

To simulate the cyclic behavior and to check stiffness degradation due to repeated earthquake in RC building this Study uses a modified Takeda hysteresis curve (fig.3) as proposed by Zarein and krawinkler (2009) [10]. For the nonlinear analysis, the frames are modeled with user-defined or with default hinges, there is no effect on base shear, yielding state of the structure by application of user-defined or default hinges. The model with default hinges emphasizes a ductile beam behavior in which a strong column weak beam mechanism is followed and the first failure occurs in a beam. (Mehmet Inel and HayriBaytanOzmen) (2006) [11]. Based on a study by Mehmet default hinges properties in SAP2000 [12] are suitable for modern code-compliant buildings.

A 3D model of the structure is prepared in SAP2000 to carry out nonlinear Time history analysis. column and beam elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of column and beam. For defining the plastic hinges, default hinge property is used and described in FEMA-356 [13] or (ATC-40) and shown in fig.4 five point A, B, C, D, E define the force deformation behaviour of plastic hinges and describe the IO limit for primary and secondary element.LS and CP limit for elements. The default hinges for column assigned as P-M2-M3 and for beam M3 hinges are assigned. Also, the default hinges model is preferred due to its simplicity in application.

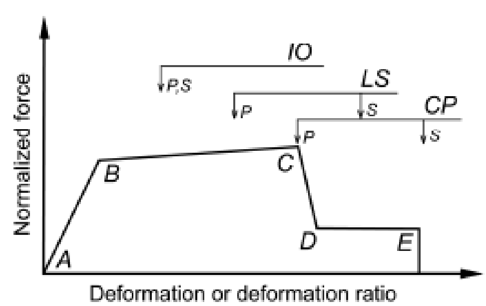

Fig. 4. force -deformation Relationship of a plastic hinge or element deformation acceptance criteria [13].

2.2. Seismic input method

To study the effect of a repeated earthquake based on Hartzigeorgiou's(2010) [7] method, The complete list of the repeated earthquake was downloaded from the strong motion database of the pacific earthquake engineering Research (PEER) center is shown in Table 2. This real seismic sequence is also used by Hartzigeorgiou's (2010) [7] for nonlinear analysis of RC frame structure. These records are compatible with the hard rock soil. Every earthquake ground motion record from the PEER database is a single ground motion record. To analysis, the structure for the study of the effect of the repeated earthquake a gap of 100 seconds between two sequential earthquake events is applied. The gap of 100 seconds with zero acceleration ordinate is provided. In100s the structures come to rest condition due to internal damping.

The selected combination of repeated ground motion with 100 s gap is presented in fig 5,6,7. To perform Dynamic Time history analysis and dynamic push-over analysis This study adopts the combination of a real earthquake with the mainshock followed by a small aftershock in two or three events.

For the study purpose, three cases are taken case-1, case-2, case -3. In case -1 single earthquake is applied to the structure. In case -2 -two sequential earthquake shock is applied on structure with a time gap of 100 secs as shown in fig.5 & Fig. 6. Case no-3 with three earthquake shocks with a time gap of 100 secs in between three GM.as shown in Fig. 7.

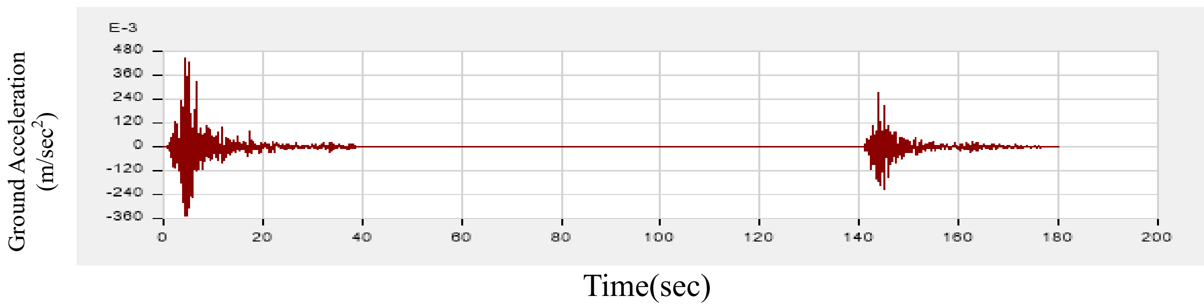

Fig. 5. Ground motion of Chalfant valley earthquake 21/07/1986 – 2 GM with 100 s gap.

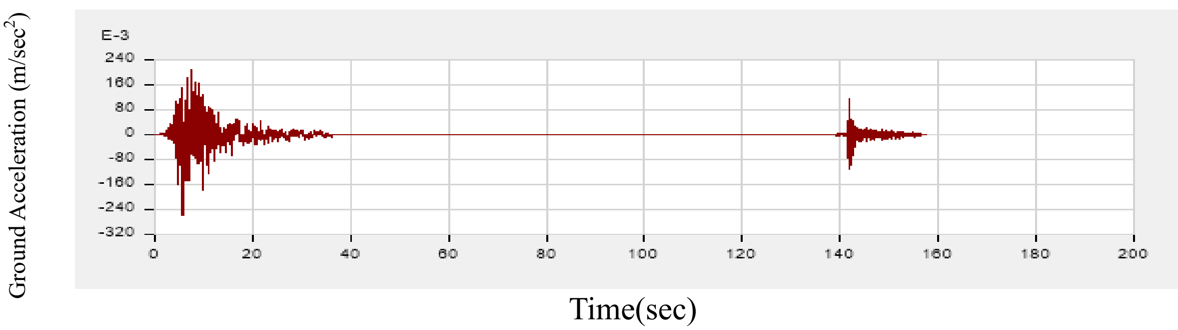

Fig.6. Imperial valley earthquake 15/10/1979 - 2 GM with 100 s gap.

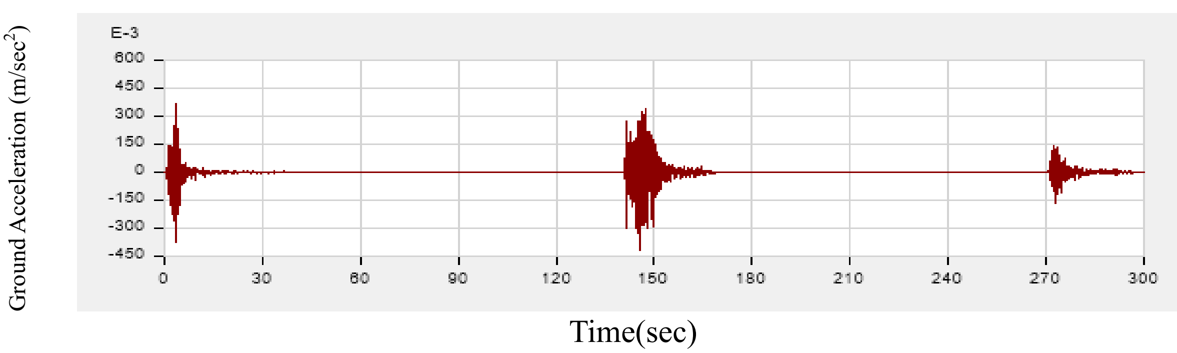

Fig.7. Ground motion of mammoth lake earthquake 25/05/1980 - 3 GM with 100s gap.

2.3. Scaling of ground motion

Moreover, all the ground motions used in this paper will be scaled to the spectral acceleration ordinate at the fundamental period of the structures, Sa (T1) as recommended by Vamvatsikos D and cornell (2002) [14]. For scaling purposes, the fundamental time period of the structure is calculated using modal analysis and tabulated in the Table 1. The different scale factors are used and list out in Table 3. The response spectrum used in this study is the design spectrum of IS code 1893(part 1): 2010 for hard rock with PGA =0.25 g with 5% damping. Also, the structure has been designed for gravity load including a combination of dead load, wall load, slab load for different load combinations as per IS 1893:2002 [3]. Before Appling earthquake load the structure is checked for stability.

The maximum inelastic displacement is obtained by nonlinear time history analysis, which is carried out on a 3D model exited by 7 types of seismic sequences. While the ductility $\mu_d$is defined in term of the maximum displacement μmax and the yield displacement **μy**

$$\mu d = \frac{\mu max}{\mu y} \tag{2}$$

The yield displacement is calculated using push-over analysis of structure with SAP2000 and maximum displacement of structure for different single and multiple earthquakes are calculate with nonlinear dynamic time history analysis method.

Table 1
Modal time period.

Building	Total height (m)	Modal time period		
		1	2	3
4 storied	14	1.0	1.0	0.89
8 storied	28	1.596	1.596	1.37
12 storied	42	2.355	2.355	1.956
16 storied	56	3.120	3.120	2.493

3. Result and discussion

The present paper focuses on investigating the influence of repeated earthquakes on multistoried structures, for this purpose, three types of ground motion cases are applied on 4-,8-, 12-,16-storied.

buildings. **Case-I** -single earthquake, a total of 17 earthquake shocks are applied. **Case-2 --** 1 major earthquake + 1 aftershock, total 5 repeated earthquakes is applied on structure. **Case-3** – 1 major earthquake +2 aftershock, total 2 repeated earthquakes are applied on structure. In this case, major shock with larger PGA is considered. To study the effect of repeated earthquake selected GM is taken from Table 2 with different PGA from 0.15 to 0.734 and magnitude from 4.06 to 15.94. For the application of GM, the first shock is a major shock and aftershocks are minor shocks that are applied on the 4- type of building i.e. 4-,8-,12-,16- storied building. Table 1 states about a modal time period. The result in terms of displacement and drift is calculated for 3 cases and for 24 GM.

This work observes the effect of a repeated earthquake on the multistoried structure and investigates the result in terms of horizontal displacement, drift, permeant displacement, formation of plastic hinges.

Table 2
Ground Motion Data.

S.No	Seismic Sequence	Station Name	Date	Rrup	Magnitude	PGA	time	Mechanism
1	mammoth lakes04	Convict creek	25-05-1980	5.32	5.7	0.363	40.0	strike-slip
	mammoth lakes01	Convict creek	25-05-1980	6.63	6.06	0.341	30.0	Normal Oblique
	mammoth lakes02	Convict creek	25-05-1980	9.46	5.69	0.138	30.0	strike-slip
2	mammoth lakes10	Convict creek	07-01-1983	6.5	5.34	0.148	40.0	strike-slip
	mammoth lakes11	Convict creek	07-01-1983	7.7	5.31	0.15	40.0	strike-slip
3	Chalfant Valley-02	Zackbrothers	21-07-1986	7.58	6.19	0.447	40.0	strike-slip
	Chalfant Valley-01	zack brothers	20-07-1986	6.39	5.77	0.2719	40.0	strike-slip
4	coalinga05	oil city	22-07-1983	8.46	5.77	0.734	21.2	Reverse
	coalinga04	oil city	09-07-1983	9.53	5.18	0.3	20.6	Reverse
	coalinga01	oil city	02-05-1983	8.41	6.36	0.3	58.2	Reverse
5	Imperial Valley 06	Holtville P.O.	15-10-1979	7.5	6.53	0.211	37.9	strike-slip
	Imperial Valley 07	Holtville P.O.	15-10-1979	10.58	5.01	0.115	19.6	
6	Whittier Narrows 02	San Marino	04-10-1987	12	5.27	0.147	22.0	Reverse Oblique
	Whittier Narrows 01	San Marino	01-10-1987	15.94	5.99	0.118	40.0	Reverse Oblique
7	"Managua_ Nicaragua-01"	Managuaesso	23-12-1972	4.06	6.24	0.372	45.7	strike slip
	"Managua_ Nicaragua-02"	"Managua_ ESSO"	23-12-1972	4.98	5.2	0.15	47.9	strike slip

3.1. Maximum horizontal displacement

The maximum horizontal displacement for single, double & triple events is presented in fig.8 to 15. In this work above ground motion records are applied with a combination of case1, case 2, case3. For example, fig 5 shows two GM of Imperial valley is applied on structures with a time gap of 100 s. In the applied Ground Motion data first GM is a major earthquake with PGA 0.211and second earthquake is with PGA 0.115 considered as a case-2. Between two consecutives earthquakes a time gap of 100 s is applied to come to the structure to rest condition and find the permanent displacement and position of plastic hinges. The result of case 2 ground motion on structures are shown in fig.8, the fig shows the displacement of a16 storied structure under the effect of a single earthquake and sequential earthquake. This shows that the displacement is increased for the repeated earthquake compared to a single earthquake by a10 to 20 u%, similar results are shown by other ground motions also. It should be noted that the displacement is increasing with no of shock and the Figs. 8-11 is absolutely identical for a single and double event. In addition, another repeated earthquake combination, which is note as case -3 is inspected and the result is presented in Figs 12-15 which represents the displacement is increasing with no. of shock.

Table 3
Ground Motion with Steps and Scale Factor.

SR.NO.	NAME OF EVENT	STEPS	DT	SCALE FACTOR			
				4 STORIED	8 STORIED	12 STORIED	16STORIED
1	mammoth lakes 04	8000	0.005	6.88	26.43	51.675	94.99
2	mammoth lakes 01	5999	0.005	5.72	4.41	11.58	20.315
3	mammoth lakes 02	5999	0.005	6.91	14.8	58.5	114.606
4	mammoth lakes 10	8000	0.005	5.72	13.989	43.648	82.0186
5	mammoth lakes 11	8003	0.005	10.01	34.86	102.118	185.7134
6	Chalfant Valley-02	7999	0.005	2.45	3.29	9.277	19.34
7	Chalfant Valley-01	7973	0.005	5.856	13.15	32.21	55.59
8	Coalinga 01	11631	0.005	1.69	4.11	12.53	23.219
9	Coalinga 05	4248	0.005	2.669	6.066	14.26	20.55
10	Coalinga 04	4120	0.005	9.857	21.61	49.08	87.79
11	Imperial Valley 06	7573	0.005	2.915	6.29	5.928	5.695
12	Imperial Valley 07	3925	0.005	20.2129	79.25	189.4184	279.36
13	Whittier Narrows 02	4399	0.005	10.819	29.16	75.31	160.92
14	Whittier Narrows 01	8000	0.005	21.05	34.59	97.43	212.59
15	"Managua_ Nicaragua-01"	9139	0.005	3.084	6.024	6.63	15.73
16	"Managua_ Nicaragua-02"	9577	0.005	4.561	4.88	9.39	20.128

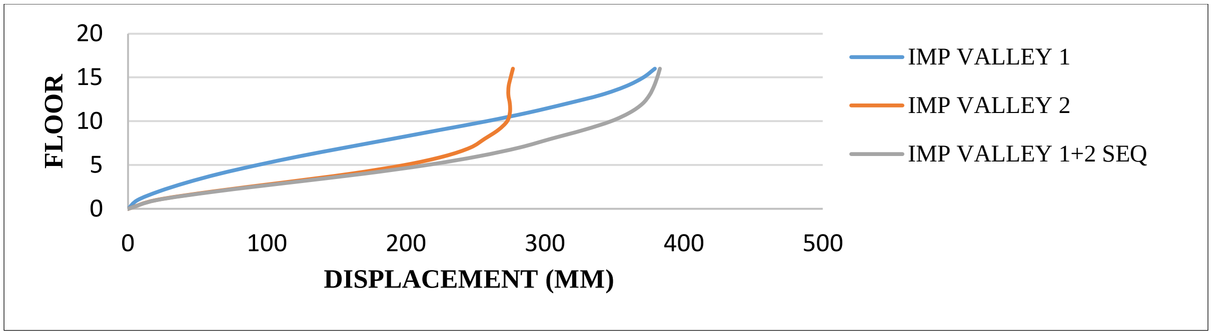

Fig. 8. Maximum Horizontal Displacement for 16 storied building under 2 repeated Imperial Valley earthquake (15/10/1979).

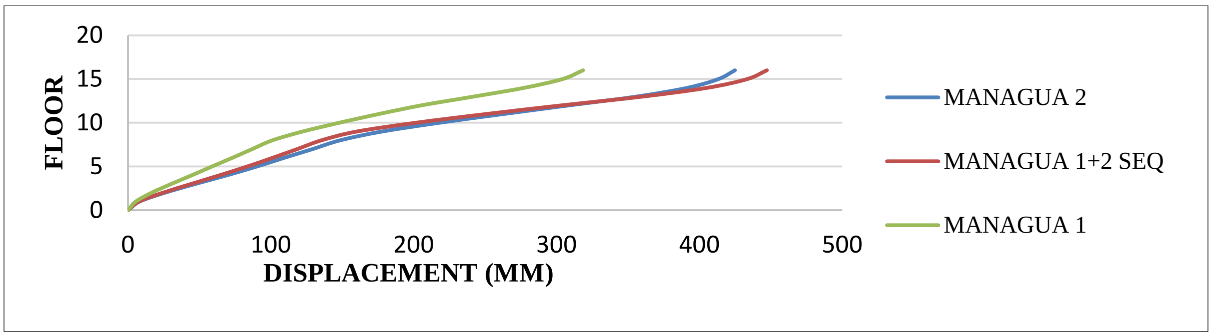

Fig. 9. Maximum Horizontal Displacement for 16 storied building under 2 repeated Managua Nicaragua earthquakes (23/12/1972).

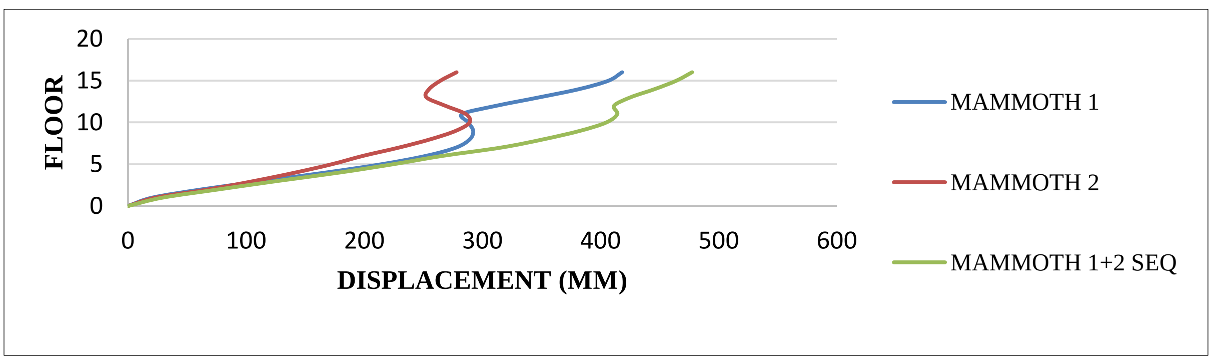

Fig. 10. Maximum Horizontal Displacement for 16 storied building under 2 repeated Mammoth lakes earthquakes (07/07/1983).

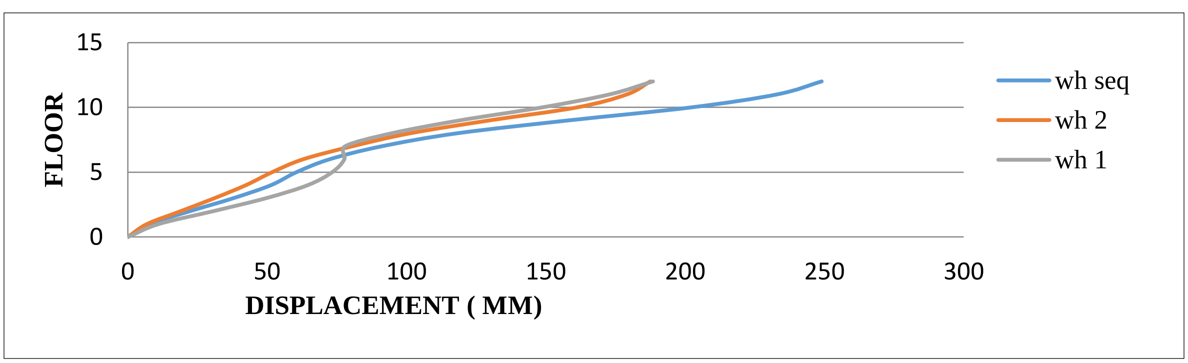

Fig. 11. Maximum Horizontal Displacement for 12 storied building under 2 repeated Whittier Narrow earthquakes (04/10/1987).

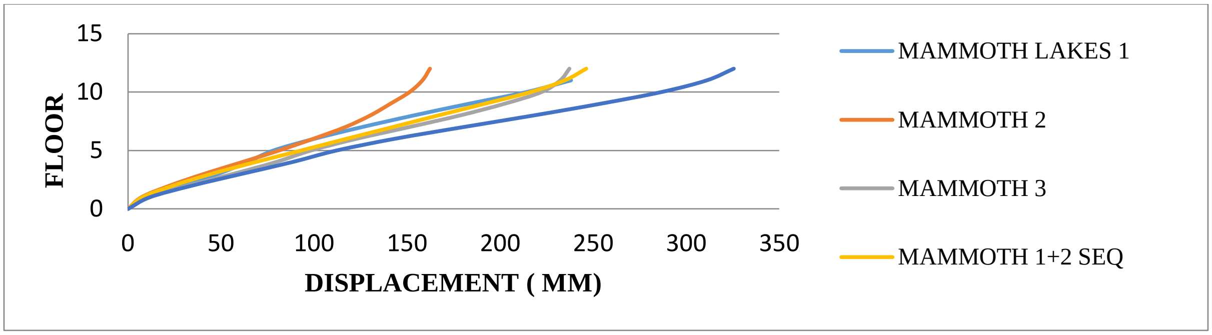

Fig. 12. Maximum Horizontal Displacement for 12 storied building under 3 repeated Mammoth lakes earthquakes (25/05/1980).

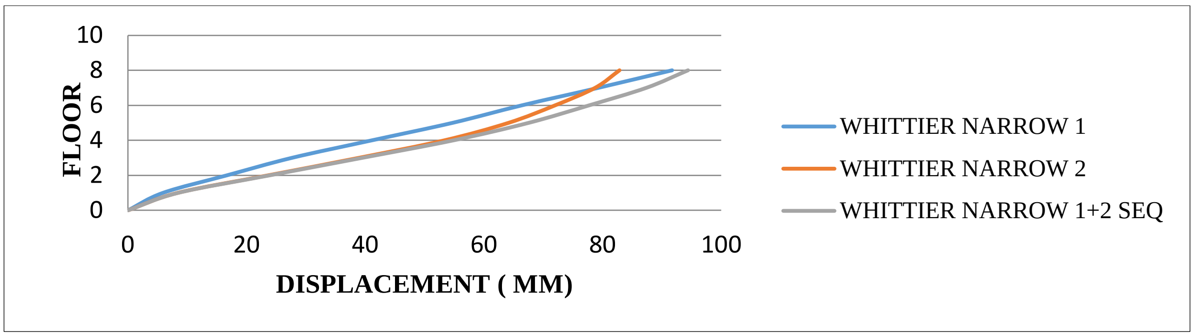

Fig. 13. Maximum Horizontal Displacement for 8 storied building under 2 repeated Whittier Narrow earthquakes (04/10/1987).

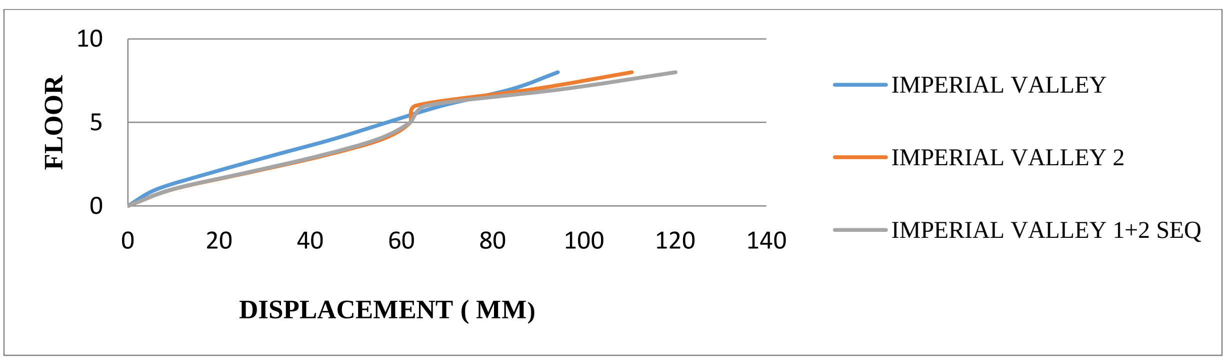

Fig. 14. Maximum Horizontal Displacement for 8 storied building under 2 repeated Imperial Valley earthquakes (15/10/1979).

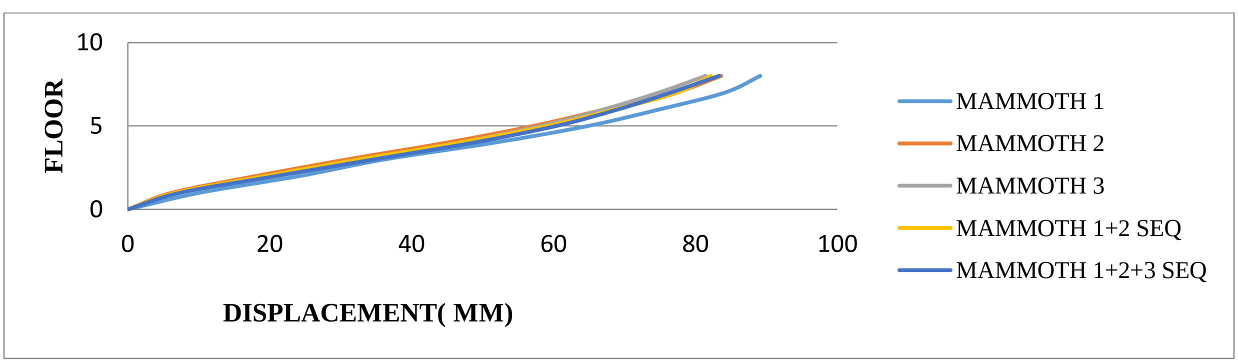

Fig. 15. Maximum Horizontal Displacement for 8 storied building under 3 repeated Mammoth Lakes earthquakes (25/05/1980).

The inelastic behavior of the studied RC structures which are subjected to above mentioned seismic sequences founds the following parameters. It is found that due to repeated earthquake horizontal displacement are increased at each floor level and it is maximum at the top floor. Also, there is a permanent displacement after yield displacement of structure and this permanent displacement is increase after each shock of an earthquake. Due to repeated earthquake accumulation of permanent displacement is taking place and after every sequential earthquake this permanent displacement and P-Delta load on structure increases, therefore, the addition of P-delta force and earthquake force increase displacement in structure. After the double event of the earthquake 10 to 15 % displacement is increased. After the triple event, 15 to 20% displacement is increased as shown in above Fig 12,15. This result shows attention is required for the analysis and design of multistoried structures subjected to repeated earthquakes.

3.2. Interstorey drift ratio (IDR)

IDR is the maximum relative displacement between two consecutive floors normalized to the storey height. Interstory drift ratio is a significant engineering parameter and pointer of structural performance. The different codes give different criteria to check the performance of structure depends on IDR. As per FEMA 356 [13] IDR> = 4% then the structure is considered as collapse. The investigation from the analysis result and the fig shows the IDR due to repeated earthquakes is increases. IDR values for single, double, triple events or sequential earthquake indicates that the interstory drift ratio is increased as the number of shocks increases and leads to larger IDR values compared to a single earthquake event. This leads that the displacement and story drift are increase with a repeated earthquake.

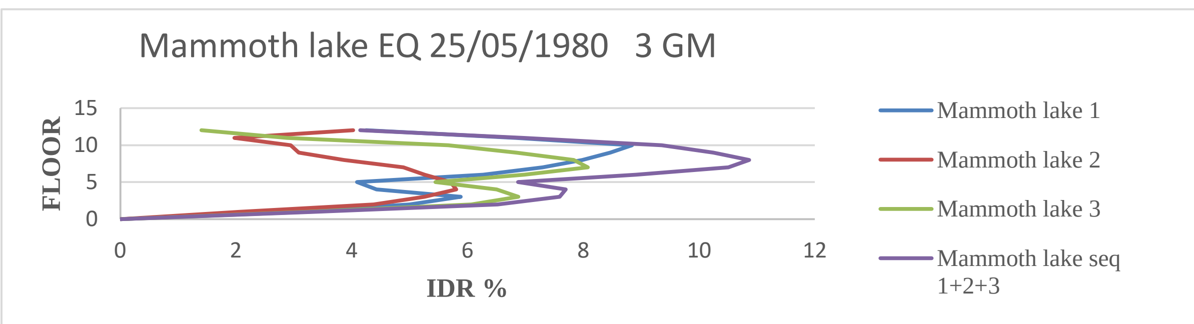

Fig. 16. Interstorey Drift Ratio for 12 storied building under 3 repeated Mammoth Lakes earthquakes (25/05/1980).

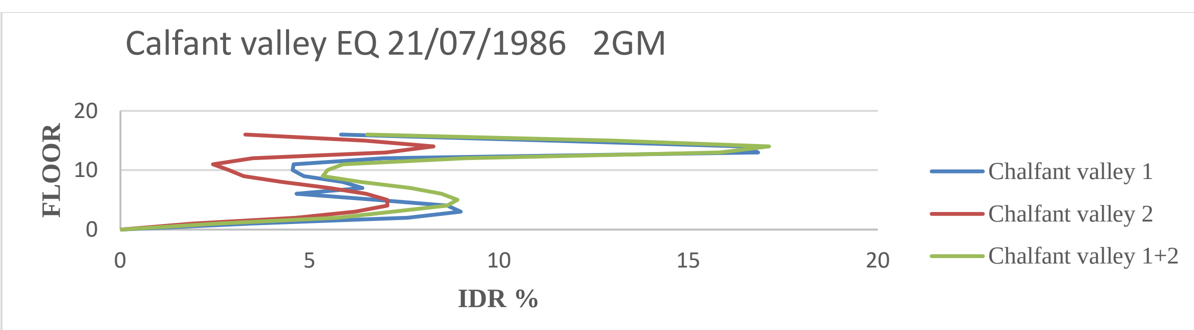

Fig. 17. Interstorey Drift Ratio for 16 storied building under 2 repeated Chalfant Valley earthquakes (21/07/1986).

3.3. Development of plastic hinges

The pattern of formation of Plastic hinges under the single earthquake and the formation of plastic hinges under the repeated earthquake are different. From the study of imperially valley and whiter narrow earthquake, it should be noted that due to repeated earthquake distribution of plastic hinges are different than the single major earthquake. Due to repeated earthquake formation of plastic hinges are increased in number and the state of hinges is changed from B-Io- LS –C.

4. Conclusions

This paper focuses on the inelastic behavior of RC frame structures under repeated earthquakes. The structure is designed for gravity and earthquake load. A detailed study of the structure leads to the following conclusions-

1) Due to Repeated earthquakes the horizontal displacement is increased by 15 to 20 % as compared to the single earthquake. This increased displacement is taken into account for the design of multistoried structures. Therefore, traditional design method is reexamined under the repeated earthquake effect, since the effect of the repeated earthquake phenomenon cannot be unnoticed and to control displacement, stiffness of column should be increased.

2) The permanent displacement is increasing by 5 to 10 % at the end of every aftershock earthquake and at the end, the P-Delta effect is also increased on the structure. This effect leads to revising the design procedure with consideration of strength and stiffness degradation due to the repeated earthquake effect. This leads to recalculate the displacement with higher stiffness in a column.

3) The formation of plastic hinges is different than the hinges formed by a single earthquake shock. The location and number of plastic hinges are changes with PGA of ground motion, no of earthquake shock. This leads to a change in the sectional dimension, ductility in beam, plastic hinge length, and design procedure.

4) The IDR values are within the 4% limit for a single earthquake but the IDR values are increased for a repeated earthquake this indicates that attention is required regarding structural modeling, analysis procedure, and frame performance.

5) The increased displacement, interstory drift ratio, and formation of plastic hinges lead to revising the design procedure to build a safe and flexural structure.

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