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Performance of RC Frames with Mass and Stiffness Irregularity under Sequential Ground Motion

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Abstract. The seismic design codes consider only single earthquake events, ignoring the possibility of multiple earthquakes. In case a structure suffers damage during first event and prior to its repair more aftershocks occur the structure may collapse. An elaborative directive study on the inelastic seismic response of 11storey RC (2-D) moment-resisting frame having mass irregularity at sixth floor, and stiffness irregularity in sixth story has been done has been done. The frame has been examined under a sequence of a main shock followed by six aftershocks. Time history synthetically generated from the design response spectrum explained in IS-1893 Pt II: 2016 has been taken for non linear dynamic analysis with the help of SAP 2000 software. A comparison is done to understand the inelastic response of the frame taking into account the location of plastic hinges, maximum top displacement, residual top displacement, and storey drift. It is seen that the structure with the stiffness irregularity is the most vulnerable amongst all.

Keywords: Non-linear time history analysis, sequential ground motion, seismic performance, stiffness irregularity,

1. Introduction

In accordance to the past studies and research works, it is seen that the earthquakes always hit a place in sequences over a period of some hours/days - that is the main shock is accompanied by a few/many aftershocks. The main shock is generally having the highest magnitude accompanied by aftershocks of varying magnitudes. In this paper, stiffness irregularity as well as mass irregularity has been introduced on the sixth floor/story by increasing the height and mass separately and together.

Many types of research are present with these considerations in mind where they have tried to study the consequences of main shock as well as aftershocks with single as well as multiple degrees of freedom. It is seen that since faster calculations are possible in SDOF, it is extensively used for the detailed study of the dynamic behaviour of structures that have been exposed to sequential earthquakes. SDOF gained higher popularity as stated by Amadio et al; [2], Hatzigeorgiou GD et al; [3], George D et al; [4], Zhai et al; [5], [6]; Zhang et al; [7]. A detailed study on regular, and irregular frames (3-, 6-, 9- storey) was conducted. The results exhibited that for both of frames there was an increment in the seismic responses [8]. The non-linear analysis was performed and the inelastic response of eight RC frames under the influence of five actual as well as 40 artificial seismic sequences was investigated. The ductility demand using an empirical formula was then calculated. It was found out that there were a higher structural response and cumulative damage under the influence of repetitive earthquakes as compared to a single event of the earthquake [9]. Faisal et al.[10] studied about the ductility demands owing to the effects of repetitive ground motions of 3,6,12,18 storey RC structures comprising of concrete frames of inelastic nature. He deduced that on being exposed to sequential ground motions, there was a remarkable increase in the ductility demands. Hatzivassiliou and Hatzigeorgiou [11] did a detailed study on four buildings (2 regular, and 2 irregular) to study the outcome of sequential ground motions found a remarkable increase in seismic demands. They also inferred that the siting configurations significantly affected the ductility demands of the structure. Loulelis et al. (2012)[12] employed the technique of incremental dynamic analysis and did a comprehensive study on the effect of artificial and real seismic events on the performance of SMRF. He concluded that repetitive ground motions led to an increase in the number of damages in the structures as against a single episode of the earthquake. The modern RC structures were studied which were modeled as MDOF systems to examine the vulnerability of the structures on being exposed to a series of earthquakes. The fragility curves were calculated with the help of incremental dynamic analysis. The conclusion drawn from the study revealed that there was an increment in the collapse fragility of the structure when it was exposed to a major main shock [13]. Goda et al. [14] used the artificial seismic sequences along with the real ones to examine the effects of aftershocks on the inelastic SDOF systems keeping in mind the ductility demands. He concluded that even the artificial main shock–aftershock sequences can be considered as a

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substitute for the real ones since they were very similar to the ductility demands of artificial sequences. Hosseinpour and Abdelnaby [15] studied the RC frames and examined the fragility curves under different parameters for multiple earthquakes. The different parameters taken into account were – damage from past events, the intensity of earthquake, vertical earthquake component, the region of earthquake, number of storey. It was observed that these parameters remarkably affected the fragility curves. Abdelnaby et al.[16] carried out research to find out the behavior of reinforced concrete structures on being subjected to multiple earthquakes. A tool was developed to model the damages employing numerical analysis.

This study investigates the seismic behavior of the regular eleven storey RC frame designed as per IS1893:2016 (Type-1), with mass irregularity on sixth floor (Type-2), with stiffness irregularity in sixth storey (Type-3), with mass and stiffness irregularity (Type-4). These frames are exposed to a sequence of synthetically generated main shock and aftershocks events compatible to IS (1893:2016) response spectrum. A comparison is made between the performances of the regular frame and frames with irregularity.

2. Building frame model

The middle frame of the building is selected for study as shown in fig [1B] includes four bays of 5 m width in each direction, in seismic zone V and soil type taken is medium according to IS code. Four models are considered to study the seismic response subjected to sequential ground motion where one is regular and other three are irregular.

Introduced stiffness irregularity is due to increasing the storey height from 3.2 to 4.5m and Mass irregularity owing to increasing live load by 100%. All the four frames (Type1 to Type4) are having column size as 500x500 mm^2 (foundation to first floor), 400x400 mm^2 (first floor to terrace) and beam size as 230x450 mm^2. Material properties are assumed to be 500MPA for the yield strength of transverse and longitudinal steel and 25MPa for the concrete compressive strength. The live load (LL) is taken as 5kN/m where as the dead load (DL) is taken as 12.5kN/m and the partition wall load is 7.5kN/m.

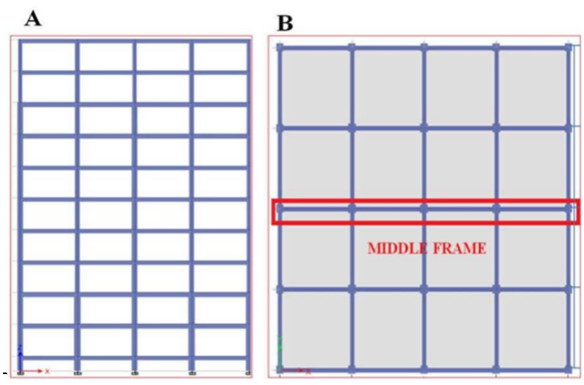

Fig. 1 A Elevation detail of (G+10) storey RC Regular Frame; B Plan view of the building

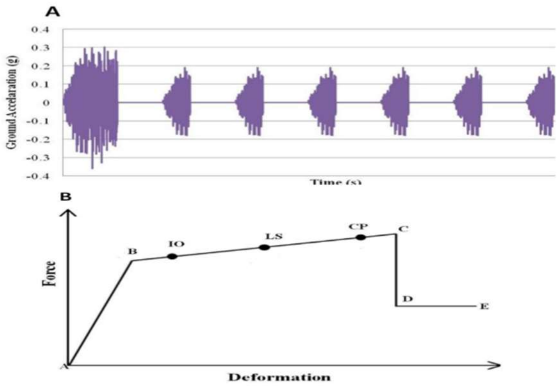

Fig. 2ATime history compatible to IS1893:2016
B Force deformation relationship of plastic hinge

3. Sequential ground motion

Making use of the software called Seismo Signal, there is an artificial generation of compatible time history of earthquakes, repetitive ground motion inputs compatible to the response spectrum (IS1893:2016) have been considered. The repetitive earthquakes taken in this study are a combination of main shock (MS) accompanied by six aftershocks named as (1STAS), (2NDAS), (3RDAS), (4THAS (5THAS), (6THAS). Each aftershock is calculated to be 0.66 times of the main shock PGA. Scaling of earthquakes to three different PGAs (0.36g (Case1), 0.4g (Case2), 0.45g (Case3)) is done. The time duration for the main shock is 30s, whereas the time duration for each aftershock is taken as 15s. To bring the structure to rest, an acceleration of zero amplitude and 100s time lapse is given in between the two consecutive events of earthquake as depicted in figure (2A).

4. RESULTS AND DISCUSSIONS

4.1 Seismic behavior

A non-linear time history dynamic analysis (NDA) is being conducted on the regular/irregular frames as depicted in fig [1A-1B] on being subjected to repetitive earthquakes with three main shocks (PGAs 0.36g, 0.4g, 0.45g,) accompanied by six aftershocks as explained using figure[2A]. Parameters discussed below are related to the response of regular/irregular frames under the seismicevents.

4.2 Maximum horizontal displacements

The horizontal transient displacement is the maximum during the last aftershock of each sequential seismic loading as shown in figures 3A, 3B, 3C and tables 1, 2, 3. It goes on increasing during every aftershock of earthquake except during first aftershock attributed to the permanent displacement and its accumulation during each aftershock. Type-1 regular frame and type-2 irregular frame both survive under main shocks 0.36g, 0.4g and their subsequent aftershocks. Though, they withstand the main shock of 0.45g and their five aftershocks that follow, yet fail to survive the last aftershock. The Type-3 irregular frame withstands the sequential loading of main shocks 0.36g, and 0.4g.

Also the frame survives during the main shock 0.45g and its four aftershocks but fails during the fifth one. Type-4 irregular frame sustains the main shocks and all aftershocks of 0.36g and 0.4g. In the case of 0.45g, this irregular frame also survives the main shock and four aftershocks leading to collapse of the structure in the fifth aftershock.

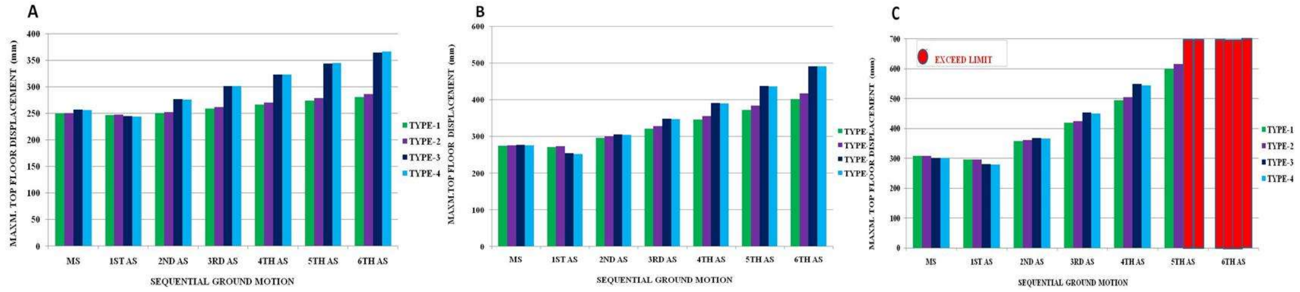

Fig.3 Maximum transient top floor displacement of different type frame (Type-1, Type-2, Type-3, Type-4) for seismic sequences for A (Case1), B (Case2), C (Case3)

Table-1 Maximum transient top floor displacement (mm) for case-1

CASE-1	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-1	249.80	246.60	250.80	258.90	266.60	273.70	280.50
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	250.50	247.20	252.70	261.80	270.40	278.40	286.20
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	257.00	244.70	276.60	300.90	322.60	343.50	364.70
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	256.40	243.40	276.00	300.80	322.80	344.20	366.20

Table-2 Maximum transient top floor displacement (mm) for case-2

CASE-2	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-1	274.10	271.30	296	321.10	346.00	372.30	401.70
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	275.90	273.30	300.10	327.40	354.80	384.10	417.40
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	276.50	254.30	305.30	348.50	390.70	437.30	491.00
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	275.80	252.30	303.60	347.10	389.60	436.50	490.60

Table-3 Maximum transient top floor displacement (mm) for case-3

CASE-3	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-1	307.40	296.10	358.10	418.80	495.10	601.50	(EXCEEDS LIMIT)
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	308.40	296.70	361.50	424.60	505.70	616.80	EXCEEDS LIMIT)
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	301.40	280.90	368.80	453.20	549.00	(EXCEEDS LIMIT)	EXCEEDS LIMIT)
MAXM. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	307.40	296.10	358.10	418.80	495.10	(EXCEEDS LIMIT)	EXCEEDS LIMIT)

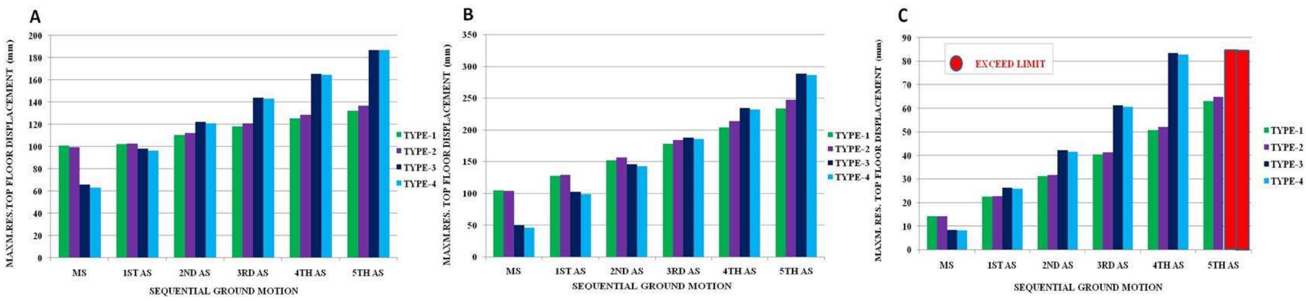

Fig.4 Maximum residual top floor displacement of different type building (Type-1, Type-2, Type-3, Type-4) for seismic sequencer for A (Case1), B (Case2), C (Case3)

4.3 Maximum residual horizontal displacements

Maximum residual horizontal displacement found increasing with each subsequent shock under the three sequential seismic loadings of 0.36g, 0.40g, and 0.45g. This keeps on adding to the prior permanent displacement and reaches a stage that leads to the collapse of the structure as depicted in the Figures 4A, 4B, 4C and tables (4, 5, and 6).

4.4 Maximum transient storey drift:

All the building codes take the cognisant of maximum story drift an important response quantity, which is obtained from maximum relative transient floor displacements of a story under seismic loading. It can be seen from the figures-5 that the storey drift keeps on gradually increasing with the advent of each aftershock. In case 1(as shown in fig 5A and Table 7), for type 1 and 2, the maximum storey drift is observed in the 6th storey for the main shock and shifts to 3rd storey in the 1st aftershock. But for the subsequent aftershocks, it is seen that the maximum storey drift is in 4th storey. For type 3 and 4, it is in the 6th storey during the

Table- 4 Maximum residual top displacement (mm) for case-1

CASE-1	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURH AFTER SHOCK	FIFTH AFTER SHOCK
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR YPE-1	100.70	102.40	110.50	118.30	125.40	132.20
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	99.72	102.90	112.10	120.70	128.70	136.60
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	65.82	98.07	122.50	144.30	165.30	186.70
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	63.23	96.24	121.10	143.30	164.70	186.80

Table -5 .Maximum residual top displacement (mm) for case-2

CASE-2	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURH AFTER SHOCK	FIFTH AFTER SHOCK
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR YPE-1	104.10	127.00	152.10	177.30	203.80	233.30
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	103.80	129.10	156.50	184.10	213.60	247.10
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	49.57	101.80	145.40	187.80	234.30	287.90
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	45.92	98.60	142.50	185.20	232.00	286.00

Table 6 Maximum residual top displacement (mm) for case-3

CASE-3	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURH AFTER SHOCK	FIFTH AFTER SHOCK
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR YPE-1	100.90	162.90	223.80	294.70	380.90	487.30
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-2	99.40	164.60	228.20	301.90	391.70	502.80
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-3	41.52	129.70	214.20	309.60	423.80	(EXCEEDS LIMIT)
MAXM. RES. TOP FLOOR DISPLACEMENT (mm) FOR TYPE-4	38.00	125.40	209.00	303.40	416.40	(EXCEEDS LIMIT)

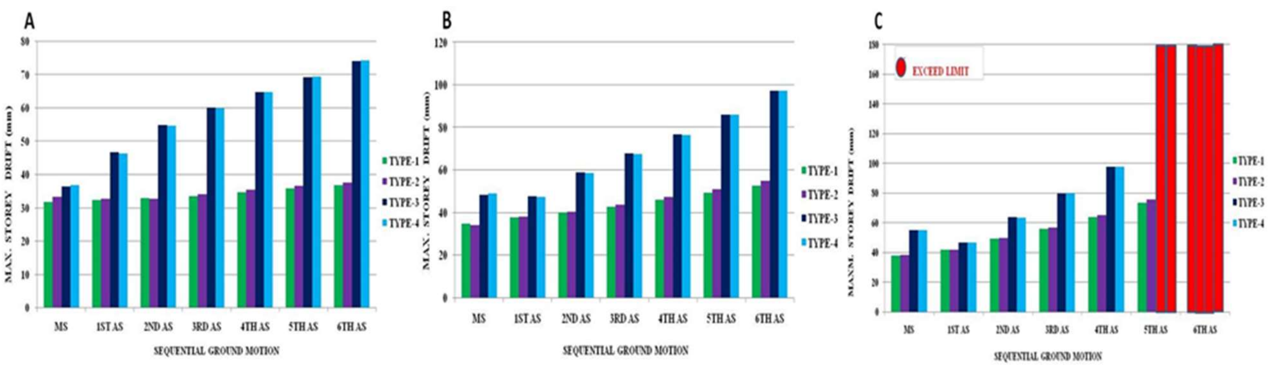

Fig.5 Maximum transient storey drift of different type building (Type-1, Type-2, Type-3, Type-4), seismic sequence for A (Case1), B (Case2), C (Case3)

main shock and all its aftershocks. In case 2(as shown in fig 5B and Table 8), for type 1, the location for maximum storey drift is 6th storey during the main shock, it shifts to the 3rd storey in the subsequent three aftershocks and again moves to 4th storey during last three aftershocks. The frames withstand the aftershocks and don't collapse as per the limit mentioned in the recommendations of FEMA 356[20]. For type 2, the maximum storey drift is observed to be in 6th storey for the main shock, moves to the 3rd storey for the first two aftershocks and thereafter it is observed to be in the 4th storey. Subsequently, for frames type 3 and 4, the maximum storey drift is observed in the 6th storey for the main shock and all the aftershocks thereafter. Type 1 of case 3(as shown in fig 5C and Table 9), gives the maximum storey drift in the 4th storey during the main shock, which shifts to the 3rd storey during the subsequent five aftershocks. The frame collapses in the last aftershock. For type 2 frame, the maximum storey drift is seen in the 4th storey during the main shock and further shifts to 3rd storey in the first four aftershocks while changing to 5th storey in the fifth aftershock. The frame does not survive the last aftershock. For frames of type 3 and 4, it is observed that the maximum storey drift is in 6th storey during the main shock and its four aftershocks but the frame fails to withstand the fifth aftershock.

4.5 Maximum permanent storey drift

This is also a crucial parameter that pertains to the everlasting damage to a frame when it is subjected to sequential seismic loading. The figures 6-A, B, C clearly exhibit that there is an increment in the residual storey drift due to each of the aftershocks followed by main shock. For Cases 1 and 2 (as shown in fig 6A and 6B and Table 10 and 11), types 1 and 2, the maximum permanent inter storey drift is observed at the 7th storey for the main shock which later shifts to 6th storey for remaining all the aftershocks. For case 3(as shown in fig 6C and Table 12), types 1 and 2, the maximum permanent inter storey drift is seen in the 8th storey for the main shock, gradually changes to 6th storey in the next five aftershocks and leads to failure in the last aftershock. Types 3 and 4 for case 3 exhibit the maximum permanent inter storey drift in 6th storey for the main shock and the next four aftershocks but fails during the fifth aftershock.

Table-7 Maximum transient storey drift (mm) for case-1

CASE-1	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXIMUM STOREY DRIFT(mm) FOR TYPE-1	31.70	32.32	32.75	33.46	34.59	35.69	36.66
MAXIMUM STOREY DRIFT(mm) FOR TYPE-2	33.30	32.68	32.69	34.03	35.35	36.53	37.56
MAXIMUM STOREY DRIFT(mm) FOR TYPE-3	36.30	46.60	54.80	60.00	64.60	69.20	74.00
MAXIMUM STOREY DRIFT(mm) FOR TYPE-4	36.70	46.30	54.60	59.90	64.60	69.30	74.10

Table- 8 Maximum transient storey drift (mm) for case-2

CASE-2	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXIMUM STOREY DRIFT(mm) FOR TYPE-1	34.80	37.55	39.90	42.58	45.80	49.10	52.70
MAXUM STOREY DRIFT(mm) FOR TYPE-2	34.10	38.18	40.47	43.60	47.20	50.80	54.80
MAXIMUM STOREY DRIFT(mm) FOR TYPE-3	48.20	47.50	58.80	67.70	76.60	86.00	97.10
MAXIMUM STOREY DRIFT(mm) FOR TYPE-4	48.80	47.30	58.50	67.50	76.30	86.00	97.10

Table-9 Maximum transient storey drift (mm) for case-3

CASE-3	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK	SIXTH AFTER SHOCK
MAXIMUM STOREY DRIFT(mm) FOR TYPE-1	38.00	41.67	49.10	55.80	63.80	73.70	(EXCEEDS LIMIT)
MAXIMUM STOREY DRIFT(mm) FOR TYPE-2	38.40	41.75	49.70	56.80	65.10	75.50	(EXCEEDS LIMIT)
MAXIMUM STOREY DRIFT(mm) FOR TYPE-3	54.80	46.60	63.70	79.80	97.80	(EXCEEDS LIMIT)	(EXCEEDS LIMIT)
MAXIMUM STOREY DRIFT(mm) FOR TYPE-4	54.80	46.60	63.40	79.60	97.70	(EXCEEDS LIMIT)	(EXCEEDS LIMIT)

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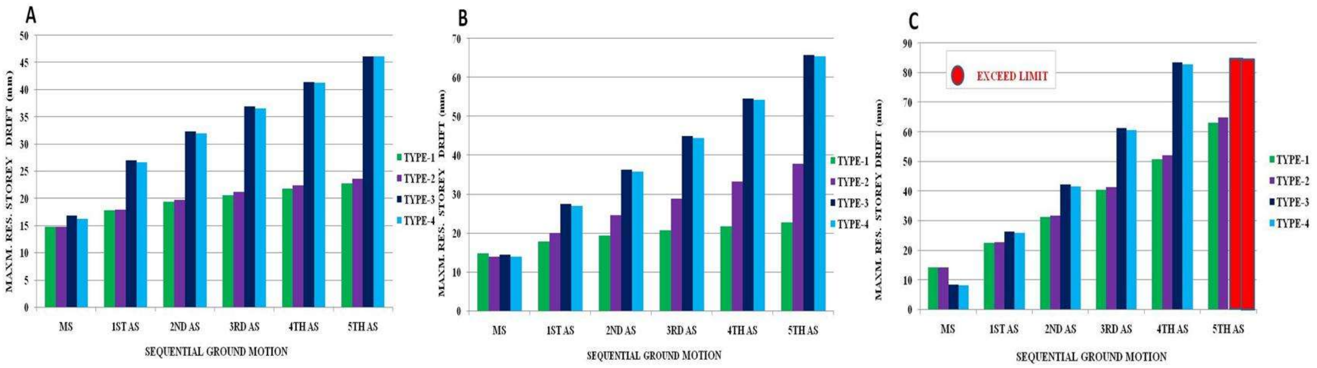

Fig.6. Maximum residual drift of different type building (Type-1, Type-2,Type-3,Type-4) for seismic sequence for A (Case1), B ((Case2), C (Case3).

Table-10 Maximum residual storey drift (mm) for case-1

CASE-1	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-1	14.76	17.76	19.37	20.64	21.74	22.78
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-2	14.81	17.97	19.73	21.14	22.39	23.57
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-3	16.82	27.04	32.28	36.87	41.43	46.15
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-4	16.23	26.60	31.92	36.58	41.24	46.11

Table-11 Maximum residual storey drift (mm) for case-2

CASE-2	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-1	13.78	19.76	23.96	27.87	33.50	36.00
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-2	13.94	20.08	24.58	28.79	33.20	37.80
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-3	14.39	27.45	36.26	44.87	54.50	65.70
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-4	13.91	26.93	35.78	44.49	54.20	65.50

Table-12 Maximum residual storey drift (mm) for case-3

CASE-3	MAIN SHOCK	FIRST AFTER SHOCK	SECOND AFTER SHOCK	THIRD AFTER SHOCK	FOURTH AFTER SHOCK	FIFTH AFTER SHOCK
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-1	14.04	22.50	31.10	40.30	50.70	63.00
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-2	14.08	22.61	31.60	41.20	52.00	64.80
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-3	8.31	26.36	42.30	61.20	83.40	(EXCEEDS LIMIT)
MAXIMUM RESIDUAL STOREY DRIFT(mm) FOR TYPE-4	8.18	25.86	41.60	60.50	82.90	(EXCEEDS LIMIT)

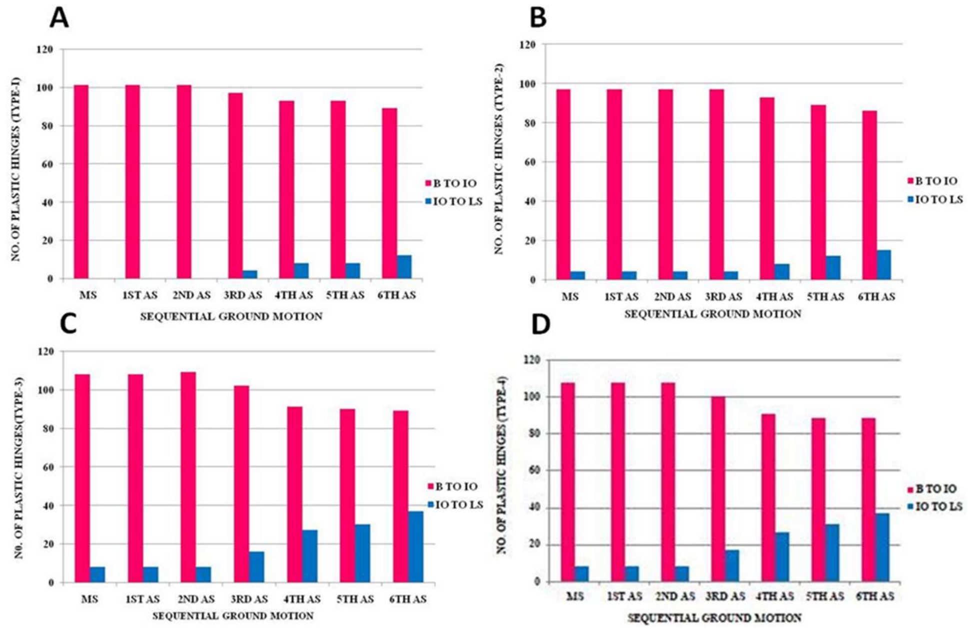

Fig.7 Number of hinges pattern under sequential ground motion (Case1) for A. (Type-1), B. (Type -2), C. (Type-3), and D. (Type -4)

Table-13. Total number of hinges pattern under sequential ground motion (Case1).

CASE1	Main Shock	Aftershocks					
		1	2	3	4	5	6
TYPE-1							
B-IO	101	101	101	97	93	93	89
IO-LS	-	-	-	4	8	8	12
Total hinge	101	101	101	101	101	101	101
TYPE-2							
B-IO	97	97	97	97	93	89	86
IO-LS	4	4	4	4	8	12	15
Total hinge	101	101	101	101	101	101	101
TYPE-3							
B-IO	108	108	109	102	91	90	89
IO-LS	8	8	8	16	27	30	37
Total hinge	116	116	117	118	118	120	126
TYPE-4							
B-IO	108	108	108	101	91	89	89
IO-LS	8	8	9	17	27	31	37
Total hinge	116	116	117	118	118	120	126

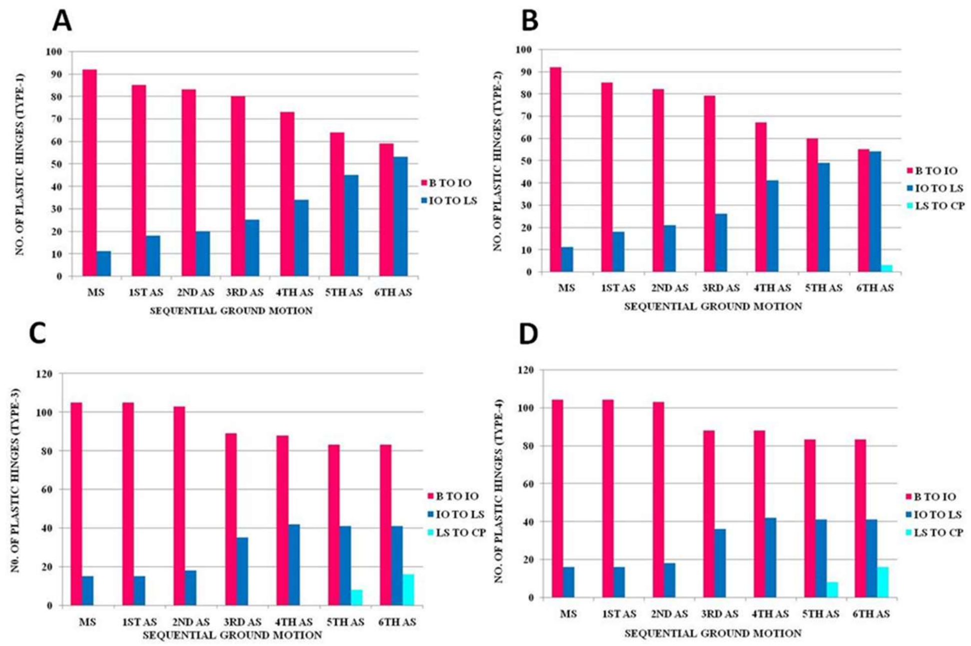

Fig.8 Number of hinges pattern under sequential ground motion (Case2) for A. (Type-1), B. (Type -2), C. (Type-3), and D. (Type -4)

Table-14 Total number of hinges pattern under sequential ground motion (Case2)

CASE2	Main Shock	Aftershocks					
		1	2	3	4	5	6
TYPE-1							
B-IO	92	85	83	80	73	64	59
IO-LS	11	18	20	25	34	45	53
Total hinge	103	103	103	105	107	109	112
TYPE- 2							
B-IO	92	85	82	79	67	60	55
IO-LS	11	18	21	26	41	49	54
LS-CP							3
Total hinge	106	103	103	105	108	109	112
TYPE-3							
B-IO	105	105	103	89	88	83	83
IO-LS	15	15	18	35	42	41	41
LS-CP	-	-	-	-	-	8	16
Total hinge	120	120	121	124	130	132	140
TYPE- 4							
B-IO	104	104	103	88	88	83	83
IO-LS	16	16	18	36	42	41	41
LS-CP						8	16
Total hinge	120	120	121	124	130	132	140

Table-15 Total number of hinges pattern under sequential ground motion (Case3)

CASE3	Main Shock	Aftershocks					
		1	2	3	4	5	6
TYPE-1							
B-IO	85	83	64	51	43	49	53
IO-LS	22	24	45	61	47	41	18
LS-CP	-	-	-	-	23	33	34
CP-C	-	-	-	-	-	-	9
C-D	-	-	-	-	-	-	13
Total hinge	107	107	109	112	113	123	127
TYPE- 2							
B-IO	86	84	63	51	45	50	53
IO-LS	22	24	47	61	46	38	15
LS-CP					24	36	33
CP-C							7
C-D							20
Total hinge	108	108	110	112	115	124	128
TYPE- 3							
B-IO	100	100	77	64	47	51	60
IO-LS	18	18	41	46	58	40	20
LS-CP	-	-	-	12	18	23	29
CP-C	-	-	-	-	-	6	3
C-D	-	-	-	-	-	10	27
Total hinge	118	118	118	122	123	130	139
TYPE- 4							
B-IO	100	100	77	64	51	51	58
IO-LS	18	18	41	46	55	40	22
LS-CP				12	18	21	29
CP-C						10	3
C-D						8	27
Total hinge	118	118	118	122	124	130	139

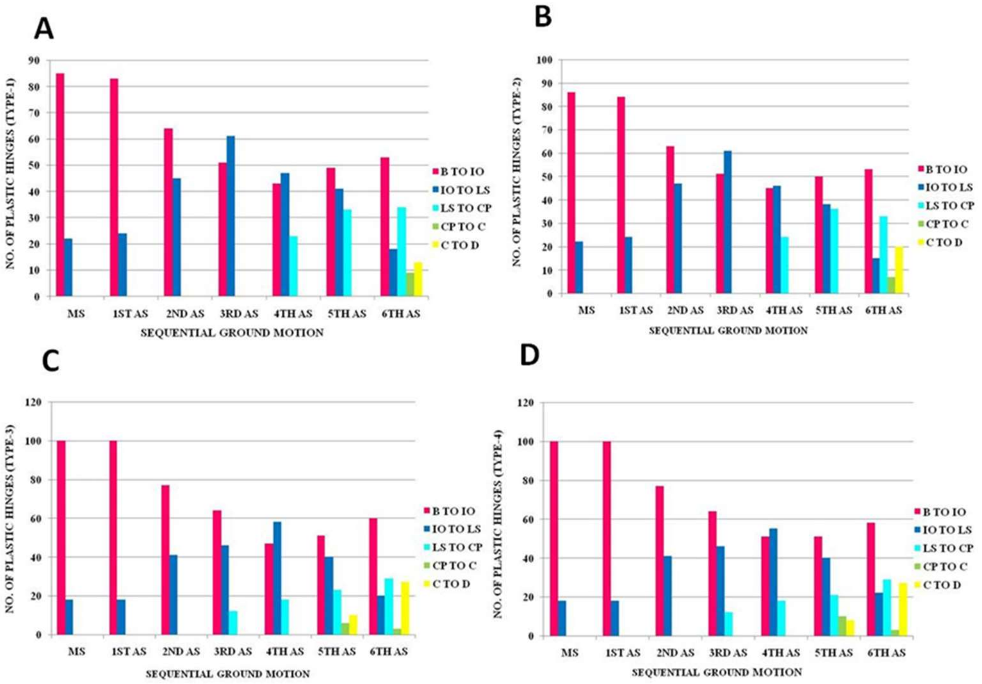

Fig.9 Number of hinges pattern under sequential ground motion (Case3) for A. (Type-1), B. (Type -2), C. (Type-3), and D. (Type -4)

4.6 Formation of Hinges

Location of hinges formed & their state in the frame, describe the damages and its degree in the structure. Hinges from all the four types of frames considered in the sequential ground motions 0.36g, 0.40g, 0.45g PGA are given in tables 13-15. The tables and figures 7-9 also reveal the total number of hinges formed and their transformation from lower state to higher state during main shock and their aftershocks. Permanent floor displacement and storey drift are because of plastic rotation taking place during the sequential ground motion considered.

5. Conclusion

From the analyses of four bays/ten storey frames with mass irregularity, stiffness irregularity, and stiffness - mass irregularity put together at sixth storey level under the sequential ground motion of 0.36g PGA, 0.4g PGA, and 0.45g PGA, following conclusion can be drawn.

1. Floor displacement:
   - All the frames, namely Type1, Type2, Type3, and Type4 survive 0.36g, 0.40g PGA sequential loadings.
   - Regular frame & frame with mass irregularity survive up to the fifth aftershock of 0.45g PGA however frame with stiffness irregularity fails during this aftershock.
   - Regular frame and frame with mass irregularity also fail during sixth after shock of 0.45g PGA sequential loading.
2. Mass irregularity: it does not contribute along with stiffness irregularity to any response of the frame.
3. The frame with stiffness irregularity on account of maximum residual top floor displacement during last aftershock of 0.45g PGA sequential ground motion is not due to plastic rotation of hinges in the top storey but in storeys over mid height of the frame.
4. Maximum transient storey drift is found to be exceeding the permissible limit in the storey of stiffness irregularity considered that is in the sixth storey under fifth aftershock 0.45g PGA.

Disclosures

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