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Pushover analysis – result borders due to hinge formation orders

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Abstract. Performance evaluation of RC frame building by nonlinear static pushover analysis that accounts for elastic and post elastic behavior is becoming very popular as a valid decision making tool in seismic hazard resistant designs. Available literature suggests great amount of interest has shown by researchers in suggesting refinements to geometric and material modelling to bridge the gap between analytical predictions and observed performances. Notwithstanding the attempts gaps still exists. Sequence of plastic hinge formation which has great influence on pushover analysis results is an area less investigated. This paper attempts to highlight the importance of hinge sequence considerations to make analysis results more meaningful. Variation in analysis results due to different hinge sequences have been quantified, compared and bounds on analysis results have been presented.

Keywords: material variations; sequence variations; plastic hinge formation; pushover analysis;SAP2000

1. Introduction

The utility of inelastic static analysis in earthquake engineering dates back to 70's, when a practical conceptual model for predicting the dynamic response of a reinforced concrete member was studied by Takeda and Sozen (1970) based on a static force – displacement relationship which reflects the changes in stiffness for loading and unloading the member. Gulkan and Sozen (1974) extended pushover analysis in earthquake engineering, by representing multi degree of freedom (MDOF) system with equivalent single degree of freedom (SDOF) system. A single mode with constant shape was assumed to be valid throughout the analysis.

Modified linear model for estimation of energy dissipation in the nonlinear range was attempted by Shibata and Sozen (1976). Linear spectral response analysis levels with inelastic response of elements of multi-storeyed reinforced concrete structures was outlined. Krawinkler (1998) introduced capacity spectrum method and adaptive techniques were suggested by Bracci *et al.* (1995). Fajfar (2000) proposed a variant of capacity spectrum method as N2 method wherein capabilities of MDOF and equivalent SDOF system were combined. Deficiencies of conventional pushover analysis were overcome by inclusion of higher modes by modal pushover analysis as

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suggested by Chopra and Goel (2001). Paspuleti's (2002) study on framed structure with flexible and brittle model highlights the effect of modelling parameters on analysis results. This study again suggests less variation in base shear values and considerable variation in displacements due to modelling attributes. Kalkan and Kunnath (2004) presented modal combination techniques and also suggested improvisations in the aspect of invariant load distribution. Inel *et al*. (2006) performed pushover analysis on a 4 and 7 story building by employing default hinge properties as per ATC 40 and FEMA 356 guidelines and also compared results with user defined nonlinear hinge properties. The influence of hinge length property on displacement characteristics has been highlighted and the invariance of base shear has also been projected.

Mao *et al*. (2008) considered redistribution of inertia forces for estimation of seismic demands and also demonstrated efficacy of modal pushover analysis in high rise structures. Bobadilla and Chopra (2008) evaluated the modal pushover analysis procedure for estimating seismic demands on 4,8,12 and 20 storey RC-SMRF buildings designed to comply with current codes due to an ensemble of 78 ground motions scaled down to four intensity levels demonstrated the adequate degree of accuracy of modal pushover analysis procedures. Goel and Chopra (2009) presented a study on three approximate procedures such as modal pushover analysis, linear dynamic analysis and linear static analysis for estimating seismic demands for bridges crossing fault rupture zones and recommends the linear static analysis procedure, for practical analysis of ordinary bridges as it eliminates the need for mode shapes and vibration periods of the bridge. Modal pushover based scaling procedure to scale ground motions for use in a nonlinear response history analysis of buildings is studied by Kalkan and Chopra (2011). Further the authors extended the study to evaluate the efficiency and accuracy of modal pushover based scaling method to scale ground motions for tall buildings (2012).

The accuracy of the three-dimensional modal pushover analysis (MPA) procedure in estimating seismic demands for unsymmetric-plan buildings due to two horizontal components of ground motion, simultaneously is evaluated by Reyes and Chopra (2011) and including its evaluation for tall buildings (2011) and also demonstrated that nonlinear response history analysis (RHA) of the building for a small set of records scaled by the modal pushover scaled procedure provided a highly accurate estimate of the engineering demand parameters (EDPs), accompanied by significantly reduced record-to-record variability of the responses (2012). Sharma *et al.* (2013) conducted experimental and analytical studies on full scale non-seismically detailed RC structure. A portion of an existing structure having stiffness and mass irregularities was replicated for the experimental setup. A large variation in the pre-test analysis results in comparison to observation during test have been attributed to high sensitivity of results to material and geometric modelling.

Panandikar and Narayan (2014) presented the sensitivity of pushover analysis results to geometric and material modeling parameters by comparing the analysis results with that of experimental investigations. An attempt was made to understand the sensitivity of parameters like the variation in material properties, inaccuracies in the placement of reinforcement, the effect of confinement of concrete and modeling techniques for elements and plastic hinges. SAP-2000 has been utilized in the current investigation and results have been highlighted suggesting strategies to enhance pushover analysis capabilities.

Available literature manifests the wide varying research interest shown by researchers in enhancement of prediction of performance. Nevertheless sequence of hinge formation and its influence on analysis results has hardly been a subject of study. This paper presents the effect of hinge formation sequence on POA results and the need for its consideration.

Pushover analysis is carried out on a single bay single story RC portal frame for 15% variations on either side of the parameters like steel strength ($f_{s)}$, concrete strength (f_c) and effective cover (d_c) considered and also analysis results for variation in hinge formation sequence have been obtained, compared, interpreted and the importance of hinge formation sequence in pushover analysis has been elaborated.

2. Details of the structure

The structure is a single bay single storey, reinforced cement concrete portal framed structure of height 3 m and width 3 m as shown in Fig. 1.

Beam and column dimensions are 150 mmX300 mm. The reinforcement details and cross sections of the beam and columns have been provided as shown in Fig. 2. According IS 1893:2002, the pushover load case has been assigned with seismic zone factor 0.16(Zone III) and response reduction factor 5.

3. Modelling details and analysis

Commercially available SAP2000 (version-14) has been used as the general finite element software for modeling and analysis. Graphical user interface has been used to create the material and geometric model and properties have been defined accordingly. M3 hinges have been considered as moment effects are predominant in all elements.

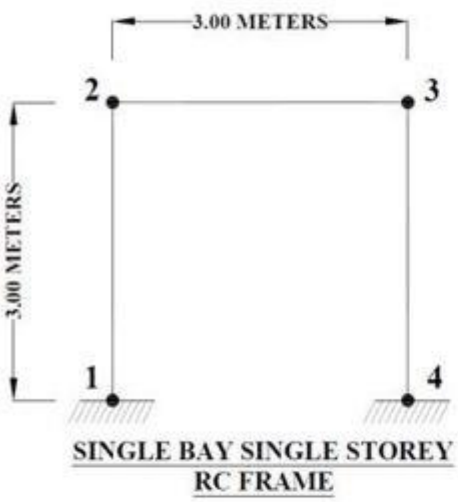


Fig. 1 RC Portal Frame

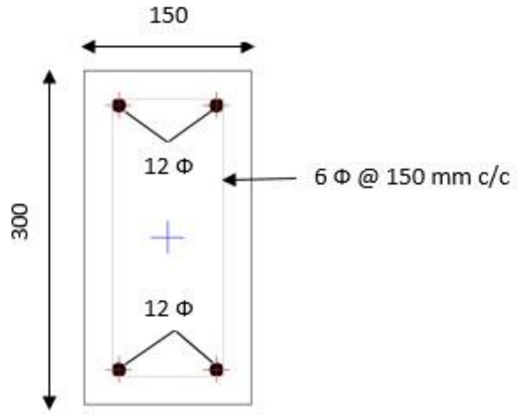


Fig. 2 C/S of beam and column

3.1 Influence of material strength and effective cover variations on pushover analysis.

3.1.1 Discrete variations

Pushover analysis is carried out on a single bay single storey RC portal frame wherein five values of steel strength (f_s) (350,380,415,445,475 MPa), five values of concrete strength (f_c) (17, 18.5, 20, 21.5 and 23 MPa) and effective cover (d_c) (25, 27.5, 30, 32.5 and 35) central being adopted in design, higher and lower values accounting for 15% variations have been considered. Analysis results for one of the covers i.e., 25 mm have been presented in Table 1.

For the effective cover of 25 mm and strength of concrete as 17 MPa, the displacement varies from 0.018716 m to 0.04019 m with 15% variation in steel strength and the corresponding base shears are 43.294 kN and 58.079 kN respectively. It can been observed, that there is considerable change in displacement and base shear for varying strength of the steel whereas change observed for varying concrete strength is negligible. This continues in a similar pattern for small changes in the cover to the reinforcement. The maximum displacement and base shear observed for 25 mm effective cover are 0.040194 m and 58.079 kN respectively and those of 35 mm cover are 0.03887 m and 55.23 kN respectively. Therefore it shows that it is the steel strength which has a notable role in governing the displacement characteristics of the reinforced concrete structures. The steel strength variation of about 15% showed the displacement range which varies from 0.018716 m to 0.04019m in the case of 25 mm effective cover, there is an increase of displacement of about 115% as steel strength increases to 350 MPa from that of 475 MPa. The Fig. 3 which shows the push over curves for material variations shows the variations in steel strength has a major influence on a push over results of the frame whereas the concrete grade has negligible effect.

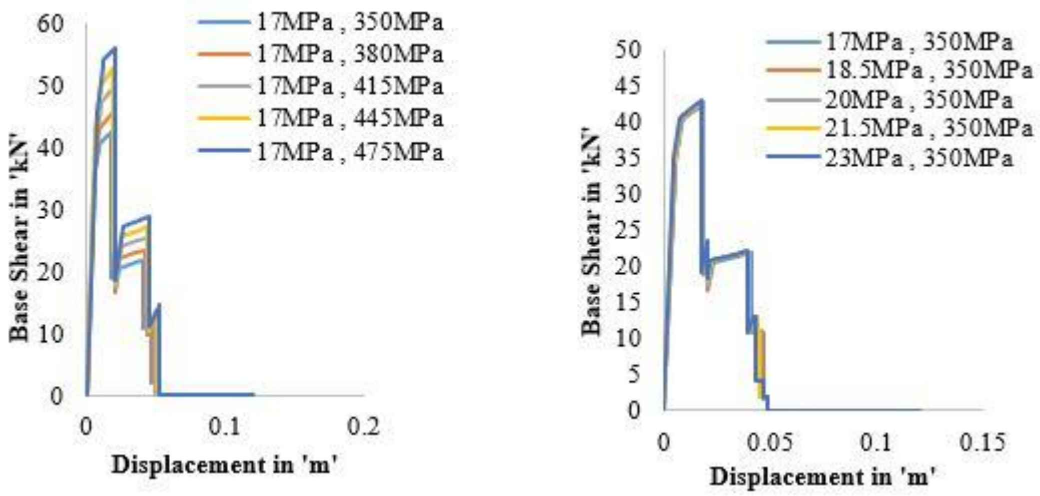
3.1.2 Pushover analysis results obtained by permitting random variations

In this parametric study pushover analysis have been performed on the same frame for randomized values over a preselected range of variations in steel strength (f_s) from 350 to 475 MPa, concrete strength (f_c) from 17 to 23 MPa and effective cover (d_c) from 25 mm to 35 mm. Base shear and displacements obtained for 101 random samples are presented in Table 2 and discussed as below.

Table 1 Discrete material variations for effective cover of 25 mm

f_c / f_s	17		18.5		*20		21.5		23	
	Disp (m)	Base Shear (kN)	Disp (m)	Base Shear (kN)	Disp (m)	Base Shear (kN)	Disp (m)	Base Shear (kN)	Disp (m)	Base Shear (kN)
350	0.018716	43.294	0.018507	43.384	0.018323	43.467	0.018069	43.526	0.018008	43.619
380	0.019138	46.937	0.018941	47.078	0.018741	47.171	0.018561	47.259	0.018399	47.342
*415	0.038578	51.006	0.01943	51.223	0.019227	51.461	0.019033	51.579	0.018856	51.672
445	0.03914	54.378	0.038892	54.632	0.038517	54.835	0.019413	55.058	0.019238	55.289
475	0.040194	58.079	0.039441	58.227	0.033196	58.227	0.03987	58.464	0.038536	58.732

*Design values adopted



(a) For varying steel strength (b) For varying concrete strength

Fig. 3 Pushover curves for material strength variations for 25 mm effective cover

From the analysis results the mean value of base shear obtained is 49.022 kN with standard deviation of 4.103 and the mean value of displacement obtained is 0.01874 m with standard deviation of 0.0005129. Confidence interval (CI) at a level of significance of 0.05 is estimated. The results obtained are as shown in Table 3.

From the above table, the 95% confidence interval states that the base shear can be as low as 40.98kN and as high as 57.06kN, while there is still a 5% chance that base shear can lie beyond this interval. Similarly, the displacement can be as low as 0.0177 and as high as 0.0197, with 5% chances of displacement lying beyond this interval.

Table 2 Radom material strength variations

Sl No	f_s	f_c	d_c	Base Shear (kN)	Displacement (m)
1	462.47	18.66	26.37	54.76	0.01964
2	405.68	19.00	30.16	47.999	0.018737
3	444.33	18.04	30.01	52.098	0.019355
4	376.15	18.62	32.82	44.397	0.01833
5	448.79	17.91	31.57	52.326	0.019365
6	386.82	18.91	31.50	45.764	0.018472
7	468.16	18.71	34.95	54.023	0.019337
8	463.09	21.42	26.19	55.296	0.019282
9	399.43	21.27	33.52	47.272	0.018283
10	449.46	17.21	32.03	52.216	0.019465
11	367.32	22.25	34.60	43.914	0.017806
12	436.52	19.63	29.13	51.631	0.019072
13	390.47	21.81	28.65	47.063	0.018312
14	471.78	22.98	31.06	55.744	0.019005
15	425.02	19.71	28.21	50.464	0.018959
16	421.30	21.91	32.75	49.835	0.01849
17	401.66	17.73	25.90	47.965	0.019013
18	389.16	17.89	30.07	46.032	0.018681
19	358.13	22.62	30.86	43.314	0.017768
20	437.97	21.15	29.70	51.953	0.018882
21	471.09	17.64	26.37	55.572	0.019916
22	432.93	20.97	26.45	51.845	0.018968
23	367.54	22.29	28.94	44.567	0.017982
24	410.78	22.64	27.91	49.456	0.018486
25	436.92	22.95	25.05	52.86	0.018849
26	396.11	20.81	27.87	47.558	0.018504
27	378.45	18.43	33.85	44.47	0.018337

Continued-

28	432.71	19.15	29.46	51.084	0.019076
29	431.88	21.87	29.88	51.382	0.018726
30	452.21	19.37	31.32	52.977	0.019207
31	411.66	18.43	27.38	48.93	0.018991
32	462.11	18.91	32.27	53.842	0.019352
33	411.40	21.72	29.19	49.231	0.018536
34	465.65	21.06	26.23	55.516	0.019355
35	357.30	20.91	28.93	43.239	0.017994
36	364.65	22.54	33.11	43.808	0.017792
37	397.18	21.32	29.28	47.611	0.018413
38	424.52	22.29	26.88	51.066	0.018711
39	365.01	21.87	27.25	44.391	0.018042
40	361.12	18.12	30.49	42.992	0.018293
41	452.97	17.06	25.98	53.532	0.019789
42	454.77	22.96	30.06	54.032	0.018859
43	421.73	21.08	33.69	49.61	0.018544
44	366.22	17.25	29.06	43.573	0.018513
45	397.94	17.45	28.69	47.107	0.018903
46	351.71	21.84	32.16	42.348	0.017723
47	470.14	17.51	34.72	54.061	0.01956
48	371.16	21.93	28.99	44.947	0.018069
49	474.86	18.10	34.44	54.715	0.019536
50	459.38	22.41	31.20	54.274	0.018923
51	410.93	17.64	26.78	48.817	0.019113
52	437.86	19.50	34.37	50.93	0.018889
53	468.98	17.36	34.96	53.877	0.01956
54	415.64	21.61	29.89	49.57	0.018569
55	389.48	22.02	32.85	46.431	0.018128
56	373.50	20.86	25.70	45.479	0.018309
57	369.11	22.77	28.78	44.832	0.017959

Continued-

58	413.43	18.89	27.34	49.207	0.018954
59	365.71	22.15	26.96	44.536	0.018028
60	406.25	19.81	30.11	48.213	0.01865
61	413.31	17.43	25.05	49.346	0.019238
62	427.83	19.97	27.92	50.864	0.018972
63	428.73	22.55	27.59	51.445	0.018706
64	362.20	20.31	28.65	43.757	0.018136
65	467.29	19.30	26.07	55.457	0.019619
66	456.50	20.43	30.87	53.687	0.019138
67	459.32	19.03	28.80	54.099	0.019447
68	463.63	21.35	32.26	54.406	0.019048
69	422.64	17.76	28.82	49.847	0.019168
70	414.00	18.06	30.90	48.645	0.018935
71	357.27	17.24	28.04	42.702	0.018437
72	439.22	21.56	34.37	51.44	0.018659
73	427.07	18.34	27.31	50.622	0.0192
74	359.18	18.82	25.51	43.59	0.018356
75	463.07	19.15	27.39	54.718	0.019535
76	351.13	17.85	27.77	42.194	0.018295
77	470.99	19.02	34.95	54.385	0.019325
78	435.89	17.49	32.47	50.711	0.019228
79	450.21	19.38	34.52	52.235	0.019045
80	375.69	18.52	33.83	44.2	0.018297
81	380.88	18.80	27.98	45.54	0.018542
82	464.18	19.80	31.34	54.356	0.019292
83	371.56	19.76	26.51	44.939	0.018372
84	386.90	19.15	28.62	46.21	0.018551
85	353.61	22.41	34.93	42.307	0.017605
86	414.59	20.91	26.92	49.743	0.018742
87	428.48	18.80	26.01	51.079	0.019203

Continued-

88	426.18	21.95	28.04	50.99	0.018723
89	355.53	17.73	29.97	42.388	0.018289
90	396.78	18.21	34.84	46.274	0.018546
91	429.92	19.27	28.87	50.887	0.019049
92	464.22	21.52	34.46	54.138	0.01894
93	359.66	18.93	27.93	43.285	0.018273
94	420.10	19.65	34.60	49.006	0.018653
95	371.93	17.64	34.65	43.536	0.018326
96	358.15	20.19	28.94	43.256	0.018089
97	370.83	17.88	34.87	43.436	0.018275
98	364.66	17.11	29.27	43.351	0.018504
99	428.36	20.24	34.06	50.13	0.0187
100	399.81	22.35	33.36	47.526	0.018189
101	458.38	20.19	30.17	53.963	0.01922

Table 3 Base shear and Displacement values with CI at 0.05 significance

Output	**Mean**	**Std dev**	**C.O.V (in %)**	**95% Confidence Interval (CI)**
Base Shear (kN)	49.022	4.103	8%	(40.98, 57.06)
Displacement(m)	0.0187	0.0005129	2%	(0.0177, 0.0197)

The coefficient of variation is determined for both base shear and displacement as it is the best measure to compare the variability of two series or sets of observations. The coefficient of variation obtained for base shear and displacement are 8% and 2%, which states that variation in material strengths and effective cover is leading to base shear variation of higher order when compared to displacement. 15% allowable range of material strength results in an increase in displacement of 13%.

3.2 Influence of plastic hinge formation sequence on pushover analysis

Section 3.2.1 and 3.2.2 represents sequence variations for the aforementioned RC portal frame. The materials considered are 20 MPa strength of concrete and HYSD (415 MPa) reinforcement. According to IS 1893:2002, the pushover load case has been assigned with seismic zone factor 0.16(Zone III) and response reduction factor 5. M3 hinge is assigned at member ends where flexural yielding is assumed to occur for both beams and columns. In this parametric study beam and columns have been modeled as an assemblage of finite elements (12 each) to facilitate change in hinge formation sequence by making sections weaker at locations desired by considering ± 15% variations in material strengths and disposition of reinforcements than specified.

3.2.1 Randomization of defects at discretely selected locations

Pushover analysis have been performed with parameter variations at discretely selected locations on a frame. Plastic hinge formation sequence as analysis progresses has been observed, recorded and reported in the following tables.

From Tables 8 and 9 it is evident that hinge formation sequence is an important behavioral aspect that needs to be recognized and considered in performance based designs. Such consideration allows analysts to establish bounds on performances commensurate with uncertainties.

Table 4 Random parametric variations at any 1 joint

Sl. No	**Sequence Obtained**	**Base Shear (kN)**	**Displacement (m)**
1	1432	31.931	0.018461
2	1423	31.694	0.018617
3	14 23	31.408	0.018799
4	3421	39.388	0.015572
5	41 23	31.671	0.017252
6	2413	28.887	0.016924
7	4123	31.966	0.018442
8	3142	39.562	0.015223
9	4132	31.170	0.018793
10	4231	30.283	0.014267

Table 5 Random parametric variations at any 2 joints

Sl. No	**Sequence Obtained**	**Base Shear (kN)**	**Displacement (m)**
1	1243	35.217	0.013761
2	4123	43.119	0.022152
3	14 23	32.391	0.018491
4	14 32	31.607	0.018889
5	1324	30.231	0.015663
6	23 14	31.266	0.018525
7	14 23	33.145	0.021527
8	4321	35.214	0.017893
9	12 34	32.126	0.019243
10	3214	31.689	0.039492

Table 6 Random parametric variations at any 3 joints

Sl. No	Sequence Obtained	Base Shear (kN)	Displacement (m)
1	1432	46.821	0.048126
2	1423	42.972	0.045223
3	2134	33.431	0.01419
4	4132	39.170	0.018993
5	14 23	31.408	0.018713
6	41 23	31.584	0.018799
7	4213	41.245	0.043267
8	3142	28.694	0.017186
9	23 41	35.296	0.015645
10	1234	30.567	0.014921
11	14 23	32.975	0.018720

Table 7 Random parametric variations at 4 joint

Sl. No	Sequence Obtained	Base Shear (kN)	Displacement (m)
1	14 23	32.679	0.018420
2	41 23	42.188	0.049421
3	2314	35.976	0.0162782
4	32 14	41.299	0.0501264
5	4231	33.725	0.0192914
6	23 14	40.196	0.0471267
7	2431	41.898	0.0501126

_ Simultaneity in formation of hinges

Table 8 Upper and lower bound of base shear values with associated displacements

Base Shear (kN)	Corresponding Displacement (m)	Sequence of Hinge formation
46.821	0.048126	1432
28.694	0.017186	3142

Table 9 Upper and lower bound of displacement values with associated base shears

Displacement (m)	Corresponding Base Shear (kN)	Sequence of Hinge formation
0.0501264	41.299	32 14
0.013761	35.217	1243

The results obtained clearly indicates the influence of sequence of plastic hinge formations on displacement characteristics unlike the results obtained from material variations.

3.2.2 Randomized defects and locations

In this study, sequence variations are generated by making random joints weak. The pushover analysis results obtained for all the possible sequence of plastic hinge formations have been presented in Table 10 (Supriya *et al.* 2017).

It can be observed that the displacement and base shear varies for every sequence of hinge formation. Here, the minimum displacement obtained is 0.013551 m and the corresponding base shear is 35.83 kN for hinge sequence 4231 and maximum displacement is 0.051407m with base shear of 42.781 kN for hinge sequence 3142. Fig. 5 (Supriya *et al*. 2017) shows pushover curves for all the 24 sequence of hinge formations.

Table 10 Pushover analysis results for varying sequence of hinge formations

Sl. No	**Sequence of hinge formation**	**Base Shear (kN)**	**Displacement (m)**
1	4132	48.985	0.050233
2	3412	45.893	0.048209
3	3142	42.781	0.051407
4	2413	42.879	0.046973
5	3124	42.65	0.043934
6	2431	42.872	0.046976
7	3214	36.923	0.04613
8	1432	48.992	0.050238
9	4213	45.285	0.047033
10	1423	45.314	0.047463
11	4123	47.437	0.019152
12	3421	44.856	0.019527
13	3241	44.59	0.020161
14	4312	49.179	0.019137
15	4231	35.83	0.013551
16	4321	36.672	0.015766
17	1243	36.402	0.015835
18	1324	35.462	0.013686
19	1342	35.529	0.013701
20	1234	30.426	0.015663
21	2143	39.154	0.015692
22	2134	39.458	0.01557
23	2314	36.921	0.015712
24	2341	37.106	0.015645

Table 11 Base shear and Displacement values with CI at 0.05 significance

Output	Mean	Std dev	C.O.V (in %)	95% Confidence Interval (CI)
Base Shear (kN)	41.106	5.445	13%	(30.43 , 51.77)
Displacement(m)	0.0295	0.0156	53%	(0.001 , 0.0601)

The pushover analysis results obtained from all other sequences of hinge formations have the displacement values between these ranges, and they are all unique. This clearly indicates the influence of sequence of hinge formation on pushover analysis results, especially on displacement characteristics. It is also observed that the base shear variations are independent of changes in displacement characteristics i.e., they are not proportional to one another. Observations are consistent with assumptions in plastic theory and design, wherein collapse load is invariant to hinge formation sequence. One of the possible reasons for variations in base shear results is due to the strength parameter variations. The plot of a first drop or the first hinge formation for all the 24 sequences is as shown in Fig. 4 (Supriya *et al.* 2017).

Confidence interval (CI) at a level of significance of 0.05 is estimated as shown in Table 11.

The coefficients of variation is determined for base shear and displacement are 13% and 53%, indicating hinge sequence influences displacement characteristics more to higher extent than base shear.

The variation in displacement characteristics due to hinge sequence formation is several orders (about 21% higher) than that due to variation in material strengths and errors in placement of reinforcement.

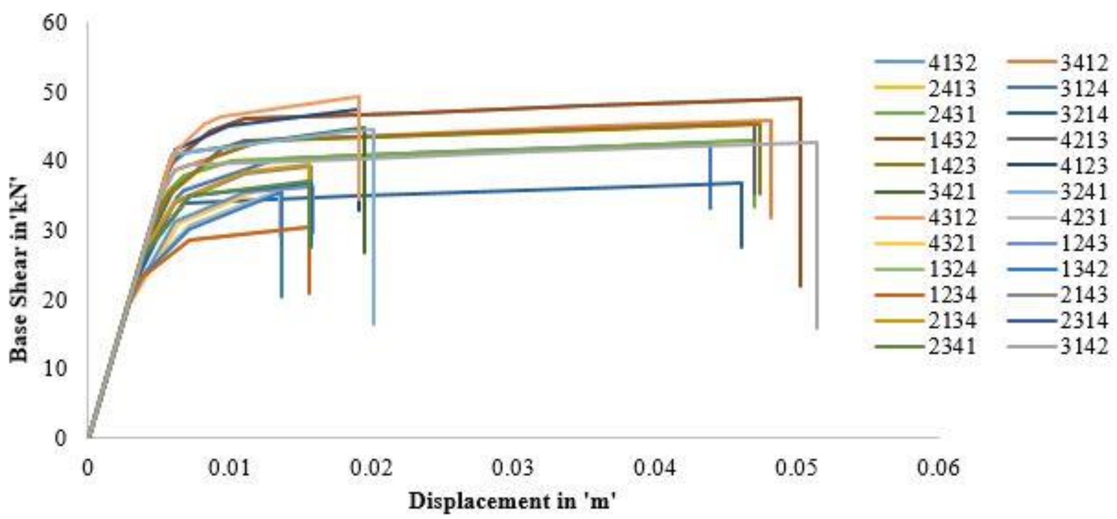


Fig. 4 Pushover curves with first drop/first hinge formation

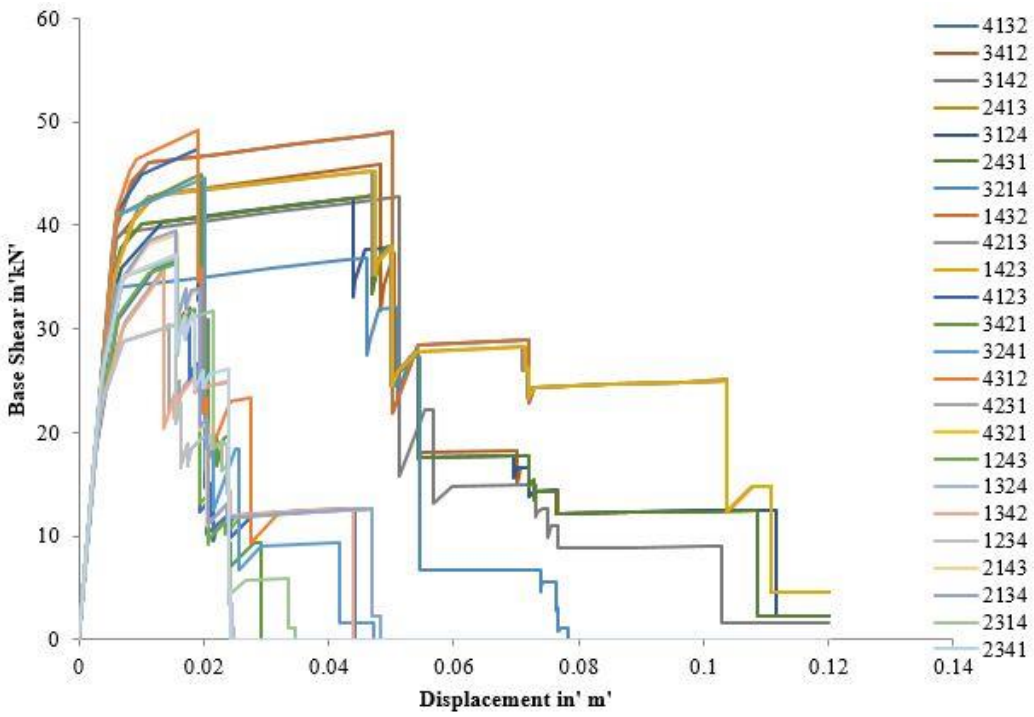


Fig. 5 Pushover curves for 24 sequence of hinge formations

4. Conclusions

Influence of variation in material strengths and construction errors in placement of reinforcement has been investigated. Parameter variation discretization and discrete zones in frames where variation has influence on results have been analyzed. Randomization of parameter variation and number and location of zones that have strength and stiffness uncertainties leading to changes in hinge formation sequence influencing analysis results have also been investigated.

From the analysis results it is very clear that hinge formation sequence leads to more uncertainties than mere variation in strength and stiffness parameters. Study is consistent with the recognized behavioral aspect of plastic analysis wherein it is demonstrated that collapse load is invariant to hinge formation sequence whereas displacement is.

Sequence of hinge formation influences displacement characteristics and hence needs consideration in performance based design for establishing bounds on performance levels, comparison with performance demands and selection, comparison, discrimination, validation and adoption of design and control strategies.

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