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Consequence of hinge formation sequence on pushover analysis results

Supriya R. Kulkarni
National Institute of Technology, Surathkal, Karnataka, supriya101@gmail.com

Research Articles

Consequence of hinge formation sequence on pushover analysis results

Supriya R Kulkarni*, Ravikumara H S, and Dr K S Babu Narayan

Email: supriya101@gmail.com

Abstract

Pushover analysis has become very popular in performance assessment and appraisal of structures in performance based design. Notwithstanding the attempts to match the analytical predictions with experimental observations, there are many unresolved issues. The mismatch between the observed displacements and the analytical predictions persists. From the available literature, it is also very clear that hardly any attention has been devoted to study the effect of sequence of plastic hinge formation leading to collapse which is the most predominant factor and which also, decides the displacement behavior. This paper attempts to present the importance of considering the hinge formation sequence in the pushover analysis.

Keywords: Performance based design, pushover analysis, plastic hinge formations, displacement capacity, SAP2000

I. Introduction

Pushover analysis has been widely used as a tool to evaluate the expected performance of a structural system by estimating its strength and deformation capacity in Seismic design by means of static inelastic analysis. It is based on three key concepts: capacity, demand, and performance. The capacity is delineated by the capacity curve, which shows the structure's capacity to withstand the incremental lateral loading. Demand is indicated by the target displacement, representing the maximum displacement that may be expected by the structure during a considered ground motion. Based on the FEMA 356 and ATC 40 guidelines, the pushover analysis is carried out.

Supriya R Kulkarni
Reseacrh Scholar, Civil Engineering Department,
National Institute of Technology, Surathkal, Karnataka

Ravikumara H S
Reseacrh Scholar, Civil Engineering Department,
National Institute of Technology, Surathkal, Karnataka

Dr K S Babu Narayan
Professor, Civil Engineering Department,
National Institute of Technology, Surathkal, Karnataka

* Corresponding Author

Geometric and material modeling capabilities in pushover analysis have been greatly enhanced by the techniques that have been redefined and refined as close to reality as possible. Techniques are available to include stiffness of infills, confinement of concrete and various formulations for hinge type, location and length. In spite of these efforts the mismatch between the analyses results for displacement with experimentally occurred persists. Sequence of hinge formation needs consideration in resolving this issue because it greatly influences the displacement.

The following sections illustrate with examples the influence of hinge formation sequence on analysis results and the need for its consideration.

II. State-of-the-art review in pushover analysis

Several publications seemed to have been appeared in recent years documenting the merits of pushover analysis and its applicability. A review of literature elaborating the state-of-the-art is presented in this paper.

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Mehmet Inel, Hayri Baytan Ozmen (2006) [1] performed the pushover analysis on a 4 and 7 story building by considering user defined nonlinear hinge properties as well as default hinge properties as per ATC 40 and FEMA-356 guidelines to study the difference in the results. For the following study, beam and column elements are modeled as nonlinear frame elements with lumped plasticity by describing the plastic hinges on both ends of columns and beams, whereas the frames are modelled with user defined and default hinge properties, respectively. The user defined hinge properties assume transverse reinforcement spacing and plastic hinge length as the effective parameters. It has been observed that the displacement capacity of frames are considerably affected by the plastic hinge length and transverse reinforcement spacing, while the same does not have any influence on the base shear capacity. Due to the length of the plastic hinge there is a variation of about 30 percent in displacement capacities. Comparisons also state that the displacement capacity increases with the increase in transverse reinforcement. The improvement in displacement capacity is much effective in the case of smaller spacing. Although the hinge locations seem to be stable, the model with default hinges emphasizes on a strong column weak beam mechanism i.e. damage or failure occur on the beams. As observed by the researchers the hinging patterns for low to medium rise buildings can be successfully captured by time history results, while the same is not adequate in the case of higher levels, it is also apparent that the user defined hinge model is more successful in capturing the plastic hinging mechanism compared to the default hinges model. Hence, the author concludes that the user defined hinge model is far better than the default hinge model in replicating nonlinear behavior compatible with the element properties.

To evaluate the performance of three framed buildings A. Kadid and A. Boumrkik (2008) [2] conducted nonlinear static pushover analysis with 5, 8, and 12 stories, respectively. The structure is subjected to monotonically increasing lateral load patterns, representing the inertial forces which are experienced due to ground shaking. It has been observed that as the loads are incrementally increased, there is a sequential increase in yielding of various structural elements and consequently the structure undergoes losses in stiffness at each event. A force displacement relationship is determined. The structures are designed as per Algerian code RPA2003 and located in high seismicity region with peak ground acceleration. From the following study it has been observed that the plastic hinges are formed at the beam ends and column base of lower stories and then propagates to upper stories and further continues with yielding of interior immediate columns in the upper stories. Since the formation of plastic hinges is within B, IO and LS level, respectively, the amount of damage in the three builds is within the limits. Hence, the author concludes that a properly designed/detailed reinforced framed building perform well under seismic loads.

Neena Panandikar (Hede), K S Babu Narayan (2015), studied the sensitivity of pushover curve to material and geometric modelling [3]. An attempt was made to understand the sensitivity parameters like discrepancy in material properties, imprecisions in placement of reinforcement, effect of concrete confinement and modelling techniques for elements and plastic hinges.

Although the researchers have devoted a lot of effort to enhance the capabilities of pushover analysis and its applications, the unresolved issues exist and persist. From the accessible literature, it has been clear that barely any importance has been dedicated to considering the sequence of plastic hinge formation in pushover analysis, leading to collapse of structure subjected to ground motions.

III. Modeling and analysis

This paper presents by way of illustrations the influence of sequence of hinge formation on the pushover analysis results. A propped cantilever and an RC portal frame have been analyzed by using a static nonlinear pushover analysis procedure with a software package SAP 2000 [4].

A. Illustration 1 – Propped Cantilever

A propped cantilever AB of Span **'l' = 2m** considered for the analysis is as shown in the Figure 1. The section considered is ISMB 300 @ 46.1 kg/m, which has the following properties.

Sectional modulus	Z_x	= 599 cm^3
Plastic Section modulus	Z_p	= 683 cm^3
Shape Factor		= 1.14
Elastic modulus,	E	= 200 GPa
Yield moment	M_y	=149.75 kN-m
Plastic moment	M_p	=170.72 kN-m

and the collapse load is given by

$\mathbf{W_c = 6Mp/l}$---(i)

Therefore, the collapse load $\mathbf{W_c = 512.145\ kN}$

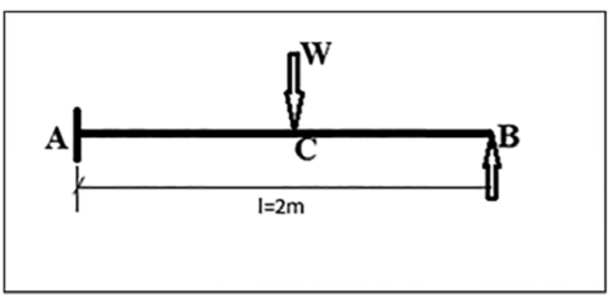

Figure 1: Propped Cantilever

To show that the displacement characteristics change with respect to the change in sequence of plastic hinge formation the following two cases have been considered.

i) Propped cantilever loaded at mid span and
ii) Propped cantilever (same as (i)) with an upward displacement of 2 mm at propped end.

The corresponding moments and displacements have been determined for incremental loads for both cases.

B. Illustration 2 – RC Portal Frame

A single bay single story 2D frame with bay height and bay width as 3000mm shown in Figure 2 has been modeled by using SAP 2000. Both the beam and the column sections are 150mm X 300mm in size. The materials considered are M20 grade concrete and HYSD (Fe415) 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 a flexural yielding is assumed to occur for both the beams and the columns.

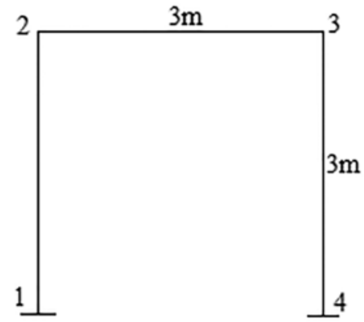

Figure 2: RC Portal Frame

The beam and the columns have also been modelled as the assemblage of finite elements (12 each) to facilitate change in hinge formation sequence by making sections weaker at locations desired. The results obtained from this analysis with respect to the sequences have been tabulated in Table 2 and the pushover curves have been plotted as shown in the Figure 4.

IV. Results and discussions

The results of pushover analysis for propped cantilever and RC portal frame are discussed in detail hereunder.

A. Illustration 1 – Propped Cantilever

In the case (i), first hinge formed at the support and the corresponding load is 455.24 kN and the displacement is 1.93mm. Once the first hinge is formed at the support, the beam will become determinate and behaves as a simply supported beam as the support is free to rotate. The displacement due to rotation also will be added to the displacement due to the additional load, so that the change in the rate of change of displacement is observed until it reaches the collapse load. Further, a second/final hinge is formed below the load at the collapse with a maximum displacement of 3.58mm. Table 1 shows the moments and displacements for the propped cantilever, which is incrementally loaded until it reaches the collapse load and the corresponding plastic hinge formation sequence is noted.

The moments and the displacements for second case have also been presented in Table 1. Here in this case as the moment due to load is countered by the moment due to displacement, the mid span moment reaches the plastic moment first, hence the first hinge is formed at the mid span and the second hinge is formed at the support. The load and the displacement at the mid span where the first hinge formed are 463.7kN and 2.15mm, respectively. Consequently, the displacement due to rotation at the mid span will also be added to the displacement due to the additional load. The maximum displacement of 4.32mm is obtained at the support where the second hinge is formed. A plot of the load vs. the displacement curves for both the cases is as shown in Figure 3.

In the first case, as the moment at 'A' reaches the plastic moment Mp, the first hinge is formed at the support for a load of 455.24 kN with a corresponding displacement of 1.93mm, whereas in the second case, as the mid span moment i.e. moment at 'C' reaches plastic moment first, the first hinge is formed at the mid span for a load 463.7kN and the corresponding displacement of 2.15mm.

The maximum displacement in the first case is 3.58mm and that in the second case is 4.32mm, which shows that the beam becomes flimsier in the second case where an upward displacement of 2mm at the propped end is assumed and created. Even though the collapse load is same in both the cases, the sequence of hinge formation changes in both the cases as shown in Table 1. The Second case shows 21% increase in the displacement during collapse as compared to the first case. This is because, the cantilever in which the hinge formed first at the mid span becomes more flexible as the structural

Table 1: Moments and displacements for Propped Cantilever

Case (i) Cantilever with no aberrations				Case (ii) Cantilever with an upward displacement at propped end		
Load in 'kN'	Moments in 'kN-m'		Max Displacement Δ in 'mm'	Moments in 'kN-m'		Max Displacement Δ in 'mm'
	at 'A'	at 'C'		at 'A'	at 'C'	
250	93.75	78.125	1.06	42.13	103.94	1.06
400	150	125	1.69	98.38	150.81	1.69
410	153.75	128.125	1.74	102.13	153.94	1.74
420	157.5	131.25	1.78	105.88	157.06	1.78
430	161.25	134.375	1.82	107.76	158.01	1.82
440	165	137.5	1.86	109.63	160.19	1.86
450	168.75	140.625	1.91	113.38	163.31	1.91
455.24	170.72	142.2625	1.93	117.13	166.44	1.93
460		144.6425	2.04	120.88	169.56	1.95
463.7		146.220	2.11	122.27	170.72	2.15
470		149.6425	2.29	128.57		2.75
480		154.6425	2.55	138.57		3.24
490		159.6425	2.82	148.57		3.72
500		164.6425	3.12	158.57		4.21
510		169.6425	3.48	168.57		4.29
512.145		170.72	3.58	170.72		4.32

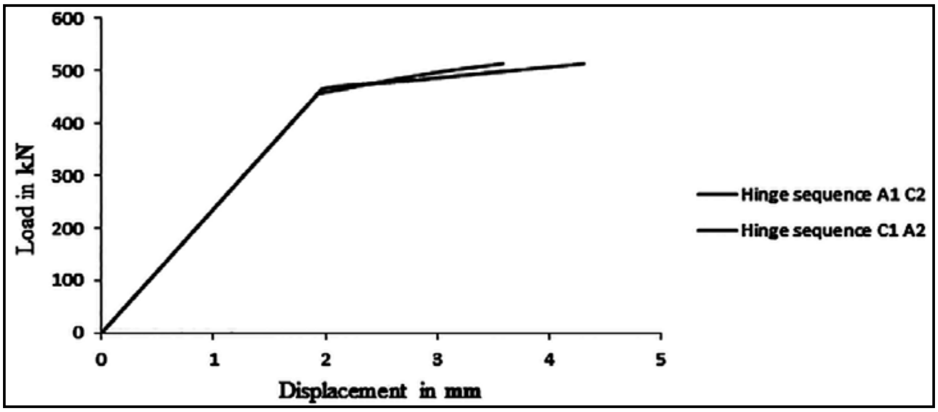

Figure 3: Plot of load vs. displacement of a propped cantilever beam

element behaves as a cantilever on one side and suspended beam on the other side.

B. Illustration 2 – RC Portal Frame

The maximum base shear and corresponding displacements from the pushover analysis results obtained for all possible sequence of hinge formations have been presented in Table 2. It can be observed that the displacement and the base shear vary for every sequence of hinge formation. Here, the minimum displacement obtained is 0.013551m and the corresponding base shear is 35.83kN for hinge sequence 4231 and maximum displacement is 0.051407m with base shear of 42.781kN for hinge sequence 3142. Figure 4 shows the pushover curves for all the 24 sequences of hinge formations. The pushover analysis results obtained for all other sequences of hinge formations have the displacement values between these ranges, and they are all unique. This clearly indicates the influence of the sequence of hinge formation on pushover analysis results especially on the displacement characteristics. It is also observed that the base shear variations are independent of the changes in displacement characteristics i.e., they are not proportional to one another. One of the possible reasons for variations in the base shear results is due to the strength degradation of the structure, which was purposely made to obtain different sequences by making the member weaker at the desired hinge locations. A plot of the first drop or the first hinge formation for all the 24 sequences is as shown in Figure 5.

Table 2: Base Shear and Displacements for 24 Sequences of Hinge Formations

Sl No	Sequence	Base Shear in kN	Displacements in 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	30.426	0.015663
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

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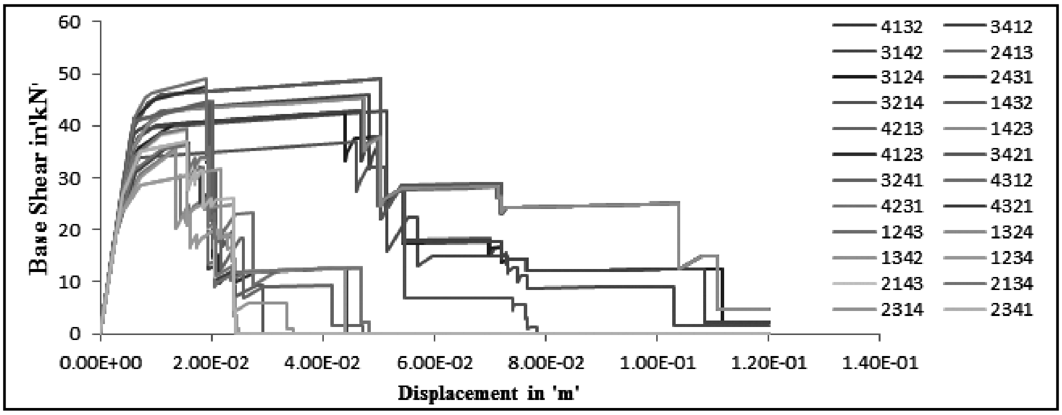

Figure 4: Pushover Curves for 24 Hinge Formation Sequences

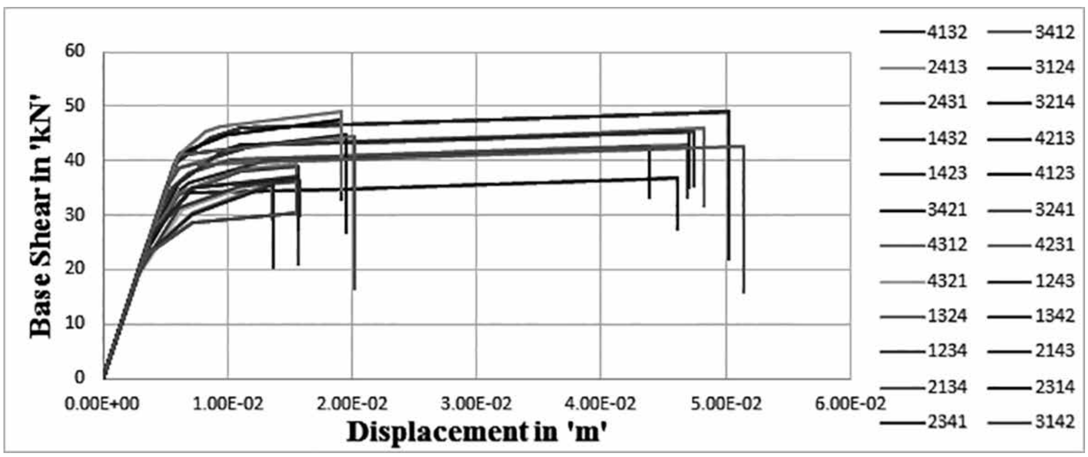

Figure 5: Plot showing he first drop for each sequence of the hinge formations

V. Conclusion

In this paper, an RC portal frame and a propped cantilever have been analyzed for the pushover loads to assess the displacement characteristics influenced by the sequence of hinge formation. The pushover analysis results obtained in both the cases indicate that the sequence of hinge formation has a notable effect on the structure's behavior. Therefore, it is concluded that the hinge formation sequence plays a major role in the performance of the structure. However, much needs to be done to justify the concept of the sequence of hinge formation by extending this procedure to more complex structures such as the tall structures.

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