# A Review on Pattern of Plastic Hinge Formation in Pushover Analysis

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***Abstract*—Performance based pushover analysis is a modern tool to understand the behavior of structures during different ground motions. The need of performance based analysis is ability to assess the seismic demands and capacities with a reasonable degree of certainty. To study the seismic estimates of RC structures, various methods have been developed based on Time History Analysis, Response Reduction factor etc., The Modal pushover analysis has also been introduced to overcome the drawback of conventional pushover analysis which is based on first elastic mode of the structure. The effects of plastic hinge properties in nonlinear analysis of RC frames by considering various parameters have been studied. However the models have failed to predict the sequence of hinge formation in actual earthquakes. Several structural engineers have an interest in this very concept, as it offers a clear strong and a robust understanding of the sequence of hinge formation in pushover analysis which may help us to predict the desired mode of failure and structural response during strong earthquake ground motions. The current work gives an overview of past work done in this recently growing concept of performance based seismic assessment using nonlinear static pushover analysis.**

***IndexTerms*—Pushover analysis, Time History Analysis, Response Reduction factor, Hinge formation.**

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## I. Introduction

Earthquakes cause serious damages to structures leading to injuries and deaths with economic loss. There is an imperative want for seismic assessment of structures. Performance based seismic design using nonlinear static pushover analysis is a modern approach to achieve desirable and predictable performance of structures. Pushover analysis could be a nonlinear static procedure adopted to estimate seismic structural deformations using simplified nonlinear technique.

The principles of performance based seismic engineering are generally used to govern the analysis where inelastic structural analysis is combined with seismic hazard to calculate seismic performance of the structure. This concept is based on many different guidelines like FEMA-273, FEMA-356, ATC-40. These guidelines helps in achieving a particular objective of a structure under different ground motions. The three key elements of the following method are

Capacity: It is the representation of structures resistance towards considered seismic demands.

Demand: It is representation of ground motions

Performance: Combination of capacity and demand.

In Pushover analysis, the structure is subjected to monotonically distributed load along its height. Base shear vs. displacement curve of the structure, referred as the pushover curve, is an important outcome of pushover analysis of plastic hinge behavior and deformation controlled actions. The analysis is carried out till the failure of the structure, wherein the deformation capacity or the collapse load are obtained. The performance level of the structure is also an important parameter during pushover analysis. It is a level which describes the extent of damage conditions which is considered satisfactory for a structure with specific ground motions. The performance levels as per FEMA-273, FEMA-356 and ATC-40 are immediate occupancy (IO), life safety (LS) and collapse prevention (CP).

## II. Literature Review

Several publications have 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.

Helmut Krawinkler and Seneviratna (1998) suggested that, the pushover analysis would be a great improvement over presently employed elastic evaluation procedures and also pointed out that a carefully performed pushover analysis would provide insight into structural aspects that control performances during severe earthquakes. Further it was concluded that, for structures that vibrate primarily in the fundamental mode, the pushover analysis would provide good estimates of global as well as local inelastic, deformation demands. These analyses also expose design weaknesses that may remain hidden in an elastic analysis [1].

A.S.Moghdam et al, (2000) [2]proposed a response spectrum based pushover procedure to obtain seismic response estimates on three types of asymmetrical buildings systems. The procedure also included some of the 3-D effects caused by the response torsion. The main features of this procedure were to use the response spectrum analysis of the building to obtain the load distributions and target displacements. A comparative study on inelastic static pushover analysis and inelastic dynamic analysis on 12 RC building frames with different characteristics was conducted by Elnashai (2001)[3]. Natural and artificial earthquake records were used for the analysis. From the analysis it was observed that static pushover analysis was more appropriate for low rise and short period framed structures. For buildings with structural irregularities, static pushover analysis showed good correlation with dynamic analysis. Further author also indicated the significance of static pushover analysis as an effective alternative method to inelastic dynamic analysis. Author analyzed the dynamic response of structures using static pushover analysis. New developments towards a fully adaptive pushover method accounting towards inelasticity, geometric non-linearity, full multimodal, spectral amplification and period elongation within a framework of fiber modeling of materials were presented and preliminary results were obtained. These developments lead to static analysis results that were more accurate than inelastic time-history analysis. One of the first examples of modal pushover analysis procedure for estimating the seismic demand of buildings was studied by Chopra and Goel (2001)[4]. The analysis was applied to a 9 storey steel frame building. Peak inelastic response was determined and it was compared with nonlinear response history analysis. From the comparison it was concluded that modal pushover analysis was more accurate for practical application in building design and evaluation.

Mehmet Inel, HayriBaytanOzmen (2006)[5] performed 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 defining plastic hinges at both ends of beams and columns, whereas the frames are modelled with user defined and default hinge properties respectively. User defined hinge properties assumes transverse reinforcement spacing and plastic hinge length as effective parameters. Its been observed that 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 base shear capacity. Due to plastic hinge length there is a variation of about 30% in displacement capacities. Comparisons also state that displacement capacity increases with increase in transverse reinforcement. The improvement in displacement capacity is much effective in case of smaller spacings. Although the hinge locations seem to be consistent, the model with default hinges emphasizes on a strong column weak beam mechanism i.e damage or failure occur at 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 case of higher levels , it is also apparent that the user defined hinge model is more successful in capturing the hinging mechanism compared to default hinges model. Hence the author concludes that user defined hinge model is better than the default hinge model in reflecting nonlinear behavior compatible with element properties.

Pushover analysis on the representative building using displacement coefficient method included in FEMA-356 was performed by N. Lakshmanan (2006)[6]. Weightage factor was assigned to number of hinges in beams and columns for each performance range, and vulnerability index was found out from which good or poor performance of building elements during earthquake was studied. To evaluate the performance of three framed buildings A.Kadid and A.Boumrkik (2008)[7] 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. Its 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 its been observed that the plastic hinges are formed at the beam ends and base columns 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 limits. Hence the author concludes that a properly designed/detailed reinforced framed building perform well under seismic loads.

Li Peng and Yi Weijian (2008)[8] compared the effects of different axial load ratio and loading path on columns under cyclic loading. It is observed that axial load ratio and loading path affect plastic hinge length and as the axial load increases, plastic hinge length increases. Further the performance of reinforced concrete frames using pushover analysis was studied by P.Poluraju et al (2011)[9]. Through the analysis it is observed that behavior of properly detailed reinforced concrete frame building is adequate as indicated by the intersection of capacity and demand curves and the distribution of hinges in columns and beams. Most of the hinges were formed in the beams and few in columns with limited damages.

K.RamaRaju et al (2012)[10] studied nonlinear static pushover analysis for a 6 storey office building with 4 types of load cases designed as per IS:456, IS:1893 and EC8. In this study stress strain curves of confined concrete and user defined hinge properties were used to conclude that the model with user defined hinge was more successful in capturing the hinging mechanism of the structure. Whereas KavitaGolghate et al (2013)[11] performed pushover analysis on a 4 storey building located in seismic zone IV designed as per IS:456 and IS:1893 considering properties available in SAP2000 which are based on the guidelines of FEMA-356 and ATC-40. From the analysis it is been observed that hinges are developed in beams and columns while the hinges in columns show limited damages as compared to hinges in beams. Further Sofyan.Y.Ahmed (2013)[12] analyzed a 10 storey reinforced concrete frame building subjected to seismic hazard of the Mosul City, Iraq. Plastic hinges were used to represent the failure mode in beams and columns and concluded that most of the hinges are developed in beams. The seismic performance of a five storey reinforced concrete residential building designed according to the Moroccan seismic code RPS2000 assessed by M. Mouzzoun et al (2013)[13]. Pushover analysis was performed using SAP2000 to detect the locations of plastic hinges and the results obtained from the study showed that designed building performed well under moderate earthquake, but it is vulnerable under severe earthquake.

To understand the contribution of infill walls in formation of plastic hinges in beams and columns SuchitaHirde et al (2013)[14] studied the effect of modelling of masonry infill on the response of multi-storied reinforced concrete frame building under seismic loading using three models. The results of the bare frame analysis and frame with infill effects were compared in the form of capacity spectrum curve, performance point and hinge formation at performance point. The author concluded that masonry infill contributes significant lateral stiffness, strength, overall ductility and energy dissipation capacity. Further Nivedita N. Raut et al (2013)[15] investigated the effect of the layout of masonry infill panels over the elevation of masonry infilled RC frames on the seismic performance and potential seismic damage of the frame under strong ground motions using nonlinear static pushover analysis. From the analysis, comparison of base shear vs. displacement of bare frame, infill wall frame and weak storey frame was done, and it was observed that displacement in bare frame was more than other two frames and displacement at ground floor in weak storey is more than other two frames. Hinges were formed in beams than in columns.

To overcome stiffness degradation and strength deterioration, which are important characteristics of reinforced concrete members under cyclic loading, causing a reduction of deformation capacities proposed cyclic pushover analysis. The cyclic lateral force distribution is developed based on the mode shapes and prescribed displacement history. The seismic demands of a 9-story reinforced concrete building are evaluated by Cyclic Pushover Procedure by PhaiboonPanyakapo (2014)[16]. Four types of loading protocol, i.e., Laboratory, ATC-24, International Organization for Standardization (ISO), and Sequential Phased Displacement (SPD) protocols are employed to investigate the effects of displacement histories on seismic demands. The seismic demands include the peak roof displacement, the peak floor displacement and the peak inter-story drift ratio. The results are compared with the exact demands resulting from nonlinear time history analyses of MDOF structure subjected to 20 ground motions, as well as the demands estimated from the Modal Pushover Analysis. The results demonstrate that the Cyclic Pushover Analysis provides a reasonable and accurate estimate of seismic displacement demands.

Sensitivity of pushover curve to material and geometric modelling was studied by NeenaPanandikar (Hede), K.S. Babu Narayan (2015)[17]. An attempt was made to understand the sensitivity parameters like variation in material properties, inaccuracies in placement of reinforcement, effect of confinement of concrete and modelling techniques for elements and plastic hinges. Whereas an attempt to assess damage and also to evaluate the performance of the multistoried structures which were already designed and analyzed using linear static analysis for seismic loads as per IS-456, IS-1893, IS-13920 was made by G.V.A Pavankumar et al (2015)[18]. A 12 storied building was designed and analyzed for seismic analysis using STAAD for the 2 seismic load cases (zone-3 and zone-5) considering both as special moment resisting frames with response reduction factor as 5. It was observed that no damage or hinge formation takes place during the initial stage and after the completion of nonlinear static pushover analysis for both the building frames for dead and live loads. In case of zone 3 design, the stiffness of the frame is less hence hinges were formed upto collapse prevention level within the target displacement. In case of zone 5 design, the stiffness of the frame is quite higher than zone 3 frame, hence hinges were formed upto life safety level within target displacement. From the study it was seen that yielding of beams takes place prior to yielding of columns, thus proving the strong column weak beam theory.

## III. Summary of Literature Review

Pushover analysis is one of the powerful tools to evaluate the strength and deformation characteristics of performance based design of structures. This paper has documented the vast amount of interest and effort devoted by the researchers to enhance the capabilities of pushover analysis and its applications. Not withstanding the efforts, unresolved issues are existing and persisting. The gap between predictions of models and observed behavior is being narrowed by strategies to make geometric and material modelling more refined.

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