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Nonlinear Pushover Analysis for Performance Based Engineering Design – A Review

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Abstract: Engineering Structures are designed to withstand all the anticipated loads without failure. Even after utmost care in assessing the expected loads as per the Codal provisions and field experience, modeling random loads like a seismic load is quite tedious and difficult. Performance based design using nonlinear pushover analysis is a highly iterative process aimed to control the structural damage under the action of earthquake forces based on precise estimation of proper response parameters. This paper reviews performance based design method using non-linear push over analysis and significant contributions published.
Keywords: Seismic Load, Nonlinear static pushover analysis, Performance based design, Higher mode effects, Invariant load distribution

I. INTRODUCTION

Earthquake is one of the most destructive natural hazards. The primary objective of designer is to prevent the havoc of earthquakes and minimize the loss of life and property. Seismic loads are quite random in nature and are to be modelled carefully to assess the real time behaviour of the structure. Traditionally, the seismic design of structures has been based on strength criteria. In spite of the design using elastic codes, the quantum of damage was very high because the elastic method of seismic design has failed to provide insight into how the structure behaves during earthquakes. Realizing that increasing strength of structure may neither enhance safety, nor reduce damage, there is a gradual shift from “Strength orientation” to “Performance Based.” Advantages in assessing the behavior of structure during strong ground motions to minimize property damage and loss of life has made Performance based design more popular choice among engineers.

Structural behaviour during an earthquake of a given severity can be assessed using linear static, non-linear static, linear dynamic and non-linear dynamic analysis methods. The performance based seismic design process evaluates how a building is likely to perform under an earthquake of expected severity; considering uncertainties inherent in the quantification of potential risk and uncertainties in assessment of the actual building response. It is an iterative process that begins with the selection of performance objectives, followed by the development of a preliminary design, an assessment as to whether or not the design meets the performance objectives, and finally redesign and reassessment, if required, until the desired performance level is achieved. The most commonly adopted method is non-linear static analysis, popularly known as pushover analysis. The static pushover analysis is gaining significance as one of the popular tools for evaluating seismic performance of new and existing structures. The expectation is that the pushover analysis will provide adequate information on seismic demands imposed by the design ground motion on the structural system and its components (Krawinkler and Seneviratna, 1998).

II. PERFORMANCE BASED DESIGN

This is the design methodology in which structural design criteria are formulated in terms of performance objectives like load, displacement, target damage state etc.,. In this method to obtain realistic estimates of inelastic deformation in structures so that the deformations may be checked against deformation limits as established in the appropriate performance criteria. Nonlinear static Push Over analysis is one of the effective procedures to do the performance based design.

III. NON-LINEAR STATIC PUSHOVER ANALYSIS

Non-Linear Static Analysis or pushover analysis is a useful tool for assessing inelastic strength and deformation demands in the structure, and for exposing design weaknesses (ATC, 1996). Its foremost advantage is that it facilitates the design engineer to

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recognize important seismic response quantities and to use engineering judgment to alter suitably the force and deformation demands and capacities that control the seismic response close to failure (Pillai and Menon, 2009).
In pushover analysis, gradually increasing lateral loads are applied on the structure until the target displacement is reached. In Displacement controlled method, used to perform Pushover analysis, the structure is subjected to lateral displacement by inducing incremental displacement gradually in the top storey of the structure. Pushover curves or capacity curves drawn between Base shear and roof displacement is obtained from pushover analysis. The intersection of these curves with the seismic demand curves gives the performance point. Krawinkler and Seneviratna (1998) studied that the nonlinear behaviour such as yielding and failure mechanism are obtained using nonlinear static pushover analysis.
It may be noted that the pushover analysis is approximate and does not account for dynamic characteristics such as hysteresis, higher mode participation etc. It is known to give good results for regular buildings (without torsional irregularity). In such cases, the pushover curve can be converted to acceleration versus displacement response spectrum, where it represents the "seismic capacity" of the structure. It is possible to include in the same plot the "seismic demand", to see whether the capacity meets the demand. The meeting of seismic capacity and demand is called a performance point.

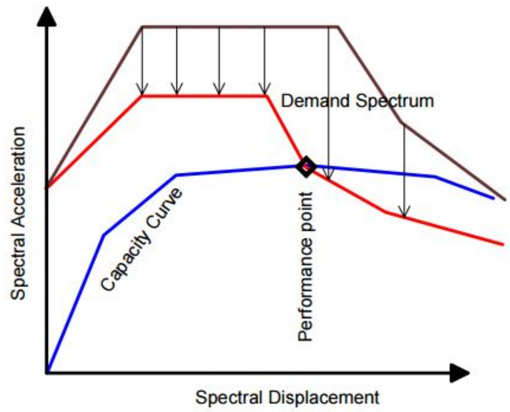

Fig. 1Schematic Representation of ATC – 40 method

In the conventional nonlinear static push over analysis, it was assumed that the response of the Multi Degree of Freedom (MDOF) system could be represented by an equivalent single degree of freedom. It is to conclude that the response is controlled by single mode and that the shape of the mode remains constant throughout, irrespective of the level of the deformation.

A. Performance

It is an intersection point of capacity and demand spectrums. The performance of a building is depended upon the performance of the structural and the nonstructural components. The performance of a structure is checked against the obtained performance levels.

B. Immediate Occupancy

It is a state of structural damage due to earthquake, where life threatening injury due to structural failure is minimal.

C. Life Safety

In spite of injuries to occupants due to the damage with some collapse margin caused to the structure there is no risk of life threatening injury. The results of the nonlinear pushover analysis of the MDOF system are used to determine the force – deformation characteristics of the equivalent SDOF system.
The pushover analysis or NSP method came into picture in late 70's. In mid 90's the potential of pushover analysis has gained importance and found its way to seismic guidelines for instance SEAOC 1995, FEMA 273/274 1997,ATC 40 1997. It's importance is well recognized and included in codes such as FEMA 356/357 2000, ATC 55 2005 , FEMA 440 2006. However pushover analysis suffers from several from several inherent deficiencies. Invariant load distribution in traditional N S P is one of the most limitations. It also cannot take higher-mode effects and torsional effects in to consideration
Hence many attempts have been made to develop enhanced pushover procedures to overcome the deficiencies.

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IV. LITERATURE REVIEW

A review of literature is presented in brief, summarizing the significant contribution of researchers on performance based non-linear pushover analysis of engineering structures.

Helmeut Krawinkler, et al., (1998) discussed the pros and cons of pushover analysis of seismic performance evaluation. Presented the basic concepts on which the pushover analysis is based, assessed the accuracy of pushover predictions and identified the conditions under which pushover will structures, but it should be complimented with other evaluation procedure if higher mode effects are to be considered

R.Martino,et al.,(2000) discussed the procedure of NSP and presented preliminary results of the NSP with a full non-linear *analysis.*NSP was performed for six ,twelve and twenty storey R C C moment resisting frames designed according to the UBC code. The resulting target displacements obtained from the pushover analyses were compared with the maximum and minimum roof displacements induced by the dynamic analyses. The authors concluded that the non-linear pushover analysis is accurate for stiffer reinforced concrete structures whose higher modes don't significantly contribute to the overall dynamic response. On the other hand the NSP appears to be not appropriate for taller, more flexible frames whose higher modes are significant to overall dynamic response

A.M.Mwafy, et al.,(2000) studied feasibility of inelastic static pushover analysis in predicting the seismic response of structures. Twelve RC buildings with various characteristics , incremental dynamic analysis employing eight natural and artificial records, static pushover analysis using three lateral load distributions and local and global limit state criteria are utilized. It is concluded that pushover analysis can provide insight into the elastic as well as the inelastic response of buildings when subjected to earthquake ground motion If adequate modeling of the structure , careful selection of the lateral load distribution ,articulate interpretation of the results are done. Static pushover analysis is more appropriate for low rise and short period framed structures.

Peter Fajfar. et al., (2000) Presented a relatively simple nonlinear method for the seismic analysis of structures, "the N2 method ," which is formulated in the acceleration-displacement format, combines the pushover analysis of MDOF with the response spectrum analysis of equivalent SDOF system. The method enables the visual interpretation of the procedure and the relation between the basic quantities controlling the seismic response. Inelastic spectra, rather than elastic spectra with equivalent damping and period are applied. Generally the results of the N2 method are reasonably accurate ,provided that the structure oscillates predominantly in the first mode. Only in a special case the ATC 40 transformation is considered equivalent to the FEMA 273 and N2 transformation. In N2 method , the assumed displacements shape and lateral force pattern are related. In this way one of the approximations present in FEMA 273 and ATC 40 is eliminated

Anil K.Chopra, et al.,(2001) Developed a pushover analysis procedure based on structural dynamic theory, which retains the conceptual simplicity and computational attractiveness of current procedures with invariant force distribution, but provides superior accuracy in estimating seismic demands on buildings. The procedure was presented in PEER report 2001/03. The standard response spectrum analysis (RSA) for elastic buildings is reformulated as a model pushover Analysis (MPA). The peak response of the elastic structure due to its nth vibration mode can be exactly determined by pushover analysis of the structure subjected to lateral forces distributed over the height of the building according to Sn* = m ϕ_n, where m is the mass matrix and ϕ_n its nth-mode, and the structure is pushed to the roof displacement determined from the peak deformation D_n of the nth-mode elastic SDF system combining these peak model responses by model combination rule leads to the MPA procedure comparing the earthquake – induced demands for the selected 9-story building determined by pushover analysis using three force distributions in FEMA 273, MPA and nonlinear RHA, demonstrates that the MPA procedure is more accurate than all the FEMA force distribution in estimating floor displacements story drifts and single plastic relation.

Anil K.Chopra, et al.,(2004) Presented the results of estimated roof displacements of the SDF system for some generic frames and six SAC buildings subjected to ground motion ensembles. Data obtained for generic frames indicate that the first "mode" SDF system overestimates the median roof displacement for systems subjected to large ductility demand, but underestimates for small ductility demand. The bias and dispersion tend to increase for longer period system. Similar data for SAC buildings demonstrate that the bias and dispersion on the SDF estimate of roof displacement increases when P-delta effects (due to gravity loads) are included. The modal pushover analysis procedure has the advantage of reducing the dispersion in the roof displacement and the underestimation of the median roof displacement for elastic or nearly elastic cases at the expense of increasing slightly the overestimate of roof displacement of buildings responding far into the elastic range

Chatpan Chintanapakdee, et al.,(2004).Presented the observations on effects of vertical irregularity on the median values of story

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drifts and floor displacements when eight no.of 12-storey high frames with strong columns and weak beams were subjected to an ensemble of 20 ground motions. The seismic demands for vertically regular and irregular frames were obtained by Modal Pushover Analysis and Nonlinear Response History Analysis and the results are compared. The accuracy does not deteriorate in the MPA procedure in spite of irregularity in stiffness, strength, or stiffness and strength provided the irregularity is in the middle or upper story. But it is less accurate for frames with strong, or stiff-and-strong first storey ; soft, weak or soft-and-weak lower half; stiff, strong, or stiff-and-strong lower half. The MPA procedure clearly identifies the stories with large drift demands and estimates them to a sufficient degree of accuracy, thereby detecting critical stories in such frames. The bias in MPA procedure for frames with a soft, weak, or soft-and-weak first storey is about the same as for the regular frame

Tysh Shang Jan, et al.,(2004) Presented an upper-bound pushover procedure for estimating the seismic demands of high-rise buildings. A new formula is proposed based on the response spectrum-based higher mode displacement contribution ratios for determining the lateral load pattern and the upper-bound (absolute sum) modal combination rule for determining the target roof displacement .This upper bound method is performed on low, medium and high-rise buildings and it is concluded that this method can more precisely estimate important response attributes of tall buildings, such as roof displacements, story drift ratios and plastic hinge rotations.

Anil K. Chopra, et al.,(2004) Extended the model pushover analysis (MPA) procedure to unsymmetric-plan buildings. In the MPA procedure, the seismic demand due to individual terms in the model expanses of the effective earthquake force is determined by non-linear static analysis using the inertia force distribution for each mode, which for unsymmetric buildings includes two lateral forces and torque at each floor level. These “Model” demands due to first few terms of the model expansion are then combined by the CᴓC rule to obtain an estimate of the total seismic demand for in elastic systems. The MPA estimates of seismic demand for torsionally-stiff and torsinally – flexible unsymmetric systems are shown to be similarly accurate as they are for the symmetric buildings; however, the results deteriorate for a torsionally – similarly – stiff unsymmetric system and the ground motion considered because (a) the elastic modes are strongly coupled and (b) roof displacement is under estimated by the CQC model combination rule. Simulations action of two horizontal components of ground motion and structural plans unsymmetric about both axes also remain to be investigated.

Erol Kalkan, et al.,(2006) investigated the effectiveness of several NSPs in predicting the salient response characteristics of typical steel and reinforced concrete buildings through comparison with benchmark responses obtained from a comprehensive set of NTH analyses. Critically examined the ability for four different type of nonlinear procedures i e FEMA-356,

MMPA(modified modal pushover analysis), UBPA (upper-bound pushover analysis), AMC (adaptive modal pushover analysis) to predict seismic demands in set of existing buildings subjected to 30 ground motions having different characteristics. It is concluded that compared to FEMA-356 and UBPA procedures, MMPA provides story drift estimates that are generally much closer to the mean NHT estimates but it is unable to reasonably predict plastic rotation demands in the upper stories .The AMC procedure which integrates the inherent advantages of the capacity spectrum method, modal combination and adaptive loading scheme provided the best overall comparison with NTH results.

W. Haung, et al.,(2008) Presented a case study considering a new 3-D pushover analysis procedure to analyse the failure of a 115 metre high reinforced concrete chimney with an unusually large rectangular duct opening , collapsed during the 1999 Kocaeli, Turkey earthquake. Results confirm that the stack could readily fail under the considered earthquake. The 3-D pushover analysis procedure provides better estimation for target displacements when compared to the 2-D pushover analysis.

Sun-Pil Kim,et al.,(2008) Proposed an alternative pushover analysis procedure to estimate the peak lateral displacement demands for building structures responding in the nonlinear range. The main advantage of the proposed procedure is that the effects of higher modes on the lateral displacement demands are lumped into a single invariant lateral force distribution that is proportional to the total seismic masses at the floor and roof levels. The applicability and validity of this Mass Proportional Pushover procedure (MPP) are critically evaluated through comparisons with multi-degree-of-freedom nonlinear dynamic time-history analysis results for a set of benchmarked three- storey, nine storey and twenty storey steel moment resisting building frame structures. These demands are compared with the results obtained from a Modal Pushover Analysis (MPA) procedure.The proposed Mass Proportional Pushover procedure provides, on an average better roof and floor lateral displacement demand estimates than the Modal Pushover Analysis procedure. The improvement from the proposed procedure is larger for the nine- storey and twenty- storey structures than the improvements for three-storey structure and is also larger for Design Basis Earthquake (DBE) ground motion set than the Maximum Considered Earthquake (MCE) set.

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M. Seifi .et al.,(2009) Presented a comparative study in estimating the capacity of the structure and inter-storey drifts of an Reinforced Concrete framed structure by the conventional and modified nonlinear static pushover analysis methods. The results of applying 5 types of NSP methods including conventional FEMA -356, “Triangular” and “Uniform” methods, “Force-basd” , “ Displacement-based” and “Interstorey drift-based” adaptive methods were evaluated referenced to the “Incremental Dynamic Analysis” The numerical outcome , demonstrated the reliability of interstorey drift-based method in evaluating the capacity of the structure as well as superiority of this method in estimating the interstorey drifts by increasing the value of control-node displacement.

Mehdi Poursha. et al.,(2008) Presented a new pushover procedure named as Concecutive Modal Pushover (CMP) procedure which can take into higher- mode effects , utilizes multi-stage and single- stage pushover analyses. In the multi-stage pushover analyses, modal pushover analyses are conducted consecutively with force distributions, using mode-shapes derived from the eigen- analysis of the linearly elastic structure. The single-staged pushover analysis is performed with a triangular or uniform load distribution. This procedure is applied to four special steel moment-resisting frames with different heights. A comparison between estimates from the CMP procedure and the exact values obtained by non-linear response history analysis (NL-RHA), as well as predictions from modal pushover analysis (MPA),has been carried out. It is demonstrated that the CMP procedure is able to effectively overcome the limitations of traditional pushover analysis, and to accurately predict the seismic demands of tall buildings

Medhi Poursha. et al.,(2011) Extended the consecutive modal pushover procedure (CMP) to estimate the seismic demands of one-way unsymmetric-plan tall buildings .The procedure uses multi-stage and classical-stage pushover analysis and benefits from the elastic modal properties of the structure. Both lateral forces and torsional moments obtained from the modal analysis are used in the multi-stage pushover analysis. The seismic demands are obtained by enveloping the peak inelastic responses resulting from the multi-stage and single-stage pushover analysis .This procedure is applied to 10, 15 and 20 –storied one-way unsymmetric-plan steel frame buildings including systems with different degrees of coupling between lateral displacements and torsional rotations i,e.torsionally-stiff (TS), torsionally-similarily-stiff(TSS) and torsionally-flexible (TF) systems. The results are compared with the results obtained by the nonlinear response history analysis (NL-RHA). It is demonstrated that the CMP procedure is able to take into account the higher mode influences as well as amplification or de-amplication of seismic displacements at the flexible and stiff edges of unsymmetric-plan buildings. The extended procedure can predict to a reasonable accuracy the peak inelastic responses ,such as displacements and storey drifts. The CMP procedure represents an important improvement in estimating plastic rotations of hinges at both flexible and stiff sides of unsymmetric- plan buildings in comparison with MPA procedure.

Barbara Ferracuti. et al.,(2009) Presented the study aims at validating pushover methodologies for RC frame structures through comparison with Incremental Dynamic Analysis. Three different pushover procedures have been considered i.e., conventional (first mode load distribution, uniform load distribution) and Displacement-based Adaptive pushover methods. With reference to the three case studies, comparison of static against dynamic results has been carried out in terms of capacity curves, interstorey drift profiles, maximum top displacement and failure modes. It is concluded that in the most instances the displacement-based adaptive pushover features the highest potential to better reproduce results of incremental dynamic analysis with respect to conventional procedures based on invariant load vectors. Prediction of interstorey drift profiles obtained from the DAP procedure are particularly accurate for both regular and irregular frame structures. The DAP procedure yields better results with respect to conventional pushover methods as prediction of failure mode is concerned.

Kazem Shakeri et al., (2010) Proposed a new adoptive pushover method i.e., story shear-based adaptive pushover procedure called “SSAP” based on the story shears which takes into account the reversal of sign in the higher modes. In each step, the applied load pattern is derived from the instantaneous combined model story shear profile. The sign of the applied loads in consecutive steps are changed and the structure is simultaneously pushed and pulled in different story levels. Another aspect of the proposed method is that at each step an assumed fundamental mode shape is derived from the load profile. Based on this adaptive fundamental mode shape and the energy concept, the multi degree of freedom system is converted in to single degree of freedom system. The results show an admirable accuracy in prediction of peak inelastic drift response, especially where the effects of higher modes are important. A combination of this method with the conventional pushover approach, called “SS-MI” results in more accurate estimation of peak inelastic drift in all story levels compared to the other pushover approaches.

Yi Jiang, Gang Li et al., (2010) Developed in energy balance concept based multimode pushover analysis to estimate the seismic demand of new and retrofitted buildings, which incorporate the concept of modal energy demand and capacity and retains computational attractiveness. The energy based energy capacity curve and modal demand curve of buildings in which higher modes

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are assumed elastic, are constructed. The dynamic target displacement is determined based on the intersection of the two diagrams. By comparing with nonlinear history analysis and other successful advanced pushover procedure (MMPA), the accuracy and higher mode effects of the proposed procedure for the benchmark frame buildings subjected to near-fault ground motions with and without velocity pulses are verified. It is concluded that the proposed procedure is an attractive alternative for practical application.

Kazem Shakeri et al., (2011) developed a single-run adaptive model pushover procedure based on the modal story shear and torque, for seismic assessment of asymmetric-plan buildings. In which the load pattern consists of the lateral forces and torques which are derived from the instantaneous combined modal story shear and torque profiles each step. The contribution of higher and torsional modes and the effects of the changes in the structural properties during the inelastic domain are considered. The effects of reversal signs in the higher modes are simulated in the load pattern. The capacity spectrum curve is obtained from a formulation based on the modal energy concept and the ambiguity of choosing controlling point to obtain the target displacement in asymmetric-plan buildings has been eliminated. The accuracy of the proposed method has been verified o three asymmetric-plan buildings under different earthquake records. The results indicate that this method could predict the results of the nonlinear time history analysis appropriately.

Akanshu Sharma et al., (2012) Presented experimental and numerical work carried out on full-scale four storey reinforced concrete structure for seismic assessment by pushover method. The structure was detailed as per non-seismic reinforcement detailing norms of Indian Standards. The experiment was carried out as a round robin exercise, in which various institutes in India participated and presented pre-test results in the form of pushover curves. A large variation in the pre-test results highlighted the result of pushover analysis is highly sensitive to the adopted modeling techniques. It is also reported details and results of the experiment and focuses on the need of modeling various structural nonlinearities to obtain realistic results. The results of pre-test analysis by various research groups, in which the emphasis was given on modeling issues as well as a more efficient post-test numerical procedure is also presented and compared. It is shown that a basic pushover analysis considering only flexural failures may not be able to achieve a realistic simulation, thus it is mandatory to develop relatively simple, yet effective models to consider more complex phenomena such as joint shear failures, to achieve realistic predictions.

Reza Abbasnia et al., (2013) developed an alternative displacement-based adaptive pushover procedure based on the effective model mass combination rule. In addition to the higher mode effects consideration and the progressive changes in the dynamic characteristics of the structures, this displacement-based adaptive modal pushover method called APAM, utilize an effective modal mass combination rule in order to take into account the sign reversals of the applied load vector in the higher modes. In this regard, a relative mode contribution factor, which is updated proportional to the instantaneous dynamic characteristic of structure, is applied to each modal load vector. The modified modal load vectors are algebraically added and subtracted and consequent load patterns are independently applied to the structure within an adaptive frame-work and the envelope of demand values are considered. These modification factors are updated proportional to the instantaneous dynamic characteristic of structure in each step. Another novel aspect of the proposed method is that the target displacement is estimated during the analysis by implementing the concept of capacity spectrum method recommended by ATC 40. In order to assess the accuracy of this method in predicting the seismic responses, the proposed methodology is applied to three different moment-frame buildings. The obtained results demonstrate that APAM procedure provides well estimation of important seismic demand parameters.

G.P. Cimellaro et al., (2014) proposed a bidirectional pushover analysis (BPA) method to overcome the limitations of current pushover methods to assess the seismic response of irregular buildings subjected to bidirectional ground motions. The extended N2 method and proposed BPA method were applied to estimate the nonlinear response of six highly irregular reinforced concrete frame structures designed according to the requirements of Eurocode 8. Results in terms of inter story drifts and floor rotations are compared with those given by nonlinear response history analysis (NRHA). It is reported that the results given by the proposed BPA method match those given by NRHA when the earthquake loadings are considered to act simultaneously in two principal orthogonal directions (X and Y) with load factors of 1 and 0.6, respectively.

Karim Tarbali et al., (2014) proposed a single-run pushover procedure to assess the seismic response of asymmetric-plan buildings, when subjected to unidirectional earthquake ground motions. The effect of the higher and torsional modes is incorporated into a single-run invariant load pattern. The load pattern is derived based on the height-wise distribution of the modal story shear and torsional moment in stories of the structure. In order to consider the instantaneous changes in dynamic characteristics of the structure in the nonlinear phase, capacity curve of the structure is obtained based on the instantaneous deformed shape of the structure, using the adaptive capacity spectrum method (ACSM). This proposed method (i.e., ST-ACS) is a single-run procedure,

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which facilitates tracing the nonlinear response of the structure during the pushover analysis. Two asymmetric-plan steel moment-resisting frames with 9 and 20 stories have been used to evaluate the accuracy of the proposed procedure against the results from nonlinear response history analyses (NRHA). Results from numerical investigations indicate appropriate accuracy of the proposed procedure in capturing the relative displacement of structures when compared to the results from nonlinear response history analyses.

V. CONCLUSION

Based on the review on the state of development of pushover analysis following conclusion can be drawn.

A. Pushover analysis is a solution for performance based design and is becoming popular tool for seismic evaluation of existing and new structure due to the simplicity compared to non-linear dynamic time-history analysis.
B. The conventional code-based method has many deficiencies as higher mode contribution, stiffness degradation and the period elongation are not considered. But this method is the most well known method in society of practical engineer due to is simplicity.
C. In recent decade, several methods such as APA, N2, MPA, MT, MMC, MMPA, UBPA, CMP, ST-ACS DAP, SSAP, SSMI, APAM, BPA etc., have been proposed to overcome the deficiencies of the conventional methods.
D. A majority of studies have been performed on the limited range of buildings imposed by selected ground motion. These are to be evaluated for a wide range of buildings and ground motion ensembles.

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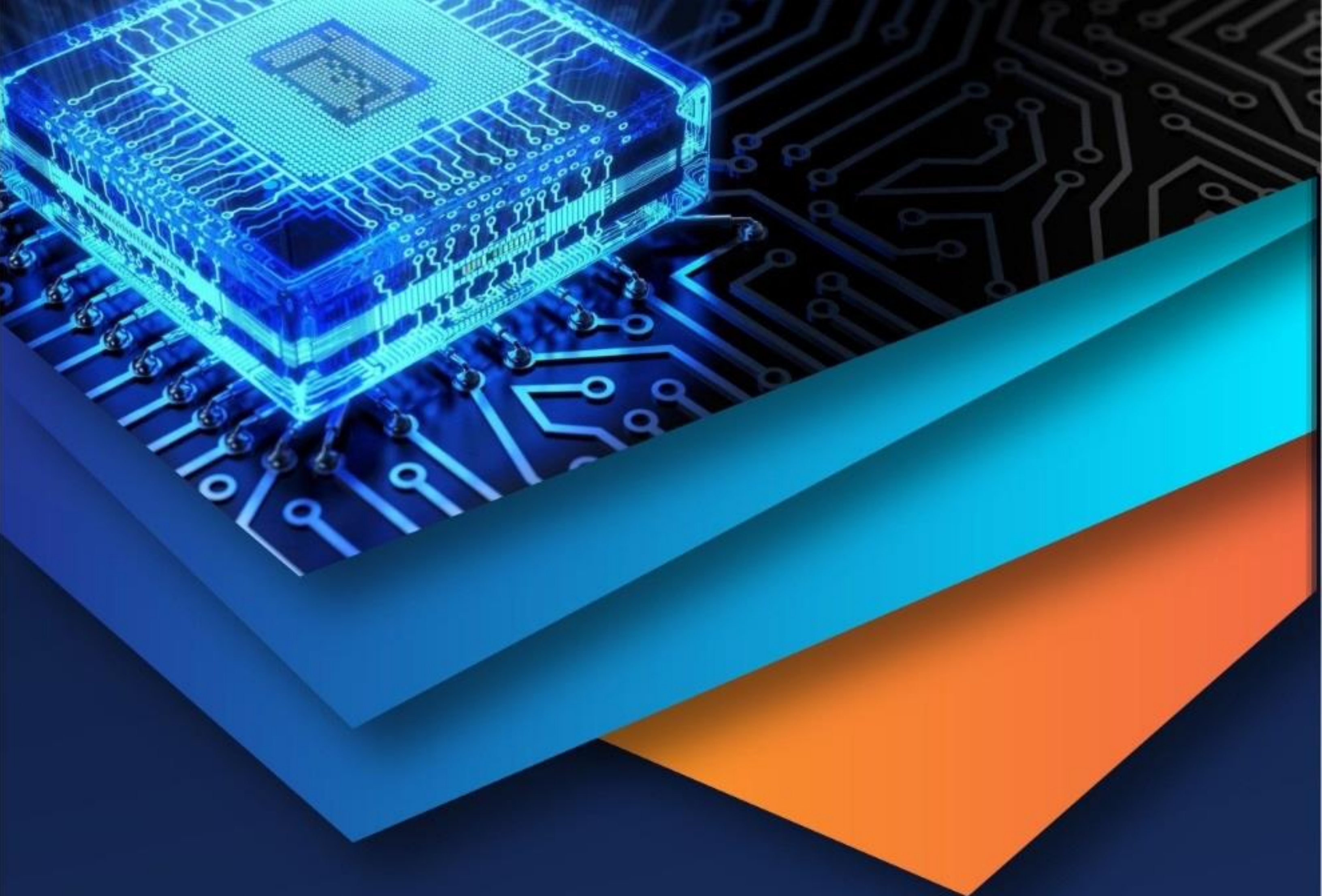

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