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A COMPARITIVE STUDY ON PERFORMANCE OF DIFFERENT CONFIGURATION OF BUILDINGS USING CONVENTIONAL AND ENERGY BASED PUSHOVER ANALYSIS

Mr. S. Siva Brahma Naidu, PG Student, Dept. Of Structural Engineering, Jaya Engineering College, Anna University, Chennai.
Ms. J. P. Praveena Carlin, Assistant Professor, Dept. Of Structural Engineering, Jaya Engineering College, Anna University, Chennai.
Ms. J. Hathari Evanglin, Assistant Professor, Dept. Of Civil Engineering, Vel Tech High Tech Engineering College, Anna University, Chennai.

Abstract

In contemporary architectural trends, buildings often incorporate numerous unavoidable irregularities in their designs. These irregularities make the structure more vulnerable during disastrous natural events like earthquakes, bomb blasts, etc., To design the structures effectively it is necessary to predict the realistic behavior, to attain this objective the type of load pattern chosen for the nonlinear static analysis is important. Indeed, nonlinear static analysis procedures, such as pushover analysis, have gained significant popularity as tools for seismic assessment of structures. These procedures offer valuable insights into the behavior and performance of structures under seismic loads, allowing engineers to better understand and evaluate their response to earthquakes.

The present study is to know the difference between Conventional pushover analysis and Energy based pushover analysis, for this purpose four building models were considered with different plan configurations of buildings having same plan area. The four models are Square shape, plus '+' shape, C-shape and L-shape with 20 stories each. The models were designed for gravity and seismic loads in accordance with IS 456 2000 and IS 1893 2002. In nonlinear analysis structure was pushed for a monitored displacement of 4% of heightof the building. Modelling and analysis of the models were carried out in the ETABS 2016.

Displacements obtained from the conventional pushover analysis are converted into Energy based displacements by using energy equations given by the Hernandez Montes the variation of displacements are in the range of 15% to 30% , time periods and performance levels are also compared, it is observed that the conventional pushover analysis overestimates the roof displacements when compared to energy based pushover analysis.

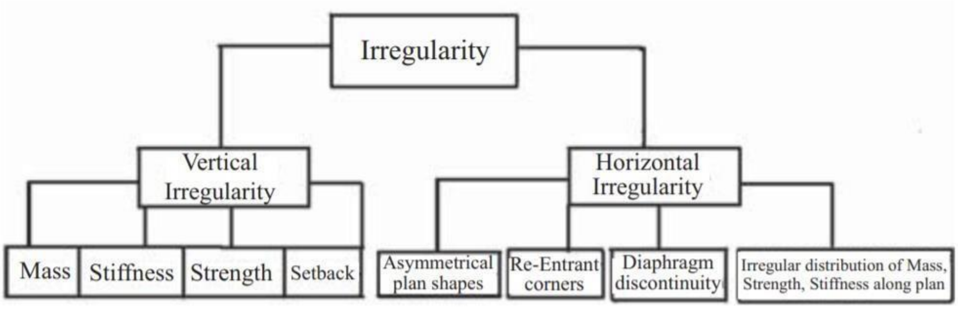
Keywords:
Conventional pushover analysis, Energy based pushover analysis, Different plan configurations of buildings.

Introduction

Irregular buildings constitute a large portion of the modern urban infrastructure. The group ofpeople involved in constructing the building facilities, including owner, architect, structural engineer, contractor and local authorities, contribute to the overall planning, selection of structuralsystem, and to its configuration. This may lead to building structures with irregular distributions in their mass, stiffness and strength along the height of building. When such buildings are locatedin a high seismic zone, the structural engineer's role becomes more challenging. Therefore, the structural engineer needs to have a thorough understanding of the seismic response of irregular structures.

1.0 TYPES OF IRREGULARITIES

Fig 01 Classification of irregularities



1.1 PLANE(HORIZONTAL) IRREGULARITIES

- Torsion Irregularity

To be considered when floor diaphragms are rigid in their own plan in relation to the vertical structural elements that resist the lateral forces. The presence of torsional irregularity is acknowledged if the maximum storey drift, calculated considering design eccentricity, at one end of the structure in the direction perpendicular to an axis, is greater than 1.2 times the average of the storey drifts at the both ends of the structure.

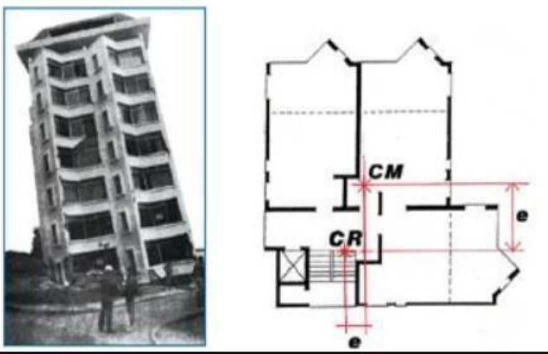
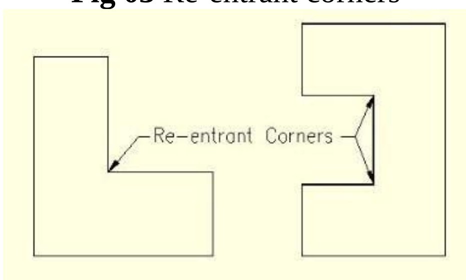


Fig 02 Torsional irregularity

- Re-entrant Corners

The layout designs of a structure and its lateral force resisting system incorporate inward-facing corners, where both extensions of the structure beyond the inward-facing corner exceed 15 percent of its plan dimension in the specified direction.

Fig 03 Re-entrant corners



- Diaphragm Discontinuity

Diaphragms exhibiting sharp discontinuities or variations in stiffness, encompassing those with cut-out or open sections that constitute more than 50 percent of the total enclosed diaphragm area, or shifts in the effective stiffness of the diaphragm exceeding 50 percent between adjacent stories.

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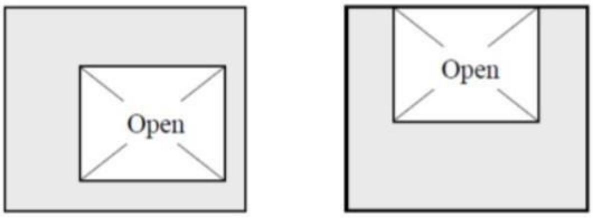
Fig 04 Diaphragm discontinuity



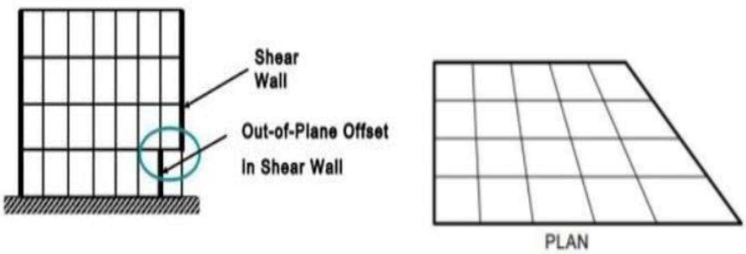
- Out-of-Plane Offsets

Irregularities in the lateral force resisting system, such as vertical elements with out-of-plane displacements or offsets.

- Non-parallel Systems

The vertical components that counteract the lateral forces are neither parallel to nor symmetrical about the principal orthogonal axes or the elements resisting the lateral forces.

Fig 05 Out of plane offset and Non-parallel system.

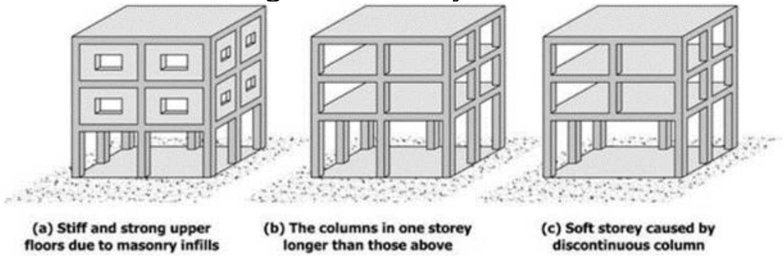


1.2 VERTICAL IRREGULARITIES

- Stiffness Irregularity (Soft Storey)

A deficient storey refers to a storey with a lateral stiffness that is below 70 percent of the stiffness in the storey above or below 80 percent of the average lateral stiffness of the three storeys above.

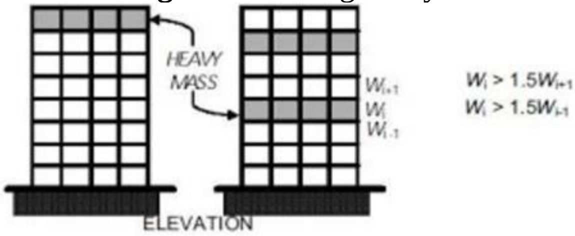
Fig 06 Soft storey effect



- Mass Irregularity

Where the seismic weight of any storey exceeds 200 percent of the seismic weight of its adjacent storeys, mass irregularity is deemed to be present. Notwithstanding, the irregularity arising from mass does not require consideration for roofs.

Fig 07 Mass irregularity



- Vertical Geometric Irregularity

Where the horizontal dimension of the lateral force resisting system in any storey exceeds 150 percent of the horizontal dimension in its adjacent storey, vertical geometric irregularity is deemed to be present.

Fig 08 Vertical Geometric Irregularity

- Discontinuity in Capacity (Weak Storey)

A deficient storey is characterized by a storey lateral strength that is lower than 80 percent of the strength in the storey above. The strength of each storey in terms of lateral forces is determined by considering the combined strength of all seismic force resisting elements that contribute to resisting shear in the specified direction.

1.1 DIFFERENT TYPES OF SEISMIC DESIGNS

- Force-Based Design (FBD)
- Displacement-Based Design (DBD)
- Energy-Based Design (EBD)

1.1.1 Force-Based Design (FBD)

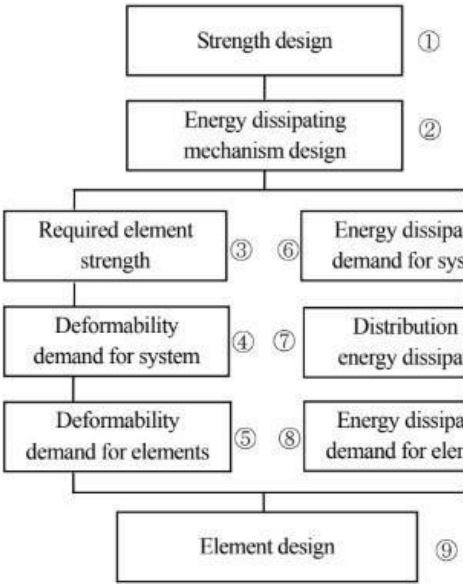
The force-based design (FBD) procedure relies on the calculation of the base shear force, which is generated by the dynamic motion of an earthquake. This calculation involves utilizing the acceleration response spectrum and the anticipated elastic period of the building. In this method the static loads are imposed on a structure with magnitudes and directions that closely approximate the effects of dynamic loading caused by earthquakes. Concentrated lateral forces due to dynamic loading tend occur at each floor in buildings, where concentration of mass exists. Moreover, concentrated lateral forces generally adhere to the fundamental mode shape of the building, meaning they are more pronounced at higher levels within the structure. As a result, the greatest lateral displacements and largest lateral forces often manifest at the topmost level of the structure. To capture these effects, most design codes employ equivalent static lateral force procedures that involve assigning a force at each story level in the structure, proportionate to its height.

1.1.2 Displacement-Based Design (DBD)

This approach relies on utilizing the displacement response spectrum as the foundation for computing the base shear force. It entails studying the building while considering its inelastic phase. This method is widely regarded as one of the simplest design approaches for analyzing multi-degree of freedom structures. In this technique, the structure is represented by the secant stiffness and equivalent damping of an equivalent single degree of freedom structure. The design approach is centered around attaining a predetermined displacement limit state, which can be defined by material strain limits or non-structural drift limits specified in design codes for the given seismic intensity level. This methodology relies on the representation of the structure using a substitute structure, which helps mitigate several challenges inherent in force-based design (FBD). The use of initial stiffness to determine an elastic period, which is a limitation found in many building codes, is alleviated through this approach.

1.1.3 Energy Based Design

Fig 09 Framework of energy based seismic design.



1.4 SEISMIC ANALYSIS

The prediction of the response of a structure to a particular type of loading is of the utmost importance for the design of a structure. The analysis procedure to be adopted purely depends uponthe engineer's choice as per the degree of accuracy required for the work.

Structural analysis methods can be divided into following categories.

a) Linear static analysis
b) Linear dynamic analysis
c) Nonlinear static analysis
d) Nonlinear dynamic analysis

1.4.1 Linear static analysis

In a linear static procedure, the building is simplified and represented as an equivalent single-degree-of-freedom (SDOF) system. This simplification assumes a linear elastic stiffness and an equivalent viscous damping for the structure. The seismic input is represented by an equivalent lateral force, which is designed to generate the same stresses and strains in the structure as the actual earthquake it represents. This simplified model allows for a simplified analysis and assessment of the building's response to seismic forces.. The coefficients used in the analysis account for a range of factors, such as second-order effects, stiffness degradation, and force reduction caused by anticipated inelastic behavior. These coefficients are essential in considering the nonlinearity and potential degradation of the structure during seismic events. By incorporating these coefficients, the analysis can more accurately capture the actual response of the structure, providing a comprehensive understanding of its performance under loading conditions.

1.4.2 Linear dynamic analysis

In time-based linear dynamic analysis, the structure's reaction to ground motion is assessed within the time domain, maintaining all phase details. This analysis method captures the time-dependent behavior of the structure and retains the temporal relationship between the applied forces and the structural response.. This analysis method considers the time-dependent behavior of the structure and captures the dynamic effects of the applied loads. It provides valuable insights into how the structure behaves and interacts with the ground motion over time. This analysis considers only linear properties and assumes that the structural response remains within the elastic range. Modal decomposition is often employed as a technique to reduce the degrees of freedom in the analysis, making it computationally efficient. Structures shall be desingned with linearly elastic stiffness and equivalent viscous damping values consistent with components responding at or near yield level.

1.4.3 Non-linear static analysis

Due to the increased inelastic demands associated with the performance objective of the structure, the uncertainty in linear procedures also increases. To address this, a high level of conservatism is required in demand assumptions. This conservative approach helps account for the uncertainties and limitations inherent in linear analysis methods, ensuring that the structure is designed to withstand potential inelastic behavior and perform as intended. assumptions and acceptability criteria to avoid unintended performance. Thus, methodologies that incorporate inelastic analysis can diminish the uncertainty and conservatism.

This approach is also known as "pushover" analysis. In essence, a pushover analysis is a set of incremental static analyses conducted to establish a capacity curve for the building. Based on this curve, an estimated target displacement is determined, representing the expected displacement resulting from the design earthquake.

1.4.4 Non-linear dynamic analysis

Within the context of time domain analysis, non-linear dynamic analysis takes into consideration the non-linear characteristics of the structure. This approach is the most rigorous and is mandated by certain building codes for buildings of uncommon configuration or of exceptional significance. However, the computed response can be highly responsive to the attributes of the individual ground motion employed as seismic input. Hence, multiple analyses are required employing distinct ground motion records.

Out of all the NL-THA is considered as the most detailed method of seismic demand prediction and performance evaluation of components. However, this method requires the selection of an appropriate set of ground motions and also a numerical tool to handle the analysis of the data whichis in many cases computationally expensive. One of the methods of the Non-Linear Static Analysiscalled as Pushover Analysis can be used as an effective alternative technique.

2 Literature

M. M. Sadeghi et al. (2015) Author develops a new seismic evaluation methods for masonry dome using energy balance method. Soltanieh dome in IRAN is used as an example under 3 groundmotions 1)EI centro 2)Northridge 3) EI centro multiple of 2 Basic assumption in energy balance method is input energy must be equal to absorbed energy. By using the roof displacement in pushover analysis in some cases wrong results are obtained. The solution for this misleading features is introduced by considering the absorbed energy. The area under the conventional capacity curve represents the amount of energy absorbed by the system. The conventional pushover analysis results are not sufficiently accurate. Top displacement in masonry domestructure cannot represent the behaviour of structure. The concept of energy balance is reasonablethan pushover analysis.

Dr. A VIMALA et al. (2014) A research work conducted on expended energy based seismic damage assessment for RC bare frame. The objective is to reveal the amount of damage to the structure and the margin left to reach the failure stage for this study 3Methods are proposed to assess the global damage state of structure. the energy dissipation capacity of a structure is estimated by a non-linear pushover analysis using SAP2000 Damage models defined the damageas '0' for NO DAMAGE and '1' for TOTAL DAMAGE but no intermediate damage was not addressed properly. A numerical study is carried out for three RC structures chosen are low and medium rise buildings in such a way that aspect ratio 3, 1 & 0.3 . Author concluded that by increasein aspect ratio decreased ductility capacity of the structure and for 11-storey structure damage concentrated at the bottom storey as aspect ratio decrease, damage shifted to upper floors.

Md. Masihuddin Siddiqui et al. (2013) Study is to developing nonlinear static procedures by Energy

Based Pushover Analysis (EBPA) with considering the effects of higher modes. A case study done by choosing 4,8,12 & 20 storey buildings in ETABS. In the conventional pushover analysis, the lateral load pattern proportional to mode shapes of the buildings were applied. Energybased approach for pushover analysis "Energy based pushover curves" are generated. The roof displacement is used in the conventional MPA approach where as Energy based displacement are used in the energy based approach. It is seen that the energy based curve for the first two modes response nearly coincides with the conventional pushover capacity curve. Energy based pushovercurve shows a gradual softening of structure rather than a quick failure (which is observed in conventional pushover analysis). EBPA overcomes the major drawback of reversal of capacity curve in the conventional analysis. This method provides better results for consideration of highermode effects.

Wen-Cheng Liao et al. (2012) Author presents first time application of performance based plastic design(PBPD) approach to seismic resistant reinforced concrete special moment frame (RC SMF).The RC structure present special challenge because of their complex and degrading hysteretic behaviour. Four baseline RC SMF (4, 8, 12 and 20-story) as used in the FEMA P695 were selectedfor this study. The inelastic static and dynamic analysis are performed using 3D program. The design base shear is determined for two level performance criteria 1) At 2% maximum storey driftratio 2) At 3% maximum storey drift ratio. Two modifications were considered for determinationof design base shear they are a)Pinched hysteretic behaviour b)P- Delta effect. The point of intersection of two curves, the energy demand curve and capacity curve become equal, gives the desired max roof displacement. The PBPD method is a direct design method which uses pre- selected target drift and yield mechanism as key performance objectives.

Ali Habibi1 et al. (2012) Application energy-based design method for seismic retrofitting with passive energy dissipation devices (EDDs) is proposed as an alternative to strength and displacement-based methods. The steel bracing members are used as energy dissipation byyielding and the effectiveness of the proposed retrofit design method is seen by comparing the nonlinear time-history response of the retrofitted dissipative structure with stiffened structure. Theproposed method is verified that the retrofitted structure remains intact while damage is confinedto the added EDDs. The effects of higher modes are not considered in this study.

Lieping et al. (2009) Author discusses about the relationship between energy-based and performance-based seismic design methods. The main idea is to control structural damage mode by keeping a main sub-system nearly within its elastic region. To attain this philosophy a preferableenergy dissipating mechanism is required for that two parameters are introduced they are capacitycoefficient and capacity ratio. By increase in capacity coefficient of major sub- system will increase the post yielding stiffness of whole system and by adjusting the capacity ratio the secondary sub-systems are expected to be damaged. The energy based seismic design is an important part in performance based seismic design and energy based seismic design is supplementto displacement based method.

2.1 Pushover analysis procedure

Although nonlinear static analysis, specifically pushover analysis, was introduced in the 1970s, it is in the last 10 to 15 years that the potential of pushover analysis has been increasingly recognized. The primary application of this procedure is to estimate the strength and drift capacity of existing structures, as well as to determine the seismic demand on these structures for specific earthquake scenarios. Additionally, it can be used to assess the adequacy of new structural designs. Pushover analysis is an analytical method that integrates the load-deformation behavior of individual building components and elements into a mathematical model. During this analysis, the structure is subjected to incrementally increasing lateral loads, which replicate the inertial forces experienced during an earthquake, until a specific target displacement is attained or exceeded. The maximum displacement, including both elastic and inelastic deformation, represents the expected displacement of the building under the selected earthquake ground motion. Pushover analysis evaluates the structural performance by estimating the forces and deformations. The point of intersection between the capacity curve and the seismic demand on the ATC-40 Displacement Response Spectrum (ADRS) curve is referred to as the performance point, which corresponds to the target displacement.

The execution of pushover analysis can be either force-controlled or displacement-controlled, depending on the nature of the load and the expected structural response. In the force-controlled procedure is useful when the load is known such as gravity loading and the structure is expected to support the load displacement controlled procedure should be used when a specified Resort When faced with seismic loading scenarios where the magnitude of the applied force cannot be determined in advance or when the structure is likely to experience strength deterioration or instability nonlinear analysis a pushover analysis of a structure is an interactive iterative procedure and the effective damping in pushover analysis is determined by the ultimate displacement as it is influenced by the amount of energy dissipation due to inelastic deformation, which, in turn, relies on the final displacement.. This makes the analysis procedure iterative. Challenges arise in resolving the problem near the ultimate load as the stiffness matrix becomes negative definite due to the structure's instability, transforming into a mechanism.

2.1.1 Energy-Based Pushover Analysis Procedure

Within the framework of the energy-based pushover approach, the capacity curve for each modal pushover is determined by evaluating the work done in the analysis. The work is assessed incrementally, usually for every iteration in the pushover analysis.

Structural Model Creation: Develop a comprehensive and accurate model of the structure, incorporating all relevant components and elements. This model should accurately represent the geometry, material properties, and boundary conditions of the structure.

1. To compute the natural frequencies (ωn) and modes (φn) for linear-elastic vibration of a structure. The conventional modal analysis has to be carried out for calculating the mass stiffness matrices. Set the determinant equal to zero: $|K - M * \omega n^2| = 0$.for a trivial solution, where n is thenumber of modes. Sequentially the modal frequency vectors are established by one of the values in the vector as 1 and solving for the other values of the vector.

a. $[K – M * \omega i^2] * \Phi in = 0$

2. Define the force distribution: $S_n = m.\Phi_n$. The force distribution over the structure is according to the mode shape of the structure and will be as defined by the mode shapes forhigher modes also.

3. Apply the force distribution characterized in step 2 incrementally, and record the base- shears and associated story-displacements. The structure should be pushed just beyond theexpected targeted roof displacement, in the selected mode.

4. Adopting the energy-based pushover strategy presented by Hernandez-Montes et al. (2004), the capacity curve associated with each modal pushover analysis is determined based on the work done/energy absorbed in displacing the structure as shown in Fig. 3.16.

The increment in the energy-based displacement of the n^{th} mode ESDOF system, $\Delta De,n$, is obtained as: $E_n = \frac{1}{2} V_{bn}.D_n(t)$ expression gives the response in the elastic domain of the structure.

$\Delta De,n = \Delta En \times Vb,n$ expression gives the response for an incremental step of the POA. where En = Increment of work done by the lateral forces in the nth mode. It represents the energy absorbed or dissipated by the structure during the incremental displacement step.and Vb,n = base-shear atthat step of the pushover analysis, which is equal to the cumulative sum of the lateral forces at that particular stage. Incremental displacements ($\Delta De,n$): These are the incremental changes in displacement associated with each step of the modal pushover analysis. The incremental displacements are

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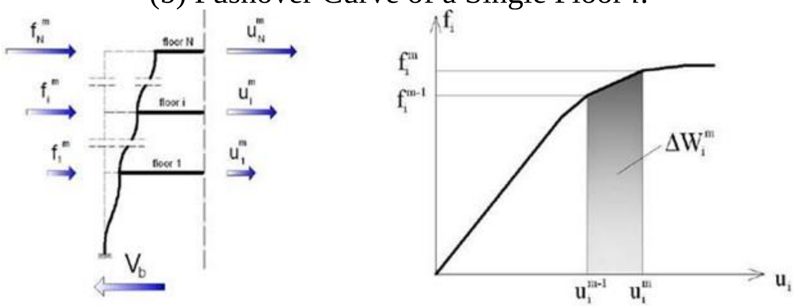
calculated for each mode (n) and represent the progressive deformation of the structure under the applied lateral forces.

Fig. 10 (a) N-Floored Moment Frame Subjected to Lateral Forces Resultingin Horizontal Floor Displacements *u* at Step m.
(b) Pushover Curve of a Single Floor *i*.



(a) (b)

5. This procedure is repeated for each mode separately and finally, the desired responses areextracted from pushover database values at the target displacement. This method is more accurate, although huge amounts of calculation are needed.

6. Determine the Demand curve for each mode as describes earlier and plot the energy based capacity spectrum and demand curve in a same graph for the respective modes, andthe intersection of this demand curve with the energy based capacity spectrum defines theperformance point.

The step by step procedure to obtain the Performance point using the Energy based pushover analysis.

2.2 Performance Point

The point where the capacity spectrum intersects the appropriate demand spectrum is typically referred to as the performance point in the context of pushover analysis. To have the desired performance in the structure it should be designed by considering these points of forces.

2.3 The Analysis of ETABS

1. Modelling
2. Static analysis
3. Design
4. Pushover analysis

2.8 Non-Linear Static Pushover Analysis Procedure in ETABS 2016

Pushover analysis can be conducted in either force-controlled or displacement-controlled mode, depending on the load characteristics and the expected behavior of the structure.

Force-controlled option: This mode is suitable when the applied load is known in advance, such as gravity loads. It is useful when the structure is expected to have sufficient capacity to support the anticipated load. In force-controlled pushover analysis, the applied lateral forces are incrementally increased until a specified force level or displacement criterion is reached. This approach is commonly used for evaluating the response of structures under known or predictable loads.

Displacement-controlled procedure: This mode should be used when specific drift or displacement targets need to be achieved, especially in seismic loading scenarios. In displacement-controlled pushover analysis, the displacement is incrementally increased until a specified drift level or displacement criterion is attained. This method is particularly valuable when the magnitude of the applied load is uncertain or not known in advance, or when the structure is anticipated to lose strength or become unstable. Displacement-controlled pushover analysis allows for a more realistic representation of the structure's behavior under dynamic or uncertain loading conditions.Following are

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the general sequence of steps involved in performing non-linear static pushover analysis using ETABS2016 in the present study:

1. A two or three dimensional model that represents the overall structural behaviour is created. Appropriate reinforcement is provided at the cross sections for reinforced concrete components.
2. Frame hinge properties are defined and assigned to the frame elements.
3. Gravity loads composed of dead loads and a specified portion of live loads are applied to the structure model initially.
4. The non-linear static analysis cases to be used for pushover analysis are defined. By sequentially adding loads and progressing through the pushover cases, the analysis captures the cumulative effects of different loading scenarios. This approach helps to evaluate the structure's capacity and behavior under increasing loads and provides insights into its overall performance.
5. Pushover analysis is set to run.
6. Lateral loads are increased until some members yield under the combined effect of gravityand lateral loads.
7. Base shear and roof displacement is recorded in first yielding.
8. In pushover analysis, the analysis is typically repeated for different mode shapes of the structure until the roof displacement reaches a certain level of deformation or the structure becomes unstable. This process helps capture the response and behavior of the structure under different lateral load patterns.

As the analysis progresses, the roof displacement is recorded for each mode shape of the structure. These displacements are then plotted against the corresponding base shear values, resulting in the global capacity curve, also known as the pushover curve, for the structure.

Fig 11 Capacity curve

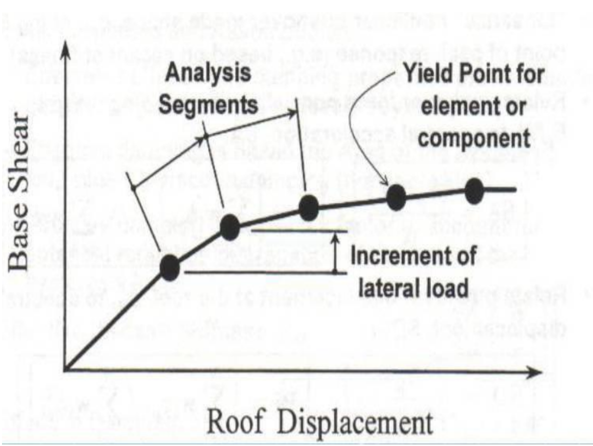

Fig 12 Flow Chart Showing the Step by Step Procedure to Obtain Performance Point UsingEnergy Based Pushover Analysis.

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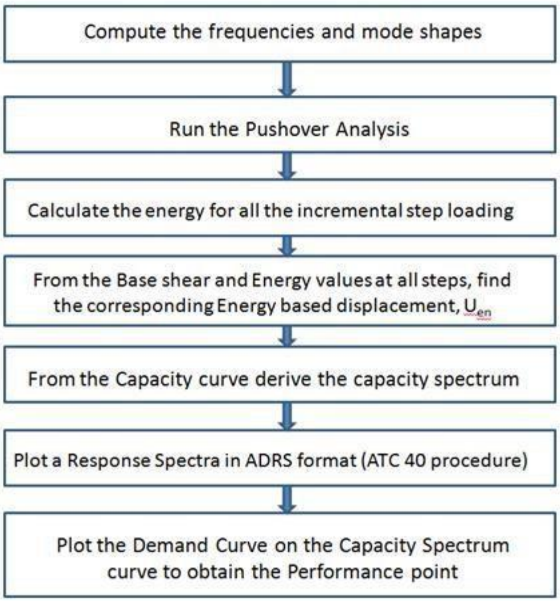

3.0 Conclusion

As recent development in the computer application has helped the structural engineering field significantly. The amount of time and effort required for the analysis decreased drastically with development of civil engineering softwares. Indeed, non-linear time history analysis (NL-THA) is a precise method for the seismic evaluation of structures. It offers a detailed and accurate representation of the structural response under actual earthquake ground motions. However, it is true that NL-THA can be tedious and requires a significant amount of data and human skill to perform effectively. To develop Non-Linear Static procedures which can yield results close enough to theNL-THA procedure to obtain this objective in this energy-based pushover analysis is performed for different plan configurations and comparison is made between Conventional pushover analysisand Energy based pushover analysis. From the results it is observed that Energy based pushover analysis is providing better responses when compared to Conventional pushover analysis.

- Energy-driven pushover analysis demonstrates a progressive weakening of the structure instead of an abrupt collapse.
- Total energy absorbed would be considered, the method does not overestimate the response ofthe structure.
- [-shape and L-shape configuration buildings would have more displacements when compared to square shape and plus '+' shape building configurations.
- Square shape building may show more stiffness when compared to other configurations of buildings.
- This method will provide better results for structural evaluation under seismic loading.

3.1 SCOPE FOR FUTURE STUDY

The application of the method for composite structures can serve as a good topic for a research program. This method can be applied by considering stiffness and mass irregularities in different zones of earthquake.

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