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Pushover Analysis of Multi-Story Reinforced Concrete Frame Structure

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ABSTRACT

Pushover analysis is a non-linear static procedure (NSP) used to examine the structural response of a building during the inelastic limit before it reaches the edge of partial or total collapse. In this study a model of multi-story reinforced concrete building along with applied loads is analyzed in powerful non-linear static procedure using computer software ETABS. A limited number of horizontal forces are then applied to imitate the impact of ground movement. The building is supposed as a 6-story building, no shear walls used in the model as the level of earthquake hazard assumed very low. Moreover, deformations are determined. The forces would then be increased gradually, NSPs convert multi-degree of freedom models to single-degree of freedom models utilizing a pushover analysis to determine capacity curve or pushover curve which is horizontal roof displacement vs base shear, This curve plot reveals the highest base motion that the structure can withstand, and then estimate the maximum global displacement by combining a ground response spectrum with the capacity curve.

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Introduction

The Modern structures should be ductile, or able to withstand severe deformations (beyond the elastic limit) without suffering significantly reduced strength. The large quantity of input energy that may be released during the inelastic motion and the advantageous stress redistribution that can be obtained in structural systems are only two of the numerous advantages that a ductile behavior really offers.

Therefore to meet the safety standards for every structure, there are many factors to ponder it. The adequate quality of the structure cannot be reached if one of the measurable safety factors is missing, the engineers are familiar with the impact of the base shear and its relation to the roof displacement which may cause a collapse of the structure or severe damage. Probably, wind and seismic activities are responsible for this base shear.

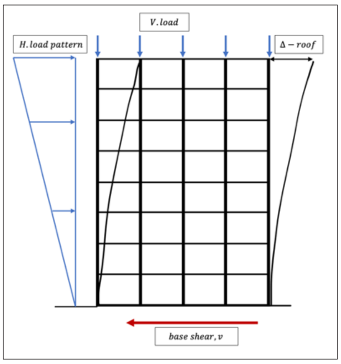

Figure 1: Roof displacement of structure

The structure can be seriously shaken by these horizontal forces, and it is important to know where the structure has shifted from its original position and the magnitude of each displacement. It's obvious that the engineers can't prevent the roof displacement of the structure because the buildings are free end at top side, but they must evaluate how far the structure can go under this situation safely, would the structure collapse under major displacement at roof or not. Conceptually, the capacity of the structure to be safe under this horizontal load is related to the ductility of the structure and its inelastic behavior. ETABS offer one of the best Non-linear Static Procedures (NSPs) for seismic evaluations of structures, the NSPs consist of two main components Pushover Analysis (POA) and Site Response Spectrum. NSPs provide a reasonable estimate of global displacement.

Non-linear Time History Analysis (NTHA) is more accurate than Non-linear Static Pushover Analysis, and it precisely estimates the inelastic demands on members in structure subjected to various types of earthquakes loads. Although the NTHA predicts more accurate estimations it's not always a good choice due to its time consuming and complex calculations during the analysis. [1].

The prediction of the damage that a structure may experience in its design life is based on probability. Many engineers and researchers, however, considered several damage assessment methods that related various engineering demand parameters (EDPs) including displacement, deformation and base shear ,and proved to be useful techniques [2].

Aim of the Study

The purpose of the of this study is to evaluate the structural response or maximum seismic capacity of 6 story model under seismic loads .the structure will be considered as ono-shear wall building. In most cases, there are two methods that may be used to determine the maximum global deflection that occurred after an earthquake. In the process of assessing the pushover curve, the Capacity Spectrum Method (CSM), in accordance with the FEMA-440 Equivalent Linearization and Displacement Coefficient Method((DCM), is utilized.The software will use CSM to transform the capacity curve into a capacity spectrum curve that shows spectral acceleration and spectral displacement. The building's performance will then be determined using ETABS software as the software can determine the performance of a building using a variety of methods, including:FEMA 440, ATC-40, FEMA 356 and FEMA 440.

Methodology

In this study, to analyze the model,The material properties and dimensions of the structure will be defined according to table 1 . Before the POA the capacity of the structure ,gravity loads will be checked using the load pattern form of the software. In this form the dead load pattern with self-weight and the live load pattern are already defined in the software. Then the hinges will be assigned for pushover analyzing hinges which typically generated from a design tables .

To perform this, material specifications are directly inputted in the modeling, The model is then subjected to an incremental "Lateral Load Patterns (LLPs)" till it reaches the desired displacement, at which point the magnitude of internal deformations and applied loads are measured. During the procedure, the sequence of fractures, the formation of plastic hinges, and the damage of structural members can be easily represented. Using this method, it is found that the objective displacement is equal to the maximum displacement that the structure will experience during the probable earthquake.

Model Assumptions and Dimensions

The model is assumed as symmetry with area of 22 m * 22m

Table 1: The material properties and dimensions

	Dimensions	Concrete compression strength
Columns Beams	0.6 m * 0.6 m 0.3 m * 0.4 m	Fc= 25 mPa
Floor height	Typical floor height = 3 m	

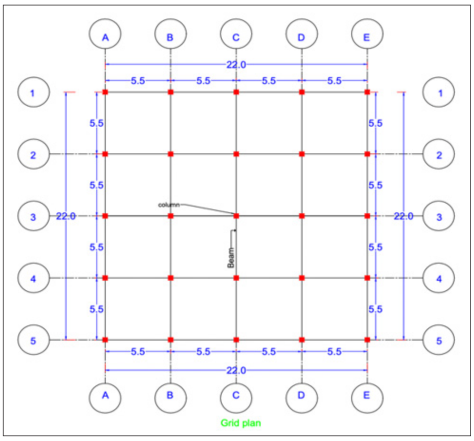

Figure 2: Model top view

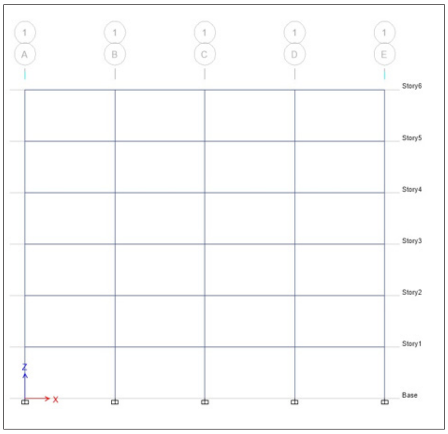

Figure 3: Model sideview

Non-Linear Static Pushover Analysis

Pushover Analysis (POA) is a non-linear static analysis also known as Non-linear Static Procedure (NSP) which used to evaluate the seismic capacity of the structure, a load-deformation curve will be plotted by the computer software [3]. non-linear static procedure is more practical and available for the structural engineers. Commonly ,The pushover analysis can be used to calculate the geometric and material nonlinearities of a structure under horizontal loads [4].

Why is the non-linear static pushover analysis preferred?

First, Performance-based methods necessitate fair and sensible estimations about the inelastic deformation including the locations of inelastic behavior, while the Elastic Analysis is incapacitated of generating these calculations. According to FEMA 451, Nonlinear dynamic or time history analysis able to provide the require estimation which really wastes a time. According to FEMA 451.

Based on the strength and deformation capacities of the structure, pushover analysis generates a capacity curve, also known as a pushover curve, that illustrates the relationship between base-shear and roof displacements. This capacity curve describes how the structure under subjected load responds during the inelastic stage [5].

In addition, A pushover analysis can be defined a series of progressive static analyses performed to create a so-called building's capacity curve. A target displacement, which is an estimation of the displacement which the design earthquake will cause on the building, is established using the capacity curve [6]. Pushover Analysis is becoming more widely used and is integrated into practically all recent design codes and standards include FEMA-440 (ATC-55) [7]. As a result of Performance Based Seismic Engineering (PBSE), which combines the plasticity analysis of structure with seismic hazard assessment to calculate Seismic strength of the structure, Engineers may observe any structure's performance when subjected to significant loads. Under a strong seismic, to calculate the structure's vibration/ structural response a Nonlinear response history analysis (NLRHA), or "Nonlinear Time History Analysis" can be used. however, this method is not favorable practically due to large number of data produced during analysis, for that reason PBSE is mostly related to nonlinear static analysis or pushover analysis. [8]. On other hand, there is an unexpected obstacle of this NSP which is its incompetence to consider the consequences of the large type of vibration [9]. Standard pushover analysis demonstrates some weaknesses and limitations that reduce its range of use and cast doubt on its reliability in precisely estimating structural seismic demand [10].

Capacity Spectrum Method (CSM) of NSPs
The capacity spectrum method is based on an equivalent linearization approach such as used by FEMA440 EL , In this procedure, the pushover curve is transformed to a capacity spectrum by transforming each point on the curve into spectral displacement and spectral acceleration, next a reduced ground motion response spectrum (RS) is changed into form of an acceleration displacement responses spectrum (ADRS) which is the demand spectrum , when the demand spectrum and capacity spectrum are plotted together their of intersection is called the target displacement also known as the performance point.

Displacement coefficient method (DCM) of NSPs
Displacement coefficient method applies modifying coefficients to the peak elastic displacement to determine to determine a target displacement as described in ASCE 41-13 based on the pushover curve an effective stiffness is determined to from which a effective period can be calculated , using this period in combination with response spectrum a spectral acceleration may be obtained which is used in an equation with the modifying coefficients to obtain the target displacement (maximum displacement)

Limitations of POA
The estimation of the target displacement, type of Lateral Load Patterns (LLPs) and identifying of failure mechanism in higher modes of vibration are considered a potential effect of the POA accuracy, therefore, these features should be defined [11]. Also, the "P-Δ" must be selected during the input, hence, its effects become more important as the lateral displacement and axial column force get larger [12]. The definition of several parameters, including the material model and model mesh refinement, is also necessary for the numerical approach of pushover analysis [13]. Another drawback of POA is that it yields inaccurate result and skips change in lateral load pattern during the inelastic stage of the structure [14]. Estimating target displacements are very difficult in POA [3].

Performance Levels of the Structure
The performance of the building also known as "building's response" to an earthquake can be recognized and understood by its collapse mechanism, which takes the shape of a curve. With pushover analysis, you can find out not only how a building fails, but also what level of performance it has, based on different FEMA and ATC approaches [15]. The plastic joint of each structural component plays a significant role in a building's performance levels, which can also be defined as the structural behavior of the building under an applied load [16].

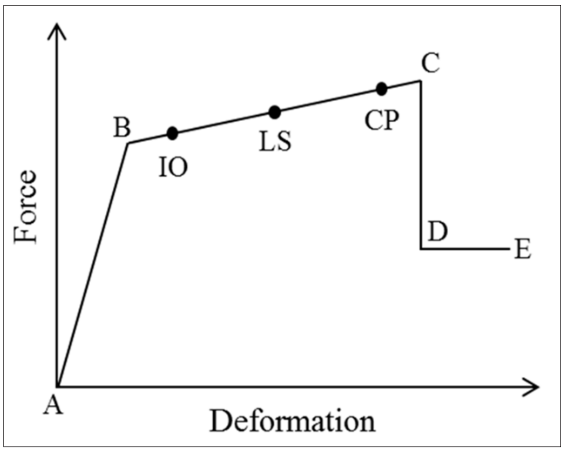

Figure 4: Force deformation curve with performance levels of the structure, source Junwon Seo, 2015, sustainability

The performance levels of the structure is categorised as a different stages that the structure underg.For the force displacement curve at the point A to point B, when it reaches at point B which is the yielding point equivalent the structure will start deformation and there will be three stages IO-immediate occupancy, The building can withstand the shaking during the earthquake and suffer neither structural nor unstructured damage , LI-life safety, The building can experience an earthquake with little structural damage, protecting the residents from its consequences and CP-collapse prevention, when an earthquake occurs the building will suffer major damage but will not collapse. at point C it's the ultimate capacity or limit of the building and the stage between point C and D the structure will start collapsing, at point E it's a total failure where the hinges breakdown will start.

The point where the pushover and seismic demand curves intersect each other is called the "performance point.", If the damage state at the performance point is satisfactory, then the structure can be considered safe. Performance point can be calculated by several methods, including the capacity spectrum method and the displacement coefficient method according to ATC 40 and FEMA 440, respectively [17].

Lateral Load Patterns for Pushover POA
The lateral load pattern (LLPs) approximates the lateral forces expected to impact on the structure during an earthquake. The most common and recommended LLPs are mentioned here a) uniform load distribution b) triangular load distributed (triangular profile), c) pattern stands for the shape of 1st mode. [18]. In a pushover analysis the initial step to assume about a particular is lateral load pattern, after which the structural model is statically analyzed. The load pattern is gradually applied until the target displacement is obtained. Therefore, in pushover analysis, selecting the right lateral load pattern is important [19].

The loss of stability of the structure may lead to its collapse where the shape of the structure may severely damage due to the combination of loads. Then the changed or damaged structure keeps changing till it reaches a new shape which is more stable, as it can't resist extra load.

The lateral load patterns (LLPs) Adoptive Pushover analysis is one of the force-based methods for pushover analysis that have been developed in recent years, where the applied load pattern is modified at each phase of the analysis based different mode properties of the structure [20]. during the POA there are factors affect the accuracy of the analysis and the predicted responses such as lateral load as well as updating the LLPs appropriate to the structural behavior, basically, the building frame is subjected to the gravitational loads. Following that, the structure is subjected to steadily increasing lateral seismic loads while maintaining constant gravity loads [21]. the LLPs which is proportionate to the story shear distribution, which is obtained by integrating the modal performance from a response spectrum analysis of the structure with the proper ground motion spectrum; this results in the lateral load distribution [22].

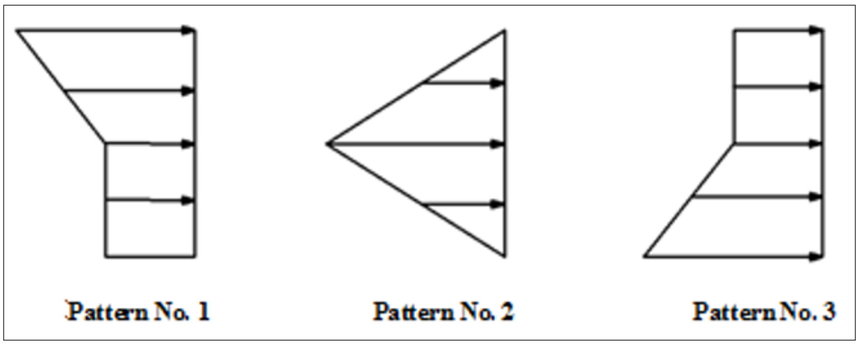

Figure 5: Different types of suggested lateral load patterns (LLPs), source: Nowak, A [23].

A study conducted by lecturers and students from universities in UK and Iran presented some suggested LLPs, the figure above shows 3 types of LLPs suggested in their research and they finally concluded that the 3rd LLPs is the most probable one due to the base reaction any seismic reaction [24]. and it is the most suitable one that can be used to do pushover analysis as the horizontal load (base reaction) is much larger than the load acting the top parts of the building.

The Performance Point (Target Displacement)
The performance point or target displacement can be defined as the maximum capacity that the structure can experience beyond the elastic limit, and it's located at the intersection of the Capacity Spectrum and the Demand Spectrum. In other words, the target displacement can be defined as an estimate of maximum displacement.

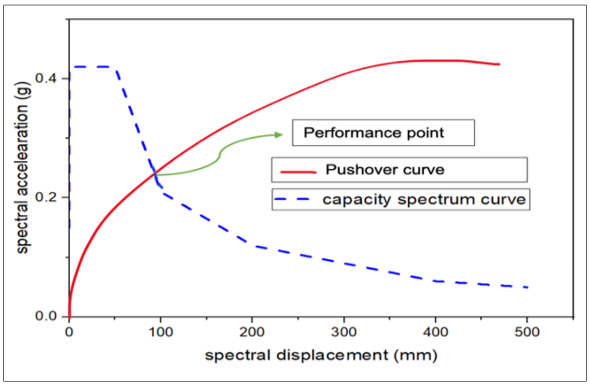

Figure 6: A general figure showing the performance point

The Equivalent Single Degree of Freedom (SDF) System
There is a concept that is being used by all the procedures to determine the performance point which is the equivalent single degree of freedom system (the equivalent SDF system). the load pattern which Is representing the pattern of the future applied loading, then the computer will apply that pattern in a monotonic manner to process the pushover curve, now that curve can be idealized in some simplified way like straight lines and convert it force deformation behavior and assign it as a behavior to single degree of freedom system which is not elastic anymore. If the pushover curve is converted to force deformation while the stiffness of SDF is represented by the force deformation, then it's an equivalent of SDF which is representing that whole three-dimensional or two-dimensional non-linear computer model.

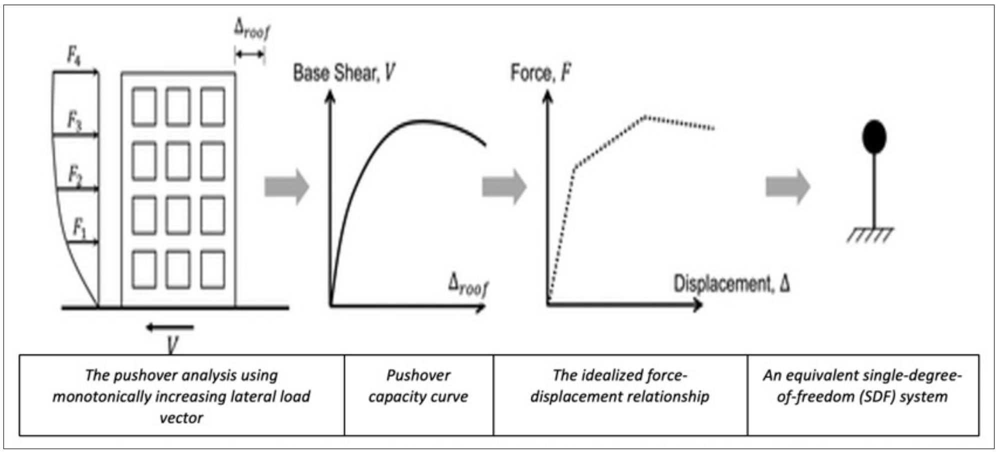

Figure 7: SDF system, source: Najam, F. A. (2017, May), springer.

P-Delta Effect

The P-delta effect is the result of gravity loads acting through the lateral displacement of the structure. This impact can set off a vicious cycle against the structural system because, at the same time as the lateral displacement is amplified because of the gravity loads acting on them, the influence of gravity loads also develops as the lateral displacement expands. The P-delta effect is also known as the geometric non-linearity [24]. For P-delta effects consideration in the displacement-based assessment (DBA) procedure, a static pushover analysis of the Multi Degree of Freedom (MDOF) system must be performed on the replacement structure capacity curve [25]. P-delta effects also improves the structures flexibility, Additionally, it lowers the ability to carry lateral loads due to the lateral shifting of gravity loads carried on by significant inelastic drift about the line of support response [26].

Non-Linear Time History Analysis (NLTHA)

In some places of this study a non-linear time history analysis(NLTHA) also known as non-linear dynamic procedure (NDP) article is mentioned, which can be used to evaluate the seismic performance of the building, For the past 20 years, this procedure has been used to evaluate the seismic performance of different types of reinforced concrete structures included shear wall structures [27]. Many engineers have observed that only lower frequencies mode responses are relevant in structural dynamics issues, particularly when earthquake forces and high-speed train impacts should be considered [28]. In contrast to the response spectrum approach, NLTHA does not suppose a particular mode combination method. Consequently, outcomes are practical rather than conservative. However, this procedure is quite costly and time-consuming, though. Massive volumes of data are produced [29]. The non-linear time-history analysis is one of the best Methods (NLTHA) engineers use to evaluate the ductility and energy dissipation behavior of structures during the strong earthquakes [30]. On the other hand, this method has some drawbacks such as it is time-consuming to make the calculations required during the analysis and the producing of complex calculations, and that's the reason for preferring NSPs, which is discussed in this study.

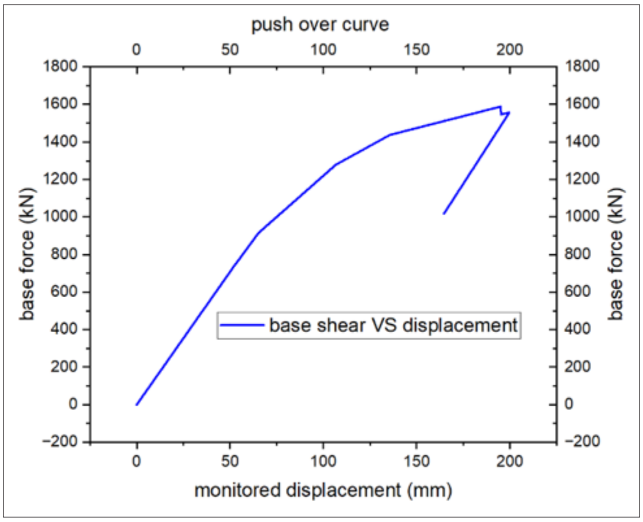

Figure 8: Pushover curve or capacity curve

Results and Conclusion

Pushover and spectral graphs

This plot curve in figure 8 is the one of the aims of pushover analysis, The displacement verses base shear can be seen. Which states a different roof displacement under a various base shear.

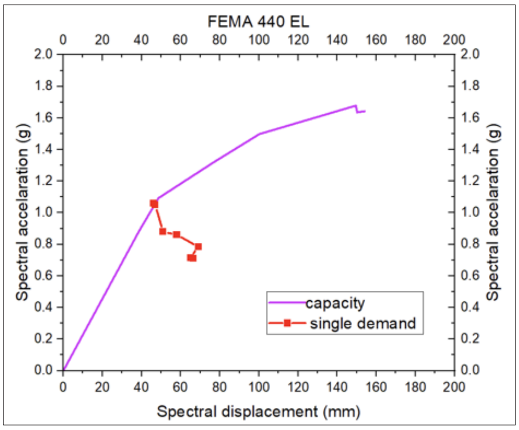

Figure 9: Capacity curve and single demand plot, FEMA 440 Equivalent Linearization

In figure 9 of the spectral curves no intersection points of demand curve and pushover curve made, therefore, a Berkeley is being used which the value of acceleration S sub_S and S sub_0 is changed. then a new plot type (figure 10) has formed which demand spectrum crosses has crossed the capacity spectrum, and that intersection point is known as performance point. If we look at the table of spectral values, we can see that the spectral displacement of 70 is in pushover analysis somewhere between the third and the fourth step.

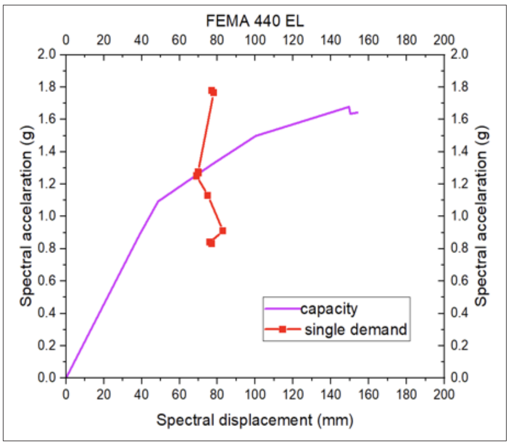

Figure 10: Capacity curve and single demand plot, FEMA 440 Equivalent Linearization

If we look at the table of spectral values, we can see that the spectral displacement of 70 is in pushover analysis somewhere between the third and the fourth step. As figure 10 is shown as well.

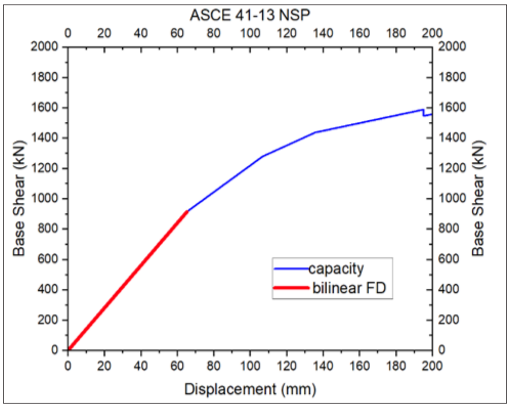

Figure 11: Capacity curve and bilinear force displacement ASCE 41-13 NSP

Figure 11 is showing the linear phase of pushover curve before it changes its way of proportionality.

Tables

Table 2: Spectral values, FEMA440 equivalent linearization

Unit	Spectral displacement	Spectral accelaration	Period
	mm	g	sec
	38.69	0.882617	0.42
	48.669	1.093025	0.423
	76.871	1.319593	0.484
	100.226	1.498011	0.519
	149.556	1.678206	0.599
	150.273	1.635649	0.608
	154.031	1.642401	0.614

Table 3: ASCE 41-13 NSP

Unit	Displacement	Base Shear
	mm	kN
	0	0
	51.92	734.3142
	65.363	915.4966
	106.726	1278.9131
	135.651	1437.4576
	195.159	1588.6875
	195.166	1546.9538
	199.703	1556.7

Table 4: Base shear vs monitored displacement

Step	Spectral displacement	Base Force	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	Total
Unit	mm	kN										
0	0	0	108	0	0	0	0	108	0	0	0	108
1	51.92	734.3142	107	1	0	0	0	108	0	0	0	108
2	65.363	915.4966	103	5	0	0	0	108	0	0	0	108
3	106.726	1278.9131	95	13	0	0	0	103	2	0	3	108
4	135.651	1437.4576	83	25	0	0	0	95	10	0	3	108
5	195.159	1588.6875	70	37	1	0	0	83	19	3	3	108
6	195.166	1546.9538	70	37	0	1	0	83	16	5	4	108
7	199.703	1556.7	69	35	3	1	0	83	16	5	4	108
8	164.611	1017.1248	69	35	3	1	0	83	16	4	5	108

Hinge response graphs

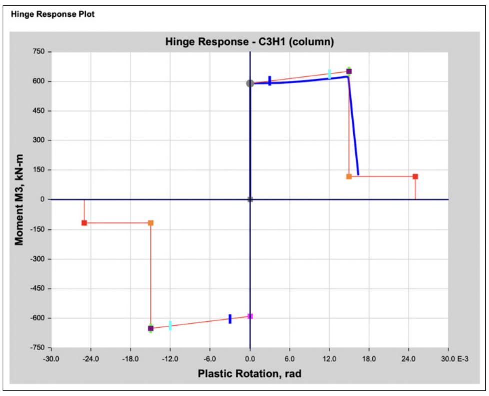

Figure 12: The plastic rotation verses the moment of C3H1column

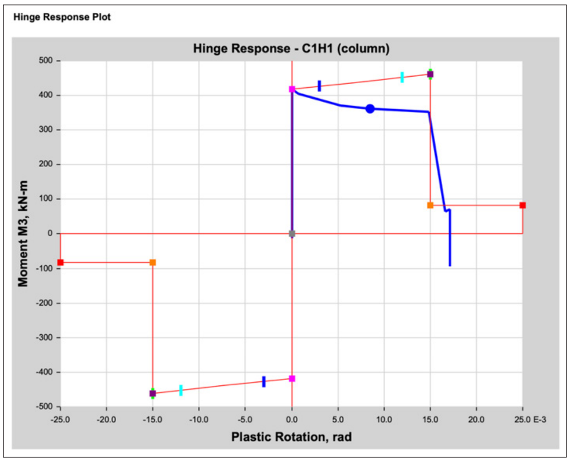

Figure 13: The plastic rotation verses the moment of C1H1 column

Hinge formation

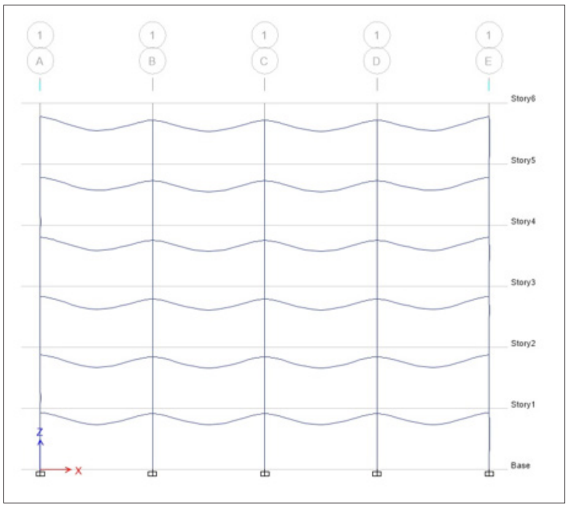

Figure 14: The effect of gravity loads

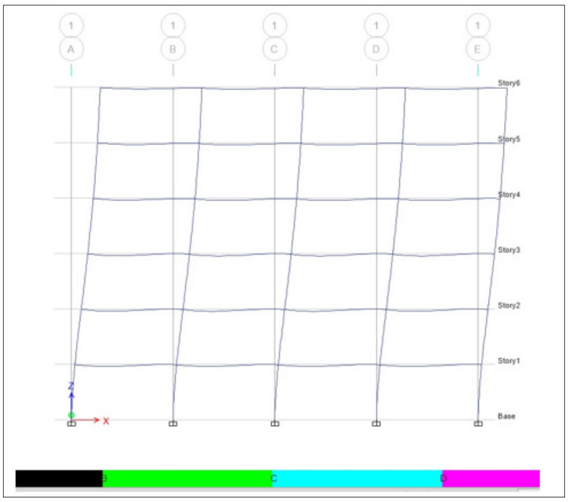

Figure 15: The effect of horizontal load patterns

In figure 15 according to the pushover analysis, the effect of lateral load patterns applied can be seen in the model simulation

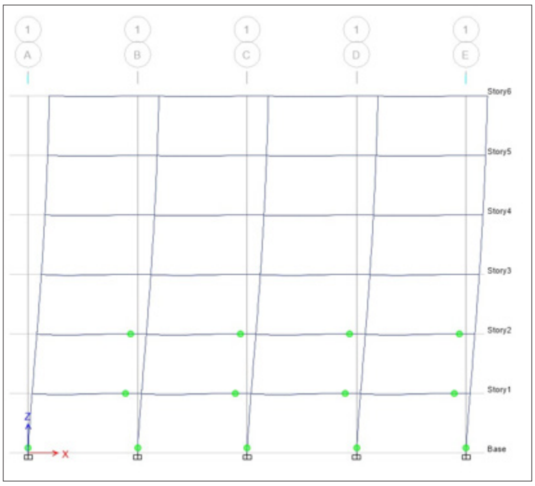

Figure 16: Formation of plastic hinges

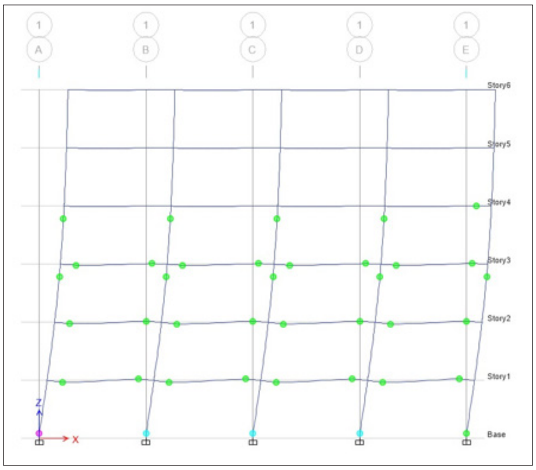

Figure 17: The final plastic hinges formation

Conclusion

In this study, a step-by-step method is used to define the performance-based design technique that should be utilized in seismic engineering using pushover analysis. which the building's seismic capacity is being estimated by using ETABS software, it can be made to behave in a manner that has been previously determined under the influence of seismic forces. The application of pushover analysis results in the acquisition of this significant result. Pushover analysis gives a comprehensive understanding of the failure pattern of the building and, as a result, makes it possible to construct the structure in accordance with the function for which it was designed.

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