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Review on Pushover Analysis Procedures

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Abstract: *Pushover analysis was the recommended method of seismic analysis before this generation. Even though Non-Linear Time History analysis is a recommended method of practice for the current generation due to its accuracy, Pushover analysis has the capability which gives much more flexibility and information on its final results. The well-known concept of 'Performance criteria', which is the specification of an acceptable level of damage to a building, can be found using this method. Using pushover analysis, it's possible to study the parent factor, which is responsible for the behaviour of buildings during seismic events. In this review, we discussed the possible lateral load combinations that can be applied during the analysis procedure and how the results can be analysed. From previous studies, it is concluded that the pushover analysis can be influenced by the geometry of the building, lateral load pattern, and the method of result evaluation.*

Keywords: Pushover analysis, Seismic evaluation, analysis procedure, Nonlinear analysis

I. INTRODUCTION

[1] Performance-based design philosophy plays a vital role in predicting the performance level associated with several levels of hazardous earthquake events. For this purpose, the building needs to be designed beyond the elastic limit of the member. The analysis procedure was broadly classified into linear and nonlinear method of analysis, in which linear is only used in case the building won't reach the collapse load. But during an earthquake, the structural loading will reach the collapse load and the material stresses will be above yield stresses. So the material and geometrical properties of the building need to be considered heterogeneous and non-linear. Again in the nonlinear type of analysis, there are two methods, which are static method and dynamic method. Here we discussed the Nonlinear Static method of analysis or also known as pushover analysis. In this pushover analysis, the building which needs to be analysed is subjected to lateral loading in some pattern (i.e. uniform, inverted triangle, etc.) and the maximum displacement of the building is recorded from the point where we considered i. The main objective of this analysis is to plot a demand curve or pushover curve plotted between base shear VB and the roof displacement Xr. This curve allows us to study the behaviour of the building during a particular event of time. From this curve, we can able to find the Seismic demand or Target displacement which denotes the maximum demand of the building during an earthquake. Several methods like the capacity spectrum method and displacement coefficient method which have been given in American Code books like ATC-40, FEMA356, and FEMA 440 are used to find this target displacement. The Pushover analysis also helps us to understand the performance criteria of the building during the earthquake event. This allows seeing whether the building is fit for occupancy or it's on the verge of collapse. Due to its nonlinearity in nature, this method is considered to estimate accurate values from the subjected structure. The analysis can be done is software like ETABS, SAP2000, MIDAS, ABAQUS, etc.

II. PUSHOVER CURVE

[3] To obtain this pushover curve a series of inelastic seismic analyses is performed on a building using monotonically increasing lateral load. The pushover curve is plotted between the base shear to the roof displacement. The common procedure to find out the performance point is by an intersecting capacity curve with a demand curve which is plotted between S_a and S_d values. It is also commonly referred to as a capacity curve since it gives the overall summary of the building's capacity during seismic events. Using the target displacement, the seismic demand or performance point of the building could be figured out.

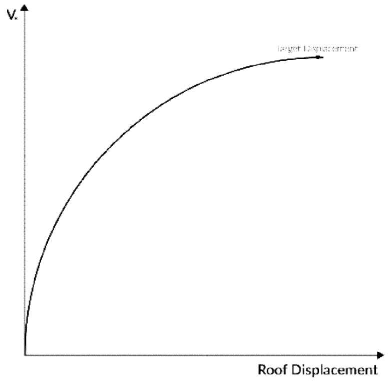

Fig. 1. Pushover curve

This can be done by using approximate methods provided in American standard code books. The performance point can be used to find some of the performance criteria like Operational (O), Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

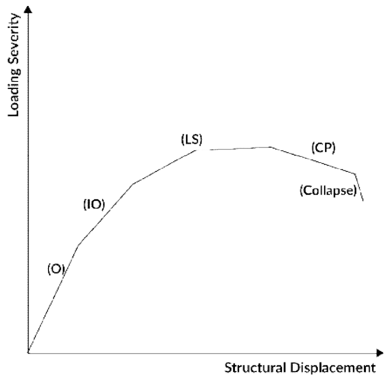

Fig.2. Acceptance criteria

III. TYPES OF LOAD PATTERN

3.1 FEMA-356(2000) Pattern

There are several load patterns derived in this codebook. [4] The building which is subjected to load pattern NSP-1 which is distributed across the height of the building is based on the following formula:

$$F_x = \frac{W_x h_x^k}{\sum W_i h_i^k} V$$

The second load pattern NSP-2 act like a uniform lateral load containing force that is proportional to story mass at each story level. In NSP-3 story shear distribution is determined by using modal responses of the building for the ground motion. [5] Five-story RC building was designed and analysed with FEMA 356 and compared with the latest Euro code-8 procedures. He observed that the plastic hinge rotation which is given according to Euro code-8 was seeming to stay constant in the column while the load increased. This makes the value lesser than the FEMA 356. Similarly, the equation to find the rotations given for beams was also not correctly given in the case of Euro-code 8 which makes the FEMA 356 values a bit more accurate. [6] In another paper, they studied the Modal pushover analysis properties using FEMA 356 force distribution and validated them using non-linear response history analysis. Comparing FEMA-356 NSP and nonlinear RHA showed that FEMA-356 lateral force distributions lead to gross underestimation of story drifts and completely fail to identify plastic rotations in upper stories compared to the values from the nonlinear RHA. The Uniform load distribution completely fails to estimate the story drift and hinge rotation compared to RHA which makes it the most inaccurate method of finding the seismic demand of the structure.

3.2 IS 1893 Equivalent Static Method

[7] Indian standard provision gives us the approximate method to calculate and distribute the lateral load to each floor of the building considering the seismic zone and soil condition of the place. This method is more similar to the FEMA 356 inverted triangle procedure where the only difference is in the calculation of the design base shear of the building.

$$Q_i = \frac{W_i h_i^2}{\sum W_j h_j^2} V_B$$

[8] Here the lateral load distribution was compared between FEMA-257 and IS 1893 for four different types of loading conditions. He concluded that for all the loading condition the performance point was close to one another. The evaluation results from FEMA 346 uniform load pattern and IS 1893 load pattern are fairly similar. [9] For this case, a RC water tank of different cross-section shapes was designed and analysed using IS 1893 code outlines and cross-checked using Response spectrum analysis. It is noted that the base shear value in the complete reservoir is greater compared to empty and partially full conditions. The Intze-type water tank accounts for greater impact and a large time period for different seismic zones.

3.3 Other Literature Methods

A. F. Khoshnoudian et.al.

[10] Two different modification patterns based on the height of the building were proposed. For low rise building 1-(X/H)0.5 and for high rise building 2-sin(πX/H)0.5. Many iterations of Time history analysis were done in 4,8,12,16,20 and 30-story buildings and compared with conventional and proposed lateral load patterns for pushover analysis. He concluded that it is inappropriate to use uniform load patterns for these types of structures as they give an approximate value with a higher degree of differences. It is not reliable for the estimation of capacity curve purposes. The above-mentioned proposal is the combination of uniform and triangle load patterns that removed the above shortcoming, giving us a more accurate value compared to other methods.

B. H. Gholi Pour et.al.

[11] The new proposed load pattern has load distribution according to weight and stiffness variation in height and mode shape of the structure. They analysed special steel moment frames with X-type bracings. It is concluded that the proposed load pattern results are closer to nonlinear dynamic analysis (NDA) compared to other pushover load patterns, especially in tall and medium-rise buildings having different stiffness and mass during the height.

$$S_i = \frac{m_i \psi_i^n h_i k_i}{\sum m_i \psi_i^n h_i^n k_i^n}$$

Where: S_i is the lateral load at Story i, m_i is weight at story i, ψ_i is Modal displacement of story i at mode n, h_i is the height of story i, k_i is Story Stiffness i and N is the number of building stories.

C. Aman Mola Worku et.al.

[12] Here they modified the first mode-based pushover analysis using some modification factors to get more accurate results compared to other methods. They analysed five, ten, fifteen, and twenty-story buildings with this method and compared it with other NSP procedures. In the conclusion, they found that the SRSS method and this modified method gives similar results and the more accurate result compared to other modal pushover analysis method. The peak error percent only varies up to 10-15% by comparing with other results.

$$S_j = \beta_j m_j \phi_j S_a(T_{1,}\varepsilon_1) \; where \; \beta_j = |\left(1 - \frac{2h_j}{h_r}\right)^{\frac{r1}{2}}|$$

D. Kalkan E, et.al.

[13] Here they performed the analysis on a 12-story building using three load pattern which is given in FEMA 356 along with their formulation of two new load pattern based on a combination of the mode shape of the building. They referred to their formulas as Modified Combination Procedure-1 which is a combination of any two-mode shape of the building and Modified Combination Procedure-2 which is based on any single-mode shape of the building.

E. Habibi A, et.al.

[14] A new lateral load pattern is developed and discussed in this paper. The Load pattern based on mode shape is estimated by the directed algebraic combination of the weighted vibration mode-shape vectors because high-rise building's effects due to higher vibration mode should be considered for better outcomes. The weight for each mode is calculated using optimization algorithm techniques. It is concluded that, in the inelastic range of structural behaviour, it is likely that higher modes have a significant effect on the optimal lateral load distribution.

3.4 Optimization Algorithm

A. Meta-heuristic optimization algorithm

[15] In this paper, they disused the possibilities of using an optimization algorithm known as a meta-heuristic algorithm to optimize the lateral load pattern which is based on the mode shape of the building to get accurate results. They implemented this method on a 20-story building and analysed the results compared with other FEMA and MPA methods. The name of this meta-heuristic algorithm is the Cuckoo Search Algorithm (CS) which is based on the parasitic behaviour of cuckoo species in combination with the flight behaviour of some birds and fruit flies. They concluded that with some innovative approaches, there's a possibility to bring the most accurate seismic results using this static pushover approach.

B. Genetic Algorithm

[16] To overcome the drawbacks of ordinary conventional methods these authors propose a method for combining a Genetic algorithm with Modal pushover analysis to get better results by optimization modal combinations. The investigation proceeded on a 12-story building given by (Kalkan, 4004). In conclusion, it is found that an optimum combination, using Sn =mØn as a load pattern, estimates the seismic responses satisfactorily with a minimum error index.

IV. TARGET DISPLACEMENT

4.1 Capacity Spectrum Method (ATC-40)

[17] To find out target displacement using this method, the capacity curve and demand curve are converted into the capacity spectrum curve which is a representation of the Sa vs Sd curve in ADRS format. For converting the capacity curve into a capacity spectrum first modal participation factor MPF and modal mass coefficient α1.

$$MRF = \frac{\sum m_i \emptyset_i}{\sum m_i \emptyset_i^2} \; and \; \alpha = \frac{[\sum m_i \emptyset_i]^2}{[\sum_{i=1}^{N} m_i][\sum_{i=1}^{N} m_i \emptyset_i^2]}$$

Where m_i is mass at level i, $\emptyset_i$ amplitude of mode 1 at level i, N the number of storied in the building. The S_a and S_d are calculated by

$$\frac{S_a}{g} = \frac{V_b}{w\alpha} \; and \; S_d = \frac{\Delta_{roof}}{MPF \; \emptyset}$$

For converting the demand spectrum into ADRS format S_d needs to be calculated for each point of the curve by using the following formula:

$$S_d = \frac{T^2 S_a}{4\pi^2}$$

[18] Here they presented the comparative study of the capacity spectrum method with another method that is given in FEMA codebooks. They conducted the test on 3, 6, 9, and 12-story buildings. In the result, they concluded that the capacity spectrum method predicts the lowest value compared to other methods but satisfies the design criteria given as SBC-301.

4.2 Displacement Coefficient Method (FEMA 356)

[4] Here the target displacement can be found by modifying the elastic response of the curve with some modification factors C_0, C_1, C_2, and C_3 by using this formula.

$$\delta = C_0 C_1 C_2 C_3 S_a (\frac{T_e}{2\pi})^2 g$$

Where T_e is the effective fundamental period.

4.3 Displacement Modification (FEMA 440)

[19] It is based on project ATC-55 which produced a modification factor that can be used on the Displacement coefficient method from FEMA 356 to get better performance points. The modification factor which is used in this method are:

$$C_1 = 1 + \frac{(R-1)}{aT_e^2} \; and \; C_2 = 1 + \frac{1}{800}(\frac{(R-1)}{T})^2$$

Where R is the ratio of elastic strength demand and a is the yield strength coefficient. [16] In this above-discussed paper, it is found that Displacement modification by FEMA 440 yields better results compared to other procedures.

4.4 Modal Pushover Analysis

[20] An improved pushover analysis procedure was developed based on structural dynamics theory which removes the drawbacks faced by the current analysis procedures. It is known as Modal Pushover Analysis. Here the seismic demand was determined by conducting a pushover analysis using the inertia force distribution for each node. Combining these demands due to the first two or three terms provides an estimate of the total seismic demand of the system. The peak modal responses are combined by an appropriate modal combination rule like the SRSS rule which leads to the MPA procedure. For this study, they modelled a nine-story steel building which is analysed by modal pushover analysis and compared with rigorous non-linear response history analysis. The approximate response gives good estimate values regarding story drift, and floor displacement and identified the rotation of the plastic hinge. But it has less accuracy in calculating plastic hinges rotation.

V. OTHER FACTORS

Some of the other factors which affect the pushover analysis outcomes are listed below.

5.1 Hinge Properties

Assigning Predefined hinges is important in the case of a nonlinear type of analysis. Usually, there are three types of hinge properties that can be applied to a structure 1) Default hinge properties, 2) User-Defined Hinge properties, and 3) Generated Hinge properties. In default hinge properties, software like E-Tabs and SAP2000 has code-defined properties based on ATC-40 and FEMA 273. [21] In this paper, an attempt was made to comparatively study the behavior of pushover analysis outcomes based on different properties of inelastic hinges. The author used FEMA's default hinge properties and user-defined hinges for this study. Two four-story building and one eight-story building was designed and used for this study. He concluded that the FEMA hinge properties aren't able to provide the required estimated values compared to user-defined hinges and it failed to properly estimate displacement capacity, especially for the frame possessing low ductility.

If User-Defined hinges are based on default hinge properties, they can't be viewed or changed since it is based on the section properties, they cannot be predetermined. If the User-Defined hinges are not based on default properties it is possible to view and change the properties of the hinges.

5.2 Geometrical Properties

[22] Irregularities in plan and in elevation usually increase the seismic demand which leads to greater damage. Since the Nonlinear Static procedure is primarily based on transitional behaviour, it's not possible to precisely calculate the

seismic demand in case of in-plan irregularities. This study discussed nine different structures of different plan shapes like L, T, C, etc. From the conclusion, it can be learned that the building shaped like Plus shape, T shape, C shape, E shape, and H shape has more displacement in both X and Y directions. Simple geometry structures like rectangle, and square has less tendency to get affected during an earthquake.

[23] Here Limitations of pushover analysis while analysing irregular structures were discussed along with that a procedure made to overcome such limitations was also discussed. An evaluation method proposed by Fajfar et al, (2005) was used to analyse a school building that has both vertical and plans irregularities. This modified pushover analysis can be able to predict good approximate values up to the failure level. At the failure level due to the development of the floor mechanism, this method becomes slightly inconsistent. So, it's been proved that this method can be implemented to analyse irregular structures due to its simplicity and accuracy.

[24] This study is done for investigating RC frames which are considered and designed only using gravity load in some parts of Saudi Arabia. Here Two 3D RC frames were considered for pushover analysis and the ATC-40 standard is used for seismic evaluation. One frame was designed only using gravity load and the other frame was designed according to SBC-301. He concluded that the frame which is designed only by using gravity load was inadequate and can't able to withstand lateral load while on the other hand, the SBC-301 frame withstands and satisfies the ATC-40 criteria's acceptance level and has an Immediate occupancy level.

[25] The frame-shear wall system in medium and high-rise buildings is designed and tested using the MPA method and compared the results using traditional pushover analysis. Two frame-shear wall system was taken from ten and eighteen-story building and was tested in this study. He suggested that Lumped mass model should be used for getting accurate force-displacement relation. SRSS load pattern gives a good approximate estimation of finding story drift and base shear. Invariant load pattern fails to give accurate results in the case of high-rise buildings while the MPA method gives a more accurate value compared to other methods.

VI. CONCLUSION

This study aims to classify and develop a better understanding regarding the improvement of Nonlinear Static pushover analysis. Still now pushover analysis plays a vital role in seismic analysis of the structure due to its versatile and coherent nature. One of the main drawbacks of using this method is its reliability. This method can be used for checking and analysing the building which is seismically designed using nonlinear Response or time history analysis. Many alternative methods have been attempted to improve the estimated values of this analysis. From the previous studies, the pushover analysis was mainly influenced by the load pattern which we apply, the method we use to find the seismic demand, and the properties of the structure which we analyse. Some of the important findings from this study are mentioned below.

- Determining the load pattern can be done using various methods. Some of the common methods which belong to FEMA-356, and ATC-40, the efficiency is proved to be less compared to other modern-day methods. Using algorithms can able to estimate accurate seismic demand values, yet there are no sufficient research papers to simplify the process. Load pattern with modal combinations and other modification factors based on height and properties of the building gives more accurate result compared to the conventional methods.
- Capacity spectrum method is a widely used method for determining the target displacement values. FEMA-356 provides a displacement coefficient method and it's been improved in the latest version of FEMA-440. For medium and high-rise buildings Modal pushover method by Chopra (2002) proved to be highly efficient compared to other methods, yet it has some shortcomings regarding estimation hinge rotations.
- Since the pushover analysis is static transversal method the geometry of the structure affects the result of the procedure. The cross-sectional shape of the building plays a vital role in seismic demand values. Simple geometry gives better result comparing to other shapes. As the height of the building increased normal conventional methods fails to give proper result so some modification factors need to be used.

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