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Pushover Analysis Of Retrofitted Reinforced Concrete Buildings By Using SAP

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ABSTRACT

This study deals the analysis of the nonlinear response of RC structures to be carried out in a routine fashion. It helps in the investigation of the behavior of the structure under different loading conditions, its load deflection behavior and the cracks pattern. In the present study, the non-linear response of RCC frame using SAP2000 under the loading has been carried out with the intention to investigate the relative importance of several factors in the non-linear analysis of RCC frames. This includes the variation in load displacement graph. To model the complex behavior of reinforced concrete analytically in its non-linear zone is difficult. This has led engineers in the past to rely heavily on empirical formulas which were derived from numerous experiments for the design of reinforced concrete structures. The proposed method is distinct from existing methods in that it allows for the inherent and accurate consideration of shear effects and significant second-order mechanisms within a simple modeling process suitable for practical applications.

Keywords: Pushover, Analysis, Retrofitted Reinforced Concrete, Buildings, Using, SAP

1. INTRODUCTION

Recent earthquakes in which many concrete structures have been severely damaged or collapsed, have indicated the need for evaluating the seismic adequacy of existing buildings. About 60% of the land area of our country is susceptible to damaging levels of seismic hazard. We can't avoid future earthquakes, but preparedness and safe building construction practices can certainly reduce the extent of damage and loss. In order to strengthen and resist the buildings for future earthquakes, some procedures have to be adopted. One of the procedures is the static pushover analysis which is becoming a popular tool for seismic performance evaluation of existing and new structures. Design of civil engineering structures is typically based on prescriptive methods of building codes. Normally, loads on these structures are low and result in elastic structural behavior. However, under a strong seismic event, a structure may actually be subjected to forces beyond its elastic limit. Although building codes can provide reliable indication of actual performance of individual structural elements, it is out of their scope to describe the expected performance of a designed structure as a whole, under large forces. Several industries such as automotive and aviation, routinely build full-scale prototypes and perform extensive testing, before manufacturing thousands of identical structures, that have been analyzed and designed with consideration of test results. Unfortunately, this option is not available to building industry as due to the uniqueness of typical individual buildings, economy of large-scale production is unachievable.

2. BUILDING DESCRIPTION AND MOTIVATION FOR PUSHOVER ANALYSIS

Building analyzed is a nineteen story (18 story + basement), 240 feet tall slender concrete tower located in San Francisco with a gross area of 430,000 square feet. Unique features of the slender concrete tower presented challenges for seismic design. Typically, a 240 feet tall concrete building in seismic zone 4 would have a lateral system that combines shear walls and moment frames. However, two architectural features made the use of moment frames difficult. First, the 60 feet long open bays limited the number of possible moment frames. Second, on the southeast side two of the perimeter columns are discontinued at the 6th story and six new columns are introduced The building height is 240 feet which is equal to code limit for concrete shear wall buildings according to 1997 UBC. A more recent 2003 International Building Code (IBC) [12] limits the maximum height of a concrete shear wall building to 160 feet. Furthermore, geotechnical studies indicated a site-specific design response spectrum (of 475 year return period or 10% probability of exceedance in 50 years) with spectral accelerations approximately 40% higher than the 1997 UBC design response spectrum in the relevant time period range for the building (Fig. 3).

3. METHODOLOGY

3.1 General

The Seismic vulnerability assessment of multistoried buildings will be carried out using pushover analysis. The different methods to be used are as follows:

- Standard pushover analysis method (FEMA 356)
- Capacity spectrum Method (ATC 40)
- Modal pushover analysis method.
- Non-linear Time history analysis method.

For the present study standard pushover method described in FEMA 356 is adopted.

3.2 Standard Pushover Analysis

The pushover analysis consists of the application of gravity loads and a representative lateral load pattern. The lateral loads were applied monotonically in a step-by-step nonlinear static analysis. The applied lateral loads were accelerations in the x direction representing the forces that would be experienced by the structures when subjected to ground shaking. A two or three dimensional model diagrams of all lateral force and gravity forces are first created and gravity loads are applied initially. A predefined lateral load pattern which is distributed along the building height is then applied. The lateral forces are increased until some members yield. The capacity of the structure is represented by the base shear versus roof- displacement graph.(Figure.1)

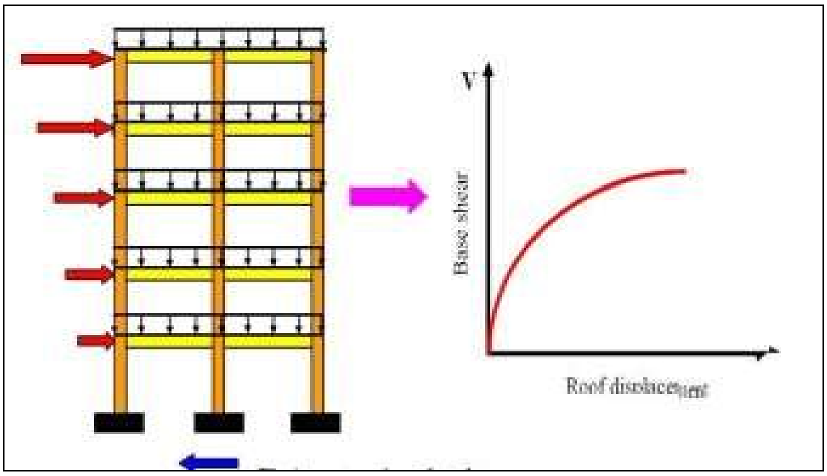
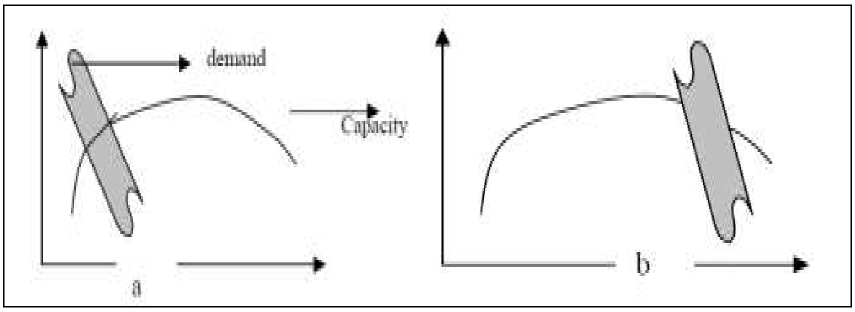


Figure. 1: Construction of Pushover Curve

3.3 Key Elements Of Pushover Analysis

- Definition of plastic hinges: In SAP2000, nonlinear behavior is assumed to occur within a structure at concentrated plastic hinges. The default types include an uncoupled moment hinges, an uncoupled axial hinges, an uncoupled shear hinges and a coupled axial force and biaxial bending moment hinges.
- Definition of the control node: control node is the node used to monitor displacements of the structure. Its displacement versus the base-shear forms the capacity (pushover) curve of the structure.
- Developing the pushover curve which includes the evaluation of the force distributions. To have a displacement similar or close to the actual displacement due to earthquake, it is important to consider a force displacement equivalent to the expected distribution of the inertial forces
- Estimation of the displacement demand: This is a difficult step when using pushover analysis. The control is pushed to reach the demand displacement which represents the maximum expected displacement resulting from the earthquake intensity under consideration, which is calculated in Response spectrum analysis.
- The main output of a pushover analysis is in terms of response demand versus capacity. If the demand curve intersects the capacity envelope near the elastic range, then the structure has a good resistance. If the demand curve intersects the capacity curve with little reserve of strength and deformation capacity, then it can be concluded that the structure will behave poorly during the imposed seismic excitation and need to be retrofitted to avoid future major damage or collapse. Depending on the weak zones that are obtained in the pushover analysis, we have to decide whether to do perform seismic retrofitting or rehabilitation.



Safe Design Unsafe Design

Figure..2: Typical Seismic Demand Versus Capacity

Under incrementally increasing loads some elements may yield sequentially. Consequently, at each event, the structures experiences a stiffness change, where IO,LS and CP stand for immediate occupancy, life safety and collapse prevention respectively.(Figure.2)

4. STRUCTURE MODELING

4.1 Material Properties

M-25 grade of concrete and Fe-415 grade of reinforcing steel are used for all members of the frame structures. Elastic material properties of these materials are taken as per Indian Standard IS 456 (2000).

4.2 Structural Elements

Two structures representing low rise and high rise reinforced concrete framed buildings are considered in this study. For the present study, structures with 5 and 12 stories are chosen. These structures are designed according to Indian Standards. The details of frame structure are as follows:

- Size of building = 24 m X 12 m (figure 4.1)
- Floor to floor height = 3.06m.
- Thickness of slab = 0.11 m.
- Dead load = 1 X 0.11 X 25 X 1.5 = 4.1 KN/m2
- Live load = 3 KN/m2 (assume)
- Modulus of Elasticity (Ec) = 25000000 KN/m2

4.3 Modeling Approach

The general finite element package SAP 2000 (Version.14) has been used for the analyses. A three dimensional model of each structure has been created to undertake the non linear analysis. Beams and columns are modeled as nonlinear frame elements with lumped plasticity at the start and the end of each element. SAP 2000 provides default hinge properties and recommends M3 hinges for columns and M3 hinges for beams as described in FEMA 356. Fig 4.3 shows the assigned hinges to buildings.

4.4 Building Geometry

The structural analysis program, SAP2000- Version 14 was used to perform analyses. Figure.3 shows 3D Computer models of the building of 5 storeys and 12 storeys.

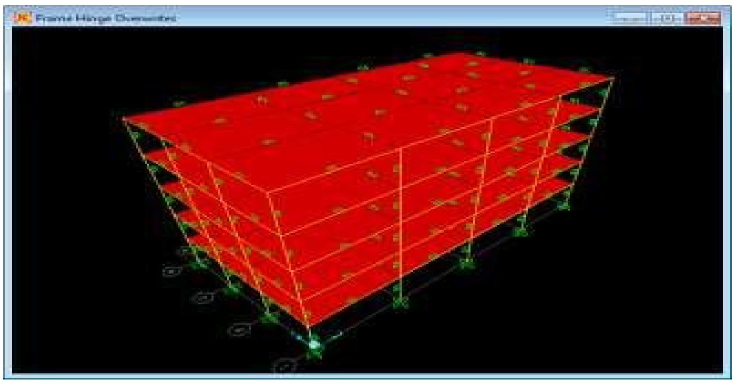


Figure 3 Frame Model Assembly

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5. RESULT & DISCUSSION

5.1 General

The selected building models are analyzed using pushover analysis. Pushover analysis was performed first by considering response spectrum analysis for defining gravity load case and then a lateral pushover analysis was performed in a displacement control manner.

5.2 Results From Response Spectrum Analysis

Period of the modes and the modal participation mass ratio for mode is shown in Table.1 & Table.2 Pushover curve for this direction.

Table 1 Result from Pushover Analysis

Building	Mode Number	Period	UX	UY
5 storey	1	0.82	0.785	0.0109
	2	0.82	0.0468	0.0707
	3	0.271	0.0109	0.785
	4	0.271	0.0707	0.0468
12 storey	1	1.51	0.77	0.001
	2	1.51	0.09	0.10
	3	0.51	0.001	0.77
	4	0.51	0.10	0.09

Table 2 Target displacement

Building	Target Displacement(m)	Elastic base shear(KN)	Inelastic base shear(KN)
5 storey	0.28 m	1621.9	1946.3
12 storey	0.5 m	1707.09	2646

5.3 Capacity Curve

The resulting capacity curves for the two buildings are shown in figure 5.1 and fig 5.2 for 5 storeys and 12 storeys building respectively. Both curves show similar nature. They are initially linear but start to deviate from linearity as the beams and the columns undergo inelastic actions. When the buildings are pushed well into the inelastic range, the curves become linear again but with smaller slope. A target displacement of 0.28m for the 5 storey building, the base shear of whole structure is 1946.3 KN which is equivalent to 1.2 times that of structure under elastic seismic design. For 12 storeys building, for a target displacement of 0.5m the base shear is 2646 KN which represents 1.55 times that of elastic base shear (Figure.4).

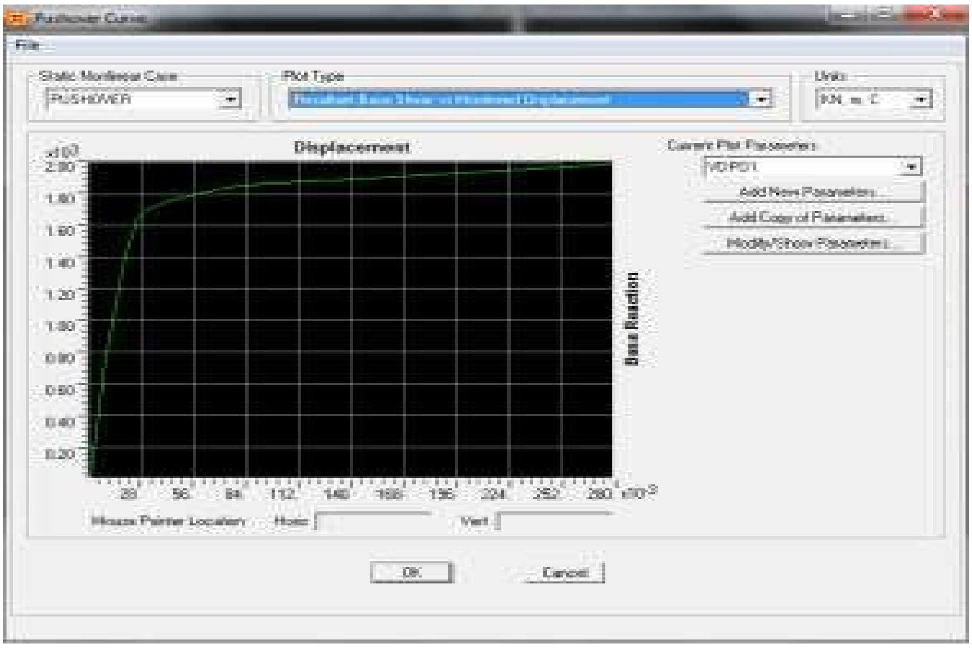

Figure. 4 Pushover Curve For 5 Storey Building.

5.4 Nonlinear Static Procedures

The MMC procedure is evaluated by comparing computed interstorey drift demands to nonlinear time history estimates and to other pushover procedures. One set of lateral load patterns was based on recommendations in FEMA-356 while the second methodology considered in the comparative study is the modal Pushover analysis (MPA) of Chopra and Goel [2]. A brief overview is presented of the different NSP methodologies used in the study.

In FEMA-356, several alternative invariant loading patterns are recommended for estimating equivalent seismic demands. In this study, two loading patterns are considered. These two patterns are permitted when more than 75 percent of the total mass participates in the fundamental vibration mode in the direction under consideration. The following notations are used in this paper to describe these patterns:NSP-1: The buildings are subjected to a lateral load distributed across the height of the building based on the following formula specified in FEMA-356:

$$F_x = \frac{W_x h_x^k}{\sum_{i=1}^{N} W_i h_i^k} V$$

where, F is the applied lateral force at level 'x', W is the story weight, h is the story height and V is the design base shear, and N is the number of stories. The summation in the denominator is carried through all story levels. This results in an inverted triangular distribution when k is set equal to unity.

NSP-2: A uniform lateral load distribution consisting of forces that are proportional to the story masses at each story level.

6. Analytical Modeling

The nonlinear evaluations were carried out using the open source finite element framework, Open Sees. A nonlinear beam-column element that utilizes a layered 'fiber' section is used to model all components in the frame models since the interaction of axial force and flexure is automatically incorporated. The element is based on a force formulation that considers the spread of plasticity. Since the objective of the evaluation is to evaluate various pushover procedures rather than simulate local connection fracture, the modeling of the members and connections was based on the assumption of stable hysteresis derived from a bilinear stress-strain model. Since the buildings are symmetric in plan, only two dimensional models of a single frame were developed for each building. In the case of the four-story building, the exterior frame along EW direction (Line-1) was modeled. Similarly, frame models for the six and thirteen story buildings were developed for the exterior frames in EW direction. The elastic models were validated using available recorded data.

6.1 Evaluation Of Interstorey Drift Demands

As indicated previously, three earthquake records were used for the nonlinear time history (NTH) analysis of the four-story building. The MMC response is based on the envelope of demands resulting from Mode 1 ± Mode 2 (using peak S of the three ground motions). The resulting lateral forces using such a modal combination is shown in Figure 6. Plots of the displacement and drift profile for both NTH runs and the various pushover methods are shown in Figure 7. The peak displacement profiles are generally similar for all methods. The variation of interstorey drift indicates that both MPA and MMC capture the demands with reasonable accuracy though the demand at the first story is slightly over-estimated. Of the two FEMA methods, NSP-1 (first mode distribution) is a better indicator of seismic demands though the drifts at the uppermost level are under-estimated. Note that NTH gives the highest demand at third story that implies some contribution of the second mode in the response.

6.2 Evaluation Of Component Ductility Demands

Another important parameter in seismic response analysis is the estimate of ductility demands in individual components. FEMA-356, for example, uses component acceptance criteria using ductility demands as the fundamental basis of its performance-based evaluation methodology. In this section, the effectiveness of the MMC procedure to estimate component demands is investigated. Tables 2 and 3 show typical ductility demands for column elements at critical story levels in the six and thirteen story buildings experiencing the highest deformation demand. Also given are the global system ductility demands which are less than the observed local story and component ductility demands.

Similar results were obtained in a more comprehensive study by the authors examining ductility demands of RC and steel buildings [12]. These results serve as evidence that designing a building to achieve a certain ductility demand may result in much larger demands at the local level. Comparisons of the ductility demand from pushover procedures with by nonlinear time-history analyses show that the predicted demands are remarkably similar to those estimated. A more visual comparison is provided in Figures 14 and 15 where the moment-rotation behavior of three typical column sections undergoing inelastic deformation is displayed. While cumulative effects cannot directly be incorporated into any static procedure,

as inter-story drifts and plastic hinge rotations. It is shown that considering sufficient number of modes, interstorey drifts estimated by MMC is generally similar to trends noted from NTH analyses unless the building is deformed far into the inelastic range with significant strength and stiffness deterioration.

Higher mode effects on seismic demand are dependent both on the frequency content of the ground motion and the characteristics of the structural system even for regular low-rise buildings (based on findings from the four-story building evaluation). In the present phase of the research, the force distributions are based on modal contributions in the elastic state of the system.

- The deformed shapes and plastic hinges of the original structure and retrofitted ones are presented in Figure 10a. It can be interpreted that the original building experiences very low strength and ductility in columns. This is a clear demonstration of soft story phenomenon at first floor will lead to complete collapse of the structure the event of earthquake.
- As it is illustrated in Figure 10a, the ductility of columns were increased noticeably due to CFRP wrapping and steel jacketing methods. Consequently, the retrofitted structures exhibit larger displacements without collapsing and also develops plastic hinges within CP level of performance. The normalized base shear-top displacement relationships obtained by pushover analysis for original and retrofitted structures are presented in Figure 10b.
- In comparison with the original structure, both retrofit techniques enhanced the strength and ductility characteristics of the building. The occupant friendly CFRP wrapping retrofit technique supplied good displacement capacity but less lateral strength than the other jacketing technique.
- On the other hand, the structure retrofitted by steel jacketing exhibited a more rigid behavior so that structural and non-structural elements could suffer less damage. Because of increased lateral stiffness, the natural frequencies of the retrofitted structures were increased as shown in ***Table 4***. In comparison between demand and capacity base shear, it is clearly shown that the capacity demand ratio has been improved significantly. Additionally, the target displacements of the structures calculated in respect to FEMA 356 (section 3.3.3.3.2) have been demonstrated in the table.
- The total cost between two methods of rehabilitations are assessed with 49% difference. The cost reduction in CFRP method in comparison with steel jacketing method shows that CFRP technique may be considered a cost effective method for retrofitting concrete structures.

6.3 Purpose Of Pushover Analysis

- The purpose of the pushover analysis is to evaluate the expected performance of a structural system by estimating its strength and deformation demands in designing earthquake resistant buildings by means of a static inelastic analysis, and comparing these demands to available capacities at the performance levels of interest.
- The evaluation is based on an assessment of important performance parameters, including global drift, inter-story drift, inelastic element deformations (either absolute or normalized with respect to a yield value), deformations between elements, and element and connection forces (for elements and connections that cannot sustain inelastic deformation).

- The inelastic static pushover analysis can be viewed as a method for predicting seismic force and deformation demands, which accounts in an approximate manner for the redistribution of internal forces when the structure is subjected to inertia forces that no longer can be resisted within the elastic range of structural behavior.
- The realistic force demands on potentially brittle elements, such as axial force demands on columns, force demands on brace connections, moment demands on beam-to-column connections, shear force demands in deep reinforced concrete spandrel beams, shear force demands in unreinforced masonry wall piers, etc.
- Estimates of the deformation demands for elements that have to deform in-elastically in order to dissipate the energy imparted to the structure by ground motions. Consequences of the strength deterioration of individual elements on the behavior of the structural system.
- Identification of the critical regions in which the deformation demands are expected to be high and that have become the focus of thorough detailing.
- Identification of the strength discontinuities in plan or elevation that will lead to changes in the dynamic characteristics in the inelastic range.
- Estimates of the inter-story drifts that account for strength or stiffness discontinuities and that may be used to control damage and to evaluate P-delta effects. Verification of the completeness and adequacy of load path, considering all the elements of the structural system, all the connections, the stiff nonstructural elements of significant strength, and the foundation systems.

6.4 Cost Estimation

The estimated cost for both steel jacketing and CFRP jacketing are provided as a comparison tool for evaluating a proper option in retrofitting. Steel jacketing cost can be calculated as the price of 3/8" steel sheets and 40-1" fully threaded retrofitting bolts including installation and bolt fastening labor. Additionally, the welding cost of steel sheets around columns has been taken into account.

- CFRP jacketing cost mostly will sum up in material cost and labor cost for installation, surface preparation and applying epoxy. In general, the surface must be clean, dry and free of protrusions or cavities before applying the fiber carbon epoxy.
- As it is illustrated between two tables, the cost of steel jacketing is 49% higher than CFRP jacketing within the same targeted performance level. Although in steel jacketing method, the structure will gain more capacity in terms of base shear, implementing the CFRP wrapping will deliver significant reduction in overall cost of the retrofitting process.
- It should be emphasized that these cost data are only estimates developed based on the experience of the author and conversations with colleagues. In practice, there may be a significant variation in costs compared to the data presented here.

6.5 Comparison

The popularity of nonlinear static pushover analysis in engineering practice calls into question the validity of conventional lateral load patterns used to estimate inelastic demands. The aim of the present work is to develop alternative multi-mode pushover analysis procedures by indirectly accounting for higher mode contributions but yet retaining the simplicity of invariant distributions in a theoretically consistent manner. A new combination scheme is investigated in this paper and compared to both time-history procedures and other pushover methods. The evaluation is based on a series of analyses of existing steel moment frame buildings. The aim of the present work is to develop alternative multi-mode pushover analysis procedures by indirectly accounting for higher mode contributions but yet retaining the simplicity of invariant distributions in a theoretically consistent manner.

7. CONCLUSIONS

The performance of reinforced concrete frames was investigated using the pushover analysis. As a result of the work that was completed in this study, the following conclusions were made:

- Both the pushover curves show no decrease in the load carrying capacity of buildings suggesting good structural behavior.
- From demand capacity curve it is concluded that both the demand curve intersects the capacity curve near the event point B. Therefore, it can be concluded that the margin safety against collapse is high and there are sufficient strength and displacement reserves.
- The behavior of properly detailed reinforced concrete frame building is adequate as indicated by the intersection of the demand and capacity curves and the distribution of hinges in the beams and the columns. Most of the hinges developed in the beams and few in the columns but with limited damage.

- In general, a carefully performed pushover analysis will provide insight into structural aspects that control performance during severe earthquakes. For structures that oscillate primarily in the fundamental mode, the pushover analysis will likely provide good estimates of global as well as local inelastic deformation demands.
- The analysis will also expose design weaknesses that may remain hidden in an elastic analysis.In the author's opinion, pushover analysis can be implemented for structures whose higher modes are judged not to be significantly important, and it can provide an effective tool to evaluate performance level of structures.
- The pushover analysis is a relatively simple way to explore the non linear behavior of Buildings.
- A nonlinear static pushover analysis is carried out for evaluating the structural seismic response.

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