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Research Paper

APPLICATION OF PERFORMANCE - BASED DESIGN TO UPGRADE UNSYMMETRICAL RC BUILDING

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Performance-based design is widely used to upgrade seismic deficient buildings. Such buildings, when subjected to severe ground motion, might suffer extensive damage or even collapse. Bhuj earthquake (2001) of India made thousands of people lose their lives and rendered millions to lose their houses. The extensive damage to RC building during this earthquake exposed the construction practices being adopted in India and generated a great demand for seismic evaluation and up-gradation of existing buildings. This paper discusses the procedure to upgrade a seismic deficient unsymmetrical reinforced concrete building and to examine the seismic performance of the upgraded building for desired performance levels. Seismic RC symmetrical building has been considered in this paper and up-gradation of this building has been done using Capacity Spectrum Method Pushover Approach. Performance point of the up-graded building has been determined by comparing the Capacity Spectrum Curve for the most critical push load case and Demand Spectrum Curve for the given site conditions. It has been shown that the performance after up-gradation lies in the linear range. It has been also demonstrated that up-gradation satisfies the life safety performance level.

Keywords: Performance-based design, Seismic deficient, Capacity spectrum, Pushover Analysis, Demand spectrum

INTRODUCTION

The widespread damage especially to RC building during Bhuj earthquake exposed the construction practices being adopted in India and generated a great demand for seismic evaluation and up-gradation of existing buildings. The existing building can become seismically deficient since seismic design codal requirements are constantly revised due to extensive experimental investigations in the research fields.

Performance-based design is experiencing a rapid development in recent years. This concept provides a new approach for

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establishing design objectives and desired performance levels for new and existing buildings. Seismic deficient buildings are being upgraded using performance-based design. Such buildings, when subjected to severe ground motion, might suffer extensive damage or even collapse. The performance-based design philosophy has also an advantage in creating confidence in users by comparing the seismic demands and capacity of a building. The confirmation of the objectives through reliable analytical procedures encourages the effective assessment and up-gradation methods in mitigating a seismic risk.

The recent advent of performance based-design has brought the nonlinear static pushover analysis procedure to the forefront. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern. With the increase in the magnitude of the loading, weak links and failure modes of the structure are found.

Mwafy and Elnashai (2001) compared the non linear static pushover analysis versus dynamic collapse analysis. The results of 100 inelastic dynamic analyses using a detailed 2D modelling approach have been utilized to develop the dynamic pushover envelopes. These envelopes have been compared with the static pushover results with different load patterns.

Agrawal and Chourasia (2003) reported that pushover analysis gives better understanding and more accurate seismic evaluation of buildings as the weaker links identified through their Demand Capacity Ratios (DCRs) can be traced for different points on the pushover curve.

Kumar and Kumar (2003) utilized the pushover analysis for upgrading of a multistoreyed building and concluded that the use of pushover analysis is an effective tool for selecting a suitable retrofitting strategy.

Sharma *et al*. (2007) presented the review on Seismic Performance of RC Buildings. It has been reported that Pushover analysis is an important tool to obtain the seismic capacity of the building, which in turn is helpful to evaluate the performance of a building.

Kadid and Boumrkik (2008) evaluated the performance of framed buildings under future expected earthquakes by conducting non linear static pushover analysis. It was shown that the pushover analysis is a relatively simple way to explore the non linear behavior of buildings. Further, it was concluded that the results obtained in terms of demand, capacity and plastic hinges give an insight into the real behavior of structures.

This paper discusses the procedure to up-grade a seismic deficient reinforced concrete building and to examine the seismic performance of the up-graded building for desired performance levels. In the present work, seismic deficient unsymmetrical RC building has been considered. Column up-gradation is often suitable to the seismic performance of a structure and has been utilized in the present work. SAP2000 is utilized to determine the performance point of the up-graded building by comparing the Capacity Spectrum Curve for the most critical push load case and Demand Spectrum Curve for the given site conditions.

APPROACHES FOR UP-GRADATION

Four approaches are available in the literature (Murti, 2008) for seismic retrofitting of existing RC frame buildings, namely (a) Code-Compliance Approach (FEMA 172 1992; ATC14 1987); (b) Capacity Spectrum Method Pushover Approach (ATC40 1996); (c) R-Factor Method Pushover Approach; and (d) Displacement Coefficient Method Pushover Approach (FEMA 440 2005).

Code-Compliance Approach is easy to implement for the designer, who is conversant with linear elastic seismic analysis and basic procedure of seismic design. The other three approaches are state-of-the-art and require comprehensive understanding of inelastic earthquake behavior of RC structures, pushover analysis and seismic strengthening of existing buildings. These approaches are popular and experienced design engineers can use these approaches with proper understanding and sufficient practice.

The Capacity Spectrum Method Pushover Approach based on pushover analysis and seismic strengthening is the most widely applied approach and can be used to for both, new and old buildings. This approach has been utilized for the up-gradation of symmetrical building in this paper.

CAPACITY SPECTRUM METHOD PUSHOVER APPROACH

The Capacity spectrum method pushover approach involves three stages: (i) Input Data Stage, (ii) Analysis Stage and (iii) Retrofit, Pushover Analysis and Verification Stage.

Input Data Stage

In this stage, data of soil conditions and modulus of sub-grade reaction is collected. Measurement of the actual geometry of the structure and its member cross-sections is further carried out to know details of the structure.

Actual strength and related properties are estimated for structurally significant frame members by conducting non-destructive tests and performing tests on core samples drawn. The extent of corrosion in the steel reinforcement bars should be carefully evaluated to make a realistic estimate of their available diameter.

Analysis Stage

In this stage, a three-dimensional (3-D) model of the building frame is prepared using measured geometry and in-situ soil and structure properties obtained from non-destructive tests and core samples drawn. Using this model of the building frame, design lateral forces on the structure are evaluated considering IS 1893 (Part I) codal provisions (2002) with design spectrum of 5% damping.

Evaluated design lateral force is applied on the 3-D model of the building frame and stress-resultants (axial force, shear force, bending moment) at all critical sections of the frame members are determined from the frame analysis.

Capacities of the RC sections using the actual cross-section geometry, material properties and reinforcement sizes are obtained applying the usual partial safety factors for loads and material as per the Limit State Design (IS456-2000).

Stress-resultants at all critical sections of the frame members and capacities of these frame members are compared. Deficient members are identified from this comparison.

Retrofit, Pushover and Verification Stage

In this stage, deficient members are up-graded by selecting suitable material and proper construction practice. After up-gradation, revised member properties are evaluated for the deficient members.

The properties of the soil springs, the load-deformation relation of the masonry infills, moment-rotation relation at the ends of the reinforced concrete beams and moment-rotation relation at the ends of the RC columns are evaluated. These properties are calculated without the partial safety factors on materials.

Pushover analysis is carried out with Dead Load and 25% Live Load using the first translation mode shape. Pushover analyzes for the other load cases are also performed. The collapse mechanism of the building is observed from most critical pushover analysis. If it is the desirable mechanism (strong-column weak-beam system) is obtained, the retrofit scheme is accepted otherwise retrofit scheme is improved and desirable mechanism is obtained. In the pushover analysis undertaken, the lateral load versus displacement roof (capacity curve) is recorded. As per requirement of the capacity spectrum method, it is necessary to convert the capacity curve (in terms of base shear and roof displacement) to the capacity curve in Acceleration Displacement Response Spectra (ADRS) format.

The Design Spectrum (S_a versus T) is drawn as per IS 1893 (Part I) (2002) for the related Site conditions. This Design Spectrum (S_a versus T) is also converted to ADRS form (S_a versus S_d).

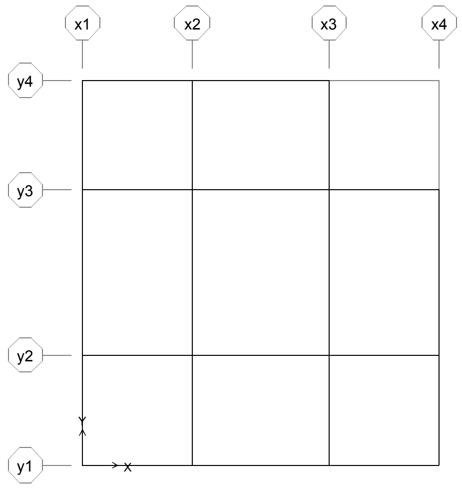
The effective damping in the structure is calculated for the assumed ultimate displacement, S_{dpi}. Effective seismic demand spectrum is modified for this effective damping. The graphs of both the Pushover Spectrum and the Effective Seismic Demand Spectrum (S_a versus S_d) are compared. If both the graphs intersect at the same displacement S_{dpi} the retrofit scheme chosen is adequate.

If both the graphs do not intersect at all or they intersect at a displacement S_d larger than the assumed value of S_{dpi} the estimate of S_d and Effective seismic demand spectrum is modified. The graphs of both the Pushover Spectrum and the Effective Seismic are compared. If the curves do not intersect even when the assumed displacement is the maximum displacement $S_{d,max}$ on the Pushover Spectrum, it seems that the retrofit scheme is insufficient and cannot provide adequate ductility. Hence, the retrofit scheme is revised to increase the ductility and/or strength.

NUMERICAL STUDY

Five storey unsymmetrical building with three bay in X and Y direction (Figure 1) is considered in the present work. Details of the building have been shown in Table 1. Seismically evaluation of this building with the present day knowledge is undertaken to avoid the major destruction in the future earthquakes. Up-gradation of the building is done if it is found to be seismically deficient.

Figure 1: Plan of Unsymmeterical Building



Evaluation of building is required at a two stages; before the up-gradation (to identify the weakness of the building) and after the up-gradation (to estimate the adequacy and effectiveness of up-gradation). In the present work, performance evaluation of this building frame is undertaken and suitable up-gradation is proposed. The performance evaluation of the upgraded building has been also verified.

It has been shown that buildings with square columns show better seismic performance as compared to rectangular columns (Gehlot, 2013). Hence, the square columns are selected in this building to ensure better seismic performance.

Table 1: Information of Building

S.No.	Particular	Detail
(i)	Type of building	Unsymmetrical
(ii)	Number of storeys	5 (G+4)
(iii)	Number of bays in x-direction	3
(iv)	Number of bays in y-direction	3
(v)	Joints restrained in x-direction frames	4
(vi)	Joints restrained in y-direction frames	4
(vii)	Height of Ground floor	3.5 m
(viii)	Height of Other floor	3.0 m
(ix)	Floor thickness including finish	150 mm
(x)	Size of all beams	300 mm x 400 mm
(xi)	Size of all columns	300 mm x 300 mm
(xii)	Grade of concrete	M 30
(xiii)	Grade of steel	Fe415
(xiv)	Foundation Soil	Hard Sol
(xv)	Seismic Zone	V

SOFTWARE USED

It is well known fact that the distribution of mass and rigidity is one of the major considerations in the seismic design of the buildings. Invariably these factors introduce coupling effects and non-linearity in the system; hence, it is imperative to use non-linear static analysis approach. Specialized programs SAP2000, STAAD, ETABS, NISA-CIVIL, ANSYS, etc., are generally used for cost-effective seismic evaluation and up-gradation of buildings (Agrawal and Chourasia, 2003).

In the present work SAP2000 (2006) has been utilized. Nonlinear static pushover analysis capabilities are provided in this software. The nonlinear behavior occurs in discrete user-defined hinges. Currently, hinges can be introduced into frame members only and assigned at any location along any frame member.

METHODOLOGY

Up-gradation of the chosen unsymmetrical RC building is performed by using following steps:

i. Estimation of the design lateral force of the building.

ii. Estimation of stress resultants (axial force, shear force and bending moment) at critical sections of the frame elements as per load combinations defined in IS 1893 (Part I) (2002) and IS 456(2000).

iii. Estimation of Capacity of the RC sections considering the actual cross-section geometry, material properties and reinforcement sizes. The usual partial safety factors for loads and material as per the Limit State Design (IS456:2000) are applied.

iv. Determination of the revised sizes of deficient members or members to obtain the Strong Column-Weak Beam mechanism.

v. Comparing the results of Pushover analysis for the existing and upgraded building.

vi. Determination of performance point of the upgraded building as per guidelines of ATC40 (1996).

The selected unsymmetrical building has been up-graded utilizing above steps. Salient features of the up-gradation process are discussed below:

Determination of Deficient Elements and their Up-gradation

Deficient members in the building are evaluated by comparing stress resultant obtained in step; (ii) and capacity of the relevant members in step; (iii). It is observed from the comparison of stress resultant and capacity of the relevant members that the column no. 26, 31, 46 and 51 are deficient. Demand Capacity Ratio (DCR) values for these members are more than 1. To obtain the Strong Column-Weak Beam mechanism during earthquakes, columns should never be the weakest components in the building structure. Hence, these members are retrofitted for the desired performance level.

Column up-gradation is often critical to the seismic performance of a structure. The response of a column in a building structure is controlled by its combined axial load, flexure and shear. There are many up-gradation techniques available in the literature. In this study, column jacketing is used to increase column shear and flexural strength so that columns are not damaged. In the present work, column section is increased from 300 mm x 300 mm to 450 mm x 450 mm by using column jacketing approach.

Pushover Analysis

The selected building with applied retrofit approach is modelled in SAP2000 (2006). The boundary conditions for the analysis for the nodes of the columns at the foundation level are fixed (the displacements, translational or rotational values were set to zero).

In this study, the first pushover load case (Push1) is used to apply DL+0.25 LL and then subsequent lateral pushover load case (Push2) is specified to start from the final conditions of the Push1.

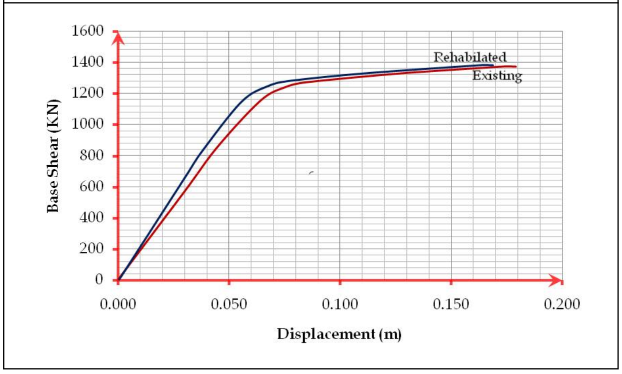
The Push2 load case applies distribution of lateral load as per IS1893 (Part I) (2002). The Push2 load case is deformation controlled and the building model is pushed to a displacement of 0.03 m at specified node in X-direction.

In Push3 load case, uniform acceleration in X-direction is applied. Similarly, uniform acceleration in Y-direction is applied in Push4 load case.

In Push5 load case, mode shape 1 is used to apply lateral load and the building is pushed to a displacement of 0.03 m at the specified node in X-direction.

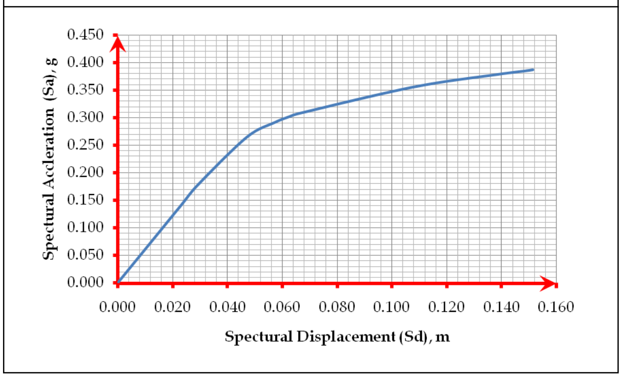
It is seen from the above pushover analyses that Push2 is the most critical push load case and is used further for the determination of performance point. Figure 2 shows the comparison of pushover curve for the existing and up-graded building for the Push2 load case.

Figure 2: Comparison of Up-graded and Existing Building for Push2



As per requirement of the capacity spectrum method, the capacity curve (in terms of base shear and roof displacement) (Figure 2) is converted to the capacity curve in Acceleration Displacement Response Spectra (ADRS) format (Figure 3).

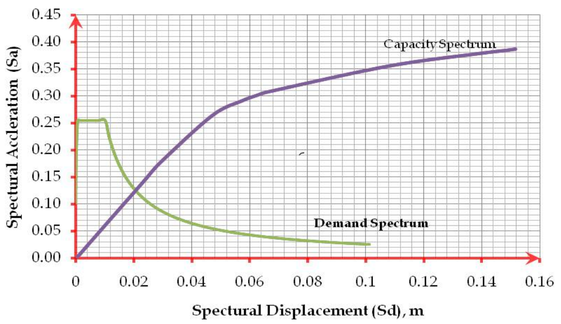
Figure 3: Capacity Spectrum in ADRS Format for Push2



Determination of Performance Point

The first choice of point spectral displacement is obtained by assuming the equal displacement approximation or it might be the end point of the capacity spectrum or it might be any other point chosen on the basis of engineering judgment. Assuming a value of the spectral displacement S_{dpi} = 0.020 m in the structure, the effective damping β_{eff} in the structure with accumulation of structural damage is calculated and is equal to 0.05. The demand spectrum for effective damping equal to 0.05 is plotted and has been shown in Figure 4. The capacity spectrum is also plotted in the same graph (Figure 4) and the performance point is obtained at the intersection of the capacity spectrum and demand spectrum.

Figure 4: Evaluation of Performance Point



It can be observed from Figure 4 that the capacity spectrum and the demand spectrum intersect at the spectral displacement of 0.021 m which is higher than assumed value of $S_{dpi.}$ Hence, the retrofit scheme chosen is adequate. It is further noted that the value of spectral acceleration (S_a) corresponding to S_d =0.021 m is equal to 0.126 m/s^2. Thus, the performance point in terms of S_a and S_d is (0.126, 0.021).

The value of Base Shear and corresponding displacement is also determined from the Figure 3. The value of Base Shear (V) corresponding to S_d =0.021 is equal to 560.11 kN and value of displacement (D) corresponding to V (560.11 kN) is equal to 0.027 m. Hence, the Performance point for the up-graded building in terms of V and D is (560.11, 0.027). This Performance point lies in linear range; hence, the structure is safe after the up-gradation.

The lateral displacement of the performance point to satisfy the performance level of life safety at Design Basis Earthquake (DBE) should be less than 2% of storey height. In the present study, lateral displacement of the performance point (0.027 m) is less than 0.031 m (2% of storey height). Thus, the proposed up-gradation of the building satisfies the performance level of life safety at DBE.

CONCLUSION

The chosen unsymmetrical building has been upgraded using SAP2000 in this work. Following observations are drawn from this study:

i) Seismic evaluation by non-linear static analysis exposes design weaknesses that may remain hidden in an elastic approach. SAP2000 is an effective tool for performing pushover analysis and can be used for seismic evaluation of both new and existing structural systems.

ii) The performance point for the up-graded building in terms of base shear and displacement is (560.11 kN, 0.027 m). This performance point lies in linear range, hence, the structure is said to be safe after the up-gradation.

iii) The lateral displacement of the performance point (0.027 m) is less than 0.031 m (2% of storey height). Thus, the proposed up-gradation of the building satisfies the performance level of life safety at DBE.

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