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Seismic Performance Assessment of Bare RC Frames and Hybrid Structures

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Abstract: Earthquakes, even though they occur rarely, induce inertia force which is dynamic and complex. Moreover, they are sometimes so devastating that it is worth going into the depth of understanding them. The current work is one step towards understanding the complex effects of this dynamic force particularly on low rise RC structures which are found in almost all parts of the world. During 2001 Bhuj earthquake of India, a major damage was observed in RC framed structures at Ahmedabad which were in the range of G+3 to G+7 storey. Most of the buildings were having a normal grid of 3m x 3m column spacing with a storey height of 3m. Hence the present work, which is expected to act as a guide line for Civil and Structural Engineers in smaller towns and cities where expert advice may not be easily available, is devoted to RC framed structures ranging from G+3 to G+7 storey. Out of the various factors affecting the earthquake and dynamic response of RC framed structures, in the current study, the shape of the column is considered to be one of the factors. The G+7 storey frame without the consideration of brick infill is subjected to push over analysis. The performance point for rectangular and equivalent square shaped cross section of columns is studied. The study incorporates two variations in the overall plan dimensions - 6m x 6m and 6m x 9m having four panes each of 3m x 3m and 3m x 4.5m respectively. The same set of models are also studied with brick infill walls modeled as 2D finite elements and equivalent strut. The performance point obtained from the push over analysis is considered as a measure of performance. Parameters like base shear, roof displacement, number of plastic hinges, severity of hinges, effective damping, etc. are compared for the mathematical models at performance point. Another important factor affecting the seismic performance of RC frames is the rigidity of the joint. Although, in case of RC frames which are monolithically cast, the joint rigidity is usually considered as fully rigid, it however may vary depending on the size of beams and columns framing into the joint. In case of precast RC frames, the joint rigidity is always an issue especially under lateral loads. Thus, the study of RC plane frames with varying joint rigidity is considered for analysis under lateral loads. RC space frame models with varying rigidity are also developed for comparing the results under push over analysis.

Keywords: G+7 storey, Earthquakes, RC framed structures.

I. Introduction

Earthquakes have occurred in every part of the globe. It is one of the natural phenomena which has a long lasting and a devastating effect on the human society at large. Although some of the regions are identified as earthquake prone zones, the risk of earthquake has been a major cause of worry for the human race. It is generally felt that the occurrence of earthquakes in the recent times has increased. But the fact is that the awareness and instrumentation has increased throughout the world. This has led to the fact that if one just sees the USGS website which is one of the major online source of earthquake data occurring throughout the world in real time, one can see that there are more than 65 significant (M>4) earthquakes recorded up to October in 205. The number of significant earthquakes is 74 for the year 2009.

Although almost all earthquakes are devastating some of the facts and figures tell us the specific reasons for caution against their effects. According to Asian Disaster Reduction Centre (ADRC), Japan, from 1991 to 2000 **38%** of world's disasters occurred in Asia and **5,88,000** people were killed which is **78%** of world's casualty. It also states that in the same period, **1.9** billion people were affected which is **90%** of people affected in the world. Economic losses amounted to **374** billion **US** dollars which accounts for **54%** of the world's total damages. ADRC data for the period of 25 years from 1975 to 2000 states that earthquakes affected only **1%** of the total people affected by natural disasters in Asia but accounted for about **50%** of the total economic damage.

1.1 BASIC CONCEPTS OF STRUCTURAL DYNAMICS

It is a well known fact that when a building is subjected to time dependant force, it is said to be subjected to dynamic force. In order to analyze a structure which is subjected to dynamic forces, the structure may be assumed to be in a state of dynamic equilibrium. In such a state it will have it's mass M changing it's position as time changes. It is usual to assume the mass as lumped at a point in structural dynamics and if one is able to specify the location of the mass at various times with reference to a datum, one can say that the problem of dynamics is solved. In order to achieve this, the equation of motion may be considered for a Single Degree of Freedom (SDF) system with specific mass, stiffness and damping.

1.2 INTRODUCTION TO SEISMIC ANALYSIS

Seismic analysis is a particular case of dynamic analysis. Here, instead of a uniform forcing function being applied, the ground motion generated by earthquakes is given as an acceleration in terms of g (gravitational acceleration) in the lateral direction to the building. The response of a building or a structure generated because of this dynamic force is studied and the internal forces and moments developed in the structure are evaluated. Generally, seismic analysis involves the steps mentioned in the previous section wherein the natural frequencies are evaluated first and the mode shapes are also found out. The seismic code of practice specifies the method to be adopted in a particular country based on the past history of earthquakes and probable risk areas. The country is usually divided into various zones (e.g. in India, the entire country has been divided into 4 earthquake zones - II, III, IV and V) based on the probability of an event occurring in that region. Some countries even go for micro zonation of the major earthquake zones as the effect of an earthquake can be affected by local soil conditions and other factors. Based on the occurrences of earthquakes, the various factors are specified by the seismic codes. The response of a structure to an earthquake force depends on variety of factors such as nature of foundation soil; materials, form, size and mode of construction of structures; and the duration and characteristics of ground motion.

1.3 TYPES OF STRUCTURAL ANALYSIS

Analysis of framed structures depends on the type of structure and also the response developed by the structure under external forces acting on them (excitation). The excitations can be due to loads, vibrations, settlement and/or thermal changes. When a structure is subjected to these excitations, it undergoes some deformations and stresses known as response of the structure. The responses can be displacements, stresses, strains and/or stress resultants. The excitations can be either static or dynamic. The structure can be either elastic or inelastic and the response can be either linear or nonlinear.

1.4 SCOPE AND OBJECTIVES OF THE PRESENT WORK

Out of the various parameters affecting the response of a structure, the soft storey and weak storey effects arise out of a poor structural framing and hence it is presumed that a responsible engineer following the codal provisions would be well aware to avoid such effects. Also, the earthquake codes give very specific guidelines on such effects. The provision of providing tie beams in both the lateral directions is a case of good engineering practice and hence it need not be stressed any further. The location of mass at certain locations so as to avoid large torsional effects on the building can also be addressed by using proper analysis tools. The present work specifically aims at giving guidelines to a structural engineer who is not very sure about the effects of column orientation or shape on the overall seismic response.

II. Literature Review

Using a conventional pushover, with triangular load distribution, in **1998, Faella and Kilar [05],** investigated the applicability of such approach on the analysis of asymmetric plan structures. They moved the load application point to fit the results from the dynamic analysis. The authors tried four possibilities, Centre of Mass (CM), CM - 0.05L, CM + 0.05L and CM + 0.15L. A single building was analysed which was symmetric but became asymmetric by changing the position of the Centre of Mass. The results obtained were that the deflection profile both on the stiff and flexible edge could be successfully matched by shifting the point of lateral load application. In many cases, it was found that the dynamic response profile can be enveloped by shifting the equivalent static forces at the minimum and maximum eccentricities.

In the year **1998, Habibuilah and Pyle [06]** presented the steps used in performing a pushover analysis of a simple 3D building. SAP2000, a state-of-the-art, general purpose, three- dimensional structural analysis program, was used as a tool for performing the pushover.

In **1999,** it was **Colina [07]** who showed by his work on time history analysis that when a structure is subjected to only one directional excitation, it gives very unreliable responses for a 3D structure. The displacement response is the one which is least reliable under uni-directional excitation.

In 1999/ Chopra and Goel [08] pointed out some of the deficiencies of the ATC-40 procedure of pushover analysis. The report deals with development of an improved simplified analysis procedure, based on the capacity and demand diagrams, to estimate the peak deformation of inelastic SDF systems. It points out that the peak deformation of inelastic systems determined by ATC-40 procedures is inaccurate when compared against results of nonlinear response history analysis and inelastic design spectrum analysis.

In **2000, Moghadam and Tso [09]** proposed a modified approach to account for torsional effects on irregular building. Accordingly, the target displacement was obtained by performing an elastic spectrum analysis of the building; since the top displacements of different resistant elements were different, many target displacements were needed to be computed. The lateral load distributions used in the pushover were taken from the spectrum analysis, as well, to take into account the higher order effects. With the target deformation and the load distribution fixed up, 2D pushover analyses of the selected elements were carried out. The elements were pushed until the target displacements, for each one, were achieved.

In **2000, Murty and Jain [11]** studied the effect of masonry infill walls in an RC framed structure and have concluded that the beneficial effects of the masonry infill walls should definitely be taken into account especially when evaluating the earthquake response of buildings. When the effect of infill walls is neglected in the seismic analysis of RC frames, the performance of the building may be far from realistic.

In **2000, Chopra and Goel [12]** proposed a modification in the simplified nonlinear static analysis procedure given in ATC-40. The authors proposed two modified procedures-based on Capacity-Demand diagrams which were similar to the procedure A and B given in ATC-40.

In **2001, Humar et at. [16]** discussed the performance of buildings during the 2001, Bhuj Earthquake of India, They observed that most of the buildings in the epicentre region of Bhuj were either load bearing masonry or RC framed structures. One of the important observations to come out of the earthquake was that masonry infills, even when not tied to the surrounding RC frame, could save the building from collapse, provided such infills are uniformly distributed throughout the height so that abrupt changes in stiffness and strength did not occur. By **2002.**

Kilar and Fajfar [17] explored the possibility of extending the N2 method, originally formulated for planar analysis, to the analysis of irregular structures. In addition, comparisons among N2 method, the MT method (proposed by Moghadam and Tso [03]) and nonlinear dynamic analyses were carried out. The modified N2 procedure consists of two independent pushover analyses of the studied 3D structural model with lateral loading in both horizontal directions, respectively.

III Methodology

3.1 PERFORMANCE OBJECTIVES

A performance objective specifies the desired seismic performance of the building. Seismic performance is described by designing the maximum allowable damage state (performance level) for an identified seismic hazard (earthquake ground motion). A performance objective includes consideration of damage states to several levels of ground motion. General structural performance levels are as follows **(Fig. 3.1)**

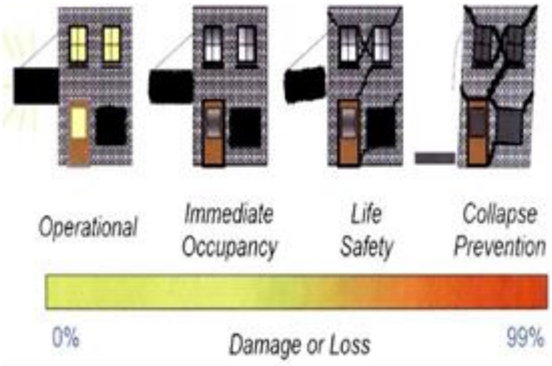

Fig. 3.1 Standard Structural Performance Levels

3.2 ATC-40 PROVISIONS

ATC stands for Applied Technology Council which is formed in the United States of America. The main objective of this council is seismic evaluation and retrofit of concrete buildings. Although the procedures recommended in this document are for concrete buildings, they are applicable to almost all types of buildings. This document provides guidelines to evaluate and retrofit concrete structures using performance based objectives. Following steps are recommended by ATC-40 [1] for evaluation and retrofitting:

- Determine the primary goal of the project.
- Select engineering professionals with experience in the analysis, design and retrofit of the buildings in seismically hazardous region.
- Decide performance objectives for specific level of seismic hazard.
- Do regular site visits and review drawings
- Check whether applied nonlinear procedure is appropriate or not for selected structure.

3.3 POTENTIAL PLASTIC HINGE ZONES

Location of plastic hinges in the structure is important because plastic hinges cause excessive deformation. In plastic hinge regions, rotation of the member is very high which leads to failure. Location of plastic hinges in beams must be clearly identified since special detailing requirements are needed in inelastic regions of. Beams of frames subjected to earthquake forces. In capacity design of structures for earthquake resistance, distinct element of primary lateral force resisting systems are chosen and suitably designed and detailed for energy dissipation under several imposed deformations. So these critical regions are well detailed. In capacity design concept, potential plastic hinge regions within structure are clearly defined. These are designed to have dependable flexural-strengths as close as practicable to the required strength. Subsequently, these regions are carefully detailed to ensure that estimated ductility demands in these regions can be reliably accommodated. This is achieved primarily by closely-spaced and well anchored transverse reinforcement.

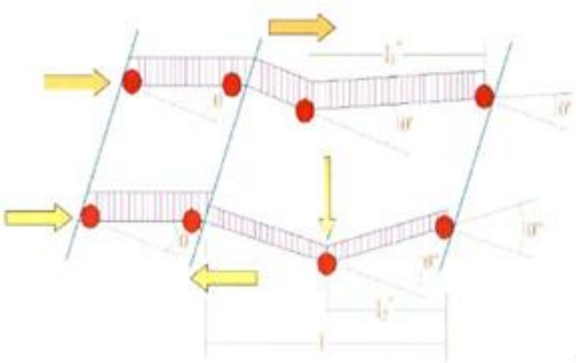

Fig. 3.2 Plastic Hinge Pattern Dominated by Gravity Loading

3.4 EVALUATION OF PERFORMANCE

Various analysis methods, both elastic (linear) and inelastic (nonlinear), are available for the analysis of existing concrete buildings. Elastic analysis methods include code static lateral force procedures, code dynamic lateral force procedures and elastic procedures using demand capacity ratios. The most basic inelastic analysis method is the complete nonlinear time history analysis. Simplified nonlinear analysis methods, referred to as nonlinear static analysis procedures, include the Capacity Spectrum Method (CSM) that uses the intersection of the capacity (pushover) curve and a reduced response spectrum to estimate maximum displacement; the displacement coefficient method that uses pushover analysis and a modified version of the equal displacement approximation to estimate maximum displacement; and the secant method that uses a substitute structure and secant stiffness's.

3.5 METHODS TO PERFORM NONLINEAR ANALYSIS

Two key elements of a performance-based design procedure are demand and capacity. Demand is a representation of the earthquake ground motion. Capacity is a representation of the structure's ability to resist the seismic demand. The performance is dependent on the manner that the capacity is able to handle the demand. In other words, the structure must have the capacity to resist the demands of the earthquake such that the performance of the structure is compatible with the objectives of the design. The key step for the entire analysis is identification of the primary structural elements, which should be completely modeled in the non-linear analysis. Secondary elements, which do not significantly contribute to the building's lateral force resisting system, need not be included in the analysis.

3.6 STEPS FOR CHECKING PERFORMANCE

The following steps should be followed in the performance check as per ATC-40 [1]. For the global buildings response verify the following:

The lateral force resistance has not degraded by more than 20 percent of the peak resistance.

The structure should satisfy the serviceability check i.e. the lateral drifts should not be more than the limits imposed.

Identify and classify the different elements in the building. Any type of the element may be present: beam-column frames, slab-column frames, solid walls, perforated walls, punched walls, floor

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diaphragm and foundations.

Identify all primary and secondary elements.

IV. Results

4.1 GEOMETRIC PROPERTIES AND LOADS CONSIDERED

A 3m x 3m panel model giving an overall plan dimension as 6m x 6m is considered. The storey height is considered as 3m and the columns are extended up to foundation level assumed to be 3m below ground level. Five different models comprising of G+3 to G+7 storey buildings are considered for the analysis. The beam sizes considered are 230 x 450 mm for all floors. The cross-sectional dimensions for all columns are considered as 230 x 450 mm when considering rectangular columns and it is taken as 322 x 322 mm for equivalent square sections. The column sizes between ground level and foundation level are increased by 50mm in columns in both lateral directions. Thus, for a typical rigid frame, five models with G+3 to G+7 storey are considered with rectangular columns and five models with equivalent square columns are considered. Similarly, ten models for semi rigid frames and ten models with hybrid frames are considered. Again, within each category of semi rigid and hybrid frames, the models are considered having four different variations in joint stiffnesses as 0, 7500, 100000 and 290000 kNm/rad. Thus, in all there are 90 models which are analyzed, 40 for hybrid frames, 40 for semi rigid frames and 10 for rigid frames.

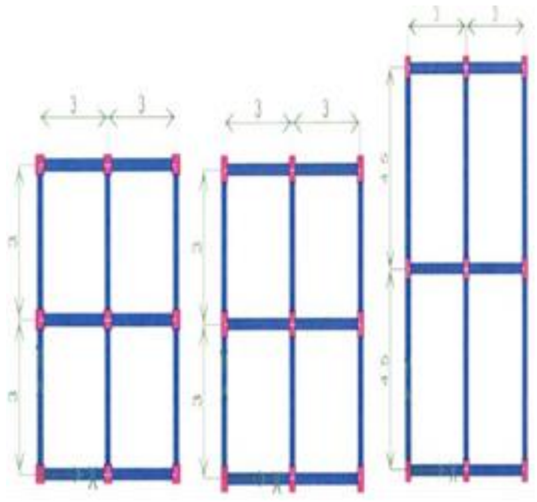

Fig. 5.1 Typical Plan Views showing Column Orientations in Models

4.2 PARAMETERS FOR PUSHOVER ANALYSIS

The mathematical models developed are subjected to push over analysis using commercial software ETABS with the parameters defined for the same. Default plastic hinges of four types are available in the software. Out of them, P-M-M type of hinges are defined at 5% and 95% of the span for all beam and column elements. Moreover, flexural plastic hinges M3 are defined at the midspan of all beams to capture the possible development of stresses beyond yield point due to gravity loads. The static analysis, is carried out for the frame models under dead, live and earthquake load cases.

Wind load is not considered as the structures are only up to G+7 storey and for RC structures, earthquake loads will govern due to heavy mass.

4.3 RESULTS OBTAINED FROM THE PUSHOVER ANALYSIS

The results obtained from the push over analysis for all the above mathematical models are presented in the form of tables and graphs. In all the tables, base shear is represented as V and roof displacement is shown as D. The type of model considered is represented by R for rigid frame, H for hybrid frame and SR for semi rigid frame.

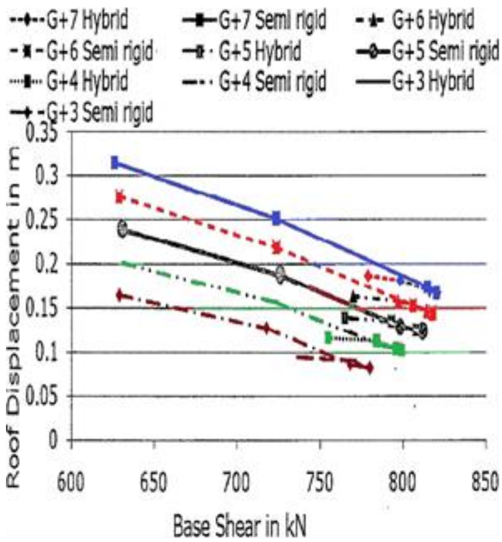

Fig. 4.3 6mx6m Frames with Square Columns under Push X

5. Conclusion

- For a G+6 storey RC frame having an overall plan dimension of 6m x 6m and a panel size of 3m x 3m, the seismic performance of frame having rectangular shaped columns is found inferior to the same frame having equivalent square columns.
- The results of the push over analysis for G+6 storey RC space frame indicates that the storey drift for model with rectangular columns shows a much higher storey drift at first storey level as compared to the model having equivalent square columns.
- The number and intensity of plastic hinges developed in a G+6 storey RC space frame with rectangular columns at performance point is found much higher compared to the same model having equivalent square columns. This fact indicates a better seismic performance of the square shaped columns.
- For an overall plan dimension of 6m x 9m for a G+6 storey building, the push over analysis indicates that the seismic performance of both rectangular and square columns is almost similar. However, the maximum storey drift for model with square columns is less than that with rectangular columns.

- When brick infill walls are considered in the form of struts in the push over analysis, the number of plastic hinges decreases but severity of plastic hinges developed at performance point increases for both G+6 storey models having square and rectangular columns as compared to the same without considering infill walls.
- In case of G+6 storey RC frames, looking at the effective damping and base shear at performance point, it can be stated that square columns perform better for overall square plan (3m x 3m panel) whereas rectangular columns perform better for rectangular overall plan (3m x 4.5m panel). This is true for push over analysis with infill walls modeled as struts and even without infill walls.
- When the plane frames up to three storeys are subjected to push over analysis considering semi rigid beam column joints, there is hardly any effect on the performance point of fully rigid frame and semi rigid frames.

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