Displacement Based Damage Estimation of RC Bare Frame Subjected to Earthquake Loads: A Case Study on 4 Storey Building

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SUMMARY

Reinforced concrete buildings constitute the dominant type of construction in the earthquake prone countries. Many researchers have studied the performance of the RC structure in seismic environment. In this study a RC building of four storeys is considered and its performance is evaluated when subjected to five ground motions.

The study is roughly divided into three parts, first part includes investigation of the dynamic characteristics of ground excitations, second part includes evaluation of the nonlinear seismic behaviour of building subjected to the given ground excitations and third part includes evaluation of damage. The present study is based on analytical investigation of seismic performance and potential seismic damage of a reinforced concrete framed building due to earthquakes in India, using nonlinear modelling and displacement-based analysis techniques. Since the seismic damage is directly correlated to the displacement (deformation) of the structure, the yield displacement of the structure is evaluated from the pushover analysis. From the displacement time history of the structure response, the peak values which exceeding yield displacement of the structure. The estimation of structural damage is calculated for each cycle to calculate the damage of the structure. The estimation of structural damage is calculated as per the model of Park and Ang. At the end, authors attempted to propose a new damage scale.

Keywords: yield displacement, pushover, time history, predominant frequency, damage

1. INTRODUCTION

Since the early 1970's, there has been considerable research on the damage assessment of the RCC buildings. As proposed by many researchers (Park et al 1984, Chung et al 1987, Williams, Sexsmith 1995, Fajfar, Vidic 1994) damage indices can be classified as local damage indices and global damage indices. A local damage index is an indicator of damage for a part of structure such as an element, frame or a story while a global index considers the damage to the whole structure. Till now lot of research is carried out to evaluate the damage of reinforced concrete structures in terms of its components. A damage model was developed by Park and Ang (1985), to assess the seismic damage of a reinforced concrete member based on experimental data. The damage is expressed as a linear combination of the maximum deformation and the absorbed hysteretic energy. After some years Kunnath et. al (1992), modified the original index, known as modified Park and Ang model. In the modified Park and Ang model, the significance of yield displacement is considered. Due to simplicity of the model many researchers used this model to compare their results.

In 2010, Siddhartha Ghosh et al, used Park–Ang damage index to estimate the damage demand on a MDOF system, by comparing with the estimates from a nonlinear response history analysis of the MDOF model. These schemes are tested for both global and storey-level damage indices

H. Estekanchi and K. Arjomandi (2007), Selected some damage indexes and compared by applying them in the nonlinear analysis of various low rise steel frames subjected to a set of seven earthquake accelerograms corresponding to a specific soil condition. Correlations between various indexes have been presented graphically and approximate conversion formulas are also provided.



A.S.moghadam, and W.K Tso (2000) used 3-D pushover analysis to estimate the damage of the building. The procedure is found to be more successful in estimating the global response parameters such as inter storey drifts than local damage indicators such as beam or column ductility demands.

In the present study modified Park and Ang damage model is used to evaluate the damage of a structure by performing the nonlinear timehistory analysis. A comparison is made between the damage calculated by Park and Ang model and the damage calculated by non linear static pushover analysis. In this study a four storey R.C building without infill walls is considered in the seismic environment and the damage is estimated under five ground motions.

2. MODEL STRUCTURE AND GROUND MOTIONS

2.1 Structure Details and Dynamic Properties

For the purpose of study, a regular four-storey reinforced concrete building is considered. The building has a rectangular plan measuring 12m x 9m. The lateral load resisting elements in X-direction consist of five identical moment resisting frames, and in Y-direction the frames are four as shown in figure 1. The spacing between the frames is 3m and uniform storey height for each frame is 3m. In X-direction each frame has four bays, and in Y-direction each frame has three bays. The structure is designed as per Indian Standard plain and reinforced concrete code of practice (IS456). Dynamic properties of the structure are shown in table 1.



Figure 1. Structure Details. (a) Building Plan (b) 3D-Frame

Table 1. Dynamic Properties of the Structure								
Mode shapes	Period (sec)	Frequency (Hz)	Mass participation factor					
1	0.387	2.57	0.8					
2	0.125	7.99	0.09					
3	0.073	13.57	0.03					
4	0.055	18.05	0.01					

 Table 1. Dynamic Properties of the Structure

2.2. Earthquakes and their Dynamic Characteristics

Five earthquake records are considered to perform the time history analysis. The PGA values of the records varies from 0.22g to 0.54g. The dynamic characteristics of earthquake records are shown in table 2 and the acceleration time history of the records are shown in figure 2. To know the predominant period of the earthquakes, fourier spectra is plotted in figure 3 for all the earthquakes.



Figure 2. Acceleration time history of ground motions. (a) For Elcentro (b) For Parkfield (c) For Northridge (d) For Bhuj (e) For Uttarkashi

S.No	Earthquake Name	Location	Year	M _w	PGA(g)	Predominant Time Period Range, sec
1	Elcentro	Lomaprieta, California,USA	1989	6.9	0.22	0.37-0.48 & 1.15-1.9
2	Parkfield	Parkfield,California, USA	1966	6	0.43	0.25-0.4 & 0.9-1.27
3	Northridge,	Northridge, California, USA	1994	6.7	0.54	0.08-0.15 & 0.7-0.8
4	Bhuj	Bhuj, Gujarath,India	2001	7.6	0.32	0.25-0.8 & 1.15-1.25
5	Uttarkashi	Uttarkashi, Uttarakhand,India	1991	6.8	0.22	0.2-0.3 & 0.5-0.7

Table 2.	Details of Earthquakes
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Figure 3. Time Period Vs Fourier Amplitude of Earthquakes and Natural Period of structure in Different Modes (a) For Elcentro (b) For Parkfield (c) For Northridge (d) For Bhuj (e) For Uttarkashi

3. DAMAGE ASSESSMENT

3.1 Damage Assessment from Pushover Analysis

Simplified analysis procedure to determine the displacement demand imposed on a building expected to deform inelastically is pushover analysis. It develops the relationship between base shear, V_b , and roof displacement, Δ . In the present study, the Seismic damage of the regular structure is evaluated using information obtained from structural response under monotonic loading(pushover analysis).

A cumulative dissipated energy function is used to evaluate the condition of damage of a multistory reinforced concrete test structure. Based on the capacity curve, at any displacement the damage state of the structure is estimated.

3-D pushover analysis is performed on test structure in SAP, and the capacity curve is plotted by $V_b \cdot \Delta$ relation from static nonlinear analysis as shown in Fig. 4. The area under this curve gives the total energy dissipated till the collapse of the structure. To represent the damage state of the structure at each displacement, a damage scale is proposed. At ultimate displacement the damage scale is normalised to 1. The damage scale at any displacement is given by the ratio of the energy dissipated up to that displacement excluding the energy dissipated due to the yield displacement to the total energy dissipated at collapse stage during the pushover analysis as Eqn.1.

$$\mathbf{D} = \frac{E_{\Delta}}{E_{T}} \tag{1}$$

Where E_{Δ} represent the total energy dissipated upto Δ displacement, and E_T represent the total energy dissipated in the pushover analysis at total collapse stage, D is the damage scale. To calculate the area under the pushover curve at any displacement, a computer program is written in MATLAB. The damage of the test structure under monotonic loading at any displacement is shown in figure 5. The yield displacement of the structure from pushover analysis is observed as 14 mm. It is observed that there is no damage upto the yield displacement. The damage is proportional to the displacement of the structure under monotonic loading.



3.2. Damage Assessment from Timehistory Analysis

The modal analysis procedure to determine the response of a structure to earthquake induced motion, at all support points of the structure is time history analysis (THA). The non linear time history analysis is performed for five ground motions (Table. 2) using SAP software package. The non linear response (hysteresis), force Vs displacement of the structure for five ground motions is ploted as shown in Fig. 6(a), Fig. 6(b), Fig. 6(c), Fig. 6(d), Fig. 6(e). As the maximum displacement occurs at top story, the response of the top story is plotted.



Figure 6. Structure Response for Five Earthquakes. (a) For Elcentro (b) For Parkfield (c) For Northridge (d) For Bhuj (e) For Uttarkashi

In Fig. 6(a), the maximum displacement imposed on the structure by the elcentro ground motion is 0.024 m. In Fig. 3(a), the first mode is predominant and its period, 0.387 sec matches with the predominant period (Table. 1) of the ground motion. This ground motion creates resonant condition, and the displacement of the structure increases. Due to this ground motion, the displacement caused to the structure is of second highest among five ground motions.

In Fig. 6(b), the maximum displacement imposed on the structure by the Parkfield ground motion is

0.058 m. In Fig. 3(b), the first mode period of the structure matches with the predominant period of the ground motion, and the displacement imposed by this ground motion is very high among five ground motions. Though the hysteresis in the response are less, due to high displacement of the structure the damage is high for this ground motion.

In Fig. 6(c), the maximum displacement imposed on the structure by the Northridge ground motion is 0.015 m. In Fig. 3(c), the second mode is predominant ant its period falls in the range of predominant period of the ground motion. As the mass participation for second mode is very less (Table. 1), though the number of hysteresis in the response is more, the damage caused by the ground motion is very less.

In Fig. 6(d), the maximum displacement imposed by Bhuj ground motions on the structure is about 0.012 m, which is lessthan the yield displacement of the structure (Fig. 4). The predominant period of the ground motions not mathches with the any of the mode periods. Though the number of hysteresis in the response are more, the damage caused by this ground motion is insignificant.

In Fig. 6(e), the maximum displacement imposed by Uttarkashi ground motions on the structure is about 0.015 5m, which is more than the yield displacement of the structure (Fig. 4). The predominant period of the ground motions not mathches with the any of the mode periods. But the displacement of the structure crosses the yield displacement, the damage caused by this ground motion is significant.

Modified Park and Ang model represented by the Eqn. 2. is used to find the structural damage for five ground motions.

$$D = \frac{x_m - x_y}{x_u - x_y} + \beta \frac{\int dE}{Q_y x_u}$$
(2)

The parameters in the damage model considered as x_m is the maximum displacement of each cycle of the hysteresis, x_y is the yield displacement of the structure, x_u is the ultimate displacement of the structure under monotonic loading, β depends on the characteristics of the earthquakes, for present study it's value is taken as 0.1, dE is the total cumulative energy dissipated in hysteresis where the damage should be calculated, Q_y is the yield strength of the structure corresponding to the yield displacement. A computer program is written to find the maximum displacement in each cycle of the hysteresis and also to find the energy dissipated in each cycle.

Fig. 8(a), represents the damage caused by Elcentro earthquake. The maximum damage caused is 0.55, this is the second highest damage among the five ground motions. As the he first mode is predominant during this ground motion (Fig. 3a), the damage caused is significant. The total duration of the earthquake is 47 sec (Fig. 2a), during this time the major part of the damage is occurred within 20 sec. In this plot it is observed the sudden increase in the damage is at 5 sec and at 20 sec, this is because of the structure displacement is high during this time.

Fig. 8(b), represents the damage caused by Parkfield earthquake. The maximum damage caused is 1.46, this is the highest damage among the five ground motions. During this ground motion the first mode is predominant and also the first mode time period matches with the predominant period of the earthquake. The total duration of the earthquake is 44 sec.(Fig. 2b), during this time the major part of the damage occurred within 10 sec. There is a sudden increase in the damage between 5 to 10 sec, this happened because of the structure displacement is high during this time.

Fig. 8(c), represents the damage caused by Northridge earthquake. The maximum damage caused is 0.09. During this ground motion the second mode is predominant (Fig. 3c). Though the second mode period, matches with the predominant period of earthquake, the mass participation factor in second mode is 0.09, the damage caused due to this earthquake is very less.

Fig. 8(d), represents the damage caused by Bhuj earthquake. The maximum damage caused is 0.1. during this ground motion the first mode is predominant but the time period of the first mode not

matches with the predominant period of the ground motion. Though the duration of the earthquake is 133 sec, the maximum displacement imposed on the structure is 0.01m (Fig. 6d) which is less than the yield displacement. The damage caused due to this ground motion is very less.

Fig. 8(e), represents the damage due to Uttarkashi earthquake maximum damage caused is 0.44 during this ground motion the first mode and second mode both are predominant but the time period of the either of the modes (table 1) not matches with the predominant period of the ground motion (Fig. 3e). But the maximum displacement imposed on the structure is 0.018m (Fig. 6e), which is greater than yield displacement 0.014m (Fig. 4) of the structure, so the damage caused due to this earthquake is significant. The sudden increase in the damage occurs between 4 to 12 sec, during which the displacement of the structure is more.

Displacement Vs damage of the structure for five ground motions is presented in figure 7.

4. COMPARISON OF DAMAGE

The base shear Vs roof displacement relation under monotonic loading is shown in figure 4. This curve shows the effective yield displacement of the structure as 0.014 m, where the inelastic behaviour of the structure is started. As the structure is pushed after the yield point, damage takes place in the structure. The damage scale is normalised to 1 at total collapse stage. The total collapse of the structure is shown at a displacement of 0.22 m, where the damage scale is 1. The damage at any displacement under monotonic loading is shown in figure 5. There is no damage in the structure upto the yield displacement. As the structure attains the inelastic state, the damage progresses in the structure.

In Fig. 8, a comparison is made between the time and the damages caused by five ground motions. From this plot, it is observed that damage is high for the ground motions which imposes higher displacement on the structure. From this plot it is clear that the major contribution in damage calculation is the displacement of the structure. As the mass participation is more in first mode, the damage to the structure should be more in that mode. In this plot it is observed that for parkfield and elcentro ground motions the damage is high since the first mode is predominant for these ground motions(Fig. 3a, Fig.3b).

In Fig. 3(c), the second mode is predominant and the damage for this ground motion is very less (Fig.8c).

In Fig.7, a comparison is made between the damage caused by monotonic load displacements and damage caused by dynamic load displacements. The damage for five ground motions is calculated by applying the modified Park and Ang model to the total structure. From this plot it is observed that the damage is more for a ground motion which imposes more displacement to the structure.



Fig. 7 Displacement vs Damage for Five Earthquake records



Figure 8. Time Vs Damage for Five Earthquakes (a) For Elcentro (b) For Parkfield (c) For Northridge (d) For Bhuj (e) For Uttarkashi

5.CONCLUSIONS

A procedure to assess the seismic damage state of a regular multistory structure is proposed. The use of the pushover analysis to assess seismic damage to buildings has been extended to include the three dimensional effect of building responses. This procedure compares the results of pushover analysis with the dynamic response (time history analysis) of a multistory structure. Considering the simplification in computation, to get the damage state of any structure, the proposed procedure is the simple approach to estimate the damage state of any structure as a whole.

Pushover analysis can be conveniently used to assess the damage of the structure when first mode is predominant.

It is worthwhile to mention a limitation of the proposed approach is to find the structural damage of RC structures.

REFERENCES

- Park Y-J, Ang A H-S. 'Seismic damage analysis of RC buildings'. Journal of Structural Engineering, ASCE; No. ST4, 111 (1985) 740-757.
- Park Y-J, Ang A H-S. 'Damage Limiting A seismic design of Buildings'. Earthquake Spectra, 1,3 (1987) 1-25.
- Williams, M.S. and Sexsmith, R.G. (1995). 'Seismic Damage Indices for Concrete Structures: A State-of the-Art Review'., Earthquake Spectra, 11(2), 319-349.
- Fajfar P, Vidic T, Fischinger M. 'Seismic demand in medium- and long-periodstructures'. Earthquake Engineering and Structural Dynamics. 18, 1989,1133–44.
- Fajfar. P, and Gasperisic. P (1996). 'The N2 Method for the Seismic Damage Analysis of RC Buildings'., J. Earthquake Engineering and Structural Dynamics, 25, 31-46
- Xia Y, Hao H, Brownjohn JMW, Xia P. 'Damage identification of structures with uncertain frequency and mode shape data'. Earthquake Engineering and Structural Dynamics. 31, 2002, 1053-1066.
- Kunnath, S.K., Chai, Y.H. (2004). 'Cumulative damage-based inelastic cyclic demand spectrum.' Earthquake Engineering and Structural Dynamics. 33:4, 499-520.
- H. Estekanchi and K. Arjomandi. 'Comparison of Damage Indexes in Nonlinear Timehistory analysis of steel moment frames'., Asian Journal of Civil Engineering (Building and Housing) 8, 6 (2007) pages 629-646
- Siddhartha Ghosh, Debarati Datta , Abhinav A. Katakdhond. 'Estimation of the Park–Ang Damage Index for Planar Multi Storey Frames Using Equivalent Single-Degree Systems' **Journal of Engineering Structures**-2010
- A.S.moghadam, and W.K Tso. 'Damage Assessment of Eccentric Multistory Buildings using 3-D Pushover Analysis'., Proc. 11th World Conference on Earthquake Engineering.
- Chopra A.K., 'Dynamics of Structures: Theory and Applications to Earthquake Engineering.' Pearson Prentice Hall, Third edition, 2007.
- Pradeep Kumar, R. (1997). 'Damage Based Life of Structure in Seismic Environment'. **Post Graduate Project Report,** Dept. of Civil Engg., Indian Institute of Technology – Kanpur India.