EVALUATION OF SEISMIC PERFORMANCE OF EXISTING REINFORCED CONCRETE BUILDINGS IN SRI LANKA USING PUSHOVER ANALYSIS APPROACH - A CASE STUDY

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Abstract: Evaluation of seismic performance of existing buildings is vital to reduce their seismic vulnerability. Performance can be evaluated by the interaction between structure's capacity and the probable seismic demands. After the evaluation, suitable retrofitting methods can be used to enhance performance by modifying the capacity. In this paper the performance of a four storied reinforced concrete building was evaluated using pushover analysis. The nonlinear behaviour of the structure was simulated using plastic hinges of which properties were determined using FEMA356. The SAP2000 finite element analysis software package was used to obtain the capacity curve of the building. The performance was evaluated using the capacity spectrum method proposed by ATC40 under the application of seismic demands derived from ATC40 document and AS1170.4 (2007) standard.Results showed that the performance of the building is satisfactory in both X and Y directions for all seismic demands determined using ATC40 document and AS1170.4 (2007).

Keywords: Seismic performance, pushover analysis, capacity spectrum method, SAP2000

1. Introduction

Although Sri Lanka is considered to be located in anaseismic zone, a recent study(Dissanayake C. B., 2005)indicates the possibility of seismic events due to a possible new plate boundary formation subdividing the Indo-Australian plate. After the 2004 Tsunami disaster, the requirement of seismic resilient structures was highlighted (Couldrey & Morris, 2005). Since most of the structures in Sri Lanka have not been constructed considering earthquake loading, there is a high vulnerability for a large scale disaster to occur even under a small seismic event due to the lack of preparedness. Therefore it is very important to retrofit existing buildings to withstand possible earthquake loads.

The pushover analysis method has been developed over the last few decades and has become popular among structural analysts and used in several guidelines (ATC, 1996) (FEMA, 2000) due to its relative simplicity and consideration of post elastic behaviour. The earlier static and dynamic linear methods were capable of predicting only the behaviour up to the yielding point and the dynamic nonlinear time history method involves more computational cost. Hence the static nonlinear pushover analysis became a frequently used tool to adequately predict the behaviour of structures under induced seismic demands.

In this study a four storeyedbuilding located within the University of Moratuwa premises was selected. A mathematical model of the structure was developed using SAP2000 (CSI, 2013) and default plastic hinge properties generated based on FEMA356 were assigned to ends of each frame element in order to illustrate nonlinear behaviour of the structure. The capacity curve of the structure obtained under the application of lateral loads was interacted with possible seismic demand curves in the same ADRS plot and the performance levels at different seismic demands were determined using the capacity spectrum method introduced by ATC40.

2. Impacts of Earthquakes

According to the plate tectonics the earth's surface consists of tectonic plates and they move in different directions relative to each other. Basically earthquakes occur as a result of relative movement of tectonic plates and major earthquakes have taken place mostly at the plate boundaries (Day, 2002) (Hosur, 2013). Inter-plate earthquakes could occur within a tectonic plate. During an earthquake the ground can be shaken in any direction and the structures resting on the ground will also be shaken back and forth in any direction. Since the buildings are designed to withstand gravity loads the vertical movement would not be a problem. But horizontal movement of buildings will create large inertia forces within the building (Karunarathne, Hewawitharana, and Karunaratne, 2010). Therefore it is required to enable buildings to withstand those impacts.

The vulnerability of short period structures to undergo more damage is high compared to long period structures due to low natural periods of vibrations, absence of lateral load carrying method, and increased flexibility due to cracking (Karunarathne, Hewawitharana, and Karunaratne, 2010 , Park & Paulay, 1975).Under the application of lateral seismic loads the elements of the RC buildings will undergo elastic-plastic deformations. RC elements exhibit ductile properties in their nonlinear force deformation relationships and it is of significance in building materials because it gives warnings before failure, allows moment redistribution and exhibits post elastic behaviour of a structure (Park & Paulay, 1975).

3. Seismic Evaluation of Buildings

For the evaluation of existing buildings several guidelines and methodologies have been developed which produce a systematic evaluation approach (ATC, 1996) (FEMA, 2000). Although earlier methods of evaluation were based on elastic and linear behaviour of structures, after identifying the deficiencies the nonlinear methods of evaluation were developed. Most of modern methods are performance based evaluations and ATC40 focuseson the use of capacity spectrum method for evaluation.

4. Capacity Spectrum Method

In the capacity spectrum method the global force-displacement capacity curve of the structure and the response spectra of the earthquake demand are plotted in the same spectral acceleration vs. spectral displacement domain.Then a performance point which describes the behaviour of the structure under the specific seismic demand is determined by interacting capacity and demand curves. Finally it is verified whether the performance at that point satisfies the predefined performance objective (ATC, 1996).

A performance objective defines the preferred performance level (maximum allowable destruction state) of the building for a given earthquake ground motion. Most commonly used performance levels (See Figure 1) are operational, immediate occupancy (IO), life safety (LS) and collapse prevention (CP)(ATC, 1996).

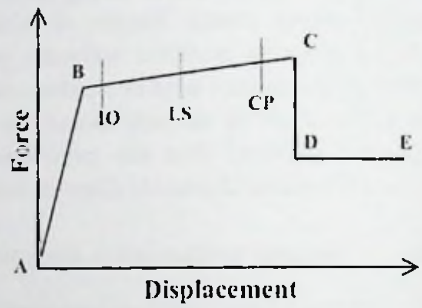

Figure 9: Performance levels

Capacity curve of the structure is a force-displacement relationship which is obtained by applying a pattern of increasing lateral loads to the model of the structure which is modelled representing its nonlinear behaviour. Capacity curve defines the building uniquely and independently of any specific seismic demand. When the building is displaced laterally during an earthquake, its response is illustrated by a point on the capacity curve. Since the global displacement of the structure is related by the deformation of all its members, a selected point on the capacity curve defines a specific damage state for the building.Demand is simply a representation of earthquake ground motion. For a given structure at a given ground motion the displacement demand is an estimate of the maximum expected response of the structure during the considered ground motion.

5. Pushover Analysis

This case study is based on pushover analysis which is a nonlinear static analysis. An elastic analysis is capable of providing a good indication of the elastic capacity and indicating the location of first yielding point. But it is unable to forecast failure mechanisms and will not consider the redistribution of forces during progressive yielding. The actual behaviour will be established by the inelastic analysis procedures by identifying modes of failure and the potential for progressive collapse. Time history analysis is a complicated analysis than the pushover analysis (Gunaratne, 2013).ATC40 also recommends the use of pushover analysis.

Pushover analysis is an incremental static analysis which is used to determine the force-displacement relationship or the capacity curve, in which the total applied shear force and the associated lateral displacement at each increment, for a structure (ATC, 1996). Pushover analysis is performed by applying the gravity loads followed by a monotonically increasing lateral loading along a prescribed direction (CSI, 2013).The structure can be pushed until either the structurecollapses(ATC, 1996) or a pre-determined target displacement (a limit state) is achieved (FEMA, 2000).The pushover analysis may be carried out using force control or deformation control. In the first option, the structure is subjected to an incremental distribution of lateral force, and incremental displacements are calculated. In the second option, the structure is subjected to a deformation profile, and lateral forces needed to generate those displacements are computed. For the displacement control the user specifies the target maximum displacement at a control point (Lakshmanan, 2006).The pushover analysis will function well compared to elastic procedures, if it is applied with caution and care, and with due consideration given to its many limitations. (Krawinkler & Seneviratna, 1998).

Standard pushover analysis is limited to single mode responses thus for symmetrical and low-rise buildings. It becomes misleading when higher modes are involved in cases such as non-symmetrical and high-rise buildings. Advanced pushover methods were developed to overcome that drawback. A research (Tarta & Pintea, 2012) which compared standard and advanced procedures has shown that adaptive pushover methods nearly approximate the inter storey drifts.

6. Case Study

Methodology: A four storeyed reinforced concrete frame structure located within the University of Moratuwa premises was used for the case study. Approximate length, width and height are 32m, 27m and 14m respectively. A three dimensional model of the structure was developed using SAP2000 v15 (See Figure 2). After defining the materials and sectional properties according to as-built details the beams columnswere modelled as frameelements. Slabs were modelled as shell elements to provide actual stiffness.Since their weights were transferred to the beams they were modelled using a weightless concrete material. Then diaphragm constraints were assigned at each floor level. Then plastic hinges were defined using default hinge properties and they were assigned to the ends of the elements since lateral deformation is predominant.

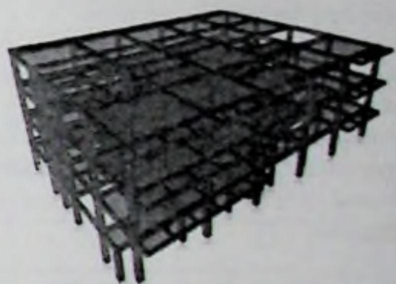

Figure 10: 3D view of the building

Then static load cases were defined and assigned to relevant members. Static load cases were run and a default concrete frame check(according to BS8110:1989) was performed to enable program to automatically determine the concrete hinge properties. Then for each direction nonlinear gravity load cases were defined which are followed by nonlinear pushover load cases. In this case study pushover loads were defined as acceleration loads. Then the nonlinear load cases were run and the results were reviewed.

Validation of the Use of Pushover Analysis:

The modal participating mass ratios of both X and Y directions were considerably high (even more than 75%)as shown in Table 1(showing modes with more than 5% mass participating only). UX and UY are the modal participating mass ratios for the structure in UX and UY degrees of freedom respectively. Sum UX and Sum UY are the cumulative values of them.The dynamic response of the building is dominated by the mode which is having the maximum modal mass participation.The participating mass ratio for a mode measures how important the mode is for computing the response to the acceleration loads in each of the three global directions and (CSI, 2013). Therefore it can be validated that the use of pushover analysis will produce more realistic and accurate results.

Table 4: Modal Participating Mass Ratios of first three modes of the structure

Mode No.	Period	UX	UY	SumUX	SumUY
1	1.013232	0.01544	0.78575	0.01544	0.78575
2	0.922953	0.77314	0.06043	0.78858	0.84618
3	0.85148	0.14102	0.07976	0.92959	0.92594

7. Performance Evaluation

The performance of the building was determined using ATC40 documentation. Capacity was determined using pushover analysis. The demand was determined using both ATC40 document and AS1170.4 (2007). Then the performance was evaluated according to the specified performance objectives.

Performance objective – for demands determined using ATC40: In this case study a dual performance objective was selected. That is an IO performance level at serviceability earthquake and a LS performance level at design earthquake.

Performance objective – for demands determined using AS1170.4 (2007): IO performance level at design earthquake (500 year return period) and a LS performance level at maximum earthquake (2500 year return period).

Capacity: The capacity curves of the building were plotted for both X and Y directions. The maximum capacity of the building in X direction was 6569 kN (see Figure 3) at a displacement of 85 mm. In the Y direction it was 6235 kN at a displacement of 82 mm.

Demand – according to ATC40: In order to determine the seismic demand on the building, seismic coefficients were determined according to the provisions given in ATC40 document. Since Colombo – Sri Lanka is situated in an aseismic zone according to 1997 Uniform Building Code (UBC) 1997 there was no demand. But for this case study in order to represent possible earthquake risk zone 1 and zone 2A (which are the smallest) were selected and demand spectra for serviceability and design earthquake levels were determined. An example of performance point evaluation is illustrated in Figure 4. Seismic coefficients related to those earthquake levels are illustrated in Table 2.C_A and C_V are acceleration coefficient and velocity coefficient respectively.

Table 5: Seismic coefficients for different earthquake demand levels

Seismic zone 1				Seismic zone 2A			
Serviceability Earthquake		Design Earthquake		Serviceability Earthquake		Design Earthquake	
C_A	C_V	C_A	C_V	C_A	C_V	C_A	C_V
0.06	0.09	0.12	0.18	0.12	0.18	0.22	0.33

Table 6: Performance levels under seismic demands derived from ATC40

	Serviceability Earthquake				Design Earthquake			
	Zone 1		Zone 2A		Zone 1		Zone 2A	
Direction	X	Y	X	Y	X	Y	X	Y
Base shear	3211 kN	3019 kN	5455 kN	4901 kN	5455 kN	4901 kN	6441 kN	6197 kN
Roof displacement	23mm	24mm	45mm	45mm	45mm	45mm	75mm	77mm
Max. Inter-storey drift ratio	0.30%	0.33%	0.58%	0.61%	0.58%	0.61%	1.24%	1.19%
Global performance	IO	IO	IO	IO	IO	IO	LS	LS

Status of plastic hinges	All are IO	All are IO	All are IO	All are IO	All are IO	All are IO	17 are LS	16 are LS
Element performance	IO	IO	IO	IO	IO	IO	LS	LS

Demand – Using AS1170.4 (2007) : Since the earthquake demands derived from ATC are not much representative for Sri Lankan conditions,seismic demand was also derived using AS1170.4 (2007). This code was selected since Sri Lanka and Australia lie on the same (Indo-Australian) tectonic plate. Two functions were defined to represent the Design and Maximum earthquake levels. The site subsoil class was selected as 'C'. Since the use of 0.12g peak ground acceleration for Sri Lankan conditions is rationalized by some researchers (Jayasinghe, Hettiarachchi, & Gunawardena, 2012) it was used in this case study also.Design earthquake: 10% probability of occurrence in 50 years – 500 year return period; Maximum Earthquake: 2% probability of occurrence in 50 years – 2500 year return period

Table 7: Performance levels under seismic demands derived from AS1170.4 (2007)

	Design Earthquake		Maximum Earthquake	
	X direction	Y direction	X direction	Y direction
Base shear	2187 kN	2001 kN	3639 kN	3421 kN
Roof displacement	15mm	16mm	27mm	28mm
Max. Inter-storey drift ratio	0.19%	0.20%	0.33%	0.39%
Global performance	IO	IO	IO	IO
Status of plastic hinges	All are IO	All are IO	All are IO	All are IO
Element performance	IO	IO	IO	IO

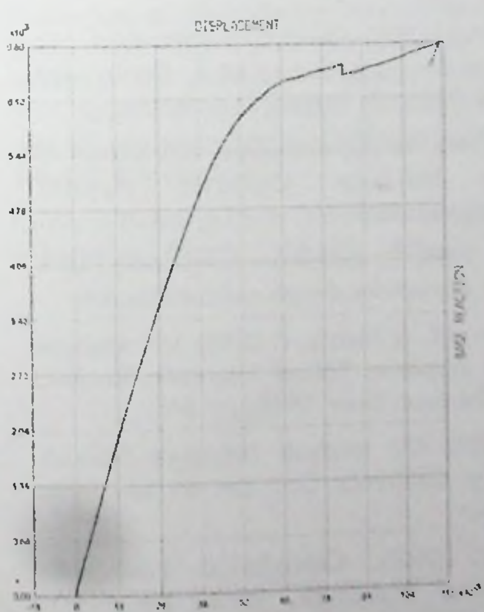

Figure 11: Capacity curve in X direction

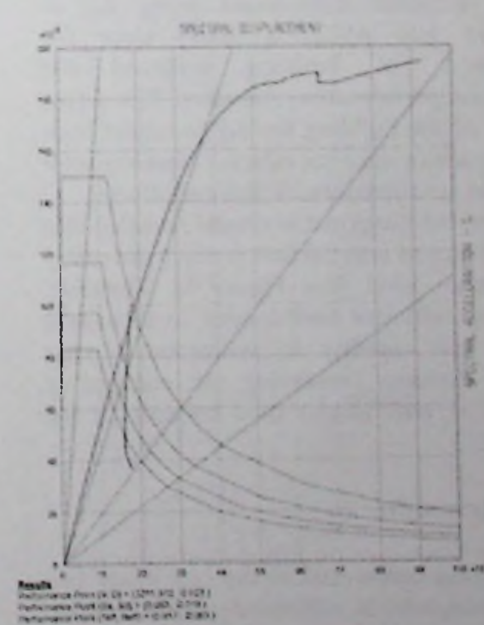

Figure 12: Performance point for serviceability earthquake (zone 1) – X direction

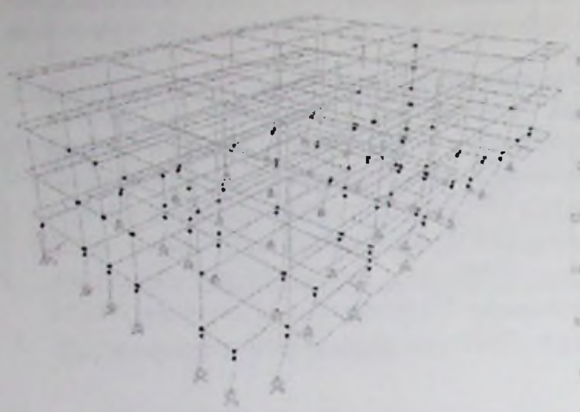

Figure 13: Hinge Formation at design Earthquake (Zone 2A) – X direction

8. Discussion on Results

The results show that the building has similar capacities in both directions. Approximately similar plan dimensions in X and Y directions,square type columns, most beamshave similar sections and similar grid spacing in both directions would also be reasons for that. Resulted performance levels under seismic demands derived from ATC40 and derived from AS1170.4 (2007) are shown in Table 3 and Table 4 respectively.

When the results are reviewed it can be seen that the performance of the building is satisfactory in both X and Y directions for all seismic demands determined using ATC40 document and AS1170.4 (2007) since the performance of building achieved the established performance objectives. The actual capacity of the building would be higher than these capacities since the effect of masonry infill walls was not considered in this case study.
Review of the hinge status results revealed that a set of columns was the first to reach life safety performance level (See Figure 5). Therefore providing sufficient confinement to them will enhance the capacity to withstand a very extreme demand preventing the collapse of columns as well as the total collapse of the building.

9. Conclusion

The building considered in the case study has adequate capacity to withstand possible seismic hazards. Although a building is situated in an area that is seismically inactive, it is worthwhile to evaluate them under possible seismic load in order to reduce the risk by reducing vulnerability.

Since a set of columns in the ground floor first reaches LS level it is highly recommended to retrofit those by increasing the confinement. It is always safer to design buildings according to strong column - weak beam method.

Although pushover analysis was used in this case study to evaluate an existing building this can be used to get an idea of a building at the design stage. It will be helpful for designer to identify the failure mechanisms of the building. Since this can be used for identification of critical points on a structure an optimum design can be obtained by strengthening only the critical locations.

Abbreviations

ADRS - Acceleration Displacement Response Spectra
ATC - Applied Technology Council
CP – Collapse Prevention
FEMA – Federal Emergency Management Agency
IO – Immediate Occupancy
LS – Life Safety
PBD- Performance Based Design
RC - Reinforced Concrete

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