Application of Pushover Analysis for Evaluating Seismic Performance of RC Building

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Abstract

Current research works indicated that parts of Kingdom of Saudi Arabia have low to moderate seismic regions. For structural engineers, seismic load should be considered as important aspect that needs to be included in the building design. However Major part of buildings are designed for gravity loading only and poorly detailed to accommodate lateral loads. The purpose of this paper is to investigated gravity supporting building its resistance to expected seismic loading in different regions (Makkah, Jeddah, Gizan and Haql). A test RC building that was designed for gravity loading only is investigated. This will be accomplished by performing the nonlinear static analysis (pushover analysis) according to ATC 40. Pushover analysis produces the pushover curves, capacity spectrum, plastic hinges and performance level of the building. This analysis gives better understanding seismic performance of buildings and also traces the progression of damage or failure. The building performance level is determined by intersection of demand and capacity curves and the hinge developed in the beams and the columns. The results show that the test building is found inadequate for Haql region and it still can be considered for Makkah, Jeddah and Gizan.

***Keywords*— seismic analysis; pushover; ATC 40; seismic zone; capacity spectrum**

1. Introduction

The Kingdom of Saudi Arabia lies within low to moderate seismic region. Seismic load should be considered as important aspect that needs to be included in the building design. In the past decades, the inclusion of dynamic loads in the design of building in Saudi Arabia was very much limited to important huge structures. Recently, the development and adoption of a national code and the experienced seismic activity at several regions in the Kingdom necessitate the detailed consideration of seismic loads in the design of all buildings. Major part of building industry are designed for gravity loading only and poorly detailed to accommodate lateral loads. The existing buildings have to be provided by some rehabilitation to sustain the expected performance level. The capacity of the building should be evaluated before rehabilitation work [4].

It is generally believe that the conventional elastic design analysis method cannot capture many important aspects that control the seismic performance of the building. The capacity of building to undergo inelastic deformations governs the structural behaviour of building during seismic ground motions. For that reason, the evaluation of building should consider the inelastic deformation demanded due to seismic loading. On the other hand, linear elastic analysis does not provide information about real strength, ductility and energy dissipation in the structure [5].

Nonlinear dynamic analysis is principally convenient approach. However, it is very complex and not practical for every design. It needs time history of ground motion data and detailed hysteretic behaviour of structural members which cannot be predicted. This analysis is appropriate for research work and for design of important structures [11].

To estimate seismic demands for building, the structural engineering profession is now using the non-linear static procedure, known as pushover analysis. It is a commonly used technique, which provides acceptable results. The term static implies that a static analysis is applied to represent a dynamic phenomenon [6].

2. Pushover Analysis

Pushover analysis is a series of incremental static analysis carried out to develop a capacity curve for the building. Figure 1 illustrates pushover analysis. This procedure needs the execution of a nonlinear static analysis of structure that allows monitoring progressive yielding of the structure component. The building is subjected to a lateral load. The load magnitude increases until the building reaches target displacement. This target displacement is determined to represent the top displacement when the building is subjected to design level ground excitation.

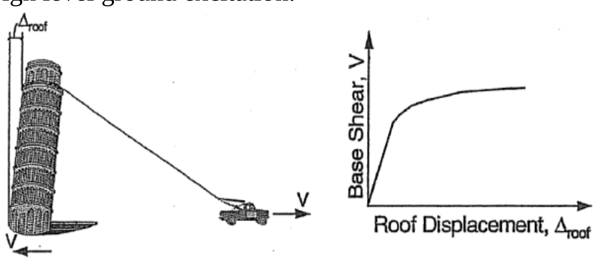

Figure 1 Illustration of Pushover Analysis [ATC 40]

Pushover analysis produces pushover curve or capacity curve that presents relationship between base shear (V) and roof displacement (Δ). The Pushover curve depends on strength and deformation capacities of the structure and describes how the structure behaves beyond the elastic limit.

Structural response to ground motion during earthquake cannot be accurately predicted due to the complexity of the structural properties and ground motion parameters. In pushover analysis, a set of lateral displacement is used directly as design condition. The displacement is an estimate of the maximum expected response of the structure during ground motion.

Once pushover analysis is defined, the performance level can be determined using demand displacement. The performance verifies that the structure is adequate the acceptable limits of performance level.

Recently, there are some codes such as ATC-40, FEMA 256, FEMA 440 adopted standards and guidance provisions regarding the assessment of existing structures. Some programs are also developed for pushover analysis such as SAP2000, ETABS, and DRAIN-2DX.

2.1. Capacity Spectrum

Building performance level can be determined by target displacement using capacity spectrum method (ATC 40). The capacity spectrum method allows for a graphical comparison between the structure capacity and the seismic demand. Pushover curve represents the lateral resisting capacity and response spectrum curve represents the seismic demand.

The capacity spectrum method, which is given in figure 2, is started by producing force-displacement curve that consider inelastic condition. The result is then plotted to ADRS (Acceleration Displacement Response Spectrum). Demand is also converted into ADRS format so that capacity curve and demand curve are in the same format [1].

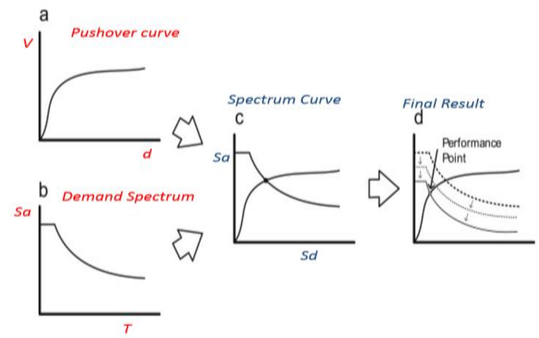

Figure 2 Capacity Spectrum Method

The performance point is obtained by superimposing demand spectrum on capacity curve into spectral coordinate or ADRS format. The capacity spectrum method has been built in SAP2000 program.

Performance levels of buildings are shown in table I.

TABLE I
PERFORMANCE LEVEL OF BUILDING

Level	Description
Operational	Very light damage, no permanent drift, structure retains original strength and stiffness, all systems are normal
Immediate Occupancy	Light damage, no permanent drift, structure retains original strength and stiffness, elevator can be restarted, Fire protection operable
Life Safety	Moderate damage, some permanent drift, some residual strength and stiffness left in all stories, damage to partition, building may be beyond economical repair
Collapse Prevention	Severe damage, large displacement, little residual stiffness and strength but loading bearing column and wall function, building is near collapse

2.2. Nonlinear Plastic Hinge

Pushover Analysis requires the development of the force-deformation curve for the critical section of beams and column by using the guideline [3]. Such a curve is presented in figure 3.

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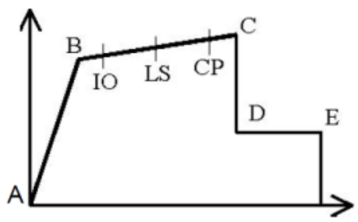

Figure 3 Typical load-deformation relation

Point A corresponds to the unloaded condition. Load deformation relation shall be described by linear response from A to an effective yield B. Then the stiffness reduce from point B to C. Point C has resistance equal to the nominal strength then sudden reduction in lateral load resistance to point D, the response at reduced resistance to E, final loss of resistance thereafter. The slope of line BC, ignoring effects of gravity effects of gravity loads acting through lateral displacement, is usually taken between 0 and 10% of the initial slope. Line CD corresponds to initial failure of the member. Line DE represents the residual strength of the member.

These points are specified according to FEMA to determine hinge rotation behaviour of RC members. The points between B and C represent acceptance criteria for the hinge, which is Immediate Occupancy (IO), LS (Life Safety), and CP (Collapse Prevention).

3. Description of Building

The test building is a 3-story reinforced concrete building, with height story 4.0 m. The overall plan dimension is 21 x 15 square meters. Figure 4 shows the typical structural layout. Beam 1 is 700/400 and Beam 2 is 500/300 mm square for all stories. The columns are rectangular 500/300 mm. Type of soil is soft rock or site class C according to Saudi Building Code 301.

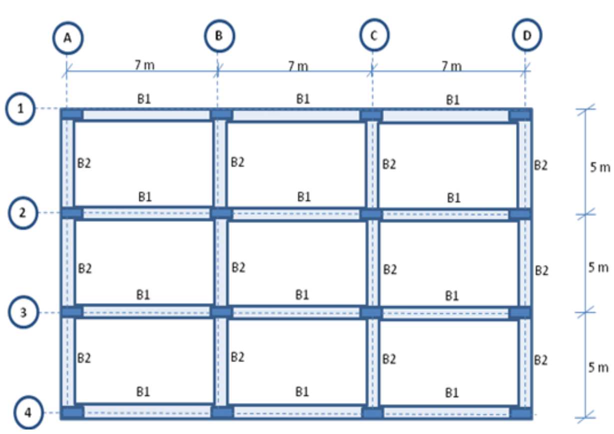

Figure 4 Structural Layout

The structural system was designed for supporting gravity load only. Longitudinal bar in beams are bent upwards at their end to resist negative moment due to gravity load. Strong lateral load can change the moment at the end span of the beam. Therefore, the bottom steel at end of the beam may be not adequate for lateral load.

Summary of modelling assumption is presented in table II.

TABLE II
MODELLING ASSUMPTION

Material	
Concrete	4000psi
Steel	A615Gr60
Loading	
Self-weight	Automatically by Software
Dead load	2.7 kN/m^2
Live Load	2.5 kN/m^2
Wind Load	Not Considered
Modelling	
Element	Linear element for beam and column; Shell element for slab
P-delta effect	Not considered
Diaphragm	Shell element for slab
Support	Fixed

4. Analytical Model

In the present paper, Pushover analysis is carried out using SAP2000 program. A three dimensional model of structure has been created as shown in figure 5.

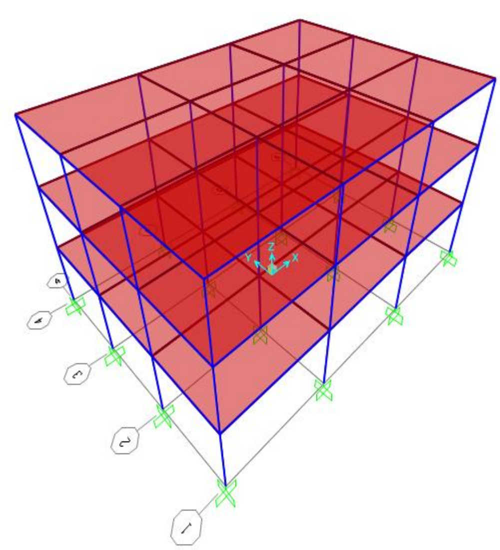

Figure 5 3D Model (SAP2000)

Beams and columns are modelled as nonlinear frame element at the start and the end of element. The FEMA

356 rule, which is built in SAP 2000 with the IO, LS, and CP limit states for hinge rotation have been used for the acceptance criteria.

The pushover analysis is executed separately for two orthogonal directions to study the performance of the building in both directions. Gravity push, which is applied for gravity load only, Push-X is the lateral push for X direction starting at the end of gravity push, Push-Y is for Y direction starting at the end of gravity push.

The pushover analysis is achieved using a displacement control strategy, where the building is subjected the lateral load pattern until the roof displacement reach a target value. The minimum number of state used is 10 and the maximum is 100.

Pushover analysis is performed in four different regions in KSA (Makkah, Jeddah, Gizan, and Haql). Parameters Ca and Cv are taken from Saudi Building Code 301 to construct response spectrum curve as shown in figure 6.

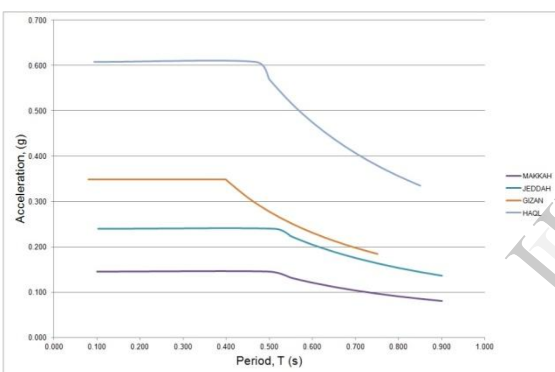

Figure 6 Response Spectrum Curve for Each Region

5. Results of Analysis

Pushover curves for the building for X and Y direction are presented in figure 7. These curves represent the global behavior of the frame in terms of stiffness and ductility. Under incrementally increasing lateral load, the structural element may be yield sequentially. At every step, the structure experience loss in stiffness. Therefore, slope of pushover curve gradually is decreasing.

The comparison of pushover curve in X and Y direction shows that the stiffness of frame is more in X direction as compared to Y direction. This is explained that Y-direction is the critical point.

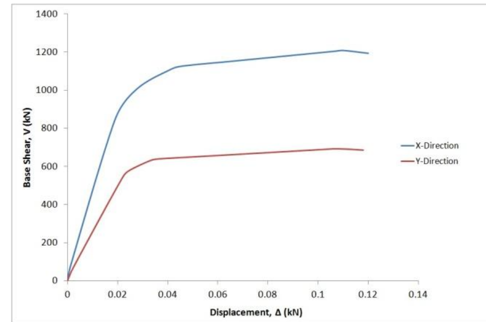

Figure 7 Pushover Curve

The performance point has been obtained by superimposing demand spectrum on capacity curve into spectral coordinate. Figure 8 shows capacity spectrum for Gizan region in X direction. It is obvious that the demand curve tend to intersect the capacity curve at the performance point. For Gizan, It can be concluded that there are sufficient strength and displacement reserves at this performance point.

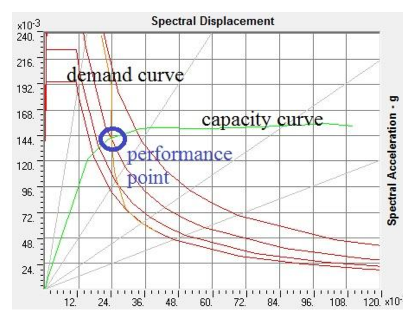

Figure. 8 Capacity Spectrum

Table III summarizes the performance point of the structure for each region.

TABLE III
PERFORMANCE POINT FOR EACH REGION

	X-Direction			Y-Direction		
	V	d	step	V	d	step
Mekkah	675.10	0.015	2	518.84	0.021	2
Jeddah	966.48	0.026	3	633.63	0.034	5
Gizan	1014.27	0.029	4	641.26	0.039	6
Haql	1155.06	0.069	7	691.31	0.110	9

At every deformation step of pushover analysis determine plastic rotation hinge location in the elements and which hinges reach the FEMA limit state, which are IO, LS, and CP using colours for identification.

Plastic hinges formation have been obtained at different displacement levels or performance points. The hinging patterns for each region are plotted in figure 9 and 10.

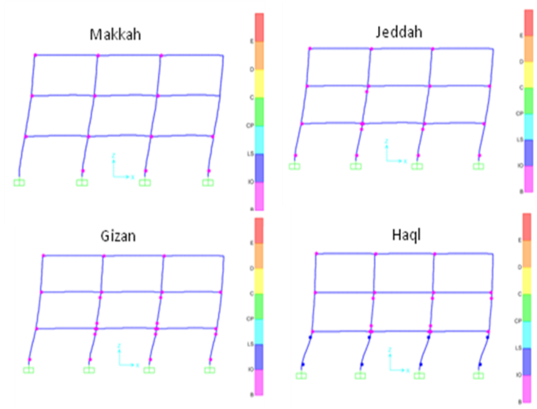

Figure 9 Plastic hinge distribution (X-direction)

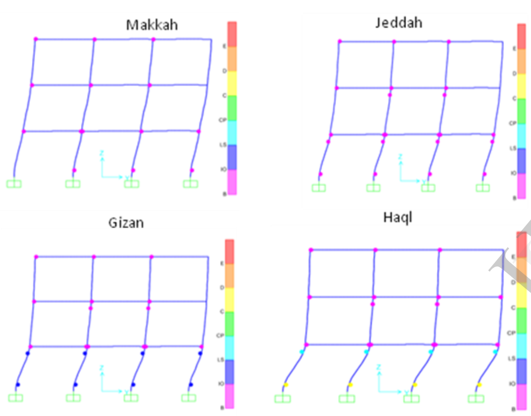

Figure 10 Plastic hinge distribution (Y-direction)

Makkah

The element response is still not dangerous at this performance point. Yield occurs in some elements but none of them exceeds IO (Immediate Occupancy) level. The outer columns still behave in elastic range.

Jeddah

Most of elements are in yield condition. The damage of the building is still limited both in X and Y direction since yielding occurs at event B (yielding) to IO (Immediate Occupancy).

Gizan

Although the element response is generally adequate at this performance point, the response is more severe in Y-direction. The yielding at the lower column occurs at event IO (Immediate Occupancy) to LS (Life Safety).

Haql

For X direction, the building is still adequate due to yielding occurs at even B to IO. However, the building is not adequate for Y direction due to the lower columns yield exceed C (Collapse) condition.

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6. Conclusion

The test building is investigated using pushover analysis. These are conclusion obtained from this analysis:

1. Pushover analysis is a simple way to investigate nonlinear behavior of the building. The result obtained gave an understanding into nonlinear behavior, which is real behavior of structure.
2. Pushover analysis is approximation method and based on static loading. It may not accurately represent dynamic phenomena.
3. The performance level of structure is indicated by intersection of demand and capacity curves and the hinges developed in the beams and the columns.
4. The results show the building that was designed only for gravity load is found inadequate for Haql region. However, the building still can be considered for Makkah, Jeddah and Gizan.
5. Pushover analysis can identify weak elements by predicting failure mechanism and account for redistribution of forces during progressive yielding. It may help engineers make action for rehabilitation work.

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