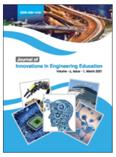

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# Higher mode effects on capacity curves

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Abstract

The effects of higher modes on the capacity curves and their effects on the formation of plastic hinges are studied herein for regular reinforced concrete structure without any weak or soft story having time period typically less than 1 sec. The theoretical validity of modal pushover analysis is explained with respect to elastic and inelastic systems. In this modal pushover analysis (MPA), the seismic demand due to individual terms in the modal expansion of the effective earthquake forces is determined by a pushover analysis using the inertia force distribution for each mode. The higher mode pushover curves show significant increase in base shear as well as significant decrease in roof displacement that are not detected by the first mode which is a part of FEMA-356 force distributions. To determine the difference of seismic response parameter at concerned point, local performance levels are used rather than global performance level for better accuracy. Fiber plastic hinges model is used instead of conventional lumped plastic hinge where stress-strain curves is directly applied for confined concrete to inner core concrete and unconfined stress- strain to outer concrete. Base Shear of Capacity Curve at IO performance level, inelastic beam component with compressive stress at 0.002 and 0.0038 increased by 14.52%, 10.825%, and 10.42% respectively. Displacement Demand of Capacity Curve at IO performance level, inelastic beam component with compressive stress at 0.002 and 0.0038 decreased by 15.84%, 15.94% and 12.86%. It is seen that up to 3rd mode is crucial and should be combined in regular structure and up to 8th mode should be combined in irregular structure.



## 1. Introduction

Most of the retrofit design practice in Nepal is beached on forced based strategy rather than demand-based design resulting in overstrength of structure and costlier as determination of deficiency of components are overlooked. In order to conduct and simplify demand-based analysis, various approaches have been derived in global context, among which Pushover Analysis [1] is considered in this paper.

The general objective of this paper is to determine the effect of higher mode on the capacity curve for low/ medium-rise building with the varying time period (decreasing stiffness, increasing story for regular/irregular building with no soft/weak story) and interpretation of plastic hinges formation mechanism. The specific objectives were to calculate a coefficient for varying time period of structure for fixed seismic hazard level imposed by modal pushover analysis [2], and interpretation of local plastic hinge mechanism for higher modes with time period variation. It will provide a somewhat greater approximation of seismic demand due to the inclusion of higher modes than fundamental pushover capacity curve analysis and design will be efficient if modal pushover is done.

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## 2. Methodology

The research was carried on the ground of positivist paradigm where modelling was done to study the capacity curve of the moment resisting frame and compare the base shear and roof displacement at different performance levels [3, 4, 5, 6, 7, 8, 9, 10, 11], concerned with characteristics of RC building, strategy for the reinforced concrete building, and analysis technique of buildings were reviewed . The buildings selected for the analysis are prevailing reinforced concrete structures taken as an arbitrary representation of prevailing reinforced concrete building of Nepal. To represent the true picture of the building for the modeling and analysis, the properties of the concrete. rebar units and mortar should be obtained from the experimental results. For this research work, the property was taken from standard data IS 875 part 1 and part 2. The simulation model of the RC building was prepared in finite element modeling using Sap2000 and Perform 3D software version 21 and 7 respectively with measured geometry and material properties, using the frame by the macro-elements (FME) method.

## 3. Numerical model

### 3.1. Building details

The building considered is not a specific and typical type, but considered in a general way so that the main scope of the thesis can be preserved. Thus, the detail plan and elevation of the selected building is not presented here, but the modeling in Sap 2000 is presented for each of regular and irregular building. The analysis model for each building is shown below.

### 3.2. Loads and seismic weight

In addition to the self-weight of the members, the imposed load of intensity 1.5 kN/m$^2$ was applied on each floor slab. Live loads were taken to be 3 kN/m$^2$ for all other floors except for the staircase and balconies for which 4 kN/m$^2$ were taken. Live loads for the roof were taken as 1.5 kN/m$^2$ if accessible and 0.75 kN/m$^2$ if not accessible. Building parameters are given in Table 1.

### 3.3. Assumptions

i Only the response spectrum method as per IS 1893:2002 is used for design.

ii The foundation is assumed to be a rigid foundation.

iii Only regular buildings are considered for the study.

iv Floor slabs are assumed to be rigid in their own plane.

### 3.4. Concrete properties

| | | |
|---|---|---|
| Grade | : | M20 |
| Modulus of elasticity | : | 22360 MPa |
| Poisson's ratio | : | 0.2 |
| Unit Weight | : | 25kN/m$^3$ |

### 3.5. Reinforcement bar properties

| | | |
|---|---|---|
| Grade of reinforcing steel | : | HYSD500 for longitudinal bars and HYSD 415 for hoops or stirrups |
| Modulus of elasticity | : | 200000 MPa |
| Poisson's ratio | : | 0.3 |
| Unit Weight | : | 7850 kg/m$^3$ |

Table 1: Building parameters

| No. of bays | Regular | Irregular |
|---|---|---|
| In X-direction | 3 | 4 |
| In Y-direction | 3 | 4 |
| Shape | Rectangular | L-shaped |
| No. of storeys | 3 | 4 |
| Story height | 3.0 m | 3.2 m |
| Column Size | 400×400 mm | 400×400 mm |
| | 450×450 mm | 450×450 mm |
| Beam Size | 250X400 mm | 250×350 mm |
| | 300×400 mm | 250×400 mm |
| | 350×450 mm | 250×400 mm |
| Secondary Beam | 250×300 mm | 250×300 mm |
| Slab Thickness | 150 mm | 150 mm |

All corner columns are of 400 mm and other interior columns of 450 mm size. The regular and irregular type of model buildings are shown in Figure 1 and 2.

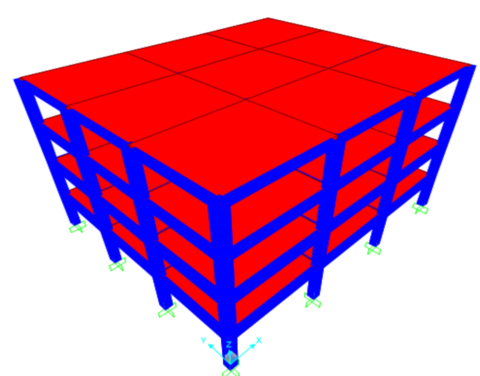

Figure 1: Regular building model

### 3.6. Load combination

For the design of the building models, the following load combinations are taken [12, 13]: 1.5(DL+LL), 1.2(DL+LL+EL), 1.2(DL+LL-EL), 1.5(DL+EL), 1.5(DL-EL), 0.9DL+1.5EL, 0.9DL-1.5EL

Where,

DL : Dead load

LL : Superimposed live load

EL : lateral seismic forces (either EQX or EQY)

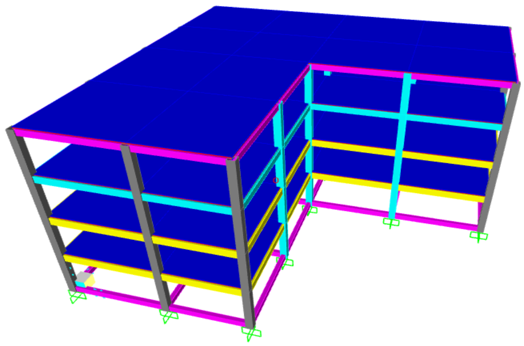

Figure 2: Irregular building model

### 3.7. Seismic weight

In this study, 25% of the live load was considered to be included in the seismic weight along with the dead load.

### 3.8. Design of buildings

The frame buildings were designed according to the Indian Standards using the response spectrum method. The seismic zone considered as Zone V with zone factor (Z) = 0.36. The importance factor (I) was taken to be 1.0 and the soil type has taken was medium soil. The Response Reduction Factor(R) was taken to be 5 considering RC building with a special moment-resisting frame.

## 4. Analysis

### 4.1. Non-linear static analysis

Static pushover analysis is becoming a widespread tool to perform the seismic assessment of both existing and new structures since provides adequate information on seismic demands imposed by the design ground motion on the structural system, where "Static" means that the force is applied to the structure statically and "non-linear", the behavioral model used for the structure resistance elements. As seismic design code requirements are a relatively recent matter and once, they have been constantly upgraded over the years, as well as the engineering knowledge, buildings can become seismically unsafe.

The purpose of pushover analysis is to evaluate the expected performance of structural systems by estimating the performance of a structural system by estimating its strength and deformation demands in design earthquakes by means of static inelastic analysis and comparing these demands to available capacities at the performance levels of interest.

## 5. Result and discussion

This study is carried out to determine the effects of higher modes on pushover analysis i.e. Nonlinear Static Analysis, in terms of system seismic parameters like base shear and roof drift (or roof displacement). Two types of structures are considered for the analysis, one is a regular RC building with respect to stiffness, vertical, horizontal mass regularity; and another is an irregular L-shaped RC building which is unsymmetrical in stiffness in both x-, y-direction but vertical symmetry in mass is maintained.

### 5.1. Regular and symmetrical building in pushover direction

The output of the pushover analysis i.e, capacity curve generated in PERFORM 3D is in terms of Base Shear vs Roof Drift, which is further synthesized and converted into Base Shear vs Roof Displacement. The capacity curve containing up to $3^{rd}$ mode in the x-direction is shown in Figure 3.

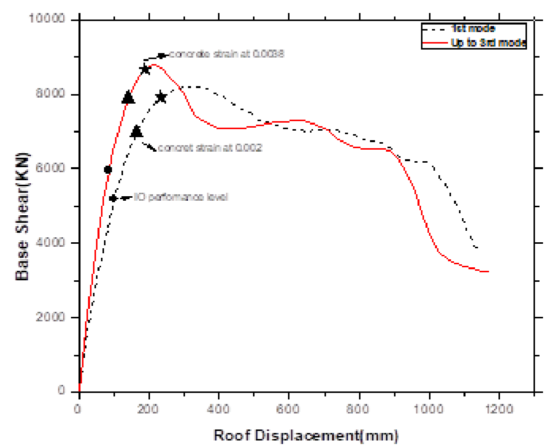


Figure 3: Capacity curve containing modes up to 3rd mode for regular structure

From Figure 3, it can be seen that the initial slope of both curves-$1^{st}$ mode and up to $3^{rd}$ mode- is the same for very low roof displacement, then the curve for 3rd modes becomes steeper than that for $1^{st}$ mode. Also, the base shear is found to be greater at shown performance levels. The ductility of structure for higher modes is also seen to decrease than that of fundamental modes. In the range of 400 to 850 mm of roof displacement range, it is seen that both curves are almost identical but randomness is prone.

The capacity curves generated runs full up to the collapse of the structure, up to 20 percent of the initial capacity. This is due to the fact that, although all the inelastic regions become plastic, the structure may able to sustain gravity load. This property is insured directly by imposing the condition in stress and strain curve of fiber hinges.

To examine the effects of higher modes different performance levels are considered. Since the plastic zone is modeled through fiber hinge modeling, it is wise to consider the limiting condition in terms of strain value rather than plastic rotation which is a conventional way to assign performance level. Also, the plastic rotation criteria as mentioned in ASCE [14], is for a generalized section based on rectangular stress-strain block, but here actual stress block is considered. Thus, the conventional plastic rotation criteria are not applicable here.

Table 2: Numerical results of regular building

| Odes | Base | Roof |
|---|---|---|
| **IO performance level** | | |
| $1^{st}$ mode only | 5193 | 101.232 |
| Up to $3^{rd}$ mode | 5947 | 85.188 |
| **Compressive strain at 0.002** | | |
| 1st mode only | 6965 | 162.96 |
| Up to $3^{rd}$ mode | 7719 | 137.04 |
| **Compressive strain at 0.0038** | | |
| 1st mode only | 7912 | 239.52 |
| Up to $3^{rd}$ mode | 8737 | 208.68 |

As [2] states that if the structure is regular and having a time period up to 1 sec, only fundamental modes should be used for Pushover analysis. Although The building used has a fundamental period of 0.67 sec (extracted from PERFORM 3D), which is typically less than 1 sec, also the structure is regular in all aspect i.e. stiffness and geometry, from table 2 it is obvious to consider higher modes as the difference in the seismic parameter is not trivial. It is found that base shear is increased by 14.52%, 10.825%, and 10.42%, and displacement demand is decreased by 15.84%, 15.94% and 12.86% for Immediate Occupancy (IO) performance level, beam inelastic fiber component compressive stress at 0.002 and that at 0.0038 respectively. The base shear of the capacity curve up to 3rd mode is increasing at a decreasing rate while displacement demand is decreasing without any pattern with respect to that of the first mode. Since the criteria for component performance level is ideal and generalized for all types of similar components, the focus is given in actual parameter- strain, rather than using standard rotation for the component.

From Table 3, the ultimate deformation ductility in terms of displacement for the capacity curve of the first mode and up to the third mode is 14.06% and 12.664% respectively. Thus, ultimate ductility in displacement term of capacity curves up to third mode decrease by 10% with respect to that of the first mode. The seismic energy dissipated during pushover for fundamental mode and up to 3rd mode is given in Table 3

Table 3: Energy equivalence of capacity curves

| Modes considered | Energy Dissipated (kN-mm) |
|---|---|
| $1^{st}$ mode only | 7473356.1413 |
| Up to $3^{rd}$ mode | 7392109.4531 |

From Table 3, it is clear that the energy released due to the merger of three modes is 1.08% lesser than that due to the first mode only. Lesser energy stored means lesser potential energy, thus, the structure may follow the path of the 3rd mode curve during pushover analysis.

## 5.2. Irregular and unsymmetrical building in pushover direction

Like the regular and symmetric building, pushover analysis in the x-direction is done for irregular and unsymmetrical building of L-shaped. The capacity curve up to $8^{th}$ mode is considered, but shown here only prominent one – $1^{st}$ mode, $5^{th}$ mode, and $8^{th}$ mode- to make eloquent understanding.

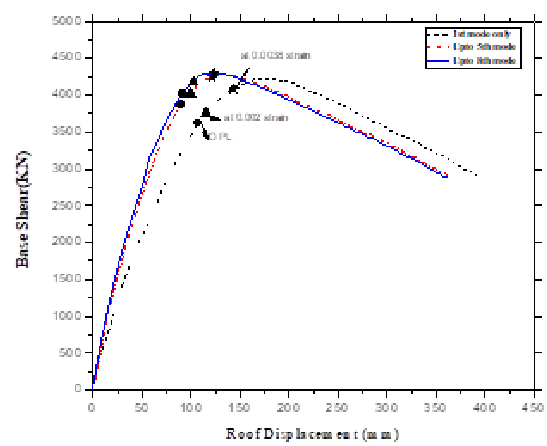


Figure 4: Capacity curves for irregular and usymmetrical building

From Figure 4, it can be seen that the effects of higher modes are prominent from initially and growing continuously up to the roof displacement corresponding to the highest base shear resisted, and after that almost constant difference with fundamental mode capacity curve occurred. The tabular form of above Figure 4 can be represented as in Table 4,

From Table 5, it is obvious to consider higher modes as the difference in the seismic parameter is not trivial. It is found that base shear is increased by 7.74%, 6.674%, and 4.09%, and displacement demand is decreased by 15.02%, 13.87%, and 15.06% for Immediate Occupancy

Table 4: Numerical result of capacity curves for irregular and unsymmetrical building

| Modes | Base | Roof |
|---|---|---|
| **IO performance level** | | |
| 1st mode only | 3588 | 106.3108 |
| Up to $5^{th}$ mode | 3866 | 90.1458 |
| Up to $8^{th}$ mode | 4018 | 91.378 |
| **Compressive strain at 0.002** | | |
| 1st mode only | 3763 | 115.0948 |
| Up to $5^{th}$ mode | 4018 | 99.125 |
| Up to $8^{th}$ mode | 4175 | 102.3824 |
| **Compressive strain at 0.0038** | | |
| 1st mode only | 4079 | 143.594 |
| Up to $5^{th}$ mode | 4246 | 121.9634 |
| Up to $8^{th}$ mode | 4298 | 123.784 |

performance level, beam inelastic fiber component compressive stress at 0.002 and that at 0.0038 respectively of capacity curve containing modes up to $5^{th}$ mode. Similarly, base shear is increased by 11.98%, 10.94%, and 5.36%, and displacement demand is decreased by 14.046%, 11.045%, and 13.79% for Immediate Occupancy performance level, beam inelastic fiber component compressive stress at 0.002 and that at 0.0038 respectively of capacity curve containing modes up to $8^{th}$ mode. The base shear of the capacity curve up to $8^{th}$ mode is increasing at a decreasing rate while displacement demand is decreasing without any pattern with respect to that of the first mode. The displacement demand of $8^{th}$ mode with respect to $5^{th}$ mode is found slightly decreased, this probably is due to the interaction of force at translation DOFs with rotation DOFs Since the criteria for component performance level is ideal and generalized for all type of similar component, the focus is given in actual parameter- strain, rather than using standard rotation for the component.

From Figure 4, the ultimate deformation ductility of the capacity curve of $5^{th}$ mode and $8^{th}$ is 6.54% and 7.74% respectively lesser than that of the fundamental mode. The seismic energy dissipated during pushover for fundamental mode and up to $3^{rd}$ mode is given in Table 5.

Table 5: Energy equivalence for irregular and unsymmetrical building

| Modes considered | Energy Dissipated (kN-mm) |
|---|---|
| 1st mode only | 1290633.509 |
| Up to $5^{th}$ mode | 1239123.669 |
| Up to $8^{th}$ mode | 1230518.209 |

From Table 5, it is clear that the energy released due to the merger of the first five modes and the first eight modes is 4% and 4.06% lesser than that due to the first fundamental mode only. Lesser energy stored means lesser potential energy, thus, the structure may follow the path of higher modes curve during pushover analysis.

Also, the analysis clearly shows that the effect of higher mode causes a decrease in deformation demand but an increase in effective base shear which is in agreement with [5] literature and concept-wise as the different author suggests. Also, the effects of higher modes force distribution considerably differ from that of FEMA 273 [15] distribution which causes a significant change in seismic parameters.

## 6. Conclution

i Base Shear of Capacity Curve at IO performance level, inelastic beam component with compressive stress at 0.002 and 0.0038 is increased by 14.52%, 10.825%, and 10.42% respectively if the effect of higher mode i.e. up to $3^{rd}$ mode for regular of time period of 0.67 sec and 7.74%, 6.674%, and 4.09% respectively up to $8^{th}$ mode for an irregular building of time period of 0.65 sec. Is also noticeable even if the structure has not any weak/soft story and even if the structure is regular and well below than a time period of 1 sec.

ii Displacement Demand of Capacity Curve at IO performance level, inelastic beam component with compressive stress at 0.002 and 0.0038 is decreased by 15.84%, 15. 94% and 12.86% if the effect of higher mode i.e. up to $3^{rd}$ mode for a regular structure of time period 067 sec and by 15.02%, 13.87%, and 15.06% up to $8^{th}$ mode for irregular building of time period 0.65 sec. Is also noticeable even if the structure has not any weak/soft story and even if the structure is regular and well below than a time period of 1 sec.

iii It is seen that up to $3^{rd}$ mode is crucial and should be amalgamate in regular structure and up to $8^{th}$ mode should be amalgamate in irregular structure.

iv Fiber hinge modeling is found to be accurate than conventional lumped plastic rotation plastic hinge modeling. Stress-strain models are justifiable for the nonlinear analysis since even if the plastic hinge collapse the component may be able to endure gravity loads.

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