MODAL PUSHOVER ANALYSIS OF RC FRAME BUILDING WITH STAIRCASE AND ELEVATOR CORE

P. Sharma¹ and K. Dasgupta²

ABSTRACT

In multi-storied buildings, presence of staircase and elevator core wall causes a localized increase of lateral stiffness of the overall system. This causes a significant change in the center of stiffness at floor level along both the directions, leading to asymmetric behaviour. Due to this, structural members are subjected to possible torsional effects during strong earthquake shaking.

In the present study, a five-storied RC frame building with asymmetric plan is considered. Four different structural models are created with varying location of staircase and elevator core across the plan of the building. In all the stories, except the foundation storey, unreinforced brick masonry walls are also modeled using diagonal strut elements along the periphery of the building model. The building is considered to be located on rocky stratum, so the translational and rotational degrees of freedom are restrained at the bottom level. The elevator core wall is modeled as layered shell element with nonlinear material properties.

Lumped flexural and shear hinges are assigned to the frame members. The models are subjected to Modal Pushover Analysis (MPA), i.e., displacement-controlled pushover analysis under different mode shapes, to compare the seismic demands with respect to the position of staircase and elevator core. The results of the first three modes were found to be accurate enough to represent the seismic demand of the building. It was also observed that inclusion of response in the second mode (150-200% increase in base shear) is essential in MPA to improve the seismic demand prediction. This is due to the severe concentration of forces around the stiff elevator core which acts as a shear wall. The seismic demand is found to be affected by the relative location of staircase and stiff elevator core in the building plan. The differential movement between the farthest points on the building plan can be minimized by locating the staircase and elevator core in the central part of the plan.

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ABSTRACT

Presence of staircase and elevator core generally causes change in the location of center of stiffness in the building plan, and leads to torsional response. In the present study, four different models of multistoried RC frame buildings are created with inclusion of unreinforced brick masonry infill walls and varying locations of staircase and elevator core walls. The seismic demands of the models are compared by carrying out Modal Pushover Analyses (MPA) procedure. Comparisons of story shear, floor displacement and interstorey drifts show that inclusion of higher modes particularly the 2\textsuperscript{nd} mode is necessary in MPA to improve the estimate of seismic demand in some cases.

Introduction

In a RC frame building primary load bearing components are beams and columns. These members account mainly for the structure’s stiffness and mass, and subsequently dominate its behavior against seismic forces. But other non-structural members like staircase, partition walls etc. do affect the behavior of structure. Out of these non-structural members Staircase and elevator are the members which are generally designed for non-seismic behavior. Staircase and Elevator core are important components of typical multistoried Reinforced Concrete (RC) moment-resistant frame building. The location and configuration of staircase and elevator core affects the strength and stiffness of the building, and therefore brings the eccentricity into mass and stiffness distribution.

The conventional displacement-controlled pushover analysis, in which the lateral displacement profile is considered to be the same as the fundamental translational mode shape, has the limitation of not being able to capture the possible higher mode effects during the dynamic response as well as the inelasticity mobilized during strong earthquake shaking. This is primarily due to the invariant nature of the displacement profile during the pushover analysis. Inclusion of at least two mode shapes in the displacement profile for pushover analysis has also been suggested to account for the contribution of higher modes in the dynamic response. Modal Pushover Analysis (MPA) is an extension of the same concept with consideration of different mode shapes for obtaining the lateral displacement profile.

In MPA, pushover analysis is done on SDOF systems for each elastic mode considered and subsequently pushover curves are bilinearly idealized ([1], [2]). Structures are subjected to invariant loading corresponding to individual elastic force pattern in each mode. Then the individual modal responses are combined according to the appropriate modal combination rule to

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estimate the seismic demand ([3], [4], [5]). It is required to take as many modes to cover the at least 90% mass participation. In this study four models are created by varying the location and orientation of the staircase and the elevator.

**Building Details**

A five storied symmetric Reinforced Concrete (RC) frame building, located in Seismic Zone - V [6], has been considered for the present study. The building plan is having dimensions 16.75 m × 13 m with the total height of the building as 17 m (Figures 1a to 1d). The floor-floor height is 3 m for all the cases and length of foundation columns is taken to be 2 m. The building is assumed to be founded on rocky strata, thus the translational and rotational degrees of freedom at the bottom nodes are restrained. The grades of concrete and steel are M25 and Fe 415 respectively.

The cross-section all the beams is taken as 300 mm × 450 mm. The size of all but foundation columns is taken as 350 mm × 350 mm; the size of foundation column is taken as 450 mm × 450 mm. The beams and columns are modeled using two-noded frame elements whereas the floor slabs are modeled using four noded shell elements. The unreinforced brick masonry infill walls are represented by two-noded frame elements with release of end moments, so that strut action is mobilised. For the staircase, mid-landing, floor-landing and waist slabs are modeled using four-noded shell elements. Appropriate discretisation of the elements is also carried out to ensure proper connectivity and load transfer during analysis. Elevator core walls behave like shear walls and they have been modeled using as four-noded layered shell elements. Each of these elements has separate layers characterizing the cover concrete, core concrete and the layers of reinforcement idealized as smeared all over the element. The modeling of layered shell elements helps in capturing the possible nonlinear behavior of core walls during pushover analyses.

The nonlinearity in frame members is modeled as lumped plastic hinges with the properties assigned according to FEMA 356 [7]. Columns were assigned the axial force-being moment interaction hinges and shear V3 hinges. The beams were assigned with flexural and shear hinges. The sections were modeled in the Section Designer module of the program SAP2000 [8] to obtain the interaction curves. The thickness of all the floor and landing slabs is taken as 150mm, while thickness of waist slab for staircase is taken as 170 mm. Unreinforced brick masonry infill walls are modelled as diagonal strut to simulate the lateral stiffness of the infill wall [9]. The axial hinges were assigned to infill strut in order to capture the crushing failure mode.

**Loading**

The dead load of the structure comprise of self-weights of the structural elements and the floor finish load. The floor finish loading for this structure on the all the slab elements is considered to be 0.5 kPa. The live load intensities on the roof and floor slabs are considered as 1.5 kPa and 2 kPa respectively as per the Indian Standard IS:875 (Part 2) [10]. It is also assumed that the staircase-slabs will bear the same live load intensity of 2 kPa as that on the floor slabs. The dead and live loads due to the elevator are chosen as 5.44 kN and 7 kN as respectively.

The mentioned four models are subjected to MPA in order to estimate the seismic demands. The loading pattern to do the MPA is applied along the width of the building models and the moments about the vertical axis. The displacement vector $\mathbf{u}$ is considered of sub vector

![Diagram of building layout](image-url)
Figure 1. Typical floor plan showing the locations of staircase and elevator core in (a) model 1, (b) model 2, (c) model 3 and (d) model 4.

$u_y$ and $u_0$ where $u_y = [u_{1y} \ u_{2y} \ u_{3y} \ \ldots \ u_{ny}]^T$ and $u_0 = [u_{10} \ u_{20} \ u_{30} \ \ldots \ u_{n0}]^T$ are respectively the motion of structure along width direction and torsional rotation about the vertical axis. The corresponding force vector for motion of the structure $S$ comprise of two sub vectors $s_{ny}$ and $s_{n0}$, where $s_{ny} = [s_{1y} \ s_{2y} \ s_{3y} \ \ldots \ s_{ny}]^T$ and $s_0 = [s_{10} \ s_{20} \ s_{30} \ \ldots \ s_{n0}]^T$ are the lateral force and torsional vectors along the direction of width and about the vertical axis. Each floor is subjected to the combination of lateral force and torsional moments, at the respective center of mass, with appropriate directions to obtain the modal peak response for each model. In the present study first three modes are considered as the errors due to truncation of modes higher than 3 will not be significant.

**Results and Discussion**

Pushover Analysis is carried out to see the influence of elevator core wall in the same analogy as an RC frame system with structural walls along with changes in the location of the walls. The lateral displacement capacities of the Models 3 and 4 are observed to be less than the capacities
obtained in Models 1 and 2 (Fig. 2(a), 2(b), 2(c) and 2(d)). This is possibly due to the orientation of the waist slab in the direction of pushover analysis and this leads to increase in lateral stiffness of the model in that direction. Also, the central locations of the staircase and elevator core lead to primarily translations and less overall rotation of the model about the vertical axis. In models 1 and 2, the staircase and elevator cores are located in the corners of the corresponding models. This leads to significant rotation of the model about the vertical axis and increases the lateral displacement level with contributions from both translational and rotational components.

Also, the lateral displacement of the frame, having parts of staircase and elevator core, is less than the frames on the farther side of the model. This is due to the large stiffness of the core wall which primarily reduces the translation. Also, the farther frame undergoes significant displacement due to the rotation of the entire model about the center of stiffness near the staircase-elevator core assembly. Although the pushover analysis was carried out with the lateral displacement profile similar to the first translational mode shape of the model, the mobilisation of rotation about the global vertical axis shows that higher modes need to be considered for the realistic displacement profile during pushover analysis. During pushover analyses, plastic hinges are mostly formed in the beams supporting the landing slabs in the lower stories with mid-floor landing slab located in the outer part of the model. The models with mid-landings located on the interior side, showed comparatively lesser hinge formation.

### Modal Pushover Analysis (MPA)

Due to the complex behavior of structure attributing to the differential movement of stairs and variation in stiffness localization due to elevator core wall structures are subjected to modal pushover analysis. Because accidental eccentricity imposed by the location of staircase would induce torsional effects in structure and it is almost impossible to capture those behaviours of structure in a single mode that is why modal pushover is performed on structure and initial 3 modes were assumed to be sufficient to provide accurate results. The models were subjected to lateral force in Y direction and torque about Z direction for every floor.

For the floor-level lateral displacements, models 1 and 2 show less difference between the first and second mode displacements as compared to the difference of displacements between models 3 and 4 in (Figs. 3a, 3b, 3c and 3d). Although the third mode of vibration does not seem to influence the floor displacements in models 1 and 2, its effect is partially reflected in the behaviour of models 3 and 4. However, it is observed that with the kind of eccentricity introduced in the building model, it becomes almost imperative to include the effect of the second mode in the estimation of seismic demand despite the structure being not so tall. Up to the first story, the displacements in all the modes for the models are close to each other; however, towards the top of the building, the behaviours are different with inclusion of different modes. Thus, global torsional effects are primarily responsible for the increasing dominancy of second and third modes in the behaviour of these models. This dominant behaviour is more evident for the lateral displacement levels obtained towards the top of the building.

For the inter-storey lateral drift, the influence of the second mode of vibration is quite clear with the drift, after inclusion of the second mode, increasing by 50%-100% as compared to the drift in the first mode (Figs. 4a, 4b, 4c and 4d). Although, the third mode has some influence in model 1, for all other models the top roof drift in third mode is almost negligible. The variation of drift profile with the height of a structure is very important for understanding of the
differential distortion of the structure. In models 3 and 4, although the top roof drift profile is same, it is different in lower stories suggesting the differential rotation or displacement of staircase in between floors. The story drift ratio in models 1 and 2 varies between 0.2 to 0.6 while in models 3 and 4, it varies primarily between 0.2 to 0.4. This most likely explanation of this observation is that in models 3 and 4 the structure both rotational and translational effects are taking place.

Figure 2. Variation of base shear with lateral displacement in models (a) 1, (b) 2, (c) 3 and (d) 4

In Fig. 5, the variation in story shear is shown against the height of the building. For each story, story shear is calculated as the sum of shears at the base point of column with the lower story slab. The unusually high story shear in lowest foundation story is possibly due to the short height of the column. The formation of plastic hinges also implies formation of soft story mechanism in the ground story. It is obvious from Figs. 5c and 5d that the inclusion of second mode in Models 3 and 4 improved the estimation of seismic demand at top level by 150% at almost every floor level; this is very important for realistic prediction of response. While for models 1 and 2, the influence of third mode is also accountable for a reasonable prediction.
The following salient conclusions are drawn from the study:

1. The distributions of story shear, story displacement and inter story drifts over the height of the building, as estimated from MPA, are more realistic as compared to the distributions obtained from the conventional pushover analysis. The contributions of the first two modes of vibration suffice in most of the cases for MPA.
2. The higher modes of vibration need to be included for the estimates of story shear with regard to increasing eccentricity and height of building; it is necessary to include at least the second mode in pushover analysis.
3. The pushover curves for an RC building with elevator core walls do not reach the dropping part due to low lateral displacement levels. The same may be achieved by considering more refined modelling of the walls.
4. For all the models, storey shear increases significantly over the bottom storey due to its lesser height leading to short column effect.
Figure 4. Variation of inter-storey drift with height for modal pushover analyses of (a) model 1, (b) model 2, (c) model 3 and (d) model 4.

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Figure 5. Variation of storey shear with height for modal pushover analyses of (a) model 1, (b) model 2, (c) model 3 and (d) model 4.


