A New Procedure to Include Torsional Effects in Pushover Analysis of Torsional Buildings

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ABSTRACT— ***Non-linear Static analysis or Pushover analysis is a very practical method fit for day to day use in the structural design field, when compared to Non-linear Time History analysis due to its computational intensity and experienced judgement required. However it is found that Non-linear Time History analysis is more accurate than Pushover analysis, the disadvantage being more pronounced in case of irregular and torsional buildings. With conventional PoA, the torsional effects are mostly pronounced in the elastic range and early stages of plastic behaviour and tend to decrease with an increase in the plastic deformations, thus failing to capture the effects of torsion in buildings. The obvious answer being the inclusion of torsional elements in the lateral load pattern, a new method by which the eigen vectors are translated to its corresponding lateral load vectors with the torsional aspect included is proposed. On investigation it is found to overcome the above drawback and gives results closer to that of Non-linear Time History analysis, especially for irregular torsional buildings.***

Keywords— Pushover analysis, Torsional Buildings, Eccentric Buildings, SAP2000

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1. INTRODUCTION

Non-linear static analysis or pushover analysis (PoA) is one of the most popular types of analysis for performance based design methods, in which the magnitude of the lateral loads is monotonically increased on a non-linear numerical computer model, maintaining a predefined distribution pattern along the height of the building [1, 2].

The Non-linear Time History analysis (NLTHA) is considered most accurate for inelastic response of a structure to a given ground motion record, but is computationally intensive and characteristic of a particular record, rendering it impractical for day to day design. Thus the PoA has gained popularity among structural designers and consultants. PoA methods have been included in seismic codes in the US and in the Eurocode-8. Capacity Spectrum Method (ATC-40 [1]) and the Displacement Coefficient Method (FEMA-356 [2]) are the two widely followed procedures for PoA of buildings. Commercial packages like SAP2000, MIDAS/Gen and STAAD.Pro now provide facility for PoA.

With conventional PoA, the torsional effects are mostly pronounced in the elastic range and early stages of plastic behaviour and tend to decrease with an increase in the plastic deformations, thus failing to capture the effects of torsion in buildings when compared to NLTHA[3]. This is because hinge formation in the structure develops and progresses in such a way that the eccentricity of the building's centre of stiffness gets reduced, resulting in a structurally non-torsional one while still remaining irregular in geometry. The lateral load pattern applied in the PoA lacks a torsional element, while the torsional distortion occur due to the inherent eccentricity of the building. Since the eccentricity gets 'balanced off' during the progress of the analysis, one finally ends up with a resulting non-torsional building, while the NLTHA counterpart retains this important aspect of the structure simulation.

Obviously, the answer is to include torsional elements in the lateral load pattern. Methods have been developed for scaling the torsional component with respect to the lateral force, when translating eigen vectors (displacement/rotation) to corresponding force/moment vectors, with much derived mathematical basis [4], or by estimating correction factors to apply to a conventional PoA [7]. Here a new PoA method by which the eigen vectors naturally translate to force/moment vectors, is proposed and investigated to find whether it predicts the responses of a torsional structure closer to NLTHA than the conventional PoA. The proposed procedure has been applied to structures with different configuration, including a non-torsional one, and the results obtained were compared with those of NLTHA.

2. ANALYSIS PROCEDURE

The analyses were done using the structural analysis package of SAP2000 [5], which has inbuilt functions for PoA based on both Capacity Spectrum Method and Displacement Coefficient Method.

The part of the procedure which is common to both the methods are modelling the structure, defining the properties for the nonlinear hinges, assigning the hinges to the members of the frame elements, and defining the gravity load cases. From this point, the procedures are different for Conventional PoA and the Proposed PoA.

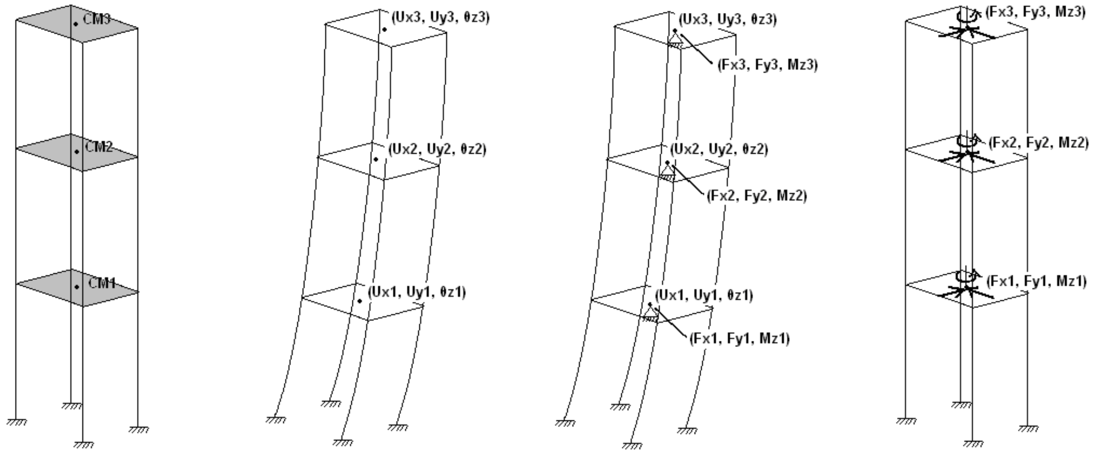


Figure 1: P-PoA procedure followed (schematic only): **(a)** Building model with centres of mass shown; **(b)** Mode shape with modal displacements (Ux, Uy, θz); **(c)** Modal displacements applied as displacement constraints on the model (Ux, Uy, θz), and resulting support reactions (Fx, Fy, Mz) obtained on static analysis; and **(d)** The resulting support reactions (Fx, Fy, Mz) applied as lateral load pattern for Pushover analysis

2.1 Conventional Pushover Analysis Method (C-PoA)

The subsequent steps for the conventional PoA comprises of defining the pushover load cases and running the nonlinear analysis for gravity load case, followed by the nonlinear pushover analysis in x-direction.

2.2 Proposed Pushover Analysis Method (P-PoA)

The subsequent steps for the proposed PoA method are as follows: (i) A modal analysis of the building is performed, and the modal translations and rotation (Ux, Uy, θz) at the centres of mass (CM) are obtained for each floor diaphragm, for the first mode in x-direction. (ii) The obtained modal displacements are applied as displacement constraints (ie, supports with displacements of Ux, Uy & θz) at the CM of each floor of the structural model and an elastic static analysis is carried out. (iii) The support reactions, (viz. forces and moments Fx, Fy & Mz) at the constraints imposed at each floor are noted down as the load pattern for the pushover analysis (Figure 1). Note that the coordinate system in SAP2000 defines x and y along the horizontal plane and z axis is along vertical direction. (iv) The floor constraints are then removed and the pushover load case is defined with the load pattern (of Fx, Fy & Mz for each floor) obtained above. (v) The nonlinear gravity load case is run, followed by the nonlinear PoA with the load pattern as the lateral load. Since the lateral load is to be monotonically incremented during the analysis, only their relative values (and not the actual intensity of the loads) is of importance.

The subsequent steps common to both C-PoA and P-PoA procedures are: The Pushover curve and the Capacity Spectrum curve are obtained from the analysis. The pushover displaced shape and sequence of hinge formation on a step-by-step basis are reviewed. Member forces are reviewed on a step-by-step basis.

2.3 Nonlinear Time History Analysis

In the present work a set of four earthquake motion records for type II soil (Table 1) are used for performing the NLTHA. Hilber Hughes Alpha-Taylor Algorithm available in SAP2000 [5] was used for the analysis, with an alpha value of -0.3333.

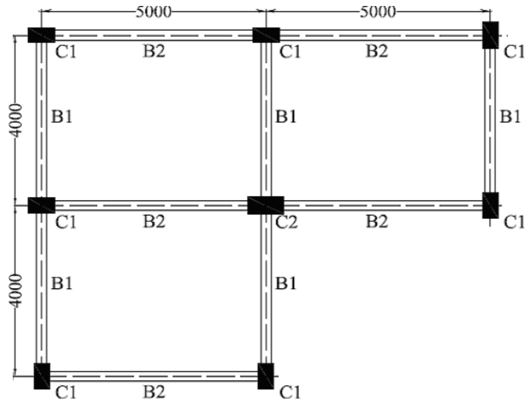
Table 1: Ground Motions Selections for Type II (Medium) Soil

Sl no	**Earthquake (date - MM/DD/'YY)**	**Recorded station**	**Intensity**
1	Loma Prieta 10/18/'89	Gilroy Historic building	0.284 g
2	Northridge Earthquake 01/17/'94	N Hollywood- Coldwater Canyon	0.292g
3	Imperial Valley Earthquake, 05/19/'40	El Centro ARRAY #9	0.312g
4	Kobe Earthquake 01/16/95	Kakagowa Station	0.345g

3. MODELS SELECTED FOR STUDY

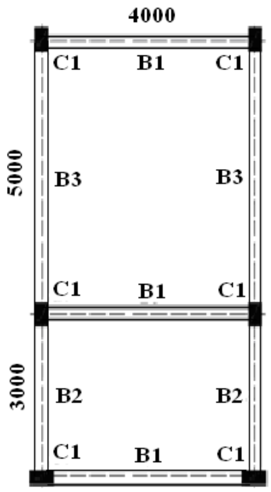
The analyses were carried out on two structural models which have asymmetric plan irregularity; and one with no asymmetry. PoA is carried out using both the conventional and proposed method on the selected models, followed by NLTHA for the selected ground motions. Comparison of the results of conventional method C-PoA and proposed method P-PoA is made with NLTHA to determine as to which method predicts responses closer to NLTHA. The supports at foundation points of the all the models were provided fixed. The Response Spectrum as per the Indian code [6] for Type II (Medium) soil was considered for the demand curve

Two types of irregular building models were selected for the models studies, viz., an L-shaped building (Figure 2a) and a Rectangular building with uni-axial eccentricity (Figure 2b), which have essential features to induce torsion. The third model (Figure 2c) has no eccentricity.



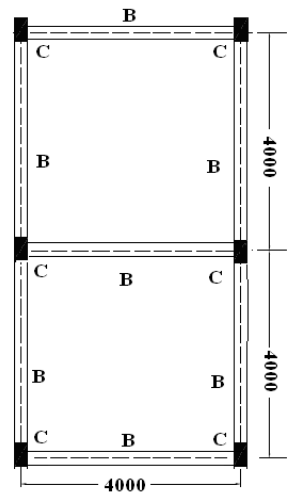
Model	L-Shaped building		
Stories	4	**Z**	0.16
Story ht	3.5 m	**I**	1
Plinth ht	1.8 m	**R**	5
Beam B1	230 × 400 mm		
Beam B2	230 × 500 mm		
Column C1	250 × 400 mm		
Column C2	300 × 500 mm		

(a)



Model	Uniaxial building		
Stories	3	**Z**	0.16
Story ht	3.5 m	**I**	1
Plinth ht	2 m	**R**	5
Beam B1	230 × 350 mm		
Beam B2	230 × 300 mm		
Beam B3	230 × 450 mm		
Column C1	250 × 400 mm		

(b)



Model	Symmetric building		
Stories	3	**Z**	0.16
Story ht	3.5 m	**I**	1
Plinth ht	2 m	**R**	5
Beam B	230 × 300 mm		
Column C	250 × 400 mm		

(c)

Figure 2: Plan configuration and seismic parameters for **(a)** L-shaped Building **(b)** Uniaxially Eccentric Building and **(c)** Symmetric Building, where Z is the seismic zone coefficient, I is the building importance factor and R is the Response Reduction factor [6]

3.1 The L-Shaped Building

The L-shaped building with biaxial eccentricity (Figure 2a) is modelled with parameters as in Table (Figure 2a), and modal analysis done (Figure 3). The modal displacements (Table 3a), are applied as displacement constraints at the CM for each floor on the model, followed by a static analysis to obtain the resulting reactions (Table 3b) which are then applied as Load vectors at CM, the applied floor constraints removed, and PoA is carried out on the model.

When the structure is laterally pushed using C-PoA and P-PoA methods one gets a series of joint displacements, from which we have to take the values of the step which is close to the time history value. The joint displacement obtained from C-PoA and P-PoA when compared to those from Time History results (Tables 3c), where the results of C-P0A was found to have a variation of 24.68% average from that of NLTHA, while P-PoA had a variation of 5.61% average (not considering variation at the plinth level), it can be seen that responses for P-PoA are closer than C-PoA to the Time History results, although the exact match found in some of the joint displacements can only be a matter of coincidence.

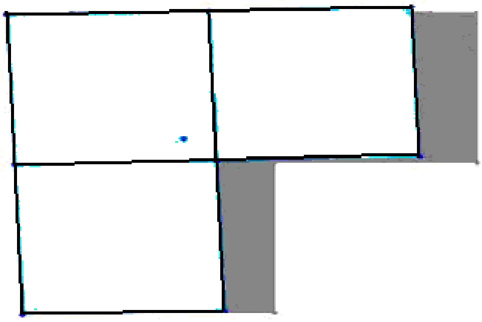


Figure 3: First Mode Shape (in plan view) of the L-Shaped Building– shown in outline is the mode shape and in grey is the undeflected structure.

Table 3: (a) Modal displacement at the centre of mass and **(b)** Joint load vectors (reactions at imposed displacement constraints) at the centre of mass of L-Shaped Building

Story	Ux (m)	Uy(m)	θz (rad)
Roof	0.0266	0.0021	0.0022
IV	0.0231	0.0017	0.0019
III	0.0173	0.0012	0.0045
II	0.0095	0.0007	0.0008
I	0.0015	0.0001	0.0001

Story	Fx (kN)	Fy (kN)	Mz (kNm)
Roof	448.911	-6.107	90.344
IV	298.979	1.978	59.739
III	233.035	6.334	67.411
II	-1.833	0.721	22.313
I	296.534	2.425	118.762

Table 3: (c) Comparison of Joint Displacements for PoA in X Direction of L-Shaped Building at each floor's centre of mass

Story	NLTHA(mean values)		*C-PoA*		P-PoA	
	x-dir.	y-dir	x-dir	y-dir	x-dir	y-dir
Roof	0.044	0.0006	0.0541	0.0009	0.0483	0.0006
IV	0.0382	0.0004	0.0473	0.0006	0.0414	0.0004
III	0.0281	0.0002	0.0351	0.0004	0.0295	0.0002
II	0.0148	0.00006649	0.0188	0.0002	0.0147	0.00008653
I	0.0022	0.00000747	0.0029	0.0000248	0.0023	0.000007414

3.2 Uniaxially Eccentric Building

The building selected for configuration with uniaxial eccentricity (Figure 2b) was also modelled (Table in Figure 2b) and modal analysis done (Figure 4). The same procedures that has been followed for the L-shaped model has been done in this case too. Comparison of joint displacement obtained from C-PoA, P-PoA and Time History methods in X and Y directions (Table 4d) where the results of C-P0A was found to have a variation of 18.56% average from that of NLTHA, while P-PoA had a variation of 6.44% average (not considering variation at the plinth level), showing that responses for P-PoA are closer than C-PoA to the Time History results.

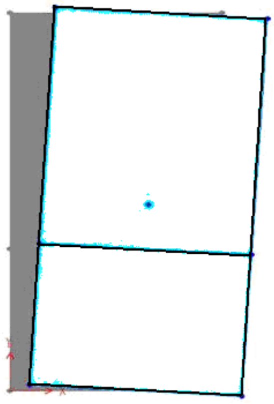


Figure 4: First Mode Shape (in plan view) of the Uniaxially eccentric building – shown in outline is the mode shape and in grey is the undeflected structure

Table 4: (a) Modal displacement at the centre of mass and **(b)** Joint load vectors (reactions at imposed displacement constraints) at the centre of mass of Uniaxially eccentric building

Story	Ux (m)	Uy (m)	θz (rad)
Roof	0.072	6.94E-10	-0.00291
III	0.0564	5.57E-10	-0.00234
II	0.0314	3.19E-10	-0.00134
I	0.0058	6.05E-11	-0.00025

Story	Fx (kN)	Fy (kN)	Mz (kNm)
Roof	145.701	2.023	423.458
III	122.547	-0.0708	398.287
II	63.768	0.442	226.579
I	93.878	0.939	266.822

Table 4 (c): Comparison of Joint Displacements for PoA in X-Direction of Uniaxially eccentric building

Story	NLTHA (mean values)		C-PoA		P-PoA	
	x-dir	y-dir	x-dir	y-dir	x-dir	y-dir
Roof	0.1793	0.0022	0.1352	0.0055	0.14344	0.00176
III	0.1119	0.0019	0.1178	0.0045	0.1068	0.0012
II	0.0432	0.0014	0.0756	0.0027	0.06216	0.00072
I	0.0051	0.0003	0.0103	0.0005	0.01464	0.00016

3.3 Symmetric Building

The building selected for configuration with zero eccentricity (Figure 2b) was also modelled (Table in Figure 2c) and modal analysis done (Figure 5). The same procedures that has been followed for the L-shaped and uniaxial models has been done in this case too. Comparison of joint displacement obtained from C-PoA, P-PoA and Time History methods in X and Y directions (Table 5c) where the results of C-PoA was found to have a variation of 25.97% average from that of NLTHA, while P-PoA had a variation of 24.59% average (not considering variation at the plinth level), show that there is not much variation between P-PoA and C-PoA. results.

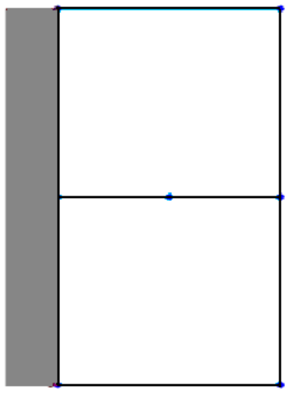


Figure 5: First Mode Shape (in plan view) of the Symmetric Building – shown in outline is the mode shape and in grey is the undeflected structure.

Table 5: (a) Modal displacement at the centre of mass and **(b)** Joint load vectors (reactions at imposed displacement constraints) at the centre of mass of Symmetric building.

Story	**Ux (m)**	**Uy(m)**	**θz (rad)**
Roof	0.00338	0	0
III	0.00264	0	0
II	0.00149	0	0
I	0.00027	0	0

Story	**Fx (kN)**	**Fy (kN)**	**Mz (kNm)**
Roof	262.353	0	0
III	-96.643	0	0
II	-55.149	0	0
I	-28.144	0	0

Table 5 (c): Comparison of Joint Displacements for PoA in X-Direction of Symmetric building

Story	**NLTHA (mean values)**	**C-PoA**	**P-PoA**
	x-dir	**x-dir**	**x-dir**
Roof	0.177	0.2277	0.2241
III	0.147	0.1899	0.1836
II	0.0878	0.1107	0.1087
I	0.0165	0.0198	0.0203

4. CONCLUSION

Three building models were investigated, one with biaxial eccentricity, one with uniaxial eccentricity, and a third with no eccentricity, to demonstrate the applicability of the proposed pushover method as compared to the conventional pushover method.

3D dynamic analysis is found to be appropriate for torsional buildings. Results obtained from the Proposed PoA method shows that for torsional buildings responses are closer than the Conventional PoA method to the Time History results, while for non-torsional buildings, both the methods have been found to give more or less the same result, suggesting that the proposed method can be applied to torsional buildings to get more accurate results.

5. ACKNOWLEDGEMENT

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