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A Study on the Effect of Second Order Geometric Nonlinearity for Asymmetrical Building

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***Abstract*— In this new millennium land acquisition is more of a relentless task in every place. With the booming population across the world, the next best option is to opt for vertical expansion which is much more feasible and practical to accommodate more households. When these high rise structure are preferred, the safety and stability requirements of the structure are very much crucial so a special care and attention is given to each and every single aspect.**

For convenience of computation, the preferred analysis is linear static analysis as the elastic behaviour is simple to predict structural behaviour, with certain properties. Since it cuts down the complex calculations, the principle of superposition is valid, different loads and/or combination of loads can be applied. Hence, we can easily find the responses for the given loads. But this is not always the case as the structural elements are flexible and due course our analysis becomes inconsiderate towards the important interaction between the vertical loads and horizontal displacements which nevertheless is an important stability parameter. While considering this interaction one has to consider nonlinearity and nonlinear analysis is complex and the accuracy is tough to achieve. In this study a structure is chosen such that, it is not symmetrical.

Conventionally there are few such structure which are symmetrical in the real world and majorly the structures are such that the orientation, plan are skewed because of this observation, for the current study a structure is chosen in such a way that it is asymmetrical and to relate to it with the prevailing situation. The structure consists of frame and shearwall system. The structure is firstly analysed and designed without the second order geometrical nonlinear effects (P-Delta effects). In the second analysis the same model is analysed and designed with the application of geometric nonlinear effects and the response of the structure has increased considerably in the story displacements, drifts, time period and the moments this is because of the relative decrease in the stiffness of the structure. With this increase in forces and displacements the design requirements have been enlarged so as to account for such second order geometric effects.

Keywords*— Geometric Nonlinearity, Shear Walls, Storey stiffness, lateral displacements, Asymmetric Structure, Etabs

I. INTRODUCTION

Generally, the analysis of buildings is done by using linear elastic methods, which is first order structural analysis. In the first order analysis, the evaluation of internal forces and displacement are dependent on material and section properties here the buckling and yielding are not considered. In the first order elastic analysis, the superposition of forces is possible and the forces are proportional to the applied loads. These form of linear elastic behaviour can't be assured in the real world and it cannot account for the second order geometric and/or material nonlinear effects are applied on deflections from the analysis. This kind of geometric nonlinearity can be analysed by performing through iterative processes which is merely practicable by using analysis software.

a. **Linear Analysis:**

Previously and conventionally we use linear static analysis, the linear static analysis of a structure involves the solution of the system of linear equations are represented by:

$$K\,u = r \tag{1}$$

Where, K is the stiffness matrix,
r is the vector of applied loads, and
u is the vector of resulting displacements

II. P-DELTA (SECOND ORDER GEOMETRIC EFFECT)

The P-Delta effect is the second order effect on shears and moments of frame members and on the shear walls due to the action of the vertical loads, interacting with the lateral displacement of buildings, resulting from the seismic and wind forces. The structures behave flexible against applied seismic and/or wind lateral loads as the columns are subjected to compressive loads.

There are two types of P-Delta effects,

1. P-Δ or P- 'big delta' effect.
2. P-δ effect or P- 'small delta' effect.

The P-δ effect or P- 'small delta' effect is concerned with load displacements of structural elements in between end nodes. The P-Δ or P- 'big delta' effect is associated with the global load-displacement of the structure.

In a first-order analysis only gravity loadings are considered. The structures are analyzed for each loading to obtain results and superimposed. However, this method does not provide accurate results. In low-rise and medium-rise buildings P-Delta analysis is not essential as the displacements are small. In taller and slender building structures having greater flexibility. The P-Delta effects are more significant.

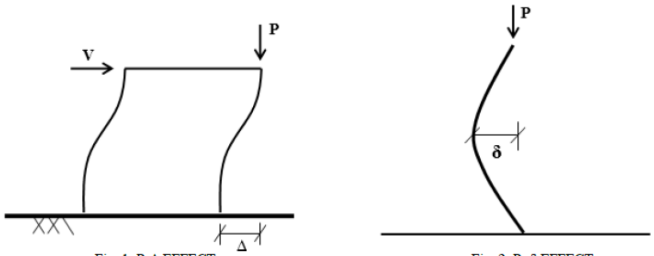

Fig. 1: P-Δ EFFECT   Fig. 2: P- δ EFFECT

Fig. 1. P-Delta

If so, then it requires larger sectional size of structural components to sustain the augmented moments and shears. In extreme cases such as very flexible, tall building structures subjected to large gravity loading, the P-Delta effects are severe enough to cause catastrophic collapse. In the design of multi-storey building structures, assessment of P-Delta effects is more important to predict whether P-Delta effects are significant, if so, P-Delta effects are accounted for analysis and design of structural elements. The P-Delta effect is critical in case of nonlinear analysis of multi-storey buildings. If the P-Delta effect causes sufficiently large lateral displacements in structures then P-Delta analysis is essential. The P-Delta effects are not considered in analysis and design of building components of high-rise building structures if the stability coefficient as obtained by the below equation is equal to or less than 0.10

$$\theta = \frac{P\Delta}{V\text{h}C_d} \qquad (2)$$

Where,
P - Total vertical design load (kN),
Δ - Design storey drift,
V - Seismic shear force (kN),
h - Height of storey (mm),
Cd - deflection amplification factor.

III. SHEAR WALLS

Shear walls which form a part of the lateral load resisting system, are vertical members cantilevering vertically from the foundation, designed to resist lateral forces in its own plane, and are subjected to bending moment, shear and axial load. Unlike a beam, a wall is comparatively thin and deep, and is subjected to substantial axial forces. The wall should be designed as an axially loaded beam, capable of forming reversible plastic hinges (usually at the base, as shown in Fig.2 with sufficient rotation capability.

The code recommends that the thickness of any part of the wall should preferably be not less than 150 mm. Walls that are thin are susceptible to instability (buckling) at regions of high compressive strain.

A minimum of 4 no's 12 mm φ bars arranged in at least two layers should be provided near each end face of the wall. The concentrated vertical flexural reinforcement near the ends of the wall must be tied together by transverse ties, as in a column, to provide confinement of the concrete, and to ensure yielding without buckling of the compression bars when a plastic hinge is formed.

Where the extreme fibre compressive stress in the wall exceeds 0.2 f_{ck}, *boundary elements* should be provided along the vertical boundaries of walls. These are portions along the wall edges that are strengthened by longitudinal and transverse reinforcement, and may have the same or larger thickness as that of the wall web.

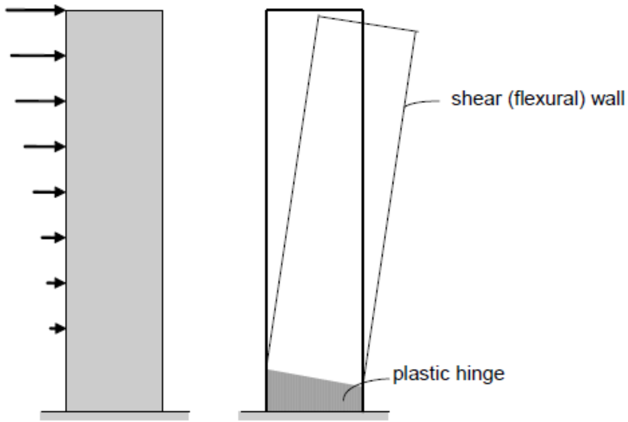

Fig. 2. Lateral loads on shear walls

IV. BACKGROUND AND MOTIVATION

There have been a lot of case studies regarding P-delta effects. Those structures have been investigated with different seismic zones, with and without shearwall and of different stories for p-delta effects but the models chosen in those studies were symmetrical and that is not always the case in real life, the structure are not of symmetry in plan and elevation. So as to examine the effects of second order geometric nonlinearity here the structure is chosen such that it is not of symmetrical geometry the L/D ratio is 2.9. The structure is longer in one direction than the other. Which also make the structure more slender. Proceeding with this perception in mind. The structure of 25 stories has been analysed and designed. The consideration of this kind of effects are vital in the analysis and design of the high rise structures

V. SCOPE OF THE PROJECT

The buildings are prone to deform laterally from original position with an eccentricity during an earthquake. When building structures are subjected to seismic, wind loading causing the structure to deform, the resulting eccentricity of the total gravity load due to inclined axes of structure causes the extra moments at the base. In taller and slender building structures having greater flexibility, the P-Delta effects are more significant. If so, then it requires larger sectional size of structural components to sustain the augmented moments and shears. In extreme cases such as very flexible, tall building structures subjected to large gravity loading, the P-Delta effects are severe enough to cause catastrophic collapse. In the design of multi-storey building structures, assessment of P-Delta effects is more important to predict whether P-Delta effects are significant, if so, P-Delta effects are accounted for analysis and design of structural elements. The P-Delta effect is critical in case of nonlinear analysis of multi-storey buildings. If the P-Delta effect causes sufficiently large lateral displacements in structures then P-Delta analysis is curial.

VI. MODEL DISCRIPTION

Here a G+24 model structure is considered, as it can be seen from the architectural plan the position of the shear walls have been changed this is to control the rotation of the structure which has come down to 2% as this location of the

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shear walls have been adopted for both the model with and without Second order effects.

TABLE I. Model Configuration

Structure data	
Length of the Structure, L =	33.3 m
Breadth of the Structure, b =	11.49 m
No. of Storeys =	G+24+Terrace+OHT
Height of each storey =	3m
Height of the Structure, h =	81 m
Type of Structure =	Frame and shearwall
Primary beam =	230x450mm
Secondary beam =	230x300mm
shear wall =	300mm
slab thickness =	150mm
Natural frequency, fa =	0.282 Cycles/s
Diaphragm used	Semi-rigid

Grade of concrete used	
For beams	M30
For shear walls	M40
Grade of steel	Fe 500
Modules of elasticity	5000√fck

TABLE II. Loading

SEISMIC LOAD DATA:	Acc. to IS 1893	
Location	Mumbai	
Zone factor	0.16	
Importance factor	1.2	
Site type	II	
R factor (SMRF)	5	
Damping	5%	
WIND DATA:	Acc. to IS 875	
Basic wind speed, Vb =	44 m/s	
Probability factor, K1 =	1	
Category =	3	
Topography Factor, K3 =	1	
Importance factor, K4 =	1	
GUST FACTOR =	3.29	
GRAVITY LOADING: (kN/m^2)	***Dead***	***Live***
For general slab	1.5	2
For sunken slab	3	2
For staircase slab	3	3
For lobby slab	2	3
For terrace slab	2	3

A. Architectural plan

Fig. 3. Typical floor

B. Etabs Model

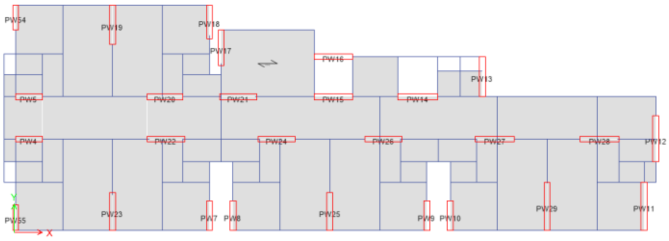

Fig. 4. Etabs model of typical plan

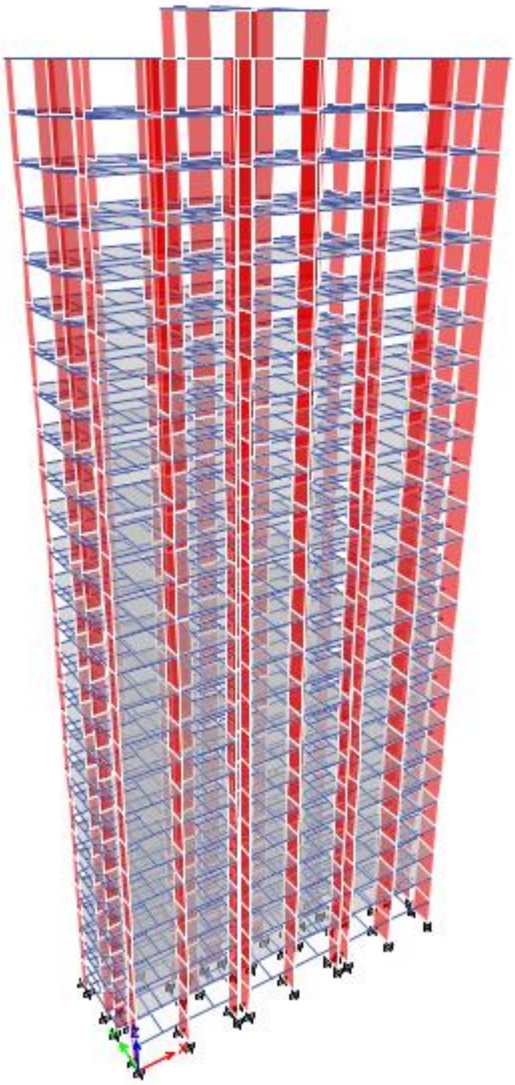

Fig. 5. 3D model of G+24 model

VII. RESULTS AND DISCUSSIONS

The structure is made into two models i.e., without the second order geometric effects and with the second order geometric effects and the results clearly reveal that the effects of second order geometric nonlinear effects are influence the response of the structure and results of all the different types of analysis such as dynamic earthquake and wind analysis, creep analysis, buckling, auto construction sequence analysis and P-Delta analysis for reinforced concrete structures are obtained and mentioned here.

A. Modal analysis:

Modal analysis is linear analysis at all times. It is be based on the stiffness of the entire unstressed structure, it also determines the system's undamped free vibration mode shapes and frequencies. These natural modes provide a fantastic insight into the structure's behaviour.

TABLE III. Model Comparison

	Without 2nd order effects	With 2nd order effects
Time Period	3.481	3.631
Translation in X Dir	70%	70%
Translation in Y Dir	67%	68%
Rotation	2.50%	1.70%
Mass Participation	95%	95%

The structure satisfies the model criteria of the IS 1893 cl.7.7.5.2. that the first mode should be in translation, here it is in, here it is in Y direction, second mode is in X direction and the third mode is in translation. All the modes are within the limits. The mass participation ratio is also above 95%. While the behavior of the structure doesn't show any drastic changes when the second order geometric nonlinear effects are applied but we can observe that the time period of the structure has increased.

B. Storey displacements:

When the structure is subjected to the lateral forces like earthquake and winds in the form of lateral loads the displacement exerted by the structure is in the form of lateral displacements and this displacement are measured in the form of storey displacements which is different for each storey depending on the intensity of lateral load, terrain category, topography, seismic zone and other factors this lateral displacements vary. The comparison of the model for the lateral displacement are shown for each and every floor individually along X-direction and in Y-direction independently.

Here, the maximum storey in the Y direction is 49mm and the limit of lateral storey displacement for the earthquake loading according to IS 16700:2017 clause 5.4.1 should be less than h/250 i.e. 78000/250 which is 315mm and it is under the limit.

TABLE IV (a). Storey displacement

Percentage increase in displacement after the application of second order effects		
Story	*For Earthquake loading*	
	X direction	*Y direction*
26	3.543	17.996
25	3.698	23.032
24	3.721	23.211
23	3.750	23.394
22	3.782	23.584
21	3.816	23.773
20	3.847	23.953
19	3.875	24.119
18	3.896	24.263
17	3.905	24.377
16	3.906	24.455
15	3.898	24.489
14	3.880	24.475
13	3.854	24.403
12	3.827	24.269
11	3.797	24.062
10	3.761	23.781
9	3.722	23.413
8	3.670	22.961
7	3.616	22.417
6	3.557	21.777
5	3.486	21.048
4	3.388	20.214
3	3.256	19.286
2	3.104	18.260
1	2.838	17.087
Average	3.669	22.619

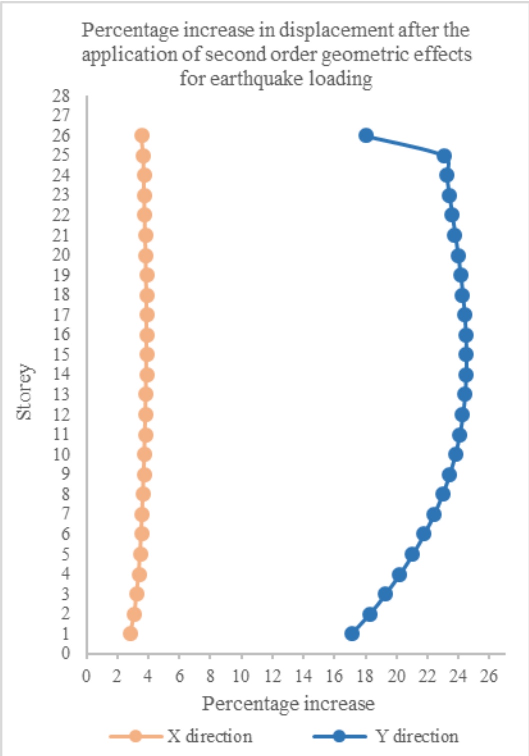

Fig. 6. Storey displacements for earthquake loading

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The maximum storey in the Y direction is 115.19mm and the limit of lateral storey displacement for the wind loading according to IS 16700:2017 clause 5.4.1 should be less than h/500 i.e. 78000/500 which is 156mm and it is under the limit.

TABLE IV (b). Storey displacement

Percentage increase in displacement after the application of second order effects		
Story	*For Wind loading*	
	X direction	*Y direction*
26	3.206	14.991
25	4.573	17.214
24	4.565	17.290
23	4.568	17.373
22	4.577	17.466
21	4.586	17.570
20	4.595	17.682
19	4.603	17.805
18	4.608	17.931
17	4.605	18.057
16	4.597	18.182
15	4.583	18.298
14	4.561	18.401
13	4.534	18.485
12	4.501	18.545
11	4.465	18.569
10	4.426	18.554
9	4.385	18.489
8	4.340	18.367
7	4.282	18.173
6	4.212	17.899
5	4.133	17.528
4	4.022	17.049
3	3.885	16.446
2	3.707	15.690
1	3.450	14.760
Average	4.33	17.57

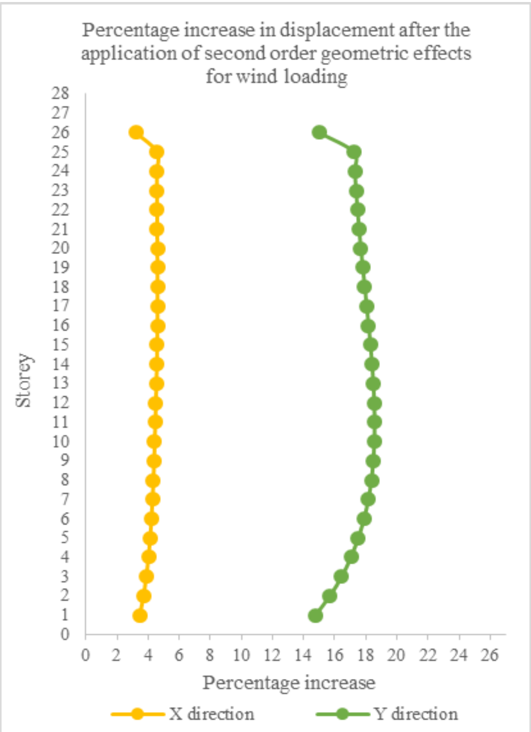

Fig. 7. Storey displacements for earthquake loading

C. Storey drifts:

The storey drift is the lateral displacements of the structure relative to the storey/floor above and below the storey considered. The comparison the model for the lateral drifts are shown for each floor along X and Y-direction individually, now the percentage increase in the drifts is shown in graphs.

TABLE V (a). Storey drift

Percentage increase in drift after the application of second order geometric effects		
For Earthquake loading		
Story	*X direction*	*Y direction*
26	2.259	8.004
25	2.524	5.833
24	2.547	5.765
23	2.545	5.807
22	2.685	5.765
21	2.829	5.794
20	2.989	6.414
19	3.173	9.956
18	3.397	13.531
17	3.579	17.168
16	3.759	19.259
15	3.837	20.460
14	3.971	21.594
13	3.974	22.613
12	4.098	23.526
11	4.046	24.300
10	4.079	24.901
9	4.012	25.254
8	3.918	25.337
7	3.994	25.098
6	3.865	24.602
5	3.909	23.721
4	3.679	22.520
3	3.596	21.182
2	3.442	19.531
1	4.082	17.653
G	0.800	15.877
Average	3.392	17.091

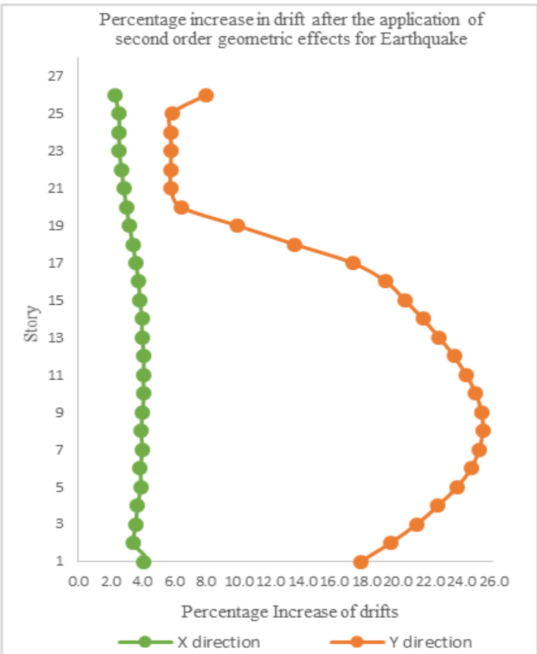

Fig. 8. Storey drift for earthquake loading

TABLE V (b). Storey drift

Percentage increase in drift after the application of second order geometric effects		
For Earthquake loading		
Story	*X direction*	*Y direction*
26	26	2.778
25	25	4.639
24	24	4.563
23	23	4.430
22	22	4.426
21	21	4.403
20	20	4.455
19	19	4.525
18	18	4.639
17	17	4.754
16	16	4.727
15	15	4.849
14	14	4.853
13	13	4.814
12	12	4.875
11	11	4.847
10	10	4.741
9	9	4.708
8	8	4.714
7	7	4.699
6	6	4.589
5	5	4.567
4	4	4.423
3	3	4.326
2	2	4.050
1	1	4.550
G	G	1.316
Average	3.392	17.091

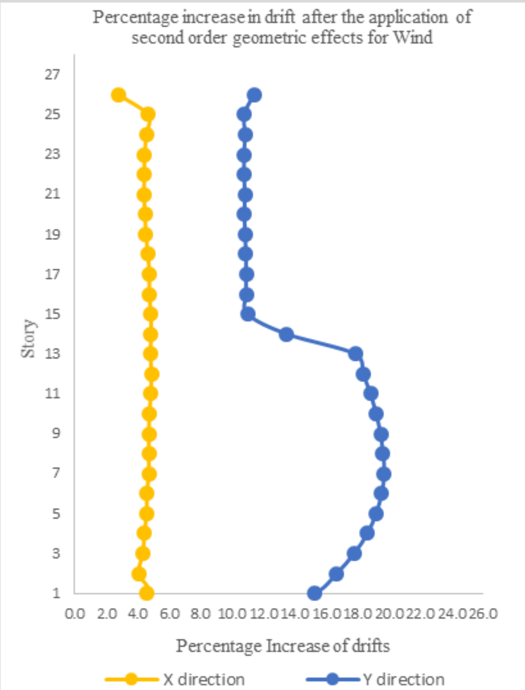

Fig. 9. Storey drift for wind loading

The lateral drifts for the dynamic load cases as per IS 16700:2017 cl 5.4.1 are restricted to the limit of 1/250 i.e. 0.004, here for the dynamic seismic load case and for the wind load case the maximum story drift ratio is under this limit, without and even with the second order geometric effects it is about 0.00095 and 0.00098 respectively. The percentage increase from the above graphs

D. Storey stiffness:

The soft storey concept is related to a discontinuity in the stiffness of building. According to IS 1893: 2002 a soft storey is one in which the sum of the lateral translational stiffness is lower than 70% of that in the storey above or less than 80% of the average lateral translational stiffness of three stories above.

The stiffness for every storey has been calculated for the dynamic seismic loading in both the X-direction and Y-direction and it has been compared.

TABLE V (b). Storey drift

Percentage decrease in stiffness after the application of second order geometric effects		
For Earthquake loading		
Story	***X direction***	***Y direction***
26	2.904	17.408
25	3.294	20.747
24	3.395	21.255
23	3.559	21.701
22	3.829	22.375
21	4.156	23.086
20	4.504	23.602
19	4.840	24.132
18	5.145	24.574
17	5.396	24.975
16	5.730	25.415
15	5.720	25.898
14	5.814	26.418
13	5.868	26.924
12	5.914	27.461
11	6.174	27.914
10	6.206	28.323
9	5.997	28.691
8	5.954	28.960
7	5.917	29.099
6	5.799	29.076
5	5.667	28.797
4	5.505	28.180
3	5.416	27.199
2	4.893	25.803
1	7.139	24.525
G	0.940	21.908

The stiffness is more in X direction than that of Y direction of about 55.75% when the second order geometric effects are not incorporated and about 65% when the second order geometric effects are incorporated. The decrease in the storey stiffness has been observed in both the X and Y direction the stiffness in y direction is more given the geometry of the building.

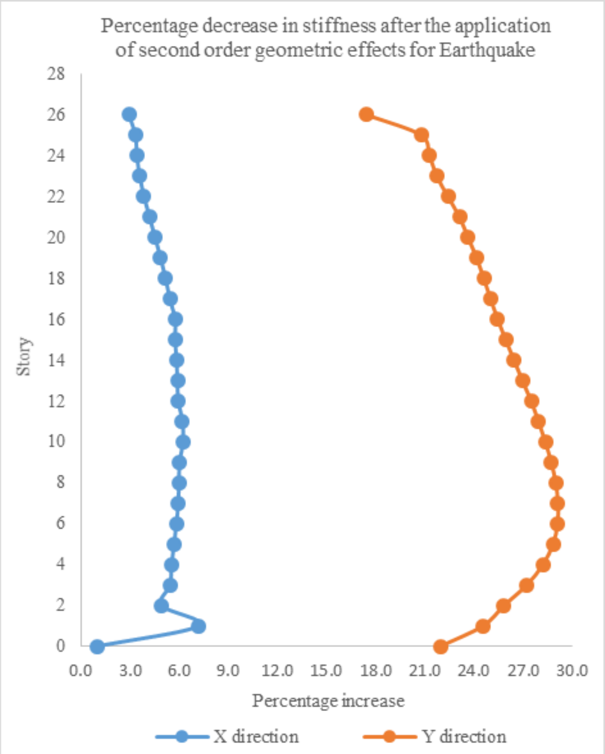

Fig. 10. Storey stiffness of each floor

E. Overturning Moments:

When lateral loads act on a structure, for adequate stability of the structure as a whole should be safeguarded at the foundation level, these are accounted as overturning moments which try to rotate the structure. These overturning moments are individually shown both in X and Y direction with and without the consideration of second order geometric effects.

TABLE VI. Overturning moments

	Without 2nd order effects		With 2nd order effects		Percentage Increase(%)	
Load Case	**MX**	**MY**	**MX**	**MY**	**X**	**Y**
EQ X	9164.8913	108545.3	9361.706	110375.3	2.1	1.6
EQ Y	58207.732	11332.76	62245.8	11786.49	6.9	4.0

The overturning moments for the dynamic seismic loading can be observed that they are increasing when the second order geometric effects are taken into consideration, the percentage increase in the other load cases like dead, live and wind are relatively less.

VIII. CONCLUSIONS

From the post-processing results and discussions as mentioned above, for each parameter the variation for the two models is clearly visible such as

- The model behaviour of the structure is same but the time period increases with the incorporation of second order effects, which in turn says that the stiffness has decreased.
- In case of the lateral displacements their magnitude is clearly increasing and it's prudent with the increased displacements the delta is going to increase which is going to increase the moments at the base hence it warrants the heavier design.
- The lateral drifts are increasing and with the increase of lateral displacements, it has a significant effect on the aesthetic on non-structural members like partition/curtain walls that needs to be checked and also on the architectural members like glazing/brick walls and this result of increased drifts may reduce the serviceability of the building with higher lateral force. In order to maintain the aesthetic of non-structural elements. We need to mitigate this second order geometric effects by accounting for the P-delta and incorporating it in the design.
- There is the redistribution of stiffness is observed clearly from the virtual work diagram when the second order geometric nonlinear effects are taken into consideration then the shearwall need to work more than the nominal and depending on the available results we can provide the steel accordingly and can be made effective.
- There were no changes in the deflection, base shear of the structure, when the second order geometric nonlinear effects were incorporated.
- The overturning moments are coming out to be slightly increased when the second order geometric nonlinear effects are taken into consideration this is because of the increased displacements.
- From the results and response of the building, the shear walls have been designed and the percentage increase in the required area of steel is more when second order geometric nonlinear effects will be taken into account. It is to be provided so as it can resists the heightened responses which are clearly visible in the results of the building.
- The second order nonlinear effects are higher for the high rise structures. Hence it is crucial that these kind of nonlinear effects should be taken into the analysis and design of the structures so that these effects and responses to be accounted for in turn making the design effective and efficient.

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