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Linear and Nonlinear Static Analysis of High-Rise Buildings Under Wind Load Using Direct Analysis Method

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Abstract: ***This study concerns with the investigation of P-Delta effects on tall steel buildings. After reviewing the different structural systems of tall buildings, bundled tube system was selected for its ability to resist lateral loads for all commonly used height ranges, including those considered in this research. Five building models ranging from 10 to 50 stories were modeled and analyzed linearly and nonlinearly using ETABS. All models are square in plan with an area of (36m × 36m), and a fixed story height of (4m). all models were braced in the along wind direction only with an X-brace system. Static wind load as per ASCE 7-10 is applied to the structure as the main lateral load. After analysis, a comparative study was presented with respect to two analysis methods (Amplified First Order and General Second Order Method), the comparison incorporated top displacements, maximum drifts, base shears and base moments. The study reveals that General Second Order method should be used for tall buildings since it yields larger values than Amplified First Order method, also P-Delta analysis is significant for buildings higher than 20 stories.***

Keywords: Direct Analysis Method, P-Delta effects, Tall Steel Building, Wind Loading, ETABS.

1. Introduction

There has been a major move towards tall steel building in recent years [1]. Stability plays an important role in determining the design of any structure. In tall buildings, stability becomes more prominent since effects such as, P-Delta effects would occur and undermine the stability of tall buildings, exacerbating the effectiveness of tall buildings to lateral loads.

There have been so many occasions in which structures failed due to instability, and thus a special type of analysis should be carried out to avert instability issues.Engineers typically use linear elastic static analysis to determine design forces and moments resulting from loads acting on a structure. In a first-order elastic analysis, equilibrium and kinematic relationships are based on the undeformed geometry of the structure; the resulting forces and moments take no account for the additional effects due to the deformation of the structure under load.When lateral loads, such as wind loads, are applied to the structure, it often assumes a configuration which deviates quite noticeably from its undeformed configuration requiring a second order analysis. A second order analysis,which applies equilibrium and kinematic relationships to the deformed structure, is always necessary for the stability consideration of structures.

The P-Delta effects are the second order effects seen in slender structures due to additional moments developed due to excessive lateralsways. Two types of secondary effects can be identified: The P-δ effect and the P-Δ effectaccording to AISC 360-10, P-δ is the effect of loads acting on the deflected shape of a member between joints and nodes, whereas P-Δ is the effect of loads acting on the displaced location of joints or nodes in a structure. **Figure 1**shows both types of P-Delta effects [2].

Wind creates inward and outward pressures acting on building surfaces, depending on the orientation of the surface. This pressure increases uplift on parts of the building, forcing the building apart if it is too weak to resist the wind loads. Therefore, it is crucial to overcome this problem by selecting an appropriate connection between beams and columns in a frame such as rigid or pin ended, moreover, a suitable bracing system must be introduced to withstand any additional lateral loads [3].

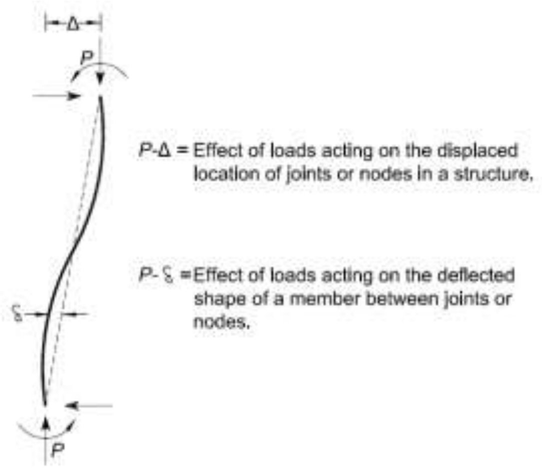

Figure 1: P-Delta effects [2]

The issue of P-Delta effects was extensively investigated in recent years,Kulkarni et al. [4] investigated P-Delta effects on tall steel structures. Earthquake loading was introduced to the structure. The results showed an increase of about 40% in displacement values and 8% in axial force values when compared with linear analysis results. Mallikarjuna and Ranjith[3] studied P-Delta effects on the stability of steel frame structure. The researchers used an 18 story steel frame structure with an X-bracing system. The displacement values for P-Delta analysis were increased from 70 to 75% for Continuous type bracing and 85 to 95% for Alternative type bracing when compared to static analysis. Mosa studied the effects of wind loading on tall concrete building. The results showed that P-Delta with large displacement analysis is important to obtain the correct displacement as well as shear forces [5].

2. Statement of the Problem

AISC 360-10 and later versions require that stability must be provided for the whole structure as well as for its individual elements. AISC 360-10 states that methods of analysis that takes into consideration the influenceof P-Delta effects (P-Δ and P-δ), geometric imperfections, out ofplumbness, and member stiffness reduction are acceptable. ASIC 360-10 has incorporated the Direct Analysis Method in chapter C to be the fundamental method of analysis as it takes into account the effect of axial, shearand flexural deformations and the memberstiffness reduction due to residual stresses. This method can appear in various formatsaccording to the choice of the engineer as allowed in the code [6].

The finite element code ETABS 2015 "Extended 3D Analysis of Building Systems" allows users to select one of the four methods of analysis that fall under The Direct Analysis Method. The four methods of analysis are as follows:

1) Direct Analysis Method with General Second Order Analysis and Variable Factor Stiffness Reduction (AISC 360-10 C1, C2).
2) Direct Analysis Method with General Second Order Analysis and Fixed Factor Stiffness Reduction (AISC 360-10 C1, C2).
3) Direct Analysis Method with Amplified First Order Analysis and Variable Factor Stiffness Reduction (AISC 360-10 C1, C2).
4) Direct Analysis Method with Amplified First Order Analysis and Fixed Factor Stiffness Reduction (AISC 360-10 C1, C2) [7].

In this paper,all models were analyzed linearly and nonlinearly using method 2 and 4 in order to emphasize the difference between the two methods and which one is more efficient and influential for tall buildings and yields critical outcome, and thus results were illustrated and compared for discussion.

The main difference between method 2 and 4 is briefly explained in**Table 1**. Amplified First Order Analysis is thoroughly explained in Appendix 8 of AISC 360-10 listed under the title ‘Approximate Second Order Analysis”, whereas The Direct Analysis Method is detailed in Chapter C of AISC 360-10.

Table 1: The Essentials and Limitations of the Design Analysis Methods [7].

Direct Analysis Method		
Option	Limitation Or Applicability	Essentials of the Method
General Second Order Analysis	No Limitation	2nd Order Analysis Reduced Stiffness $EI^* = 0.8\tau_b EI$ $EA^* = 0.8EA$ $\tau_b = 1$ B_1 and B_2 not used $K_2 = 1$ used for P_n otional load coefficient = 0.003 (typically)
Amplified First Order Analysis	No Limitation	1st Order Analysis Reduced Stiffness $EI^* = 0.8\tau_b EI$ $EA^* = 0.8EA$ $\tau_b = 1$ $K_1 = 1$ for B_1 $K_2 = 1$ used for P_n and B_2 Notional load coefficient = 0.003 (typically)

Where
EI and EA = the flexural stiffness.
τ_b = factor.
K_1 and K_2 = effective length factors in the plane of bending.
B_1 and B_2 = amplifiers to account for P-δ and P-Δ respectively.
P_n = first order axial force.

3. Description of Models

Models adopted throughout the present study are essentially multi-story steel buildings with different number of stories. Mainly, all models are square in the plane and divided into 9 bays in each direction (X and Y), each panel has a span of 4 meters. The story height is fixed at 4 meters, and the number of stories is ranging from 10 to 50 with 10 stories increment (5 models in total).

The floor system is set to be composite concrete deck slab with properties conforming to the stipulations stated in AISC 360-10. The total depth is assumed to be 100 mm which includes both slab and rib depths. Constant number of shear studs connecting the deck slab to secondary steel beams (joists) to simulate full composite action. Default meshing of floor system is selected, which auto cookie cuts the horizontal floors at beams and walls, and consequently 3 elements for each panel are created.The models were braced in the X-axis direction along which wind loading was applied. X-bracing system was implemented for its efficiency to resist lateral loads as shown in **Figure 2**.

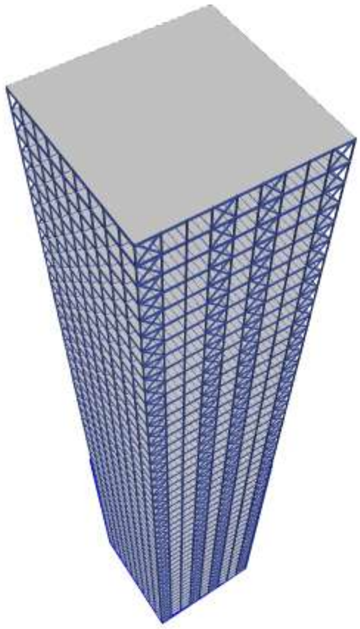

Figure 2: Three-Dimensional ETABS building model.

Moment at ends of columns and girders are assumed continuous, whereas pinned connections are assigned for cross bracing and secondary beams (joists). The superstructure model was isolated from its surroundings, and placed upon idealized rigid supports. The support under each column is assumed fixed boundary condition.**Figure 3**shows the plan for the main study models, a square plan (36 by 36) with the columns' major axes along the X-axis.

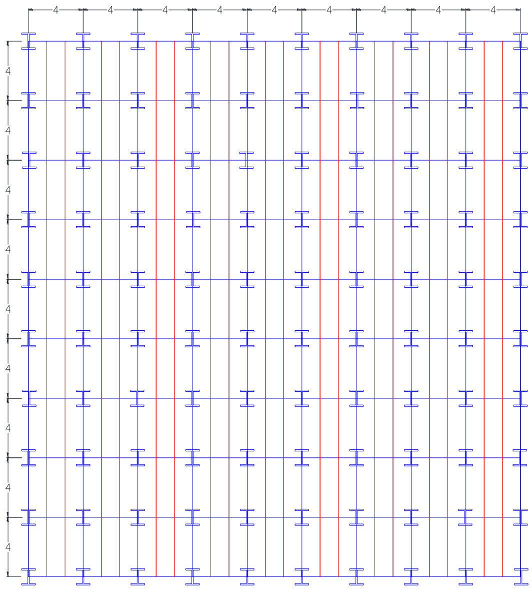

Figure 3: Model Plan

Load cases and wind coefficients adopted in the present study are listed in **Table 2**.Property data for concrete and steel are shown in **Table 3**.Sections of the different structural components incorporated in the present study such as, girders, joists, bracing, and columns, are selected to satisfy strength, serviceability, and stability limit state under static gravity and wind load.

Table 2: Load cases and wind parameters.

Case	Value
Super Dead Load	2 kN/m^2
Live Load	2 kN/m^2
Line Load	1.5 kN/m
Wind Speed	100 mph
Exposure Type	B, C, D
Topographical Factor	1
Gust Factor	0.85
Directionality Factor	0.85

Table 3: Material properties.

Property	Steel	Concrete
Modulus of Elasticity, E	199999 MPa	≈25000 MPa
Poisson's Ratio, U	0.3	0.2
Coefficient of Thermal Expansion, A	0.00001171/C	0.00000991/C
Shear Modulus, G	76903 MPa	10356 MPa
Compressive Strength, f'c	-	27 MPa
Minimum Yield Stress, Fy	344 MPa	-
Minimum Tensile Strength, Fu	448 MPa	-
Weight Per Unit Volume	77 kN/m^3	23.5 kN/m^3

Buildings are symbolized or labeled according to their height as (B10, B20, B30, B40, B50), starting from 10 story building and up to 50 stories, respectively. Different columns, girders and bracing sections are selected with increasing values as the height of building or the number of stories increased to accommodate building flexural stiffness requirements for strength and stability.

4. Design Load Combinations

Buildings are designed to withstand all applied loads with a reasonable safety factor, in other words, the design strength of the building must exceed the factored loads stipulated in the various international design codes. The default design combinations are the various combinations of the already defined load cases such as, dead load, live load, and horizontal wind load. AISC 360-10 was used to generate the various load combinations regarding both steel frame design and composite beam design.

5. Analysis Results

As mentioned in earlier sections, The Direct Analysis Methods allows users to incorporates any of the four analysis methods. In this section, analysis results of method 2 and 4 are laid out in separate subsections.

5.1 Amplified First Order Analysis

To incorporate P-Delta effects in this type of analysis, an amplification of the first order analysis results is recommended by ASIC 360-05 and later versions, and as stated in Table 1, which lays out two equations 1 and 2. In this case the method is termed amplified first order analysis which accounts for second order effects by amplifying the axial forces and moments in members from a first-order analysis.

In this subsection, five models were analyzed using Amplified First Order Method, and analysis results were depicted in figures and tabulated in order to be compared with General Second Order Analysis Method. **Table** 4displays the maximum displacement and drift for five models varying in height analyzed using amplified first order method. Results indicate that the values increase as the number of stories increases.Following the same idea in Table 4, **Table** 5 indicates that moment values increase as the number of story increases.**Error! Reference source not found.**shows story displacements for the different models, and results show that displacement increases with height as a result of stiffness reduction of the building model and the increase of wind load as we go above the ground. **Error! Reference source not found.**exhibits story drift ratios due to equivalent static wind load, maximum values occur in mid-height stories. The jumps along the curve are the result of change in columns' sections up the height.

Error! Reference source not found.and**Error! Reference source not found.** depict story moments and story shears respectively. Moments and shear increase with height due to the increment in wind load with height.**Table** 6displays the superiority of P-Delta analysis over linear analysis in terms of top story displacement and maximum drift for all building models.

Table 4: Maximum displacement and drift values for different building models

Building	Top Displacement (mm)		Maximum Drift Ratio	
	Linear Static	P-Delta	Linear Static	P-Delta
B10	40.4	44	0.001327	0.001458
B20	125.3	139.8	0.002133	0.002411
B30	251.3	286	0.00287	0.003327
B40	403.7	464.7	0.003138	0.003646
B50	555.6	643	0.003315	0.003877

Table 5: Moment values for different building models.

Building	Base Moment (kN.m)		%Increase in B.M due to P-Delta
	Linear Static	Nonlinear Static (P-Delta)	
B10	1945311	1948081	0.14%
B20	4060504	4078051	0.43%
B30	6390798	6444542	0.84%
B40	8936630	9051384	1.28%
B50	11654375	11850073	1.68%

Table 6: Percentage increase in top displacement and maximum drift due to P-Delta effects.

Building	% Increase in building top displacements due to P-Delta	% Increase in drift due to P-Delta
B10	8.91%	9.87%
B20	11.57%	13.03%
B30	13.81%	15.92%
B40	15.11%	16.19%
B50	15.73%	16.95%

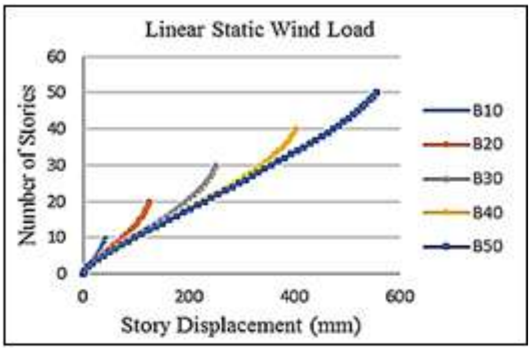

Figure 4: Story displacements

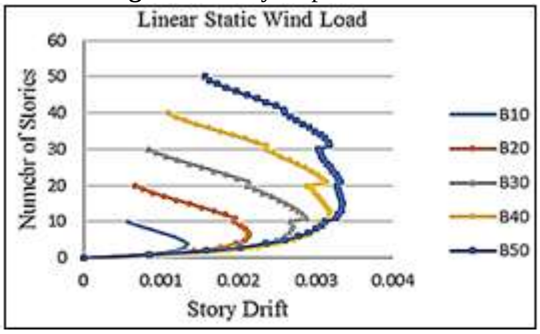

Figure 5: Story drift ratios

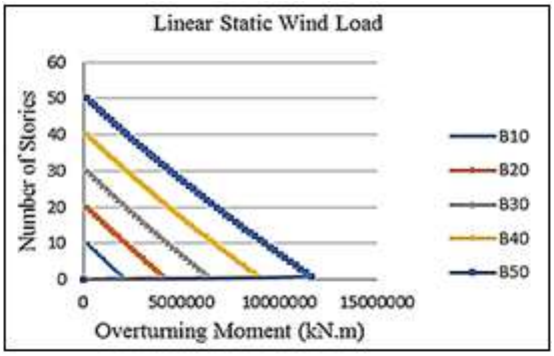

Figure 6: Overturning moments values

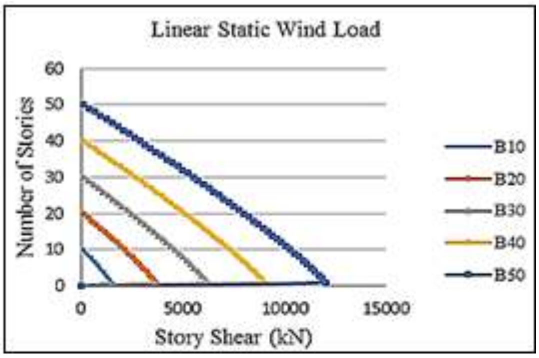

Figure 7: Story shear values

5.2 General Second Order Analysis

This particular type of analysis incorporates geometric nonlinearity in the form of P-Delta and P-Delta with large displacement/rotation. Equilibrium equations are written with respect to deformed geometry.

All models were analyzed under General Second Order analysis method, and results were compared with those of amplified first order method. Table 7expresses a simple comparison in terms of top displacements for the various models, and percentage increase of General Second Order analysis over Amplified First Order analysis is outlined for all models. Following the same idea ofTable 7, **Table** 8shows the same comparison, but in terms of maximum drift. **Error! Reference source not found.** and **Error! Reference source not found.** illustrate in a more comprehensive way the information in Table 7 and Table 8. Results of absolute base shears and moments in both methods of analysis are identical as exhibited in **Table** 9 and **Table** 40.

Table 7: Comparison in terms of top story displacement

Building Label	Top Displacement (mm)		% Increase
	Amplified 1st Order	General 2nd Order	
B10	40.4	50	23.76%
B20	125.3	154.3	23.14%
B30	251.3	308.7	22.84%
B40	403.7	495.6	22.76%
B50	555.6	682.7	22.88%

Table 8: Comparison in terms of maximum drift

Building Label	Maximum Drift Ratio		% Increase
	Amplified 1st Order	General 2nd Order	
B10	0.001327	0.001643	23.81%
B20	0.002133	0.002627	23.16%
B30	0.00287	0.003521	22.68%
B40	0.003138	0.003912	24.67%
B50	0.003315	0.004088	23.32%

Table 9: Comparison in terms of base shear

Building Label	Base Shear (kN)	
	Amplified 1st Order	General 2nd Order
B10	1543.2612	1543.2612
B20	3741.1643	3741.1643
B30	6290.9247	6290.9247
B40	9099.8971	9099.8971
B50	12118.8272	12118.8272

Table 40: Comparison in terms of base moment.

Building Label	Overturning Moment (kN.m)	
	Amplified 1st Order	General 2nd Order
B10	1945311	1945311
B20	4060504	4060504
B30	6390798	6390798
B40	8936630	8936630
B50	11654375	11654375

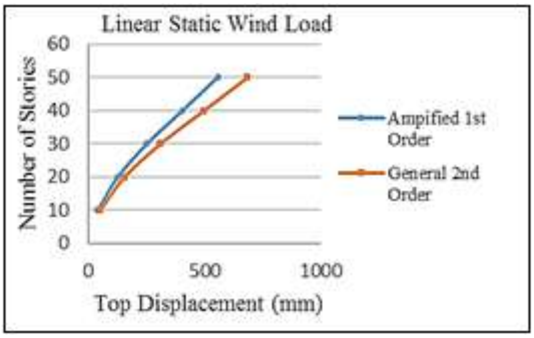

Figure 8: Top displacements for all models

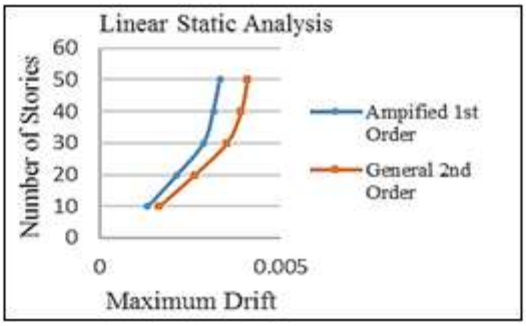

Figure 9: Maximum drifts for all models.

For more distinctive comparison, below are the displacements and drifts of each model analyzed under both methods of analysis illustrated graphically.

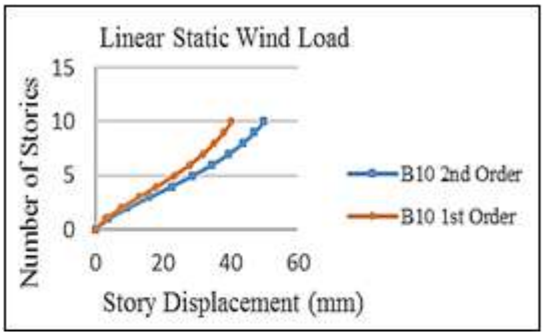

Figure 10: Story displacement for B10

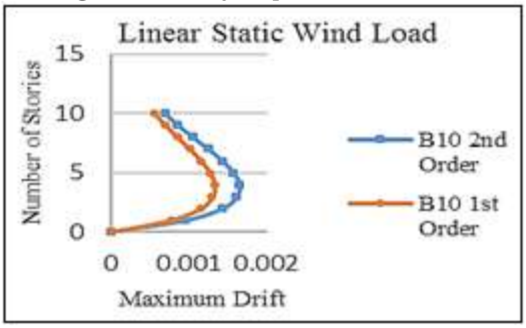

Figure 11: Story drift ratio for B10

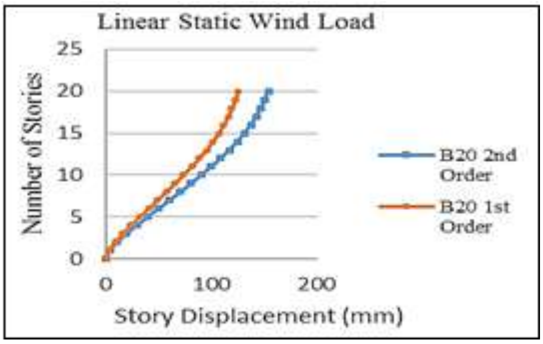

Figure 12: Story displacement for B20

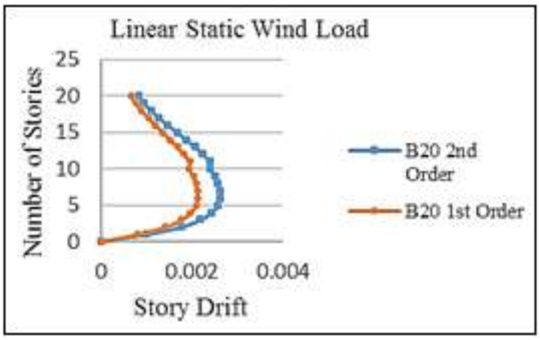

Figure 13: Story drift ratio for B20

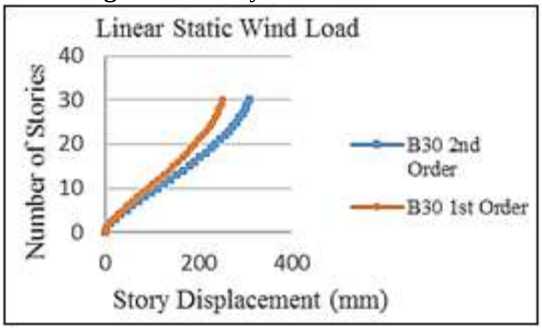

Figure 14: Story displacement for B30

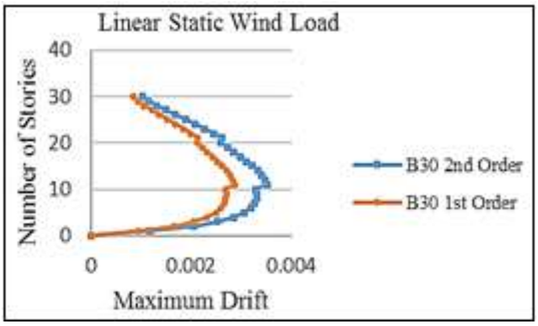

Figure 15: Storydrift ratio for B30

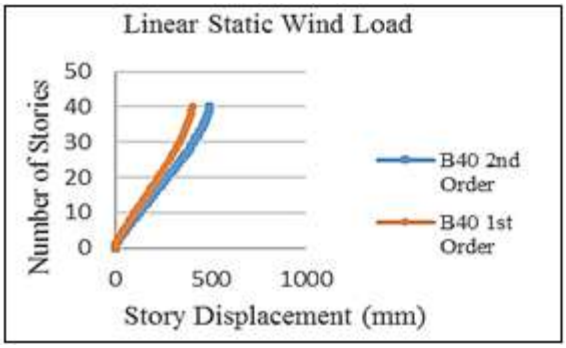

Figure 16: Story displacement for B40

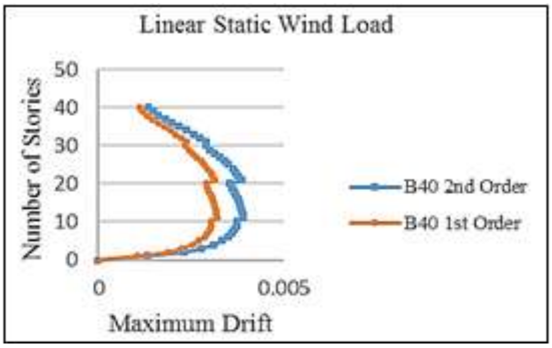

Figure 17: Storydrift ratio for B40

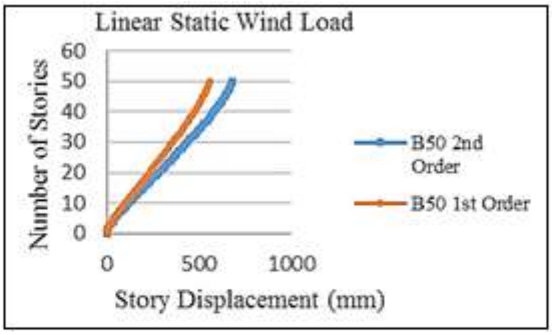

Figure 18: Story displacement for B50

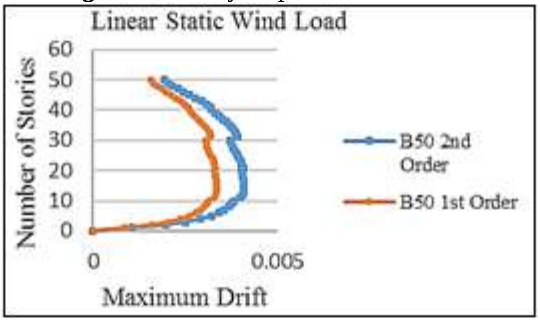

Figure 19: Story drifts ratio for B50

6. Conclusion

In this paper, an attempt is carried out to investigate the effects of P-Delta on tall steel buildings, and thus a conclusion is drawn down below.

1) Five models were analyzed statically for wind load using amplified first order method. Expectedly, nonlinear results were greater in magnitude than linear results in terms of top displacement and maximum drift. The percentage increase due to nonlinear analysis over linear analysis was (8.91%-15.73%), and (9.87%-16.95%) for top displacement and maximum drift respectively.
2) A comparison between amplified first order method and second order method was conducted and laid out as percentages. Second order analysis method imparted greater values than amplified first order. Results of top displacement and maximum drift showed that the percentage increase of second order analysis over amplified first order was approximately 24%, whereas both methods yielded the same results for base moments and base shear.

7. Recommendation

It is prudent to keep the following takeaways in mind in designing tall steel buildings subjected to lateral load.

1) Second order method is to be used in analysis and design of tall steel buildings, and it is preferable depending on the height of the building to incorporate P-Delta effects as well.
2) Nonlinear P-Delta analysis should be used for building higher than 20 stories.

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