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SECOND ORDER ANALYSIS OF OIL AND GAS PROCESS PIPE RACK STEEL STRUCTURE FOR LATERAL LOADS

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Abstract: The technological platforms and pipe racks are structures in oil and gas refineries, Petrochemical, chemical and power plants are primarily steel structures which occupy large space for critical operations and effective routing of large diameter pipes. Technological platforms and process pipe racks are the main arteries of process plant as they are designed to support pipes, power cables and instrument cable trays. The seismic evaluation of these pipe rack supporting structures in refineries is one of the most important part of structural analysis for safe and stable production. Pipe racks are mostly long, narrow structures that carry pipes in longitudinal as well as transverse direction. These pipe racks are prone to large displacements during major earthquake ground motions. These earthquake loads acting laterally causes large displacement and thus sway criteria become critical. This sway can lead to large deformation of structure and may collapse easily. To avoid these problems, we consider Second Order Effect i.e., P – Delta effect in designing. As the height of structure increases, P- Delta effect becomes important. The P-Delta analysis can be done for both static and dynamic analysis. In this study, static analysis is carried out on pipe rack structure and results based on storey displacement, moments and storey drift are observed. It is observed that 9% displacement of column is increased when second order analysis is carried out. The use of Second Order analysis results in more realistic behaviour of the structure. In this dissertation it is observed that for wind loads and mid-scale earthquakes, bracing members get failed after performing second order analysis. Since this study is done for short run, the displacement variation is observed by 9%. Due to these variations in displacement and moment, bracings have failed. If this analysis carried out on long run, then variations will increase definitely and it may cause failure in structure.

Keywords: Second Order Analysis, P-Delta effect, Direct analysis method, Oil and Gas, Pipe Rack, Seismic analysis, Static analysis, etc.

I. INTRODUCTION

The pipe rack is the structure in oil and gas refineries, petrochemical, chemical and power plants are primarily steel structures which occupy large space for critical operations and effective routing of large diameter pipes. The pipe networks are considered as main components of process plant as they transfer toxic fluids and gases which are highly dangerous for human health if it exposed with open air or open to surface. The pipe rack carries the pipes and cable trays from one equipment to equipment within a process unit or carries the pipe and cable trays from one unit to another unit. Pipe racks are mostly long, narrow structures that carry pipes in longitudinal direction. The design, fabrication and erection of pipe racks in high seismic zone require special attention. To make structure stable, stability analysis should be done. Implementation of stability analysis in design has historically been difficult as calculations were performed by hand. Various methods were created to simplify the analysis and allow engineers to partially include the effect of stability via hand calculations. Various methods were developed in powerful analysis software to account stability analysis. Most engineers now have access to software that will complete a rigorous stability analysis. According to the 2016 AISC specification for Structural Steel Building (AISC 360-16) stability analysis shall consider the influence of second order effects (P- Delta effects), flexural, shear and axial deformations, geometric imperfections and member stiffness reduction due to residual stresses. Collapse of the structure is the main reason for the loss of life of people. It is said that natural calamities never kill people, it is badly constructed structure that kill. Hence it is very important to analyse the structure properly for different natural calamities like earthquake, cyclones, floods etc. Therefore, omitting stability analysis in the design of structures creates unnecessary risk and it is unjustified.

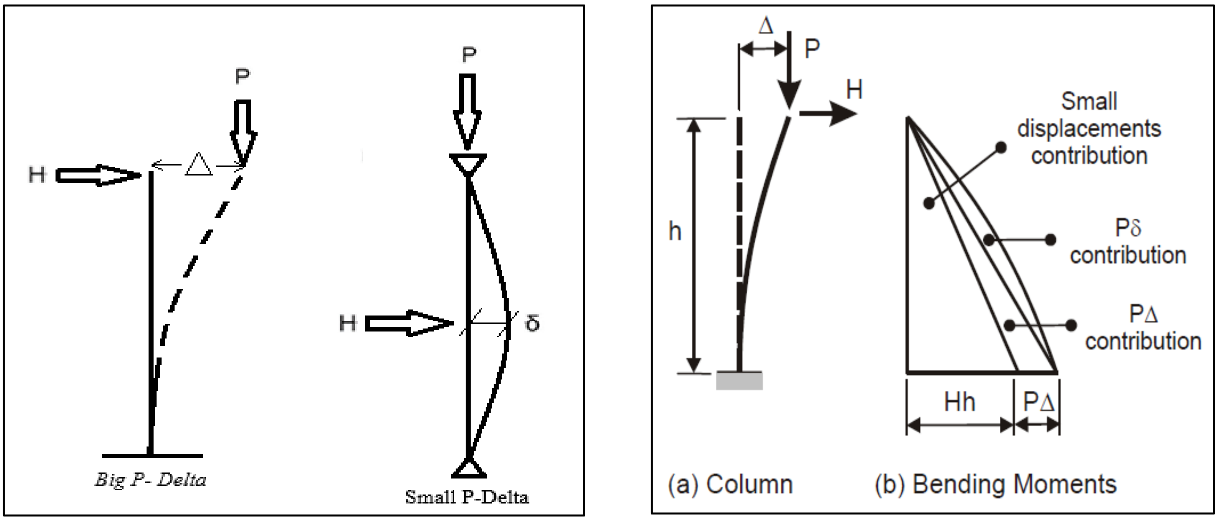

Figure 1. Concept of P-Delta analysis

P-Delta analysis: P-Delta is geometric non-linear effect that occurs in structures that are subjected to gravity loads and displacement due to lateral loads. Due to gravity loads and lateral displacement, slender structures experiences additional stresses and deformation due to the change of position of the structure. First order analysis normally considers small displacements and compute the equilibrium of the structure and internal stresses based on the undeformed geometry. However, second order analysis consider the deformed geometry of the structure and may require an iterative approach for the computation of equilibrium. During the simultaneous action of vertical and horizontal loads, the structure deflects due to the action of the horizontal load. As the structure deflects, the position of the vertical load (P) shifts by a distance Δ such that the vertical load instead of acting axially along the column now induces a moment reaction at the base P·Δ. The interaction of the gravity load P and lateral displacement Δ to produce additional secondary effects in a structure is handled under P-delta analysis. There are two types of P-delta effects which are: 1) P- “Large” delta (P-Δ) – a structure effect 2) P- “Small” delta (P-δ) – a member effect

Large delta is associated with the global displacements and effects on the structure, small delta takes into account the local effects and displacements of the members. The sensitivity of a structure to P-Delta effect is related to the magnitude of the axial load P, stiffness/ slenderness of the structure as a whole, and slenderness of individual elements. Second order effects are prominent in structures under high compressive load with low stiffness or high slenderness. The structure is more sensitive to P-Delta effects as the compressive load exits the critical buckling load.

II. LITERATURE REVIEW

According to worldwide rules and standards**, Nitesh J Singh et. al.** [1] have optimized the design and assessed steel pipe racks for the oil and gas sectors. Wind and earthquake factors were applied to the structure, as well as piping stress loads from Kuwait's standard organization. The increased distance between supports allows stress and deflection values within safe limits. To support pipes greater than 30 mm diameter, support beams are separated at 6 m c/c. As a result, the total number of continuous beam members was lowered. Horizontal bracing was used to resist lateral deflection and transmit the lateral load through vertical bracing. From this study it is observed that bracings are used to transfer the load also to lower the size of the component and the overall cost of construction.

Richard M. Drake et. al. [2] summarized building code and industry practice design criteria, design load, and other design factors for pipe racks. ASCE 07 specifies a variety of loads. AISC 360-05 specifies the majority of structural steel material references. Additional design parameters for pipe racks have been published by Process Industry Practices, PIP STC01015 (PIP 2007). Because most codes were written for buildings, the study claims that several standards remain unclear as to how they relate to pipe racks. Client requirements or regional practices might impact engineering practices. Additional, updated design guides should be required so that design methodologies remain standard. This research helps to understand the codal provisions and the various loads to be considered for the pipe rack.

Mario DE STEFANO et. al. [3] investigated the seismic performance of a double-spanned, 8-story RC frame designed for high ductility class using the most recent version of Eurocode 8. A nonlinear dynamic analysis was used to determine the structure's seismic response, which took into consideration major degradation elements that affect RC structures' cyclic behavior. To check the structure's seismic response, top displacement and interstorey drift were considered as response parameters and compared to the limit values published by the Structural Engineers Association of California for RC-framed structures. 13.5% deformation in story drift was observed. The study reveals that P-Delta effects cause a significant rise in deformations, since the maximum interstorey varies along the frame.

Mohammad Karimi et. al. [4] used ETABS to analyze the structure, including equivalent static analysis and linear dynamic analysis with torsion and P-Delta effects. For seismic evolution of the foundation system, gravity and lateral load combinations have been examined. Gravity and lateral stresses, as well as lateral displacements, cause overturning stability and rising of foundation systems. Because the P-Delta effect is taken into account in the analysis, loads and displacements are calculated with it in mind. The structure is controlled using the Allowable Stress Method (ASD), and the concrete section is assessed using ACI 318-02. Later it was found that the connection failure was caused by an external issue such as corrosion and environmental conditions. Seismic loads generate lateral movement of these structures. From this study, we can conclude that all the environmental conditions and factors must be keep in mind while designing the structure to keep it safe.

The author, **Pushparaj J. Dhawale et. al.** [5] studied the effect of linear static analysis (without P-Delta) and nonlinear static analysis (with P-Delta) on high-rise buildings with various storey counts. He used SAP 2000-12 software to model residential buildings with G+19, G+24, G+29, i.e., 20,25, and 30 storey RCC framed buildings for earthquake load zone III. He found the results for the 20, 25, and 30 storey buildings individually. He discovers that the Bending moment changes by 2 to 6 percent, 2 to 4 percent, and 2 to 4 percent at the base. Changes in deflection are also 1-11 percent, 2-14 percent, and 3-15 percent. In a 20-story building, the change in bending moment of beams is less than 10%, but it can be up to 15% in a 25-story or 30-story structure. At the 20-story level, the bending moment of the column increases by up to 20%. The bending moment of a column changes by 8-30% at the 25th storey level. It's more noticeable on the external columns and beams that surround them. At 30 stories, the bending moment of a column changes by 10-35%. From this study, we can conclude that the P-Delta effect becomes increasingly important as the number of stories increases. For buildings with 25 stories (height= 75m), it is required to compare the findings of the analysis with and without the P-Delta impact.

Sabade Madhuri et. al. [6] used the analysis software STAAD.PRO to compare the Effective length Method (ELM) and Direct Analysis Method (DAM) methodologies for pipe rack structure. General requirements such as the second order effect, flexural, shear, and axial deformations, geometric flaws, and member stiffness reduction due to residual stresses were taken into account. When compared the direct analysis approach to the effective length method, the drift ratio was slightly higher. This demonstrates how a decrease in stiffness can amplify second-order effects. In the case of pipe rack stability analysis, the author suggests the Direct Analysis approach. Direct Analysis involved the most accurate data and has no drawbacks.

V. Guruprasad et. al. [7] used ETABS software to investigate the detailed behavior of structural abnormalities in high-rise buildings with and without the influence of the P-Delta effect. He looked at how buildings behaved in different irregular shapes and heights, such as C, L, H, and T shape buildings with 10, 15, 20, 25, and 30 storey heights. The building was assessed using the static approach for a basic wind speed of 50 m/s, while the dynamic wind study was done using the Gust factor method. Considering the influence of P-Delta for high-rise buildings, even for wind loads, is critical, and that it is required when the structure contains structural imperfections. From this study we can conclude that P-Delta effect should be taken into account for high rise building and when there are imperfections in structure, this effect must be considered always.

Tejas Jain et. al. [8] used IS 456, IS 1893, and IS 16700 to analyze and design a G+60 RCC framed structure. The deflection and storey drift of buildings with the P-Delta effect were compared to buildings without the impact. He discovered that the displacement of a building without the P-Delta effect is 218.806 mm, while the displacement of a building with the P-Delta effect is 232,61 mm, indicating a 6.67 % extra displacement. From this article, it is observed that after taking into account the second order effect, the values of storey drift and displacement alter significantly.

G+29 RCC framed structure was modelled in ETABS 2016 by **Phanikumar V. et. al.** [9]. The model was subjected to seismic and wind loads in accordance with IS 1893(2002) and IS 875 (Part 3) 2015. By considering the P-Delta effect and introducing shear walls at different positions, the displacements, narrative drifts, Bending Moments, and shear pressures were compared to the different models. In comparison to models evaluated without the P-Delta effect, it is observed that storey drifts in building models with the P-Delta effect were greater. In addition, when the P-Delta effect was taken into account, the bending moment in the shear wall increases by 18%.

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Pipe rack PR 18-01 was designed by **J. K. Sumanth et. al.** [10] based on the bails of standard load data provided by the mechanical and piping departments. It was designed in accordance with ASCE 07 and PIP STC 01015 (2007). Method LRFD in American Code AISC 360-10 used to model and analyze the structure. The structure's tonnage was 1365.068 tons. Column position kept in an I and H shape, which would be determined by the moment of inertia. Bracings were provided as required. Fixed supports were given to columns for lateral loads such as wind and earthquake loads, where fixed in one direction and pinned in the other. This paper helps to understand the general arrangement and design methodology of pipe rack structure.

As per **Abhijeet Dhavale et. al.** [11], lateral load produces an increase in lateral displacement, sway criteria significant. Author has prepared a case study for Second order analysis with Non sway (braced) and Sway frames (moment resistant frames). In member sizes, storey displacement, base shear, and economy was compared. Due to second order analysis, it was observed a 28.56% increase in top storey deflection in the X direction and a 25.76% rise in top storey deflection in the Z direction. From this study we can conclude that designing with second order analysis saves a lot of steel as compared to first order analysis for this particular structure.

III. DESCRIPTION OF STRUCTURE

A three-tier pipe rack uncladded all over of the length 30m in longitudinal direction, width 6m, and total height is 7.6m. Height of first tier is 3.6m and height of second and third tier is 2m each. 15 mm thick fire proofing agent AVIKOTE AV 650 of weight 10 kN/m^3 is considered for entire height. Temperature difference is 25°C. This pipe rack is modeled in STAAD PRO software for first order analysis and second order analysis design as per AISC code.

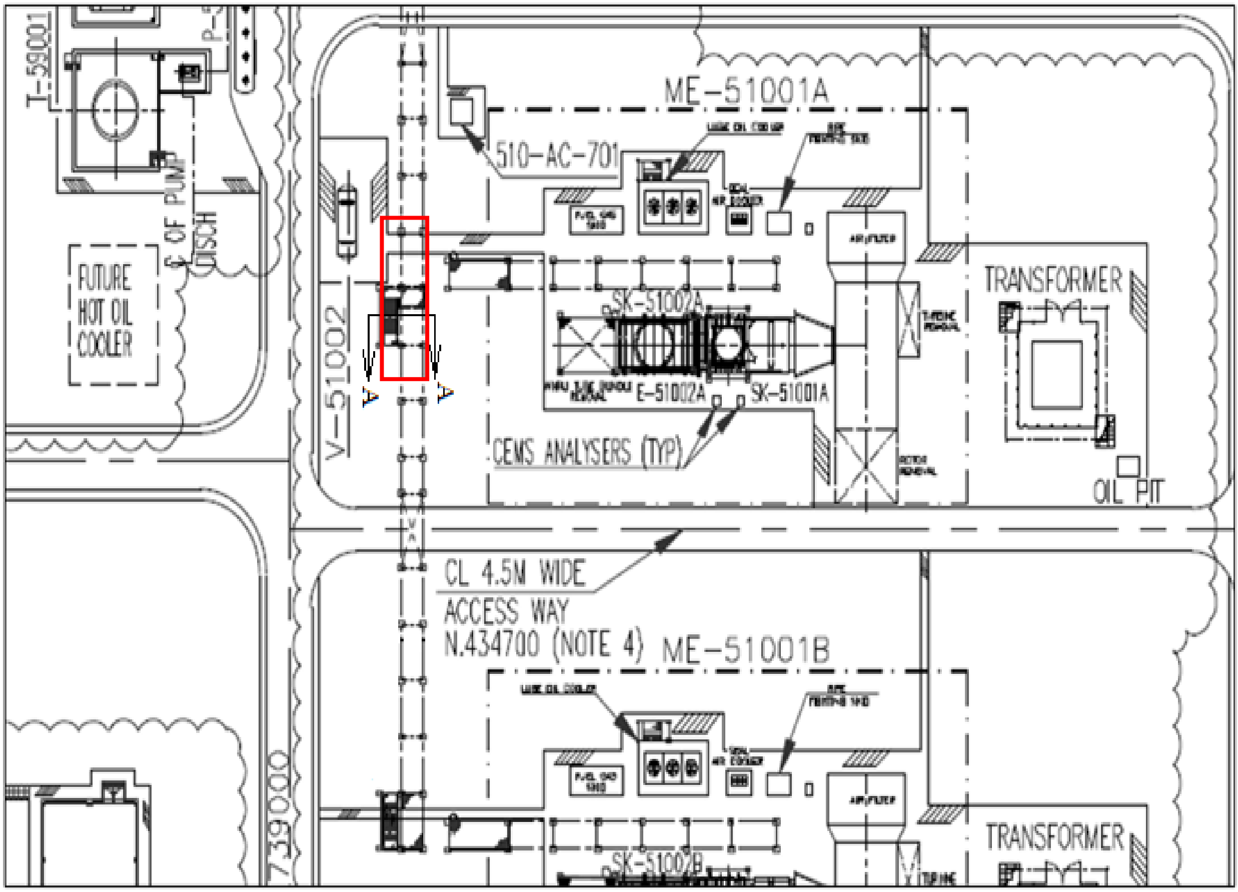

Figure 2. Key plan

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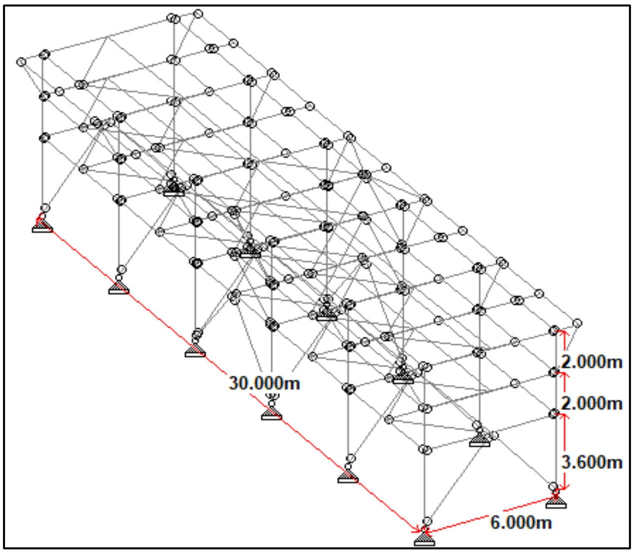

Figure 3. Modeling in Staad Pro

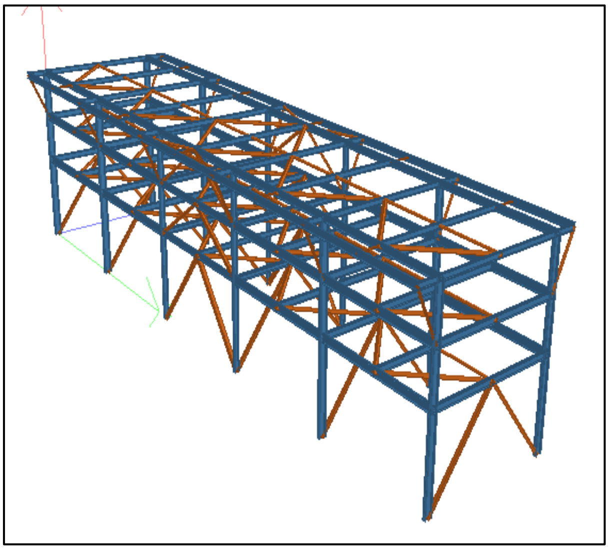

Figure 4. Render view 3D

The pipe rack is divided in 5 bays in longitudinal direction. There is an Anchor Bay placed at the center from the piping department. From the Key plan, actual place of the pipe rack in the refinery can be understand. The modeled pipe rack is shown in figure 3 and the 3-D rendering is shown in figure 4.

IV. DESIGN LOAD CALCULATION

Basic loads are applied in Staad model, as applicable in the structure and its elements in the form of load cases. Load cases includes all the basic loads such as Dead load, Live load, Wind load, Seismic load, Test load, Operational load, etc. Each load case is described in brief in ASCE 7 – 05.
Primary loads are as follows,

- Earthquake load on Structure (+X ETS) & (+Z ELS)
- Earthquake load on Pipe (+X ETP) & (+Z ELP)
- Dead load & Cable tray load DL & CTC
- Pipe Empty Load PE
- Pipe Content Load PC
- Pipe Test Load PT
- Pipe Friction Load (+X PFT) & (+Z PFL)
- Pipe Axial Load (+X PAT) & (+Z PAL)
- Pipe Contingency Load PCL
- Live Load LL
- Temperature load TL
- Wind Load (+X. -X) & (+Z, -Z)

Wind load calculation:

- Velocity Pressure (qz) = 0.613 x Kz x Kzt x Kd x V^2 x I (Clause 6.5.10 of ASCE7-05)
- Basic Wind speed – V = 44.5 m/s (Given in design criteria)
- Wind exposure category - K_z = C (Given in design criteria)
- Topography – Kzt = 0.85 to 1.04 (Figure 6-4 of ASCE 7-05)
- Importance factor – I = 1 (Given in design criteria)
- Wind directionality factor – Kd = 0.85 (Table 6-4 of ASCE 7-05)

Seismic load calculation:

- Site class = D
- Occupancy category = III

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- Importance factor = 1.25
- Response reduction factor = 3.25

V. DESIGN PARAMETERS

Design parameters has been applied in Staad model under two different sections namely, Strength Design Check & Serviceability Check. LRFD (Load and Resistance Factor Design) method has been used. The same structure is analysed for first order analysis and second order analysis.

Serviceability Check
- Deflection DJ1 & DJ2 to all bemas
- DFF 360
- Ratio 0.9

Strength Check
- Tensile Strength
- Yield Strength
- KY 1 to columns
- KZ 1.2 to column
- Net section factor for tension member 0.8
- Ratio 0.9

VI. RESULTS AND DISCUSSION

1) Displacement

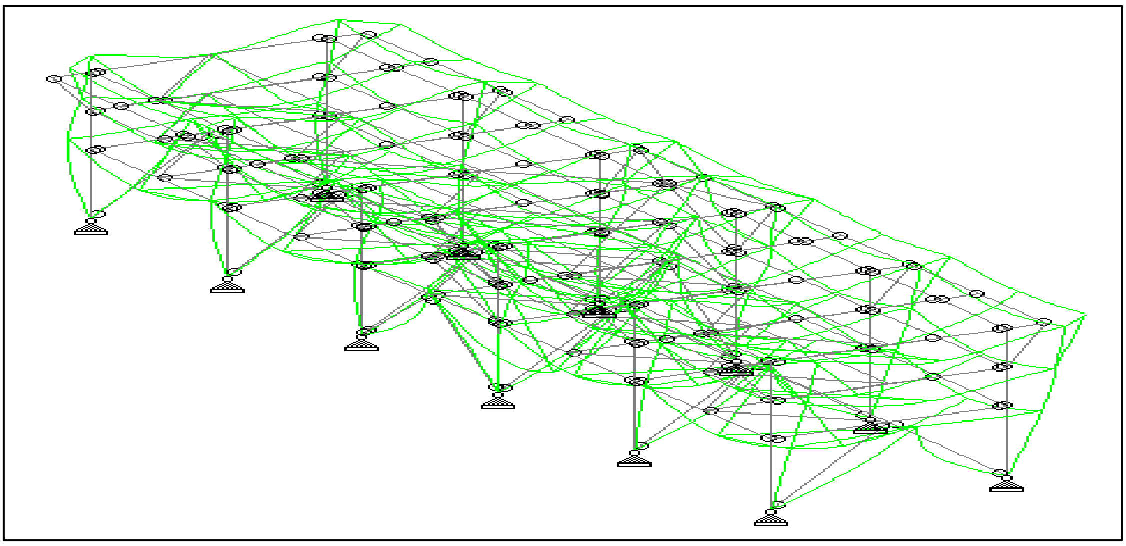

Figure 5. Displacement of pipe rack structure

Displacement of columns are compared for 1st order analysis as well as 2nd order analysis. According to AISC Steel design guide 3, allowable deflection limit is given Height/500 for column sections. Height/500 is 7600/500 = 15.2 mm. So here, displacement is within the limit for both type of analysis.

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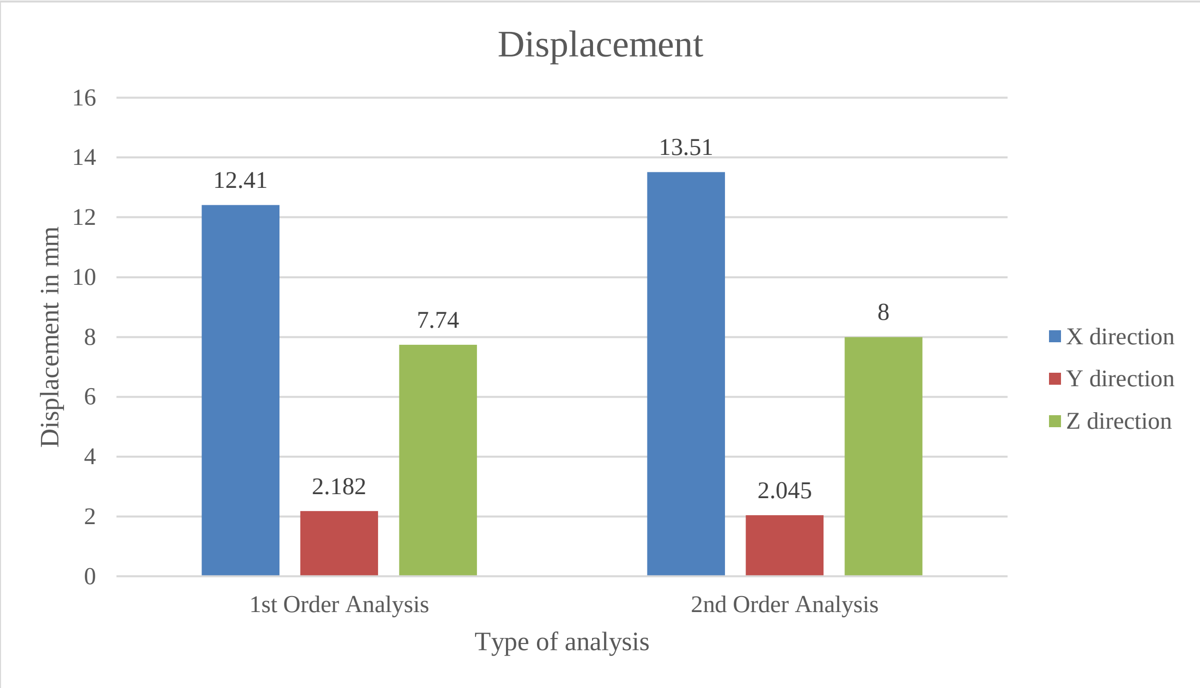

Figure 6. Displacement graph

2) Bending Moment

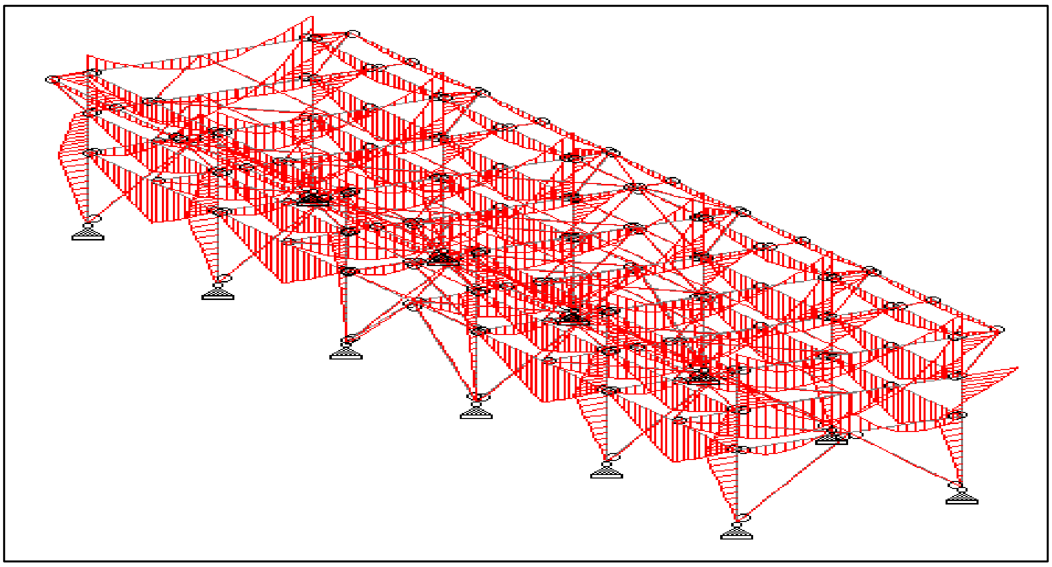

Figure 7. Bending moment diagram of pipe rack

Bending moment of columns are compared for 1st order analysis as well as 2nd order analysis. In second order analysis, extra bending moment is observed as displacement of column increases.

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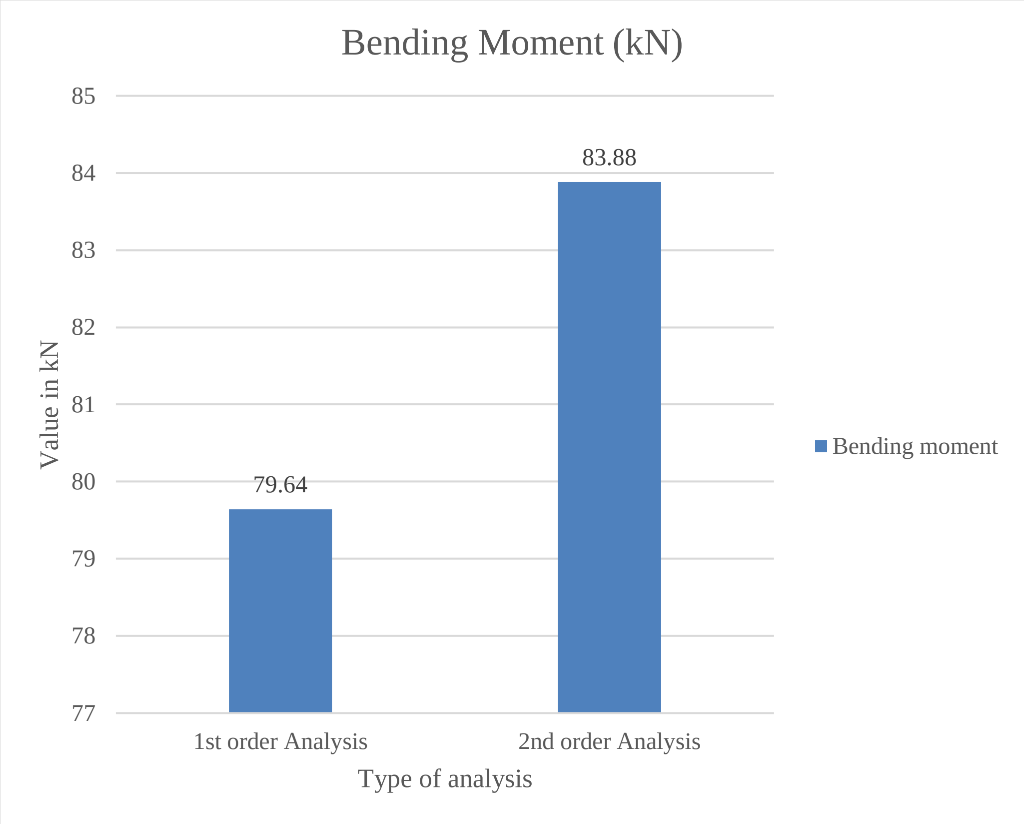

Figure 8. Bending moment graph

3) Story Drift

Storey drift of columns are compared for 1st order analysis as well as 2nd order analysis and it is shown in graphical column chart.

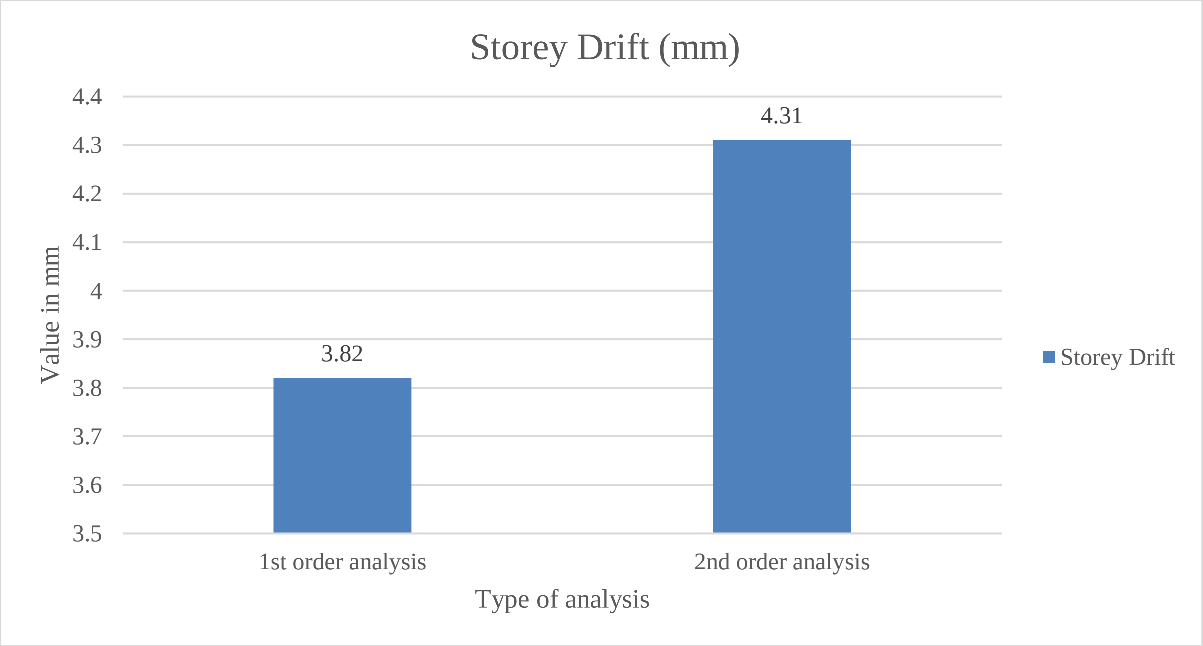

Figure 9. Story drift

4) Utilization ratio

Utilization ratios of the members are compared for 1st order analysis as well as 2nd order analysis and it is shown in graphical column chart.

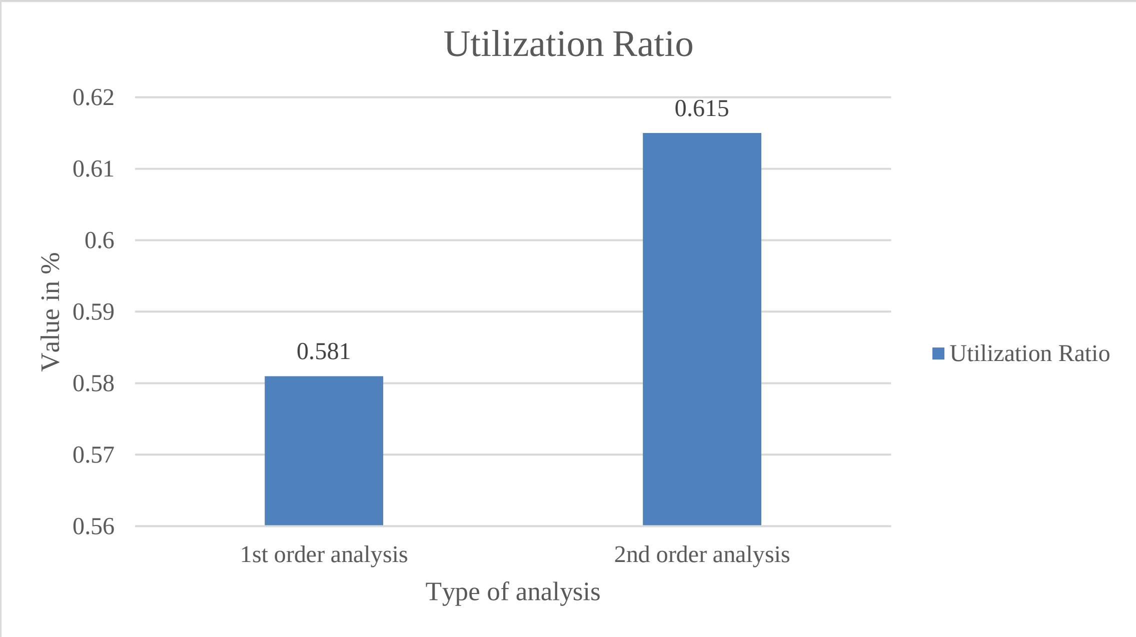

Figure 10. Utilization ratio

VII. CONCLUSION

After Second order analysis carried out on structure, following conclusion are observed.
When the vertical dead load is predominant with lateral load, it generates additional moment results,

- Displacement of column increases by 9% when second order analysis is carried out on structure. This effect is observed in Dead load and seismic load combination.
- It is observed that as column deflects, 5% increase in bending moment are observed extra in second order analysis compared to first order analysis.
- As the extra moments / forces induced in member, section capacity gets reduced and heavy section need to be provided.
- The story drift at the top tier increased by 13% as compared to first order.
- Utilization ratio of middle column gets increased as 6% additional strength is used due to extra moments.
- Four bracings get failed after performing second order analysis. This may lead to major structural loss in industry.
- From this study it is concluded that it is important to consider effect of Second order analysis for structures where the dead load and lateral loads are predominant to prevent structure from failure.

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