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Stability Analysis of Pipe Rack in Petrochemical Facilities

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Abstract: *Both AISC 360-05 and AISC 360-10 recognize at least three methods i.e. first order method, effective length method and direct analysis method for stability analysis. The new AISC specifications define the general requirements for stability analysis and design and give engineers the freedom to select their own methods. In this thesis a study has been conducted on the pipe rack structure to compare these methods using the 3D structural analysis program STAAD.Pro V8i considering general requirements such as influence of second order effects (P-Δ and P-δ effects), flexural, shear and axial deformations, geometric imperfections and member stiffness reduction due to residual stresses. Pipe racks are structures in petrochemical, chemical and power plants that are designed to support pipes, power cables and instrument cable trays. The design requirements found in the building codes are not clear on how they are to be applied to pipe racks. This thesis also summarizes industry practice design criteria, design loads and other design consideration for pipe racks.*

Keywords: *Direct analysis method, Effective length method, First order method, Pipe Rack, etc.*

1. Introduction

1.1 Stability analysis of Steel Structures

The AISC 360-05 Chapter-C specifies that the stability shall be provided for the structure as a whole and for each of its elements. That means the stability needs to be maintained for the individual members, connections, joints and other building elements as well as the structural system as a whole. The code recommends using any method that ensures the stability of the structure as a whole and for individual building elements, and meets with all the following requirements are permitted.

1. Flexural, shear and axial member deformations and all other deformations that contribute to displacements of the structure.
2. Second-order effects (both *P*-Δ and *P*- ẟ effects)
3. Initial geometric imperfections
4. Stiffness reduction due to inelasticity
5. Uncertainty in stiffness and strength

From stability consideration of a structure, AISC chapter C suggests the three approaches for determining the required flexural and axial strength of a member in the structure.

1. Effective Length Factor method (ELM) (C.2.2a)
2. First Order Analysis per C2.2b
3. Direct Analysis Method (DAM) (Appendix 7)

The application of these methods for stability analysis in design of structures varies greatly from firm to firm and from engineer to engineer. If stability analysis is not performed or a method of analysis is incorrectly applied, the ability of the structure to support the required load is potentially jeopardized. The analysis of nearly all complex structures is completed using advanced analysis software capable of performing various methods of analysis. Therefore omitting stability analysis in the design of structures creates unnecessary risk and is unjustified.

1.2 Pipe racks in petrochemical facilities

Pipe racks are structures used in various types of plants to support pipes and cable trays. Although pipe racks are considered non-building structures, they should still be designed with the effects of stability analysis considered. Pipe racks are typically long, narrow structures that carry pipe in the longitudinal direction. Pipe routing, maintenance access, and access corridors typically require that the transverse frames are moment-resisting frames. The moment frames resist gravity loads as well as lateral loads from either pipe loads or wind and seismic loads. The transverse frames are typically connected using longitudinal struts with one bay typically braced. Any longitudinal loads are transferred to the longitudinal struts and carried to the braced bay. (Drake and Walter, 2010).

Pipe racks are essential for the operation of industrial facilities but because pipe racks are considered non-building structures, code referenced documents will usually not cover the design and analysis of the structure. The lack of industry standards for pipe rack design leads to each individual firm or organization adopting its own standards, many without clear understanding of the concepts and design of pipe rack structures. (Bendapodi, 2010) Process Industry Practices Structural Design Criteria (PIP STC01015) has tried to develop a uniform standard for design but it should be noted that this is not considered a code document.

The lack of code referenced documents can lead to confusion in the design of pipe racks. The concept of stability analysis should not be ignored based the lack on code referenced documents AISC 360-10 should still be used as reference for stability analysis and design.

1.3 Objective of work

The main purpose of this thesis will be to analyze various types of pipe rack structures, compare the results from stability analyses, and describe both positive and negative aspects of each method of stability analysis as it applies specifically to pipe rack structures. The paper will also look at some of the various issues with applying each of the methods.

Some engineers are accustomed to braced frames structures, which are not susceptible to large second order effects, therefore those designers can tend to neglect or incorrectly apply methods of stability analysis. This thesis will not only show the importance of stability analysis, but also provide suggestions on practical implementation of each method. This could potentially save time in analysis and design because the process of selecting the appropriate stability analysis method will no longer be based on trial and error but rather on educated considerations that can easily be verified after analysis.

2. Pipe rack loading

Pipe racks are unique structures that have unique loading when compared to typical buildings and structure. Pipe racks design is not covered under Minimum Design Loads for Buildings and Other Structures (ASCE 7-05) or International Building Code (IBC 2009) however the design philosophies should remain the same as that for all structures. Most company design criteria and Process Industry Practices (PIP) documents will list ASCE 7-05 or IBC as the basis for load definition and load combinations.
Basic load definitions used in STAAD pro V8i in thesis are as below:

LOAD 1 Dead Load (DL)
LOAD 2 Live Load (LL)
LOAD 3 Pipe Empty Load (Pe)
LOAD 4 Pipe Operating Load (Po)
LOAD 5 Pipe Hydro/ Test Load (Pt)
LOAD 6 Thermal Load(TL)
LOAD 7 Pipe Friction Load (FL)
LOAD 8 Pipe Anchor Load (AL)
LOAD 9 Equipment Empty Load (Ee)
LOAD 10 Equipment Operating Load (Eo)
LOAD 11 Equipment Test Load (Et)
LOAD 12 Wind Load in X direction (WLX)
LOAD 13 Wind Load in -X direction (-WLX)
LOAD 14 Wind Load in Z direction (WLZ)
LOAD 15 Wind Load In -Z direction (-WLZ)

Below is listed the combined load combinations to be used in this research for design of pipe racks referenced from ASCE 7-05 Allowable strength design.

FOR FOUNDATION STABILITY, BEARING PRESSURE CHECK & BASE PLATE DESIGN
*EMPTY CONDITION WITH WIND LOAD
LOAD 101 0.6 DL + 0.6 PE + 0.6 EE + 1.0 WLX
LOAD 102 0.6 DL + 0.6 PE + 0.6 EE - 1.0 WLX
LOAD 103 0.6 DL + 0.6 PE + 0.6 EE + 1.0 WLZ
LOAD 104 0.6 DL + 0.6 PE + 0.6 EE - 1.0 WLZ
*OPERATING CONDITION
LOAD 105 1.0 DL + 1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO
LOAD 106 1.0 DL + 1.0 LL + 1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO
LOAD 107 1.0 DL + 1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO

LOAD 108 1.0 DL + 1.0 LL + 1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO
*OPERATING CONDITION WITH WIND LOAD
LOAD 109 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO +1.0 WLX
LOAD 110 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO -1.0 WLX
LOAD 111 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO +1.0 WLZ
LOAD 112 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL + 1.0 AL + 1.0 EO -1.0 WLZ
LOAD 113 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO +1.0 WLX
LOAD 114 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO -1.0 WLX
LOAD 115 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO +1.0 WLZ
LOAD 116 1.0 DL + 1.0 LL +1.0 PO + 1.0 TL - 1.0 AL + 1.0 EO -1.0 WLZ
*TEST CONDITION
LOAD 117 1.0 DL + 1.0 PT + 1.0 ET + 0.5 WLX
LOAD 118 1.0 DL + 1.0 PT + 1.0 ET - 0.5 WLX
LOAD 119 1.0 DL + 1.0 PT + 1.0 ET + 0.5 WLZ
LOAD 120 1.0 DL + 1.0 PT + 1.0 ET - 0.5 WLZ
LOAD 121 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET + 0.5 WLX
LOAD 122 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET - 0.5 WLX
LOAD 123 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET + 0.5 WLZ
LOAD 124 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET - 0.5 WLZ

FOR SUPERSTRUCTURE DESIGN
* EMPTY CONDITION WITH WIND LOAD
LOAD 201 0.6 DL + 0.6 PE + 0.6 EE + 1.0 WLX
LOAD 202 0.6 DL + 0.6 PE + 0.6 EE - 1.0 WLX
LOAD 203 0.6 DL + 0.6 PE + 0.6 EE + 1.0 WLZ
LOAD 204 0.6 DL + 0.6 PE + 0.6 EE - 1.0 WLZ
* OPERATING CONDITION
LOAD 205 1.0 DL + 1.0 PO + 1.0 TL + 1.0 FL + 1.0 AL + 1.0 EO
LOAD 206 1.0 DL + 1.0 LL + 1.0 PO + 1.0 TL + 1.0 FL + 1.0 AL + 1.0 EO
LOAD 207 1.0 DL + 1.0 PO + 1.0 TL - 1.0 FL - 1.0 AL + 1.0 EO
LOAD 208 1.0DL + 1.0LL + 1.0PO + 1.0TL - 1.0FL - 1.0AL + 1.0EO
* OPERATING CONDITION WITH WIND
LOAD 209 1.0DL + 1.0LL + 1.0PO + 1.0TL + 1.0FL + 1.0AL + 1.0EO + 1.0WLX
LOAD 210 1.0DL + 1.0LL + 1.0PO + 1.0TL + 1.0FL + 1.0AL + 1.0EO - 1.0WLX
LOAD 211 1.0DL + 1.0LL + 1.0PO + 1.0TL + 1.0FL + 1.0AL + 1.0EO + 1.0WLZ
LOAD 212 1.0DL + 1.0LL + 1.0PO + 1.0TL + 1.0FL + 1.0AL + 1.0EO - 1.0WLZ
LOAD 213 1.0DL + 1.0LL + 1.0PO + 1.0TL - 1.0FL - 1.0AL + 1.0EO + 1.0WLX
LOAD 214 1.0DL + 1.0LL + 1.0PO + 1.0TL - 1.0FL - 1.0AL + 1.0EO - 1.0WLX
LOAD 215 1.0DL + 1.0LL + 1.0PO + 1.0TL - 1.0FL - 1.0AL + 1.0EO + 1.0WLZ
LOAD 216 1.0DL + 1.0LL + 1.0PO + 1.0TL - 1.0FL - 1.0AL + 1.0EO - 1.0WLZ
* TEST CONDITION
LOAD 217 1.0 DL + 1.0 PT + 1.0 ET + 0.5 WLX
LOAD 218 1.0 DL + 1.0 PT + 1.0 ET - 0.5 WLX
LOAD 219 1.0 DL + 1.0 PT + 1.0 ET + 0.5 WLZ
LOAD 220 1.0 DL + 1.0 PT + 1.0 ET - 0.5 WLZ
LOAD 221 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET + 0.5 WLX
LOAD 222 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET - 0.5 WLX
LOAD 223 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET + 0.5 WLZ
LOAD 224 1.0 DL + 1.0 LL + 1.0 PT + 1.0 ET - 0.5 WLZ

*** FOR LOCAL CHECK OF TRANSVERSE BEAMS SUPPORTING PIPES**
LOAD 501 1.0DL + 1.0LL + 1.0PO + 1.0TL + 2.0FL + 2.0AL + 1.0EO
LOAD 502 1.0DL + 1.0LL + 1.0PO + 1.0TL - 2.0FL - 2.0AL + 1.0EO

3. Stability analysis

From stability consideration of a structure, AISC chapter C suggests the three approaches for determining the required flexural and axial strength of a member in the structure.

A. <u>Effective Length Factor method (ELM) (C.2.2a</u>)

Unless the *First –Order to Second Order drift ratio* is not greater than 1.1, this method demands the determination of actual "K" value of compression members. It is a conventional method which has been adopted by engineers for designing steel columns for a long time. Determination of the Effective Length factor "K"of a member is the cornerstone of this method. The K value accounts for the contribution of boundary conditions to the axial load carrying capacity of a steel column. Since the ELM approach is based on several assumptions on geometry, boundary condition, and material properties of columns, sometimes this approach may be very conservative and inappropriate for the design of compression members.

B. <u>First Order Analysis per C2.2b</u>

This method suggests performing the first-order elastic analysis using nominal geometry and nominal stiffness. Although the method is derived from the DAM, it is only applicable when the sidesway amplification factor B2 <1.5.

$$B_2 = \frac{\Delta_{2nd-order}}{\Delta_{1st-order}} \leq 1.5$$

Detailed explanation is covered in chapter C2.2 of AISC 360-05.
Following are the few limitations of this method.
(a) Structure supports gravity loads primarily through nominally vertical columns, walls or frames.
(b) Second-order effects must be limited.
(c) Inelastic effect must not be significant.

C. <u>Direct Analysis Method (DAM) (Appendix 7)</u>

Appendix-7 of the AISC 360-05 introduced the DAM which is a new method addressing all the necessary stability requirements suggested by the code. Performing the rigorous Direct Analysis is an advanced approach of stability analysis which considers both geometric and material non-linearity and is far more accurate when compared with the other approximate methods.

Three basic parameters addressed by the DAM.

a. Consideration of the P-∆ and P- δ effect

To address the geometric non-linearity, this method strictly demands the consideration of P-∆ and P- δ effect in a member and the overall structure.

The AISC chapter C2.1 specifies using the Second Order analysis to address those effects.

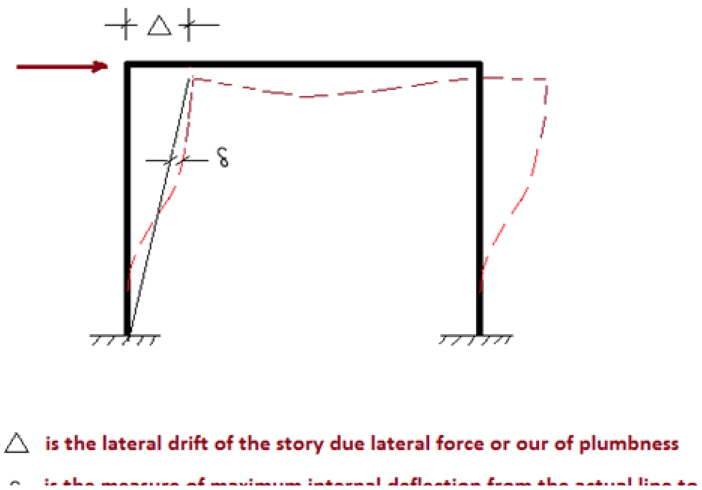

Fig 3.1

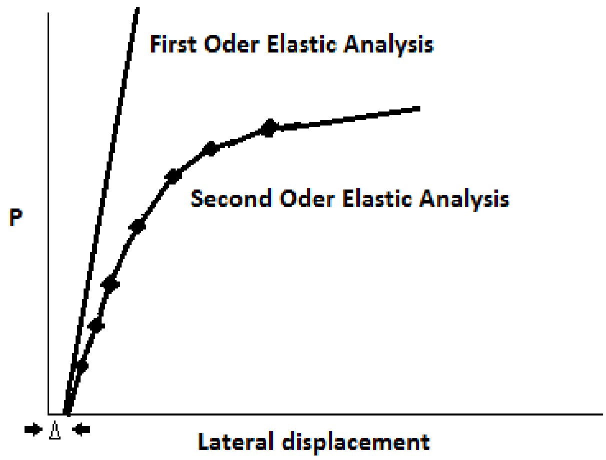

Fig 3.2

The AISC 360-05 code states that any second order method that includes the $P\text{-}\Delta$ and $P\text{-}\delta$ effect may be used, but the following two methods are mostly used.

(a) Moment Magnification factor method per C-1b

(b) This is a second order analysis done by magnifying the moments determined in the first order elastic analysis. This is an approximate method which is also popularly known as B1 - B2 method as the code specifies the equations eqn- C2-2 and C2-3 to determine the amplification factors for a member's internal deformation (B1) and for the drift (B2) respectively and use them to calculate the second order flexural and axial strength of the member by eqn- C2-1a and C2-1b.

(c) Direct, Rigorous Second order analysis. Due to the iterative process involved in determining the actual value of forces and displacements on account of the second order effect, it is mostly performed by the computer programs.

(2) Geometric Imperfection. Any column used in real life situation never follows the ideal column straightness. Presence of crookedness, initial deformities or out of plumbness are very much feasible.

To account for these pragmatic considerations, AISC came up with the concept of notional load.

Notional Load is a pseudo lateral load to imitate the initial crookedness and out of plumpness of a member. The magnitude of Notional Load at each level is $N_i = 0.002Y_i$, where Yi is the gravity load acting on the ith level. The 0.002 factor is equivalent to the allowable tolerance for initial out of plumbness of each story (1/500 times of story height).

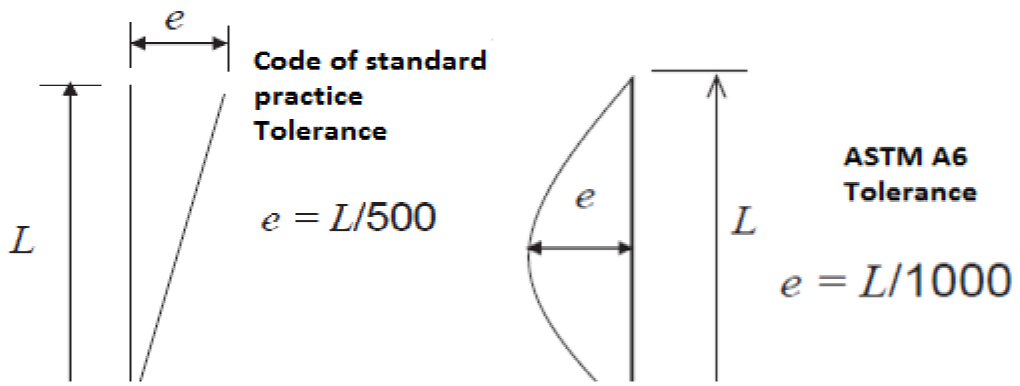

Fig 3.3

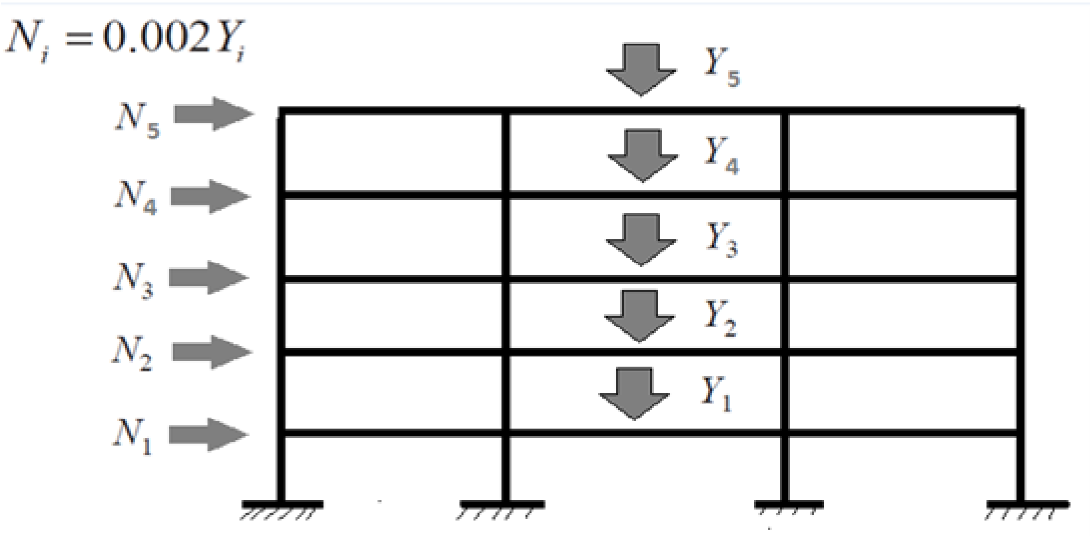

Fig 3.4

(3) <u>Stiffness reduction due to the material Non-Linearity.</u>

Stiffness of the members needs to be reduced to account for the inelastic effects due to residual stress and the uncertainty in strength and stiffness. Inelastic effect which is caused by residual stress include stresses due to temperature , as some elements of the hot rolled cross-section cools faster than others, and also due to the effects of straightening that must be done to meet ASTM A6 tolerances. Areas with residual stress yields prior to the overall yielding of the section, causing some elements to soften in-elastically prior to reaching their design strength. The loss of stiffness due to residual stresses also increases the frame and member deformations. And this effect is addressed in the DAM by the reduction of Axial Stiffness (EA) and Flexural Stiffness (EI).

The reduced Axial Stiffness is EA* = 0.8 EA

The reduced Flexural Stiffness is EI* = 0.8 EI τ_b

The calculation of τ_b which is dependent on the level of axial stress is elaborated in chapter 7.3.3 of the AISC 360-05.

when $\alpha P_r/P_y \leq 0.5;$ $\quad$ when $\alpha P_r/P_y > 0.5;$

$$\tau_b = 1.0 \qquad \tau_b = 4\left[\frac{\alpha P_r}{P_y}\left(1 - \frac{\alpha P_r}{P_y}\right)\right]$$

$\alpha = 1.0$ (LRFD) $\qquad \alpha = 1.6$ (ASD)

However, τ_b can be assumed 1.0 if the additional notional load of 0.001 times of gravity load is applied.

The advantages of DAM:

(a) Plain, direct and simple approach.
(b) Eliminates the ambiguity and the intricacy involved in calculation of effective buckling length factor as required by ELM. An engineer needs to assume K=1 in the DAM.
(c) Can be used for all types of steel structures like Braced frame, moment frame and combined frame system.
(d) Convenient and safe design approach with stability consideration.
(e) Performs accurate and exact analysis considering both the geometric and material non-linearity.

4. Research Plan

A general plan for the research that was conducted is presented here and is described as follows:

1. Describe in detail a typical pipe rack to be used for comparison of the methods.
2. Develop general loads and load combinations for use in the analysis models.

3. Develop a general STAAD.Pro V8i model that can be used for analysis of the Equivalent Length Method, Direct Analysis Method and First Order Method with input from [2] and [3].
4. Complete a first order analysis of the pipe rack structure developed in [4] for use in calculation of the Δ2/Δ1 ratio as well as for use in the First Order Method and discuss the results and validity of the method based on AISC limitations.
5. Optimize strength only design of test pipe rack structure developed in [4] using Equivalent Length Method and determine validity of method for current structure based on AISC limitations
6. Optimize the strength only design of the test pipe rack structure developed in [4] using the Direct Analysis Method and compare the results to the Equivalent Length Method.
7. Use the models developed in [6] and [7] and vary member sizes and base fixity based on the serviceability limits and compare the results.
8. Compare the results of [5 to 8].

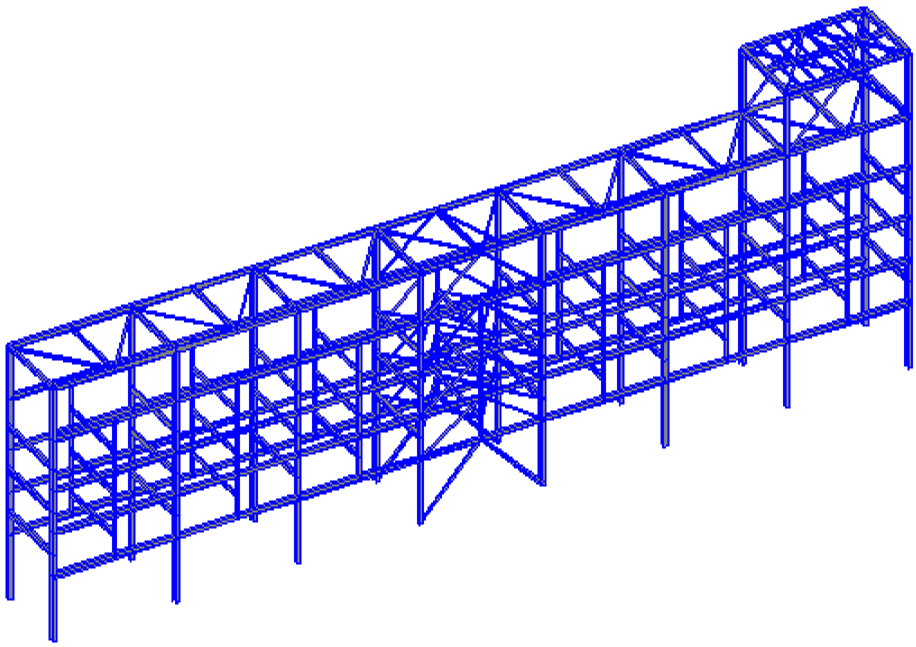

Fig 4.5

5. Results and Conclusion

The first model was analyzed with a pinned base along major axis and fixed along minor axis column. The member sizes were chosen without regard to serviceability and picked only to satisfy the load demand. First order method, effective length method and direct analysis method were all applied to the model and the results compiled. A first order linear elastic analysis was completed to provide a benchmark for comparison and calculation of the ratio of second order drift to first order drift.

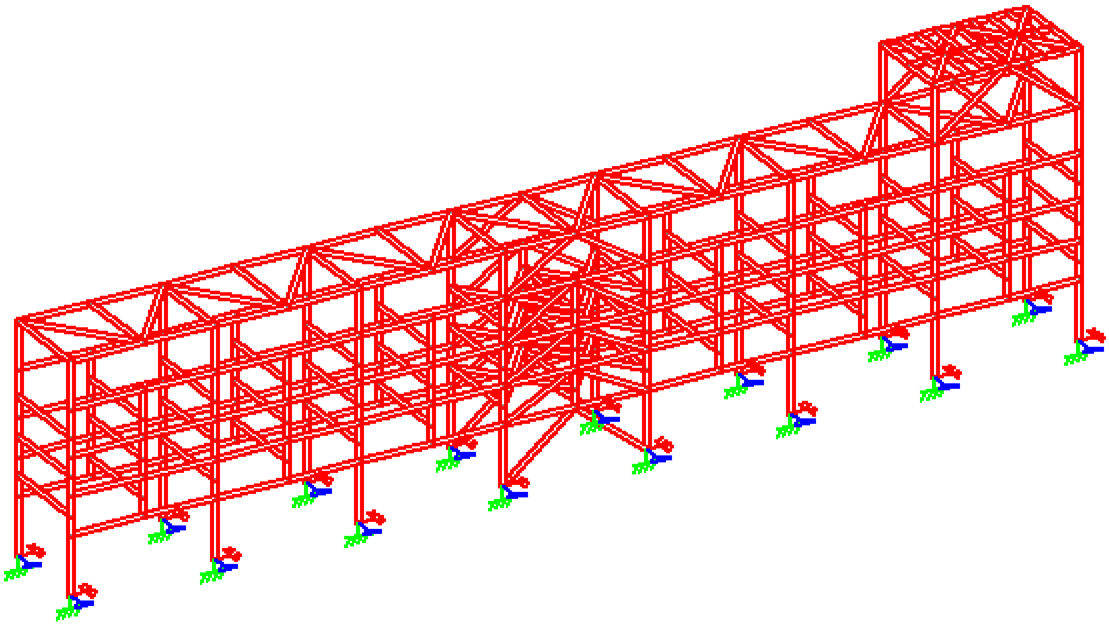

Fig 5.6

Table 5-1 shows the ratio of second order to first order drift (Δ2/Δ1) based on the comparison of the benchmark linear elastic analysis to the effective length method analysis. It should be noted that these maximum deflections are based on ASD load combinations. The maximum Δ2/Δ1 ratio is calculated as 1.00. Therefore, for the representative pinned base pipe rack, the first order method is a valid method for stability analysis. Also, AISC 360-10 sets limitations for use of notional loads. Because the maximum Δ2/Δ1 is less than 1.5, notional load only need be applied to the gravity only load combinations for use in the effective length method.

Table 5.1 Ratio Δ_2/Δ_1 effective length method

ASD Load Combination	Linear Elastic Analysis Maximum Deflection (mm)	Effective length method Maximum Deflection (mm)	Δ2/Δ1
101	0.001	0.001	1.00
102	0.001	0.001	1.00
103	23.037	22.567	0.98
104	15.408	14.937	0.97
105	1.661	0.263	0.16
106	2.05	0.263	0.13
107	1.146	0.251	0.22
108	1.536	0.251	0.16
109	0.264	0.264	1.00
110	0.262	0.263	1.00
111	24.616	22.83	0.93
112	16.461	14.674	0.89
113	0.251	0.251	1.00
114	0.25	0.251	1.00
115	24.604	22.818	0.93
116	16.474	14.687	0.89
117	0.002	0.002	1.00

118	0.001	0.001	1.00
119	12.682	11.285	0.89
120	8.865	7.467	0.84
121	0.001	0.001	1.00
122	0.001	0.001	1.00
123	13.071	11.285	0.86
124	9.254	7.468	0.81
		Maximum Δ_2/Δ_1 =	1.00

Table 5-2 shows the ratio of second order to first order drift (Δ2/Δ1) based on the comparison of the benchmark linear elastic analysis to the direct analysis method analysis. As expected, the ratio Δ2/Δ1 is slightly higher based on the reduction in stiffness. The benchmark first order linear elastic analysis for this comparison included a reduced stiffness used in analysis. The increase in the ratio Δ2/Δ1 seen in Table 5-2 shows that the reduction in stiffness can amplify the second order effects. The maximum ratio Δ2/Δ1 is 1.10. Because the ratio Δ2/Δ1 is less than 1.7 (reduced stiffness is used to calculate drift), notional load need only be applied in the gravity only load combinations. (AISC 360-10)

Table 5.2 Ratio Δ_2/Δ_1 direct analysis method

ASD Load Combination	Linear Elastic Analysis Maximum Deflection (mm) reduced stiffness	Direct analysis method Maximum Deflection (mm)	Δ2/Δ1
101	0.001	0.001	1.00
102	0.001	0	0.00
103	28.796	29.479	1.02
104	19.259	19.845	1.03
105	2.012	2.139	1.06
106	2.499	2.678	1.07
107	1.497	1.624	1.08
108	1.984	2.163	1.09
109	0.266	0.265	1.00
110	0.264	0.264	1.00
111	30.706	33.4	1.09
112	20.641	22.64	1.10
113	0.25	0.251	1.00
114	0.249	0.25	1.00
115	30.691	33.381	1.09
116	20.656	22.647	1.10
117	0.002	0.002	1.00
118	0.001	0.001	1.00
119	15.852	17.002	1.07
120	11.081	11.966	1.08
121	0.002	0.002	1.00
122	0.001	0.001	1.00
123	16.339	17.766	1.09
124	11.568	12.649	1.09
		Maximum Δ_2/Δ_1 =	1.10

Both Table 5-1 and 5-2 show the importance of consideration of stability analysis in design for above mentioned base conditions. For the representative support condition base model, stability analysis can amplify the deformation by up to 10% for this specific model. Deformation may not always be the focus of analysis and design but when checking serviceability limits; stability analysis can increase deformations significantly when compared to an elastic first order analysis.

The first order method was performed on the same model but as the method name implies, only a first order analysis is done and therefore the ratio $\Delta2/\Delta1$ cannot be directly calculated based on the drifts alone. However, based on the results of the previous two analyses, the ratio $\Delta2/\Delta1$ will be well below the 1.5 limitation set be AISC 360-10. Therefore the first order method is a valid type of stability analysis for the representative pinned base along major axis and fixed along minor axis base pipe rack.

Demand to capacity for members should also be used when comparing the types of stability analysis methods.

Column Maximum Demand to Capacity Ratio			
Linear Elastic Analysis	First Order Method	Effective Length Method	Direct Analysis Method
0.68	0.88	0.94	0.84

Beam Maximum Demand to Capacity Ratio			
Linear Elastic Analysis	First Order Method	Effective Length Method	Direct Analysis Method
0.86	0.98	0.91	0.95

Table no. 5.3

When comparing the direct analysis method and the first order method, it can be seen that the demand to capacity ratio is slightly higher when using the first order method. This is to be expected since the first order method is a simplification of the direct analysis built on conservative assumptions which will envelope the design. The effective length method has slightly higher ratios for column design and slightly lower for beam design. For the effective length method, the column strength equations are adjusted using K to account for reduction in stiffness, but the moment can be underestimated for beams and connections which resist column rotation. The actual demand forces are listed in Table 5-4.

	Column Maximum Forces			
	Linear Elastic Analysis	First Order Method	Effective Length Method	Direct Analysis Method
Strong Axis Moment (KN.m)	54	55	53	59
Axial Load (KN)	425	430	435	436.8

	Beam Maximum Forces			
	Linear Elastic Analysis	First Order Method	Effective Length Method	Direct Analysis Method
Strong Axis Moment (KN.m)	78	76	74.56	80.96
Axial Load (KN)	46	48.3	48.6	47.5

Table no. 5.4

Based on Table 5-3 and 5-4 good correlation can be seen between the methods. The demand to capacity ratios for each method show results that are expected based on the theory used to develop each method. The member forces have slight variation between methods based on the slight differences required in analysis in the methods. All results show similar relationships between each method. It should be noted that varying geometry could have a significant effect on the ratio $\Delta2/\Delta1$ which could limit the use of either the first order method or effective length method. Large moments are developed in both the columns and beams and therefore the majority of the member capacity is used to resist the moment demand.

Based on the above results and observations, I recommend the direct analysis as the first choice in stability analysis for pipe racks. While both the effective length and first order method provide relatively accurate results as long their respective requirements are met the direct analysis provides the most accurate results and has no limitations for use. The direct analysis method can also be the simplest method to apply if modern software analysis is utilized as no front end calculations or post-analysis verification are required.

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