Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Grapevine, Texas, April 18-21, 2012

3D Second Order Analysis of Industrial Buildings

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Abstract
Second orders effects were included historically by the effective length method (K concept), all the studies about that methodology were developed in frames on plane, and with regular rectangular frames. The new way to include those effects is the uses of second order analysis, direct analysis method or alternative simplified options. This methodology was included in ANSI AISC360 in the 2005 version an in the 2010 version. As before, the studies already developed for DAM analysis are in plane. In this paper is revisited the "*K concept*", by numerical analysis, and extended to the 3D space. Using models of industrial steel structures symmetric and non-symmetric, plane and 3D stability analysis were developed, and the results are compared with plane behavior. Several conclusions and recommendations are exposed in lieu of the analyzed models.

1. Introduction and Background

The evolution of the engineering give the opportunity to build structures more complex and non-regular shapes, new structures with unknown behavior and the necessity of study it. This complex shapes they are not only used for buildings, they are also used for any kind of structures as it could be industrial structures or bridges.

Project of buildings in 3D and with geometry uncommon is a field with lack of research, specifically focusing on industrial structures with irregularities is mainly responsible for such ill conditions in design practice. There are still a lot of questions about the behavior of these types of structures waiting to be answered. Some parts of the stability analysis where studies haven't been deep in it and some design procedures should be necessary evaluate new procedures for industrial steel structures.

A great effort of research in quantity and quality has been developed in the last four decades about the non-linear behavior of steel structures. See Chen and others (1984,1991, 1994).

Nonlinear seismic analysis of industrial steel structures with irregularities was studied by Canela(2010) with models with lower irregularities, and showed that equivalent lateral force procedure should be studied for irregular structures like ours in order to obtain more conclusions

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and maybe modify the code for the design. The whole procedure should be revised too in order to avoid or decrease large rotation on floors and torsion appearance in some members. Design process only considers earthquake in 0º and 90º direction in a conventional way where torsion is not conceived, it should be modified to consider it since is created because of this irregularity.

Until 2005 the only prescriptive or professional practical method was the effective length method or known as the K concept. This last is based in stability analysis in plane considering boundary conditions for isolated bars, or trough stiffness of both extreme of the bar, also in plane behavior, and applied only to frame structures (frame is a rectangle form, orthogonal beams an columns) regulars, i.e., same load applied and other conditions that does not agree with real and common applications.

In the same decades, was researched about nonlinear analysis with the advance of the computational capacity, turning feasible second order analysis more complex . In AISC 360:05 (2005) a great change was the inclusion of Direct Analysis Method (DAM) where k = 1, using imperfections or even substituting them by notional loads. Again simplified methods using linear analysis were introduced, First Order Method (FOM), but only applied to frame plane structures.

The simplified methods for the amplification method for pin jointed and rigid frame were exposed by Lemessurier (1976, 1977).

In no part at all of AISC 360:05(2005) or AISC 360:10(2010) have commentaries or indications of how to deal with sway in space frame structures non-symmetric.
One important problem of the conflict of FOM is when is applied to pitched-roof frames, problem with a solution published by Silvestre and Camotin (2007), the first buckling mode is none sway mode, when the FOM is expected to have a sway buckling mode. In three dimensional with beams and columns none disposed in orthogonal layout, the first or the first modes are non-sway, in general are torsional.

In Europe the EC3-EN(2005) states that if parameter α_{cr} is greater than 10 is necessary a second order analysis or the P-Δ effects must be taken in consideration.

$$\alpha_{cr} = \frac{F_{cr}}{F_{Ed}} \tag{1}$$

Where

F_{cr} - Critical loading associated with elastic buckling in global sway mode
F_{Ed} - Frame applied vertical loading

This last parameter has good behavior when the frame have has main or first mode of buckling sway modes, but does not works in other kind of buckling modes.

2. Linear Buckling Analysis utility

Today most of the software commercial or free has the option for a linear buckling analysis, but this qualitative alternative for the stability analysis is not used. As exposed in the previous item with this analysis is feasible to have parameter to take a decision on the use or not of the second order analysis, using the prescription of the Eurocode (2005).

However, additional information can be accessed from the buckling modes, has how to improve the global stability trough the location of bracings, or even to known as the structure will work, that is torsion, sway mode, or other alternatives. This matter is the great importance because most of the modeling for second order analysis is based on drift displacement in two main directions, and if the main buckling mode is not of lateral behavior what to do?

3. Ilustrative Examples

To expose the main ideas behind the second order analysis, after the study of several models was choose two, one framed and regular (RF), and a second one framed but irregular (IF).

The first model is represented in Fig.1, the beams are welded columns and beams, having three levels of 3m each, two bay of 6m, and frame of 8m. The model were analyzed as two dimensional frame and three dimensional, with second order analysis (DAM), and also using the First Order method, and also the elastic Buckling analysis. In Figure 2 can be seen the model loaded with vertical loading and lateral loads from wind.

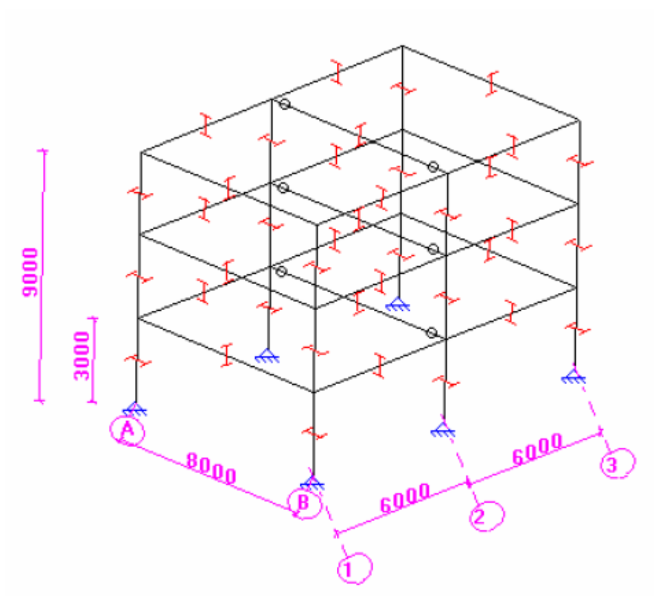


Figure 1 – Model Regular Framed

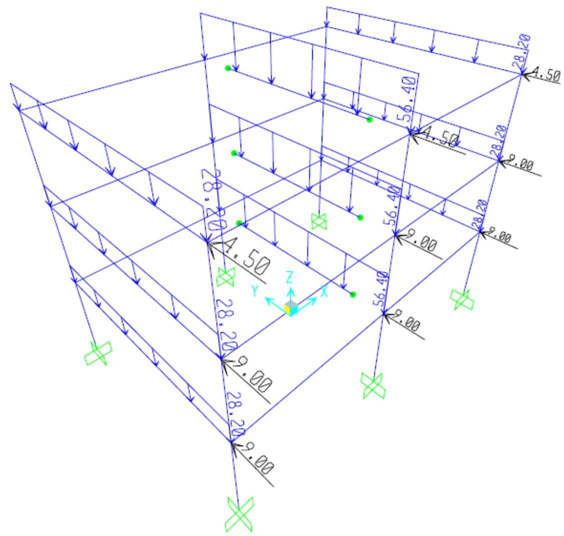


Figure 2 – Regular Frame Model with loads

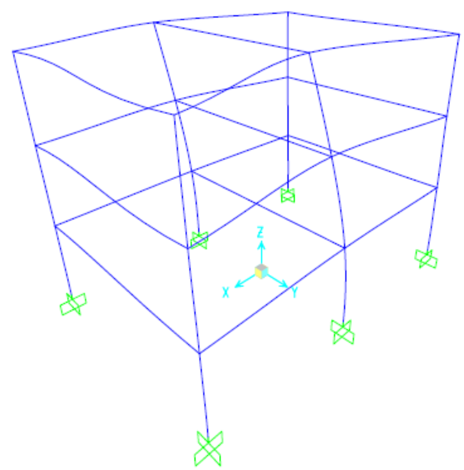


Figure 3 – First buckling mode with $\alpha_{cr} = 4{,}67$

The results for the second order analysis (DAM) and FOM are presented in Table 1. As seen the results from two dimensional models are more conservative compared to the three dimensional analysis, in both cases the First Order Method works well with some differences no essentially. The critical factor 4.67 is below 10 meaning the structure has some sources of nonlinearity and the first buckling mode is a sway mode.

Table 1 – Results from model RF

Level	Model 2D		Model 3D	
(mm)	Δ_2/Δ_1	FOM	Δ_2/Δ_1	FOM
	(DAM)	B_2	(DAM)	B_2
3000	1.08	1.04	1.06	1.07
6000	1.08	1.04	1.09	1.07
9000	1.09	1.03	1.08	1.06

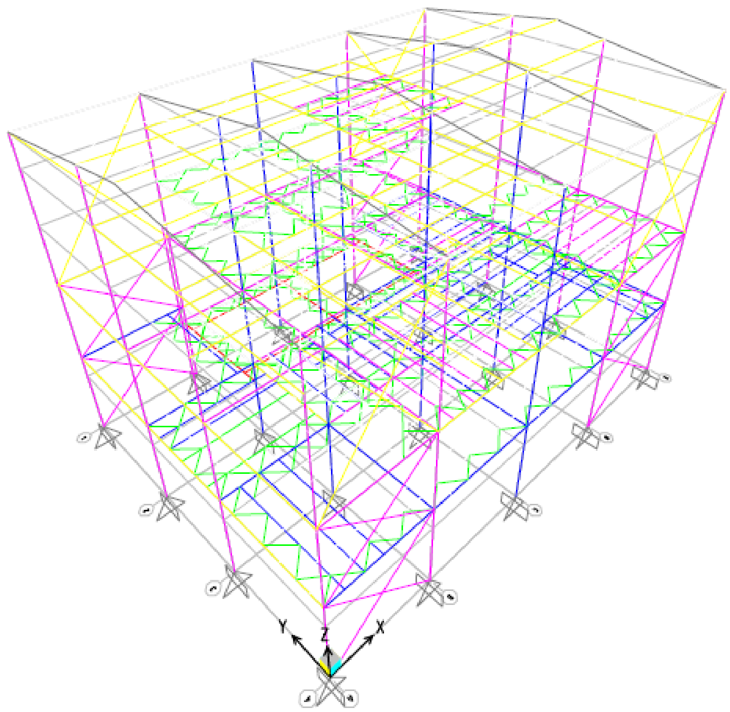


Figure 4 – Irregular Frame model

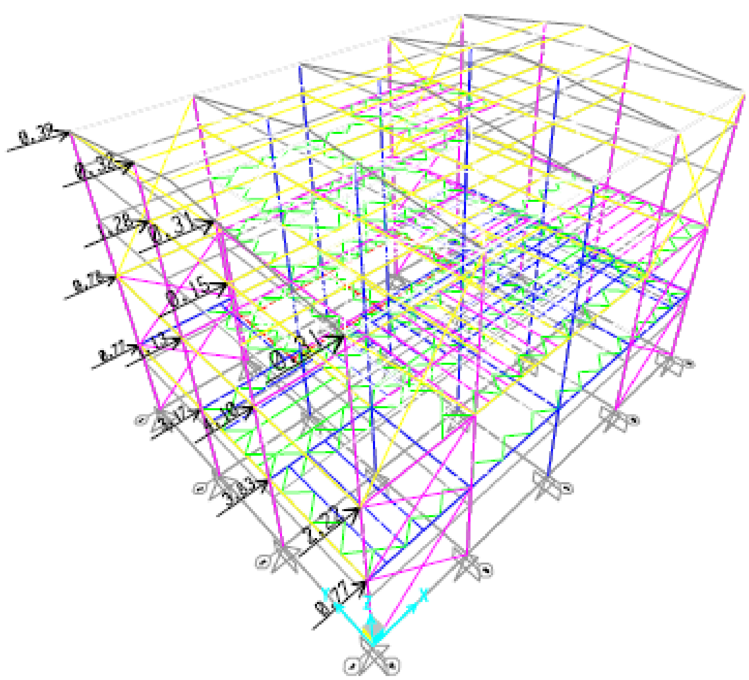


Figure 5 – Notional Loads applied as lateral loads

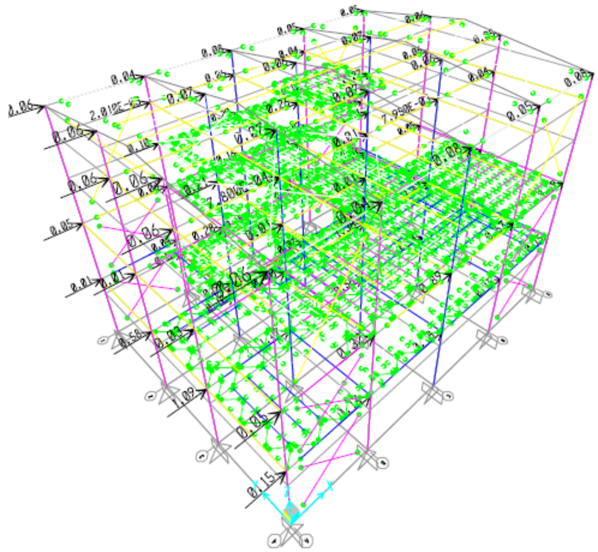
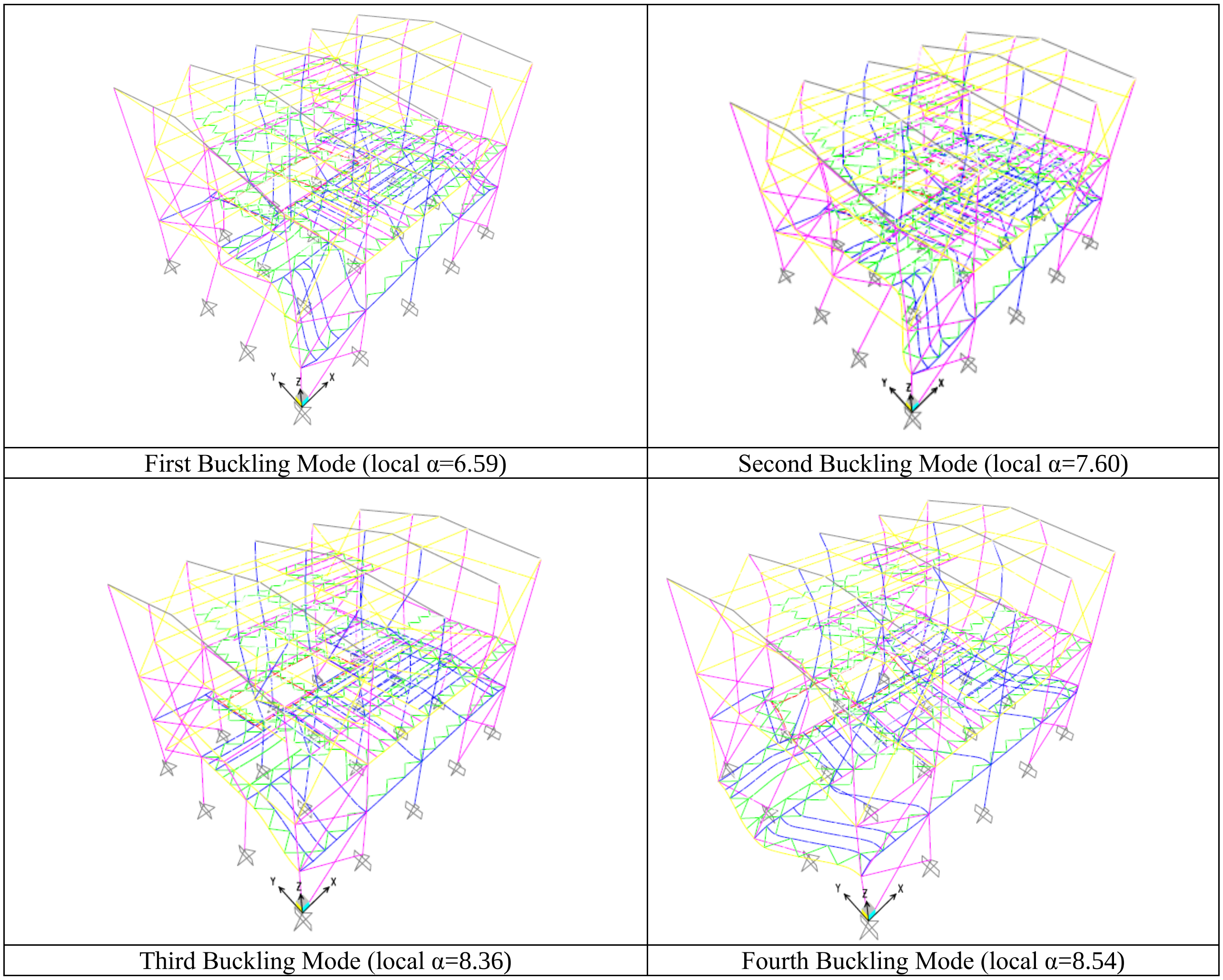


Figure 6 – Notional loads distributed over the levels



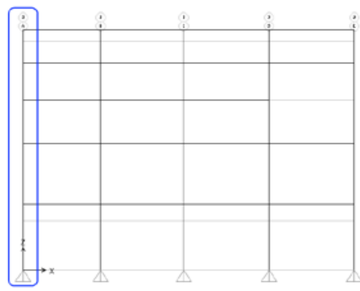
First Buckling Mode (local α=6.59)	Second Buckling Mode (local α=7.60)
Third Buckling Mode (local α=8.36)	Fourth Buckling Mode (local α=8.54)

Figure 7 – First four buckling modes for IF model

The second model is a real project of an industrial building with geometry irregular in each level to locate equipment, in plane the rectangular dimensions are 22.2 m wide and 29.9 m in length, column height of 20.8 m and outer ridge of the building, 22.7 m with five platform access for use of the building.

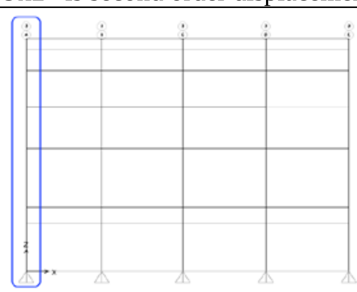
Only in the thirteenth mode appears a sway mode, i.e., a mode with lateral displacement with the value of α=12.49, according EC3 (2005) it is not necessary consider the second order effects, but if we use the concept of the relation of displacements of second to first order analysis, from AISC 360 (2010), exist the need to reduce stiffness and need to consider second order effects, according to the value of 2.45 at node 1308 at the elevation 18800 mm, which is greater than 1.7 allowed by AISC 360, when the notional loads are applied as lateral loads.

Table 2 – Displacements of first and second order analysis notional load applied as lateral load (Ux2* is second order displacements)



	Elevation	U_{x1}	U_{x2}	U_{x1}*	U_{x2}*	U_{x2}*/U_{x1}*
	mm	mm	mm	mm	mm	
Node 20	6000	1.38	1.84	1.38	1.84	1.33
Node 606	11500	1.76	2.24	0.37	0.39	1.06
Node 1311	15400	1.74	2.20	-0.01	-0.03	**2.45**
Node 1308	18800	1.62	2.07	-0.12	-0.13	1.06
Node 6	21840	1.41	1.86	-0.20	-0.21	1.02

Table 3 – Displacements of first and second order analysis notional load applied to all columns in each level (Ux2* is second order displacements)



	Elevation	U_{x1}	U_{x2}	U_{x1}*	U_{x2}*	U_{x2}*/U_{x1}*
	mm	mm	mm	mm	mm	
Node 20	6000	1.35	1.81	1.35	1.81	1.34
Node 606	11500	1.73	2.21	0.38	0.41	1.07
Node 1311	15400	1.76	2.23	0.03	-0.01	**0.39**
Node 1308	18800	1.62	2.08	-0.14	-0.14	1.06
Node 6	21840	1.40	1.85	-0.23	-0.23	1.02

When loads are applied at all columns in each level, in the same node the relation of second order to first order is less than one, with no meaning at all. In all the other level the Table 2 and 3 are similar.

In the model with irregularities when existing member with one extreme free, did not allow convergence in the second order analysis, to overcome this situation secondary members were retired from the model.

The only way to deal with frames unsymmetrical or with irregularities in its layout, is using both second order analysis and linear buckling analysis, to know as the whole structures works.

4. Conclusions

The methods proposed in the standards for steel framed structures were developed based in regular framed models, basically for drift behavior or lateral displacement (sway), when the building analyzed is irregular in geometry or load disposition the methods have some lacks. The alternative is using the second order analysis wit elastic buckling too, to have qualified information about the behavior of the system.

To continue this study more models will be studied, including the imperfections changing the coordinates at the point where element cross.

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