

# Design of High Rise Steel Structure using Second-Order Analysis

Abhijeet Dhavale<sup>1</sup>, Dr. M. R. Shiyekar<sup>2</sup>

<sup>1</sup>PG Scholar, Applied Mechanics Department, Government College of Engineering Karad, Maharashtra-415124, India

<sup>2</sup>Adjunct Professor, Applied Mechanics Department, Government College of Engineering Karad, Maharashtra-415124, India

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**Abstract** – High rise buildings has strong influence of wind loads and earthquake loads acting laterally. This increases the lateral displacement of the frame and thus sway criteria becomes a critical one. Classification of frame into two types i.e. sway frame or non-sway frame becomes essential. Effective length factor which plays an important role in design varies largely by these classifications. Problem faced during computing effective length of column for the sample problem is discussed. Thus second-order analysis which eliminates the use of effective length calculations is discussed in details. The use of second-order analysis results in more realistic behavior of the structure.

The present work discusses the issue involved in using the design procedure for the particular type (sample problem) of steel structure using conventional first-order analysis. In particular the design procedure using second-order analysis is developed and applied on the sample problem. The design procedure developed follows IS 800:2007 provisions and use of other standard codes like AISC 360-16 and BS 5950-1:2000. The ease of adopting the respective procedure is discussed. Comparison between the two methods is made in terms of storey displacement, base shear and economy obtained in member sizes.

**Key Words:** Second-order analysis, correction factor, effective flexure stiffness, effective length factor, etc.

## 1. INTRODUCTION

Axial force acting on axially loaded member induces flexure to the member due to side-sway of the frame and curvature of the member. These additional effects on the member are referred to as second-order effects. Second-order effects include P-Δ effects - the effects of loads acting on the displaced locations of joints or nodes in the structure and P-δ effects - the effects of loads acting on deformed shapes of individual members. Use of these second-order effects leads to more practical behavior of the structure.

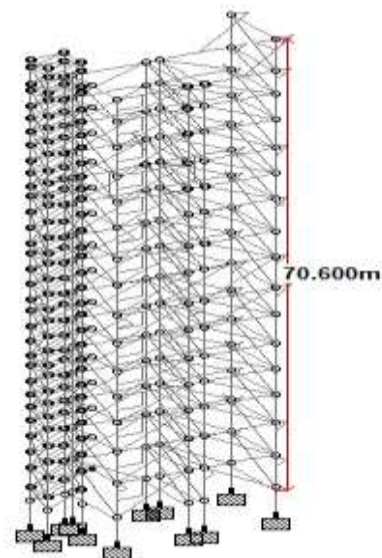
For large-scale and complex structures, traditional design procedure were time consuming and inefficient. It was due to the fact that second-order effects were indirectly considered by virtue of design specifications for individual member instead of system analysis for whole structure. In the year 1759, Euler derived equation to study P-δ effect on simple elastic long column. In the year 1961,

Timoshenko and Gere studied the flexural buckling of column with different boundary conditions. Using this theoretical equations, P-δ effect on an ideal column with different support conditions were evaluated by the imaginary member length, called as effective length.

Increase in height of structure also increases the practical imperfections, mostly out-of-plumbness. The out-of-plumbness induces eccentricity to the axially loaded compression member (i.e. column). Hence, decreases the load carrying capacity of the member. AISC 360-16 had limited the practical out-of-plumbness on site to be not more than h/500. IS 800:2007 [cl.no.4.3.6] had mentioned out-of-plumbness limited to h/200 in terms of notional load. Where, h is the total height of the compression member.

### 1.1 Case study

A high rise steel structure of about 71 m tall and least lateral plan dimension of about 7.5 m is used.



**Fig-1: Three dimensional view of sample problem**

Following are some of the key points about the sample problem for the basis of this paper:

- Beam to column connections throughout the structure are shear connections i.e. beam will only transfer axial loads (no moments) to the column.
- Frames are braced in both directions.

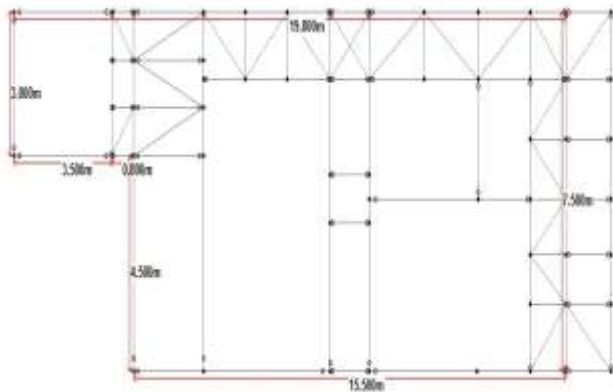


Fig-2: Plan with dimensions

### 1.2 Problem statement

As per IS 800:2007 [cl.no.7.2.2], for carrying out first-order analysis (which does not consider equilibrium in deformed shape) effective length factor from ANNEX D-1 should be used. Now as per ANNEX D-1, the frames are classified in two types:

- a. Non-sway Frames (Braced Frames)
- b. Sway Frames (Moment Resisting Frames)

As per previous code IS 800:1984, the frame if braced was considered as non-sway frame. Therefore if the connections between beams and columns of braced frame were shear connections, by using ANNEX D-1 FIG. 27, the maximum value of effective length factor equals 1. But according to the revised IS 800:2007 [cl.no.4.1.2c)3)], the frame that dissatisfy IS 800:2007 [cl.no.4.1.2c)1)/2)], are to be considered as sway (though braced).

These classifications are to be carried out by using IS 800:2007 [cl.no.4.1.2]. As per IS 800:2007 [cl.no.4.1.2c)], classifications of the above is to be done on basis of interstorey drift results after applying notional loads to the structure.

After applying notional load on the structure with gravity loads acting simultaneously, interstorey drifts for each storey are calculated. First-order elastic analysis is performed to carry-out this result. The limitation given in IS 800:2007 [cl.no.4.1.2c)2)] for unclad frame (as sample structure consists of unclad frames) is,

$$\delta \leq \frac{h_s}{4000}$$

where,

$\delta$  = maximum interstorey drift

$h_s$  = storey height

If  $\delta$  is within the specified limit the frame should be categorized as non-sway frame. It was found that the sample structure does not satisfy IS 800:2007 [cl.no.4.1.2c)2)] limitation.

According to the obtained results in 3.1 below, the structure is to be classified in category of sway frames, though it is braced.

As discussed above the frame is categorized as sway frame, IS 800:2007 ANNEX D-1 b) is used for effective length factor calculation. Equation for finding effective length factor is as given below,

$$K = \left[ \frac{1 - 0.2(\beta_1 + \beta_2) - 0.12\beta_1\beta_2}{1 - 0.8(\beta_1 + \beta_2) + 0.6\beta_1\beta_2} \right]^{0.5}$$

Where,

$$\beta_1, \beta_2 = \frac{\sum K_c}{\sum K_c + \sum K_b}$$

$K_c, K_b$  = effective flexural stiffness of the columns and beams meeting at the ends of the columns and rigidly connected at the joints, and calculated by:

$$K = C (I / L)$$

C = correction factor

I = moment of inertia

L = length of member

The sample problem consists of shear connections between beam and column. As per IS 800:2007 ANNEX D, for calculating  $\beta_1$  and  $\beta_2$  values effective flexural stiffness of column ( $K_c$ ) and beam ( $K_b$ ) meeting at joint is required. For shear connection flexural stiffness of beams ( $K_b$ ) cannot be computed as beam to column joint provides no resistance to flexure. Hence for shear connections  $\beta_1$  and  $\beta_2$  values are taken as 1 (i.e. pinned). The effective length factor calculated after computing  $\beta_1$  and  $\beta_2$  values equal to 1 in equation from ANNEX D-1 b) tends to infinity. This is practically impossible.

The effective length factors mentioned in sway frames does not consider the stiffness effects of bracings to the structure.

This leads to the conclusion that for shear connections (in sway frame) the effective length of columns mentioned in ANNEX D of IS 800:2007 cannot be used effectively.

### 1.3 Objectives

The objectives of this thesis are as listed below:

- a. To study the concept of second-order analysis.
- b. To find the solution for the above mentioned problem in 1.2.
- c. To overcome the above problem and get results from conventional first-order analysis procedure.
- d. To develop and design accordingly the sample problem using second-order analysis fulfilling all parameters from IS 800:2007.

- e. To compare the results obtained from conventional first-order analysis and second-order analysis.

## 2. METHODOLOGY

### 2.1 Design using second-order analysis

Steps adopted for design of the sample problem using second-order analysis are as follows:

- a. Simply switch to ANNEX B without considering the moment amplification factor rather than trying for the options mentioned in IS 800:2007 [cl.no.4.4.3.1].
- b. Assume  $\lambda_{cr}$  value is less than 5. Hence, changes in effective stiffness due to axial forces are to be implemented.
- c. Use 0.8 reduction factor for stiffness [5]. Use this factor for reducing modulus of elasticity of members instead of moment of inertia. Eliminate  $\tau_b$  factor, as sample problem consist of shear connections only.
- d. Apply notional load to each storey of the sample problem. 0.5% of all vertical loading on the structure are applied horizontally (in one direction at a time) as per the respective storey.
- e. The notional load only need to be added to load combinations in which the notional load is larger than lateral load on the frame. However, if a designer wishes to simplify the design process, it is always conservative to include the notional loads. Hence, include notional load in all load combinations.
- f. Conduct a direct, rigorous second-order analysis of the structure in the software.
- g. Reset modulus of elasticity E to default value (i.e. excluding stiffness reduction factor of 0.8). This is to consider full strength of the members while designing.
- h. Take effective length factor equal to 1.
- i. Design the members according to IS 800:2007 provisions.

### 2.2 Design using first-order analysis

Method for design of sample structure using first-order analysis is also developed to overcome the above mentioned problem. Note that the developed methods are for comparing first-order design results with results obtained from design using second-order analysis.

Two procedures for calculation of effective length factors are used to carry-out design using first-order analysis, are as follows:

### 2.2.1 Procedure for calculating effective length factor using correction factor from IS 800:2007

As discussed in 1.2 the value of  $K_b$  for the sample problem cannot be computed as sample problem consists of shear connections. In Table 35 of IS 800:2007 has mentioned a correction factor to overcome the above mentioned problem. The correction factor applies to the effective flexural stiffness of beams according to the end conditions and type of frame i.e. braced or unbraced. Following is the formula used for finding flexural stiffness of beams,

$$K_b = C (I / L)$$

where,

I = moment of inertia of the member about an axis perpendicular to the plan of the frame

L = Length of member

C = correction factor as per Table 35 of IS 800:2007, is as displayed below,

**Table-1: Correction factor**

Sr. No.	Far End Condition	Correction Factor, C	
		Braced Frame	Unbraced Frame
1	Pinned	1.5 (1 - $\bar{n}$ )	1.5 (1 - $\bar{n}$ )
2	Rigidly connected to column	1.0 (1 - $\bar{n}$ )	1.0 (1 - 0.2 $\bar{n}$ )
3	Fixed	2.0 (1 - 0.4 $\bar{n}$ )	0.67 (1 - 0.4 $\bar{n}$ )

Note:

$$\bar{n} = \frac{P}{P_c}$$

where,

P = applied load

$P_c$  = elastic buckling load

While using the correction factor table, the formula for braced frame or unbraced frame according to the far end conditions must be carefully chosen. The sample problem is braced in both directions as well as all the end conditions (i.e. beam to column connections) are shear connections (i.e. pinned connection). Thus correction factor to be used is for braced frame with pinned end condition.

The elastic buckling load determines the buckling load of column section using Euler's buckling formula,

$$P_c = \frac{\pi^2 EI}{L^2}$$

In the above mentioned formula length of the column should be taken center-to-center of the intersecting members. By using the above equations, find value of  $K_b$ . Then by using the following equations, find effective length factor,

$$K = \left[ \frac{1 - 0.2(\beta_1 + \beta_2) - 0.12\beta_1\beta_2}{1 - 0.8(\beta_1 + \beta_2) + 0.6\beta_1\beta_2} \right]^{0.5}$$

where,

$$\beta_1, \beta_2 = \frac{\sum K_c}{\sum K_c + \sum K_b}$$

The use of correction factor for the sample problem actually increases the stiffness of beams due to the stiffness provided by bracings. This increase in beam stiffness decreases the effective length factor of the column. Hence in some measures it performs considerably as partial sway bracing.

### 2.2.2 Procedure for calculating effective length factor using BS 5950-1:2000 procedure

The problem mentioned above for effective length factor calculation is encountered by using BS 5950-1:2000 code [6]. Following is the procedure given in BS 5950-1:2000 E.3 for finding the effective length factors of the partial sway bracing frames:

- a. Find relative stiffness ( $k_p$ ) of effective bracing in any storey is given by the following formulae,

$$k_p = \frac{h^2 \sum S_p}{80E \sum K_c} \text{ but } k_p \leq 2$$

where,

E = modulus of elasticity of steel

h = storey height

$\sum K_c$  = sum of stiffness coefficients  $K_c$  of columns in that storey of the frame as given in step c.

$\sum S_p$  = sum of spring stiffnesses of the panels in that storey of the frame as given in step b.

- b. Formula for finding  $\sum S_p$  is as follows,

$$\sum S_p = \frac{P}{(\delta_2 - \delta_1)}$$

Where,

P = a load in kN at top of Storey in which column to be considered is located

- c. Formula for finding  $\sum K_c$  is as follows,

$$\sum K_c = (K_{c2a} + K_{c2} + K_{c2b})$$

Where,

$K_{c2a}, K_{c2}, K_{c2b}$  = stiffness coefficients of columns in that storey

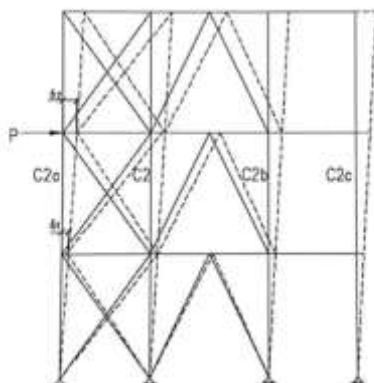


Fig-3: Diagrammatic representation of finding spring stiffnesses

[Note: Only columns forming part of bracing are to be considered as they contribute stiffness]

- d. BS 5950-1:2000 has provided charts for finding effective length factors as per following values of  $k_p$ ,
  - i.  $k_p = 0$  (Refer fig. E.2)
  - ii.  $k_p = 1$  (Refer fig. E.4)
  - iii.  $k_p = 2$  (Refer fig. E.5)

[Note: The effective length factors for column may be derived by linear interpolation between values obtained from the charts for  $k_p = 0, k_p = 1$  and  $k_p = 2$ ]

The same problem as discussed earlier occurs while using graph E.2 when the value of  $k_p$  lies in between 0 and 1. Hence, for study purpose point of view, we will restrict to the comparison of those columns whose  $k_p$  value lies in between 1 and 2.

### 2.2.3 Summary of procedure adopted for design of sample problem using first-order analysis

- a. Apply notional load 0.5% of vertical dead load plus live load. Remove all other horizontal loads like wind load, earthquake load, temperature load, etc. Perform first-order analysis.
- b. Classify the frame into sway or non-sway category using the results of inter-storey drifts carried out in step a. above. Once a braced frame (with shear connections) is classified as sway frame, then adopt the following procedure.
- c. For calculation of effective length use following procedure:
  - i. First run the program by using first-order analysis.
  - ii. From output file note down the maximum axial force values for every compression member.
  - iii. Use this axial force values to find the effective length factors using correction factor from IS 800:2007 as discussed in 2.2.1 or use BS 5950-1:2000 factors as discussed in 2.2.2.

[Note that effective length factors of only those members are to be computed whose  $k_p$  value lies between 1 and 2, for BS 5950-1:2000 procedure as discussed in 2.2.2].

- d. Perform the conventional first-order analysis and carry-out design of compression members using the effective length factors as obtained from step c.

### 3. RESULTS

#### 3.1 CLASSIFICATION OF SAMPLE PROBLEM

A sample calculation of plain frame is displayed for classification of the sample problem using the procedure of notional load application as discussed in 1.2 above. The values of actual interstorey drift and permissible interstorey drift are calculated from the formulae mentioned below:

$$\text{Actual interstorey drift} = \frac{\text{upper storey} - \text{lower storey}}{\text{storey height}}$$

$$\text{Permissible interstorey drift} = \frac{\text{Storey height}}{4000}$$

**Table-2: Classification of sample problem**

Sr. No.	Storey height	Upper storey	Lower storey	Actual interstorey drift	Permissible interstorey drift
1	4000	2.464	1.553	0.911	1
2	4000	2.276	1.226	1.05	1
3	4000	2.31	1.276	1.034	1
4	4000	2.296	1.048	1.248	1

(All dimensions are in mm)

From Table-2 it can be noted that the actual interstorey drift is greater than permissible interstorey drift for some members.

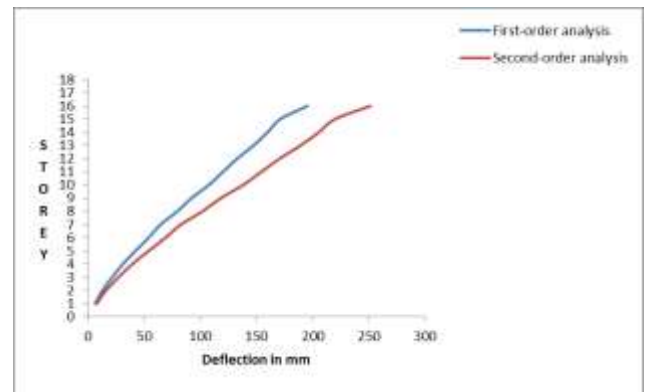
#### 3.2 Top storey deflection

Increase in top storey deflections due to second-order analysis are as follows:

- X direction: 28.56 % increase than first-order analysis
- Z direction: 25.76 % increase than first-order analysis

#### 3.3 Storey-wise deflection

A particular column is chosen for comparing its deflection at each storey. Chart-1 displays the graphical representation.



**Chart-1: Graphical representation of storey-wise deflection comparison**

### 4. CONCLUSIONS

The methods defined above are applied on the case study structure and the following conclusions are made:

- The case study is classified in category of sway frame though it is braced.
- Difficulties in determination of effective length factor for the columns while performing first-order analysis was resolved using correction factor from IS 800:2007 and BS 5950-1:2000 procedure.
- Value of the effective length factors is more conservative in BS 5950-1:2000 as compared to IS 800:2007 by 9.4 % and 18.7 % for minor axis and major axis respectively. This affects finally design of steel frame involving 28 % saving in steel.
- Considerable saving in steel is observed when design as per second-order analysis is performed compared to that by first-order analysis. This saving for the present case study is around 24.7 %.

### ACKNOWLEDGEMENT

The case study used for this paper was provided by Thyssenkrupp Industrial Solutions (India) Pvt. Ltd., Pune office. The authors thank the Head of Department Mr. P. D. Deshpande for providing his time, project information and resources to fulfill the paper requirements.

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