On the Current AISC Approach to Stability Analysis and Design of Steel Structures

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ABSTRACT

In 2005, the American Institute of Steel Construction (AISC) stability analysis and design requirements changed significantly compared to procedures required prior to 2005. The most significant change related to stability analysis and design is the requirement to include geometric imperfections in the calculation of the required strength. Direct Analysis Method (DAM) is currently the recommended code method, while a modified version of the traditional Effectiveness Length Method (ELM) is now referred to as an alternative method of design. The critical changes appeared in the 13th edition (AISC, 2005) and continued to the present 14th edition (AISC, 2011). The objectives of this paper are to: 1) provide an overview of the rationale behind the code change that took place in 2005 and remained in the current specifications and 2) present the current features of ELM and DAM methods. A case study is presented to assess the differences in structural response when DAM and ELM methods are used. It was shown that DAM predicts higher demand on beams and columns of the structural system at the lower levels, but the difference in demand between DAM and ELM methods decreases at the upper levels of the structural system. This is due to the variation of effective length factor required in ELM for compression members, from top levels to bottom levels of the system. DAM, however, permits the use of an effective length factor of 1.0.

KEYWORDS: AISC approach, Stability analysis and design, Steel structures.

INTRODUCTION

Prior to the 2005 specifications, stability analysis and design of framed steel structures followed an approach that is described by a form of the Effective Length Method (ELM) to determine the required strength. ELM required the consideration of second-order effects, but neither inelasticity due to residual stresses nor geometric imperfections were required to be included in the model. However, the pre-2005 AISC specifications required the incorporation of effects of inelasticity and geometric imperfections on the strength of individual components. In post-2005 AISC specifications, strength of individual components continued to incorporate effects of inelasticity and geometric imperfections.

Since 2005, AISC specifications covered stability analysis and design in Chapter C (AISC, 2005, 2011). Three methods are presented in the AISC specifications for stability analysis and design. The recommended approach is DAM. Two alternative methods are prescribed in Appendix 7 of the current specifications (AISC, 2011), which are: ELM and First-Order Analysis method.

Current AISC specifications require that the calculation of the required strength based on the recommended DAM or the alternative ELM must

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consider: 1) all deformations, 2) second-order effects, 3) geometric imperfections, 4) stiffness reduction due to inelasticity, 5) uncertainty in strength and stiffness. It is worthy to note, however, that AISC specifications offer the flexibility for the designer to implement any rational method other than the prescriptive methods.

This paper discusses the rationale behind the new change in stability analysis with emphasis on the incorporation of the effects of inelasticity and geometric imperfections on the calculation of the required strength. The salient features of DAM and ELM are discussed and a case study is presented to understand the differences in structural demand calculated using both methods.

Theoretical Background

This section presents a theoretical background related to the methods used for stability analysis and design in AISC specifications.

Quantifying Geometric Imperfections

Initial imperfections in steel buildings affect both structural demand and member strength. The effect on structural demand may be included in the structural model as the maximum imperfection permitted by the AISC Code of Standard Practice for Steel Buildings and Bridges (AISC, 2010). The primary imperfections considered in current specifications include: 1) member out-of-straightness and 2) frame out-of-plumbness.

Member out-of-Straightness

Imperfections in structural elements affect both the demand on structural elements as well as the load carrying capacity. Member imperfections are accounted for in the current AISC specifications in different ways, depending on the stability analysis and design method. If DAM is used for stability analysis and design, member imperfections are accounted for by reducing the stiffness of members, contributing to building stability. The maximum member out-of-straightness is equal to L/1000, where L is the member length between brace or framing points. Location of worst-case scenario for out-of-straightness in a column is near the column centroid.

Frame out-of-Plumbness

This type of imperfection results from misalignment of structural joints during construction, which affects structural demand, but not structural capacity. Such imperfections may be accounted for through direct modeling based on Section C2.2a (AISC, 2011) for both DAM and ELM. Direct modeling of imperfections considers a maximum frame out-of-plumbness equal to H/500, where H is the story height. Alternatively, the effect of frame out-of-plumbness on structural demand may be accounted for through the application of notional loads as described in Section C2.2b (AISC, 2011). Notional loads are lateral forces, N_i is applied at each floor level and given by:

$$N_i = 0.002Y_i$$

where Y_i: gravity load at floor level $i = 1,2,3, \ldots$.

Notional loads are shown in Figure 1. The maximum column out-of-plumbness according to AISC code of standard practice is:

$$e = \frac{L}{500}$$

where:

e: out-of-plumbness at one end of the column.

L: column clear height.

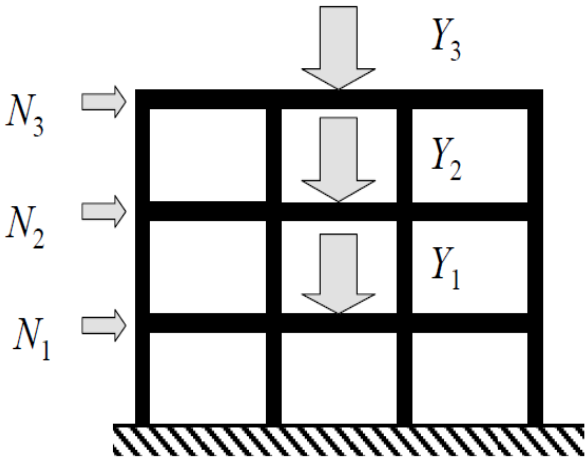

Figure (1): Notional loads

Geometric imperfections in the current AISC specifications apply to strength limit states and must not be considered in serviceability limit states.

Effect of Inelasticity on Member Stiffness

At the strength limit state, yielding at various sections, exacerbated by residual stresses, produces softening of the structure, represented by reduction in the stiffness of structural elements as well as the structural system. This contributes to further destabilizing of the structural system. Stiffness reduction due to inelasticity caused by residual stresses affects both structural demand and member strength. Figure 2 shows the loss of stiffness represented by change of slope of the force-deformation relation for a member under pure compression.

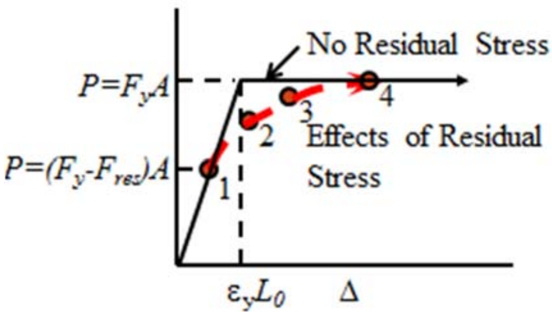

Figure (2): Loss of stiffness due to inelasticity

When DAM is used for stability analysis and design, the effect of inelasticity on structural demand is accounted for through modeling the structural system using stiffness specified in Section C2.3 (AISC, 2011). The effect of inelasticity on member strength is accounted for by calculating the member strength formulae in Chapter E of the specifications using the same reduced stiffness. The reduced stiffness is given by:

Flexural stiffness: $EI^* = 0.8\tau_b EI$;

Axial stiffness: $EA^* = 0.8EA$.

If the structural system contains members that fail by inelastic buckling, the factor $0.8\tau_b$ accounts for the inelastic softening prior to reaching the design strength. The factor τ_b by itself accounts for stiffness reduction under compression load ,P_r, exceeding 50% of the yield load, P_y. The factor 0.8 accounts for the additional loss of stiffness due to combined bending and axial compression. This may be interpreted as having an available system strength of 80% of the elastic stability limit. This is approximately similar to the available strength in elastic compression members in Chapter E of the AISC specifications:

$$\emptyset P_n = 0.9(0.877P_e) = 0.8P_e.$$

Effective Length Factor Stability

The effective length factor, K, has been historically associated with stability analysis based on ELM. ELM itself existed in the AISC specifications since 1961 and evolved from one edition to another. The commentary to the current AISC specifications recommends calculation of "K" from sidesway buckling analysis. Moment resisting frames that are designed using ELM to resist lateral forces must take into account the destabilizing effects of leaning columns that support gravity. This is done by incorporating such effects in the calculated effective length factor, K. One method known as the Story Stiffness Approach (SSA) (LeMessurier, 1976, 1977) provides K as:

$$K = \sqrt{\frac{\sum P_r}{(0.85 + .15R_L)P_r}\left(\frac{\pi^2 EI}{L^2}\right)\left(\frac{\Delta_H}{\sum HL}\right)} \geq \sqrt{\left(\frac{\pi^2 EI}{L^2}\right)\frac{\Delta_H}{1.7HL}}$$

where:

H: shear force used to calculate the story drift Δ_H.

P_r: vertical column load.

$R_L = \frac{\sum P_{r\ leaning\ columns}}{\sum P_{r\ all\ columns}}$.

The effective length factor, K, for individual columns in moment resisting frames may also be calculated using the alignment charts in AISC Appendix 7. Despite numerous limitations, the method remains popular. This method is used in the case study described later in this paper. The effective length factor, K, is determined for columns in unbraced frames from the following equation:

$$\frac{G_A G_B(\pi/K)^2-36}{6(G_A+G_B)}-\frac{(\pi/K)}{tan(\pi/K)}=0 \qquad \text{AISC Eqn. C-A-7-2}$$

where; $$G=\frac{\sum E_c I_c/L_c}{\sum E_g I_g/L_g} \qquad \text{AISC Eqn. C-A-7-3}$$

The subscript "g" in AISC Eqn. C-A-7-3 refers to beams at end A or B of the column under consideration, while the subscript "c" refers to columns at end A or B of the column under consideration.

Second-Order Effects

Stability analysis typically requires the consideration of second-order effects at the system level $P-\Delta$ and member level $P-\delta$. In the 14th edition of the steel construction manual, section C2.1 permits a significant simplification of second-order analysis, in which $P-\delta$ effects may be neglected for certain types of structures. The two important conditions for neglecting $P-\delta$ effects are:

- Ratio of second-order drift to first-order drift is less than 1.7.
- No more than 1/3 of the total gravity load on the building is on columns that are part of the moment resisting frames.

Contribution of Leaning Columns on Second-Order Effects

Columns that contribute to resisting only gravity forces are known as *leaning columns*. When second-order analysis is conducted to determine the amplified moments and forces on moment resisting frames, forces on leaning columns tend to increase second-order effects. This is typically true when there are lateral forces to displace the structure laterally in the presence of gravity forces. Similarly, leaning columns amplify second-order effects when geometric imperfections exist.

Uncertainties in Strength and Stiffness

The effects of uncertainties in strength and stiffness on structural demand and member strength are accounted for in the current specifications in different ways, depending on the stability analysis method. For both DAM and ELM, the effect of uncertainties related to member capacity is incorporated in the member resistance factor, $\emptyset$. In addition, when using DAM for stability analysis, the reduced stiffness described in this paper (AISC, 2011) is also considered to account for the effects of stiffness uncertainties on structural demand and member strength.

When ELM is used for stability analysis and design, the use of effective length $K\geq 1.0$ is considered to account for effects of stiffness uncertainties on structural demand and member strength.

Overview of Pre- and Post-2005 Stability Analysis Procedures

The following part of this paper provides an overview of the stability analysis procedures in the 2005 and 2011 specifications, highlighting the differences in structural demand.

Determination of Demand and Capacity Prior to 2005

AISC specifications prior to 2005 (AISC, 2000) didn't require incorporating the effects of inelasticity and imperfections on structural demand of moment resisting frames, as shown in Figure 1. However, second-order effects were required to be considered when calculating structural demand.

The primary method for estimation of structural demand prior to 2005 is a form of ELM, which required the calculation of the effective length factor "K", typically greater than 1.0 in sway frames. The same effective length factor is used in estimating the strength of individual members. The equations for estimating load-carrying capacity of structural members included the effects of both imperfections and inelasticity. This is the case prior to 2005 specifications and remained the case in subsequent specifications. Two issues transpired from the pre-2005 specifications:

- There is more than one method for estimating the all-important effectiveness factor (Kavanagh, 1962; White and Hajjar, 1997). The most commonly used method for estimating the effective length factor is the use of the alignment charts (Kavangh, 1962). However, Appendix 7 in the commentary of the AISC manual (AISC, 2011) lists nine different conditions for the use of *alignment charts* which are only applicable to highly idealized structures.
- It is believed that neglecting the effects of geometric imperfections and inelasticity on the assessment of structural demand leads to underestimation of forces in beams, which also impacts the design of connections in moment resisting frames. This was one of the primary motivations for the changes incorporated in the current stability analysis requirements. The pre-2005 approach didn't necessarily lead to columns that were undersized. Figure 3 summarizes the process for stability analysis and design using pre-2005 specifications.

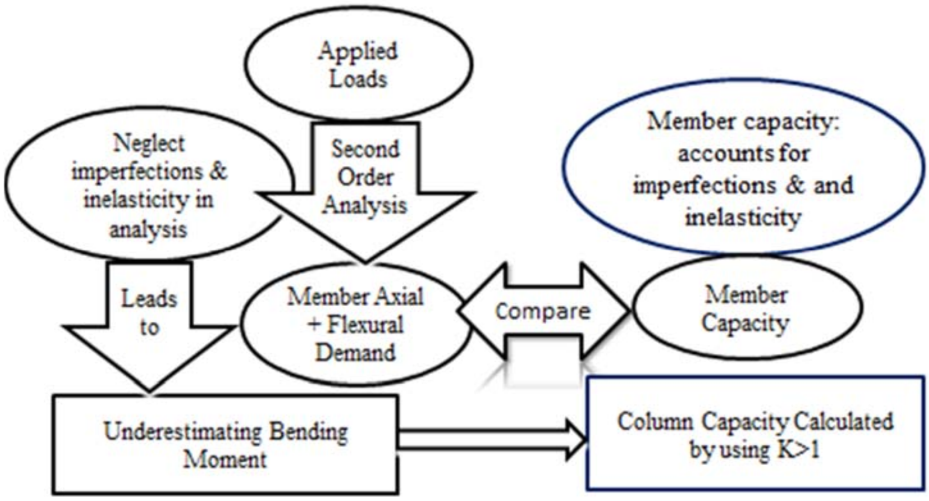

Figure (3): Assessment of demand and capacity per AISC specifications prior to 2005

Determination of Demand and Capacity from 2005 to Present

Three prescriptive methods are currently outlined in the AISC specifications; namely, DAM, ELM and First-Order Analysis. Discussion in the following paragraphs is limited to the recommended DAM and the prevalent ELM methods.

Current AISC specifications require that the estimation of structural demand must take into account geometric imperfections in individual members and stiffness reduction due to inelasticity, which were both introduced in a previous section of this paper.

Similar to pre-2005 specifications, the current DAM and ELM are required to take into account second-order effects on structural demand.

In both DAM and ELM, Section C2.2b of the current specifications requires that joint-position imperfections (out-of-plumbness) must be directly incorporated into the structural model.

Direct Analysis Method (DAM): There are no restrictions on the use of DAM. In addition, DAM permits the use of effective length KL equal to actual column length L, even for moment resisting frames. It is likely that the use of effective length factor equal to unity in calculating structural demand in moment resisting frames will appeal to many engineers, as it removes the well-known uncertainties associated with the estimation of the effective length factor $K \geq 1.0$ in ELM.

Figure 4 shows how DAM is used to determine structural demand and capacity while satisfying the current AISC specifications.

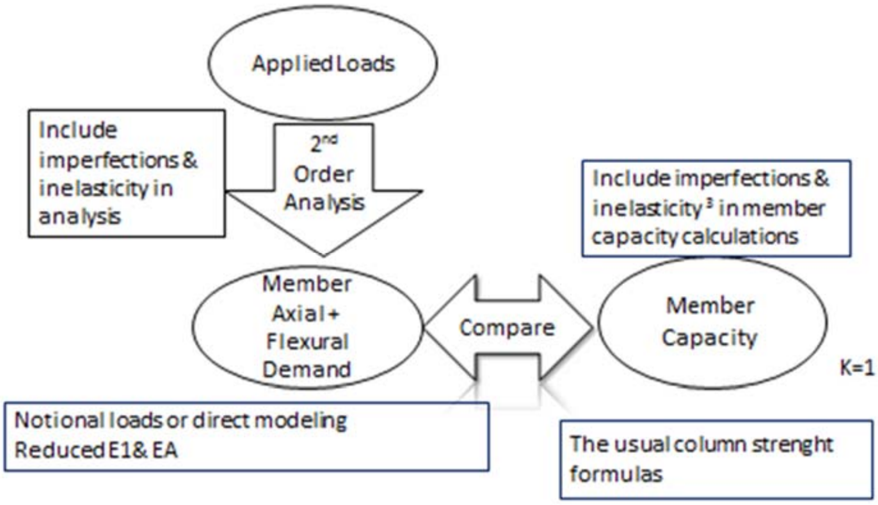

Figure (4): Direct analysis method 2005 to present (13th and 14th editions of AISC manual)

Effective Length Method (ELM)

ELM remained in the current specifications as an alternative to DAM. Engineers opting to ELM for stability analysis and design still need to estimate the effective length factor. All of the stability requirements of AISC Section C1, which were outlined in the introduction of this paper, are addressed in the ELM method. In ELM, a number of requirements in AISC Section C1 are considered to be addressed by the use of effective length factor greater than 1.0. The following requirements for the assessment of structural demand and member strength were incorporated in the use of effective length factor, K, greater than 1.0:

1. Member imperfections (out-of-straightness), discussed in the theoretical background of this paper.
2. Reduction in structural stiffness due to inelasticity, or spread of plasticity, discussed in the theoretical background of this paper.
3. Uncertainties in strength and stiffness.

When ELM is applied for braced frames, typically idealized as vertical pin-connected truss systems, the effective length factor, K, is taken as one, unless a smaller value is justified by the analysis.

Comparative Study between DAM and ELM in Current Specifications

The differences between modeling methods required by AISC specifications for DAM and ELM were outlined in a previous section of this paper. In order to understand the difference in structural response when DAM and ELM are used, a case study structure is modeled and designed in ETABS software (Computers and Structures, 2013).

For ELM, the effective length factor for the braced condition is taken as K = 1.0, while the effective length factor for the unbraced condition is calculated based on the alignment charts described in Appendix 7 of the AISC commentary.

Case Study Description

Structural Framing: W-shapes are used in moment resisting frames, bracing elements, as well as gravity elements. Figure 5 shows a plan view of the case study.

Floor Systems: composite concrete with steel decking.

Concrete properties: 28-day concrete compressive strength = 4000 psi (27.6 MPa).

Steel property: ASTM A992 Grade 50, F_y = 50 ksi (344.7 MPa).

Framing System:

Beams in moment resisting frames are W21 x 68; columns are W14 x 145.

Vertical geometry: number of stories = 10; base floor height = 4.5 m, typical story height = 4.0 m.

Gravity Load:

Superimposed dead load = 3.5 kN/m^2.

Dead load (floor system): ASTM A992 steel deck with concrete fill.

Live load = 4.5 kN/m^2.

Lateral Loads (ASCE 7, 2010):

Wind speed = 100 mph; Importance factor, I = 1.0. Directionality factor, k_d = 0.85; Gust factor, G =0.85.

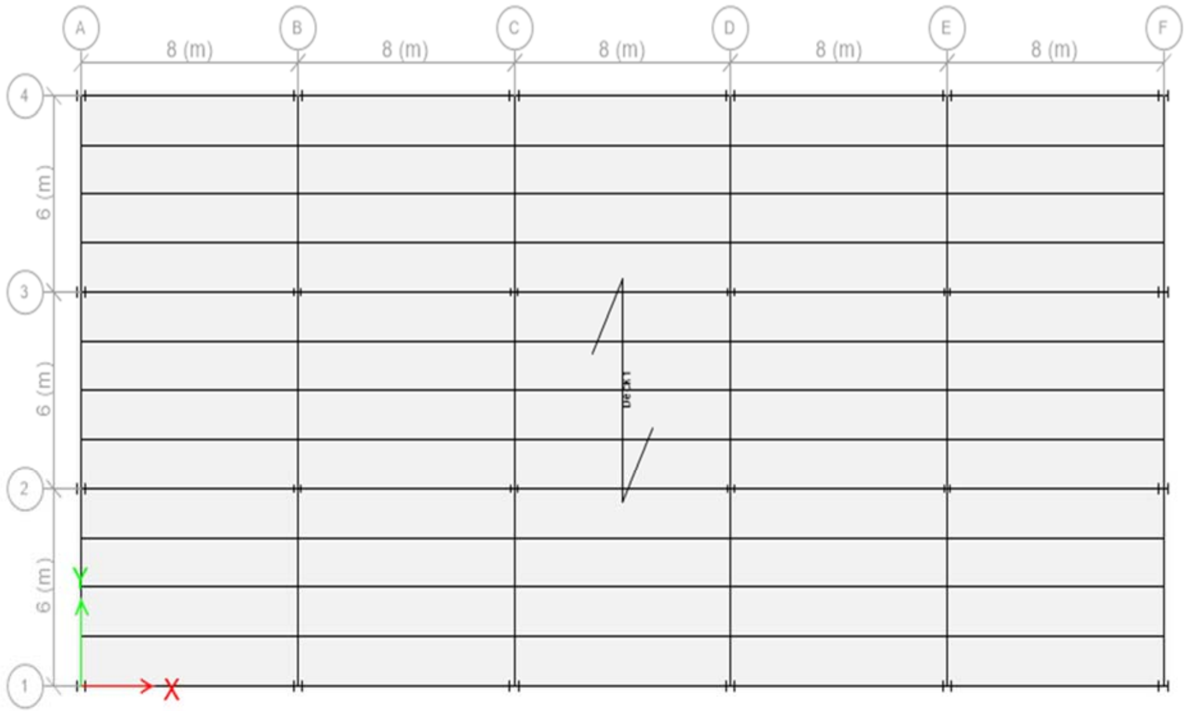

Figure (5): Plan view showing dimensions of case study

Figure 6a shows the bracing system for lateral force resistance with inverted V-bracing along grid lines A and B, while Figure 6b shows typical moment resisting frames along grid lines 1, 2, 3 and 4.

Analysis and design were conducted using AISC ELM and DAM. Second-order analysis was conducted in each case as per AISC Section C2.1(2). Notional loads were applied per AISC Section C2.2b (4). The demand/capacity ratios accounting for the interaction of flexure and axial compression were determined per AISC Chapter H, as follows:

When $\frac{P_r}{P_c} \geq 0.2$

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \qquad \text{AISC Eqn. H1-1a}$$

When $\frac{P_r}{P_c} < 0.2$

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \qquad \text{AISC Eqn. H1-1b}$$

In both cases, a design load combination containing (lateral wind load = 1.2 dead Load + 1.0 live load + 1.0 wind load) is examined. The demand/capacity ratios for moment frame elements calculated using ELM and DAM are shown in Figure 7(a) and (b), respectively. All beams are W10x60 and all columns are W12x65.

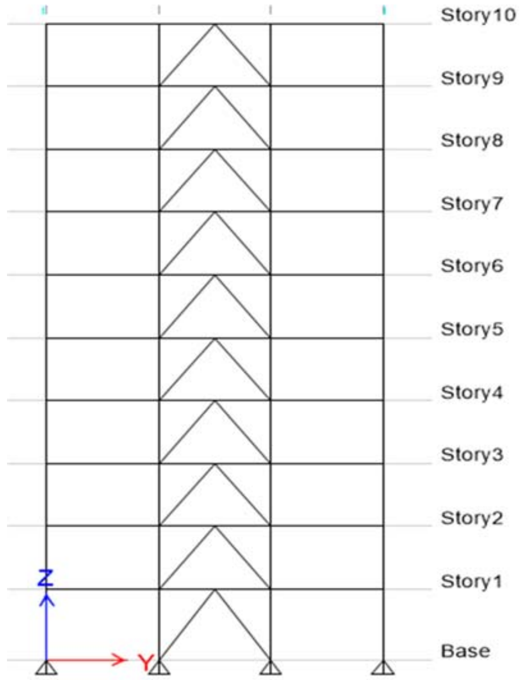

Figure (6a): Inverted V bracing along grid lines A and B

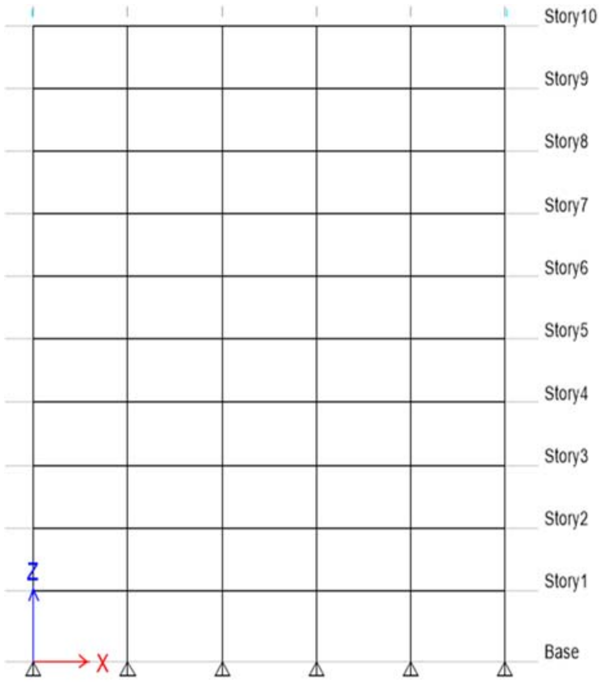

Figure (6b): Moment resisting frames along grid lines 1, 2, 3 and 4

Comparing demand/capacity ratios in Figure 7, it can be seen that ELM predicts higher structural demand than DAM on columns and beams in lower floors. In upper floors, however, demand/capacity ratios calculated using DAM and ELM are not too different. The primary contributing factor is the calculated effective length factor which increased for column line 1F from 4.3 in columns at the lowest floor level to 2.5 at the highest floor level.

Structural demand in beams at the lowest floor is higher when calculated with ELM compared to DAM. This affects the design of beams and moment connections in this frame.

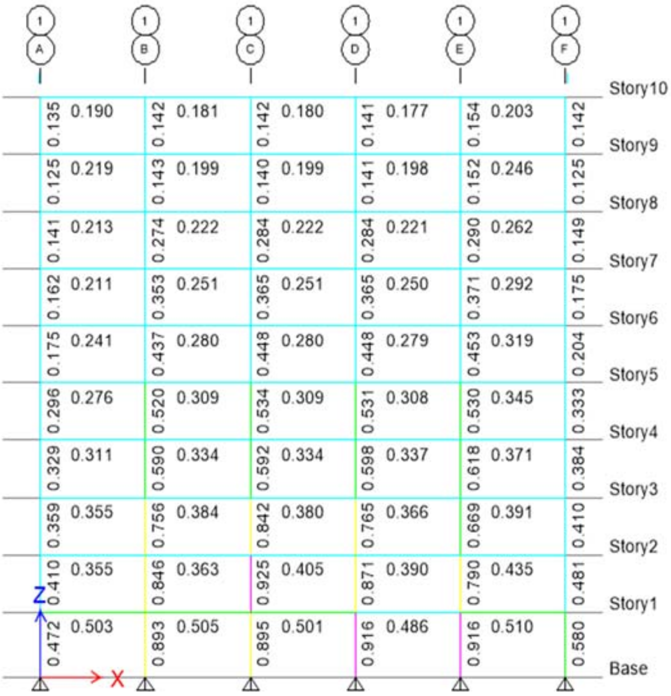

Figure (7a): Demand/capacity ratio for load combination (1.2D + 1.0L + 1.0W) stability analysis using DAM

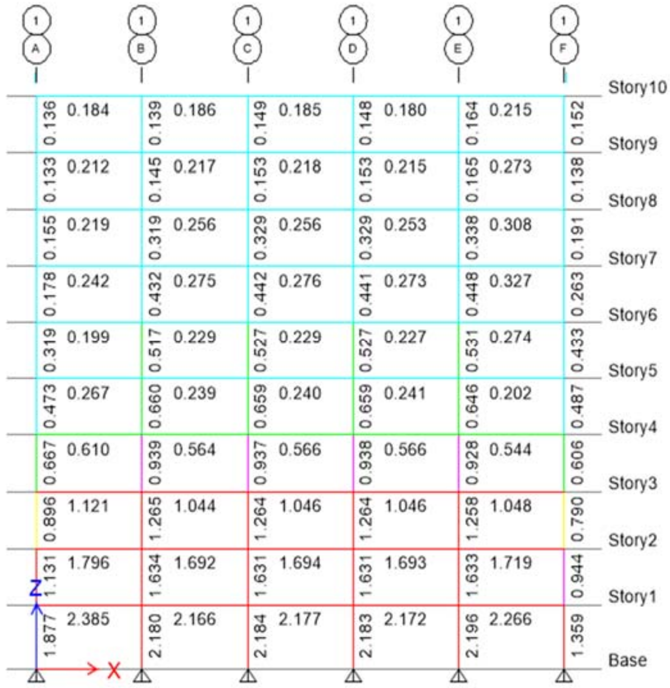

Figure (7b): Demand/capacity ratio for load combination (1.2D + 1.0L+ 1.0W) stability analysis using ELM

Figure 8 shows the Demand/Capacity ratio for load combination 1.2 D + 1.6 L + 1.2 Notional (D) + 1.6 Notional (L). For the same W-shapes used in Figure 8, it is clear that ELM predicts higher demand on beams and columns, especially at the lowest floor. The effective length factor for column line 1D is 3.3 at the lowest floor and decreases to 1.9 at the highest floor.

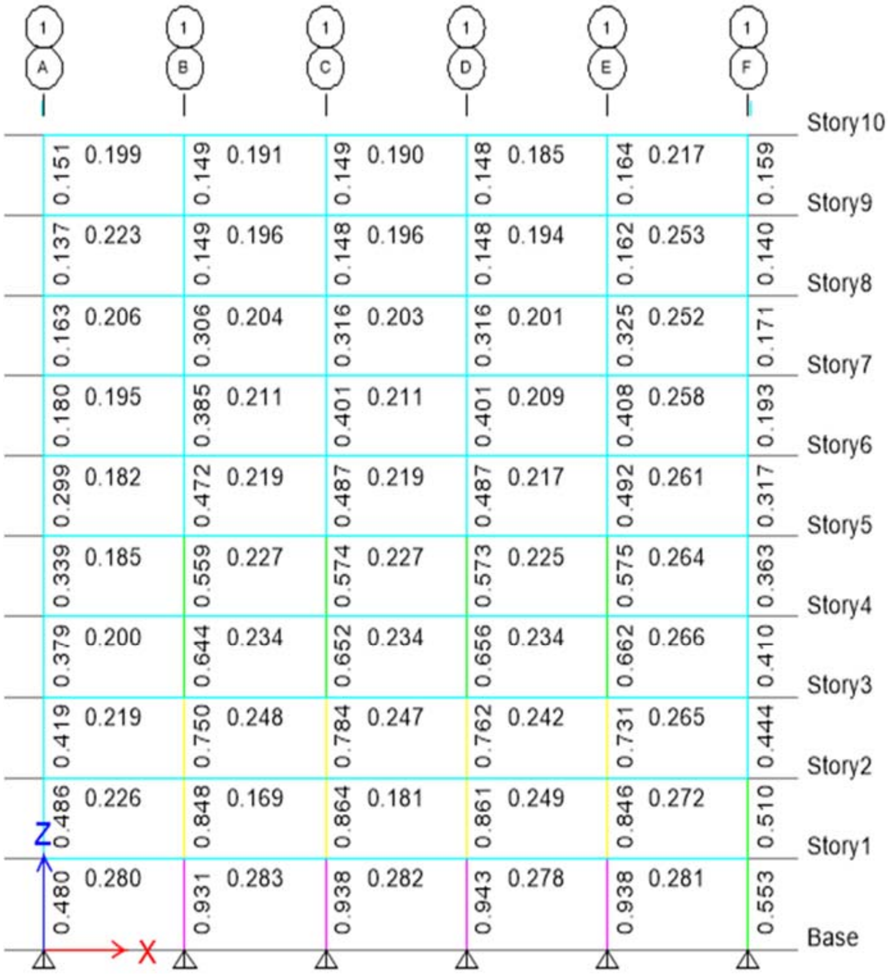

Figure (8a): Demand/capacity ratio for load combination 1.2D + 1.6L + 1.2 notional (D) + 1.6 notional (L) stability analysis using DAM

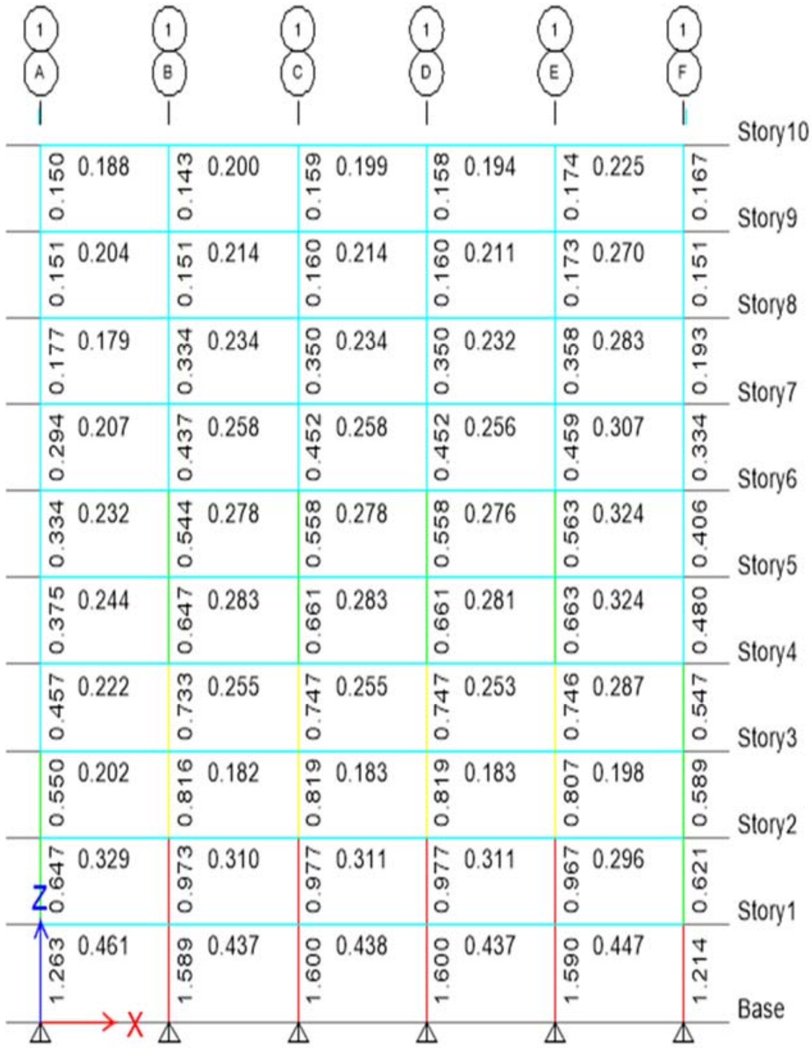

Figure (8b): Demand/capacity ratio for load combination 1.2D + 1.6L + 1.2 notional (D) + 1.6 notional (L) stability analysis using ELM

RESULTS AND CONCLUSIONS

- In current AISC specifications, DAM and ELM require the use of notional loads to account for the effects of frame imperfections on structural demand.
- Demand-to-capacity ratios calculated based on DAM are lower than those calculated based on ELM for beams and columns at lower levels of a steel framed structure. However, the demand-to-capacity ratios are not very different at the upper levels of the frame when predicted using DAM or ELM. In other words, ELM may determine beams and columns at the lower levels of a relatively tall building as failing elements, while DAM may determine the same elements as passing.
- ELM predicts higher demand-to-capacity ratios on beams at the lower floor level compared to DAM, which leads to increased demand on the beam-to-column moment connections. Therefore, ELM is more conservative for connection design compared to DAM.
- ELM requires the calculation of effective length

factor, which accounts for member imperfections and stiffness reduction caused by inelasticity. All methods currently available, including alignment charts, involve significant uncertainties and apply to highly idealized structures. Calculation of the effective length factor for complex buildings is complicated and analysis results vary based on the method of calculation.

- DAM permits the use of an effective length factor of one. The stiffness reduction due to inelasticity and member imperfections is independently addressed from the effective length factor and directly incorporated into the structural model.
- Depending on the method of calculating the effective length factor, ELM predicts higher responses on beams and columns of moment resisting frames, compared to DAM. Response of beams predicted by ELM is particularly high, impacting both beam and connection design.
- Engineers should avoid loading moment resisting frames with more than 1/3 of the total gravity loads. This limits the effect of $p - \delta$ on structural response and permits ignoring their effect on structural response.

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