การออกแบบอย่างเหมาะสมสำหรับโครงสร้างเหล็กด้วยวิธีฮิวริสติกร่วมกับวิธีวิเคราะห์โดยตรง

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OPTIMAL DESIGN OF STEEL STRUCTURES USING HEURISTIC ALGORITHM WITH DIRECT ANALYSIS METHOD

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วิสุทสมบัติคี:
การออกแบบอย่างเหมาะสมสำหรับโครงสร้างเหล็กด้วยวิธีฮิวริสติกร่วมกับวิธีวิเคราะห์โดยตรง. (OPTIMAL DESIGN OF STEEL STRUCTURES USING HEURISTIC ALGORITHM WITH DIRECT ANALYSIS METHOD) อ.ที่ปรึกษาวิทยานิพนธ์: ศ.ดร.ทักษิณ เทพชาตรี 74 หน้า

การศึกษานี้เป็นการนำเสนอวิธีการออกแบบโครงสร้างเหล็กโดยนำเอาวิธีฮิวริสติกมาใช้ร่วมกับวิธีวิเคราะห์โดยตรงจากมาตรฐาน AISC 2010 เพื่อให้ได้ขนาดหน้าตัดองค์อาคารที่เหมาะสม โดยมีน้ำหนักรวมของโครงสร้างน้อยที่สุดภายใต้ข้อกำหนดการออกแบบตามมาตรฐาน AISC-LRFD/2010

การออกแบบเริ่มต้นจากนำขนาดหน้าตัดองค์อาคารที่ได้จากการวิเคราะห์และออกแบบโครงสร้างเหล็กโดยโปรแกรมสำเร็จรูป CSi SAP 2000 ไปผ่านกระบวนการเลือกขนาดหน้าตัดใหม่ด้วยวิธีฮิวลิสติก ซึ่งเขียนขึ้นจากภาษาวิชวลเบสิก (visual basic) และมีความสามารถเชื่อมต่อกับโปรแกรม CSi SAP 2000 ได้ หลังจากได้ขนาดหน้าตัดใหม่ โปรแกรม CSi SAP 2000 จะทำการตรวจสอบความสามารถในการรับแรงต่างๆ ของขนาดหน้าตัดชุดนั้นๆ กระบวนนี้จะทำซ้ำจนได้ขนาดหน้าตัดใหม่ที่เหมาะสมโดยมีน้ำหนักรวมโครงสร้างน้อยที่สุด และผ่านเกณฑ์ข้อกำหนดการออกแบบตามมาตรฐาน AISC-LRFD 2010 อนึ่ง การศึกษาจะพิจารณาจากวิธีวิเคราะห์โดยตรง วิธีวิเคราะห์อันดับหนึ่ง ซึ่งไม่รวมผลของ P-Delta และวิธีวิเคราะห์อันดับสองซึ่งรวมผลของ P-delta

ผลการศึกษาจากโครงสร้างเหล็กข้อแข็ง 3 ตัวอย่าง พบว่าวิธีการออกแบบอย่างเหมาะสมที่นำเสนอให้ผลลัพธ์ที่ดีกว่า หรือเท่ากับผลลัพธ์ที่ได้จากโปรแกรม CSi SAP 2000 นอกจากนี้ยังได้ทำการศึกษาและเปรียบเทียบกับผลลัพธ์ต่างๆ ที่ได้จากการศึกษาในอดีตด้วยวิธี GA (Genetic Algorithm) วิธี ACO (Ant Colony Optimization) และวิธี HS (Harmonic Search Algorithm)

ภาควิชา ....วิศวกรรมโยธา......... .... ลายมือชื่อนิสิต..

สาขาวิชา............วิศวกรรมโยธา............. ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก.....................

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This study proposes a Heuristic Algorithm for the optimal design of steel frame structures using the Direct Analysis Method of the AISC 2010 Specification. The objective of the design algorithm is to obtain the minimum weight of the steel frame sections where the design constraints are imposed by the AISC-LRFD specification requirements. In this paper we combine the CSi SAP2000 commercial structural analysis program with the Heuristic Algorithm which is written in Microsoft Visual Basic program for the optimal design of steel frame structures. The analyses are performed by using the first-order analysis method without P-Delta effects and the rigorous second-order analysis with P-Delta effects to illustrate their effects on structural optimal design. Through three examples of planar steel frames, we firstly compare the results between the Direct Analysis Method and the conventional methods which are the Effective Length Method and the First-Order Analysis Method, and then followed by the comparison of the efficiency of the Heuristic Algorithm with the optimization algorithm such as Genetic Algorithm, Ant Colony Optimization, Harmonic Search algorithm, and the virtual work based optimization for lateral deflections in software CSi SAP2000.

Department: ……Civil Engineering.......................... Student’s Signature …………….
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CHAPTER I
INTRODUCTION

1.1 Introduction

During the last four decades, many mathematicians have developed programming methods for solving optimization problems (Gallagher and Zienkiewicz 1973). However, there is no single method that has been proved to be totally efficient enough for the wide range of engineering optimization problems (Rajeev and Krishnamoorthy 1992). Most of the design applications in civil engineering are related to the selection of values for a set of design variables that best satisfy the design requirements of the specification. There are many optimization techniques that have been used for the structural design especially for steel structures such as genetic optimization algorithm (GA), ant colony optimization (ACO), harmony search algorithm (HS)… etc.

A genetic algorithm is a search strategy that relies on the principle of the survival of fittest and the concepts of the natural selection and genetics. It works on a set of potential solutions rather than a single solution improvement. This optimization method was proposed by Holland in 1975, and it has been widely used for discrete structural optimization by many researchers (Goldberg and Samtani 1986; Jenkins 1991, 1992; Rajeev and Krishnamoorthy 1992; Adeli and Cheng 1993, 1994; Koumousis and Georgiou 1994; Rajan 1995; Camp et al. 1997; Kocer and Arora 1997; Jenkins 1997; Pezeshk et al. 1997; Rajeev and Krishnamoorthy 1997; Camp et al. 1998; Shrestha and Ghaboussi 1998, Voss and Foley 1999; Pezeshk et al. 2000; Pezeshk and Camp 2000; Hayalioglu 2000, 2001; Kameshki and Saka 2001, 2003; Foley and Schinler 2003; Kaveh and Kalatraji 2002, 2004; Hayalioglu and Degertekin 2004, 2005; Foley and Schinler 2003; Kaveh and Rahami 2006).

The ant colony optimization algorithm has been originally developed by Dorigo et al since 1992. The optimization is based on the concept that ants collect their food from the food source to put into their nest in the shortest distance. This method of optimization has been applied to the design of planar and space steel trusses and planar steel frames (Camp and Bichon 2004, Camp et al. 2005, Camp, Bichon, and Stovall 2005, Kaveh and Talatahari 2009).

The harmony search algorithm is a new meta-heuristic search algorithm which uses the analogy between the process of the natural music performance and the searching for optimization solutions. This optimization method was first proposed by Geem et al in 2001, and later it has been adapted to the optimal design of planar and space trusses by many researchers (Lee and Geem 2004, 2005; Lee et al. 2005; Degertekin 2007; Lee, Han, and Geem 2011).

The heuristic search algorithm was originally defined by Polya in 1945 in the AI literature. And from the mid 1950's to the mid 1980's, the heuristic notion played an important role in the AI researcher's descriptions of their work. The concept of heuristic firstly appeared in the early 1950's AI literature and it was well-recognized in ten years later. The term "Heuristic" means serving to find out or discover, it refers to the experience-based techniques to solve the problems or discover the objectives. According to the study of Feigenbaum and Feldman in 1963, the heuristic term was first used as a noun meaning heuristic process. They defined that a heuristic for a problem is a process that may solve the given problem, but it does not guarantee of doing so. The heuristic method is basically an effective method in solving the problems, where the solutions are not guaranteed to be found but will surely reduce a large amount of computation. In the geometry program paper by Gelernter in 1959, he also seriously mentions that it is necessary to employ heuristics in the problem in order to get rid of the exhaustive search. He is one of the first to claim that heuristic work effectively by eliminating impractical options from the vast set of possibilities. Moreover, according to the discussion in 1960 of Tonge, he also uses heuristic program to minimize the number of workers required on an assembly line. He takes heuristics as a shortcut and simplified method in contrast with many other algorithmic methods that guarantee solutions. Another study from Minsky in 1961, who was one of the first to employ heuristic in a vast problem space, also agree that a heuristic is an effort-saving method that improve the efficiency over some other methods. Furthermore, the heuristic method has been developed and applied by many researchers in various types of structures such as reinforced concrete, prestressedconcrete, and steel (Perea, Alcala, Yepes, Hospitaler 2007; Martinez, Vidosa, Hospitaler, Yepes 2009; Marti, Vidosa 2010; Semelawy, Nassef, Damatty 2011; Lamom, Thepchatri, Rivepiboon 2008).

1.2 Motivations

The current trend of steel structural design has been leaning towards a larger, more complex, and taller structural system as the population and technology has grown rapidly in the 21th century. The AISC 2010 specification has also updated its methods of design for stability in order to keep up well with the actual structural behavior. Traditionally, both of the effective length method and the first-order analysis method have been used to analyze and design the steel frame structures for stability. However, both methods are performed based on the very highly idealized assumptions which restrict their limitations of application. For instance, in the design of the large, complex, or tall buildings, these assumptions cannot be the same as the real structural behavior. Therefore, the effective length method and the first-order analysis method are not suitable for the design of more large or complicated tall structures. And whenever the actual behavior of the structure falls outside the limitations of the two methods above, the AISC 2010 specification requires that the direct analysis method must be used instead for the analysis of design for stability. Thus, all of the structures in this study will be analyzed and designed using the direct analysis method and the results will be compared with those of the effective length method and the first-order analysis method.

On the other hand, for the design of large or high-rise structures, cost-effective is a very important issue to be considered. Normally, the cost-effective depends on many factors such as the materials, weight, labor, construction technology, etc. However, those factors vary from situations to situations such as locations, times, etc. Thus, it is assumed that the objective function of the optimization in this study depends on the weight of the cross-section of the member only. The optimization method which will be used in this study is the Heuristic optimization algorithm. Therefore, this study will apply all of the analysis methods in the AISC 2010 specification in combination with the Heuristic optimization Algorithm. And the obtained results will be used to compare with the previous research study of the Harmony Search algorithm, Ant Colony Optimization, and Genetic optimization Algorithm.

1.3 Research Objectives

There are three main objectives of this research:

1. Select the Lightest Steel Profile using the Heuristic optimization algorithm with the direct analysis method in AISC 2010 Specification.
2. Compare the Results from (HA) with the Results obtained from:
   - ❖ Harmony Search Algorithm (HS)
   - ❖ Genetic Optimization (GA)
   - ❖ Ant Colony Optimization (ACO)
   - ❖ Virtual Work based Optimization for Lateral Deflections(CSi SAP2000)
3. Compare the Results from Direct Analysis Method (DAM) with Methods of :
   - ❖ First Order Analysis Method (FAM)
   - ❖ Effective Length Method (ELM)

1.4 Scopes of Research

The scopes of this research are listed as follows:

1. Design using the AISC 2010 Specification’s Stability Design Methods:
   - ❖ First-order analysis method
   - ❖ Effective length method
   - ❖ Direct analysis method

   where the effects of geometry imperfection are negligible.
2. Perform the analysis using rigorous second-order analysis
3. Optimal design using Heuristic optimization algorithm
4. Discuss and recommend design guidelines

CHAPTER II

THEORETICAL CONSIDERATION AND METHODOLOGY

2.1 Introduction

The DAM was first introduced in the AISC 2005 as the Appendix 7, while both the ELM and FAM were in section C.2.2a and section C.2.2b respectively. But in the AISC 2010, the DAM has been moved to section C.2 while both the ELM and FAM have been moved to the Appendix 7 as the alternative methods of design.

Table 1: Comparison between AISC 2005 and AISC 2010

	AISC 2005	AISC 2010
Member Stability	C.1.2	C.3
Direct Analysis Method	Appendix 7	C.1.5.1
Effective Length Method	C.2.2a	Appendix 7.2
First-Order Analysis Method	C.2.2b	Appendix 7.3
Amplified First-Order Analysis Method	C.2.1b	Appendix 8

2.2 AISC 2010 Specification's Design Method for Stability

Chapter C of the AISC Specification requires that the stability shall be provided as a whole structure as well as its individual elements. The effects which shall be taken into account for the design for the stability are:

1. All kinds of deformations that affect the deformations of the structure.
2. Geometric Nonlinearity/ Second-order effects: Both P-Δ and P-δ effects.
3. Geometric/ Initial Imperfections: Out-of-plumbness and out-of-straightness
4. Inelasticity/ Residual Stresses.
5. Uncertainty in stiffness and strength.

The AISC 2010 specification offers three analysis methods of design for stability:

1. Direct analysis method (DAM)
2. Alternative methods:
    a. Effective length method (ELM)
    b. First-order analysis method (FAM)

Or in further detailed sub-division, they can be classified as follows:

1. General Second Order Elastic Analysis
2. Second Order Analysis by Amplified First Order Analysis
3. Limited First Order Elastic Analysis
4. Direct Analysis Method with General Second Order Analysis
5. Direct Analysis Method with Amplified First Order Analysis

However, any analysis method of design that can consider all of the effects mentioned above is allowed to be used.

2.3 Analysis Methods: First-Order Analysis vs. Second-Order Analysis

There are two types of analysis methods which are allowed to use in the AISC specification, namely are first-order analysis method and second-order analysis method.

The first-order analysis method is a method whose equilibrium equations are formulated under the undeformed configuration. And the impact of the axial load on the bending moment is neglected within the beam-column. The material used in this kind of analysis is assumed to be linear-elastic. It follows the same path at the time of loading and unloading and remains the same as the undeformed configuration after removing the loading completely. The superposition method is valid due to the linearity – the response is proportional to the loading. The first-order analysis method is very limited in real world applications due to its many unrealistic assumptions. Once its limit of application becomes invalid, the second-order analysis is inevitably required.

The second-order analysis method is a method whose equilibrium equations are formulated under the deformed configuration. And it must consider the effects of vertical load on the deformed shapes which namely are P-Δ and P-δ effects. The P-Δ effect is the effect of vertical compression force, P, acting on the horizontally displaced joint of the member which causes additional bending moment in addition to that from the first-order analysis. And the P-δ effect is the effect due to the vertical compression force, P, acting on the deflected shape of the member between its ends, which also causes additional bending in addition to that from both the first-order analysis and the P-Δ effect. And the material is assumed to be linear-elastic. Most materials have the behavior of both elastic and inelastic, depending on the level of loading.

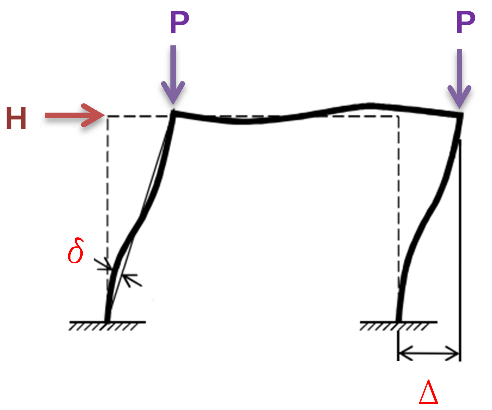

Figure 1: P-Delta Effects

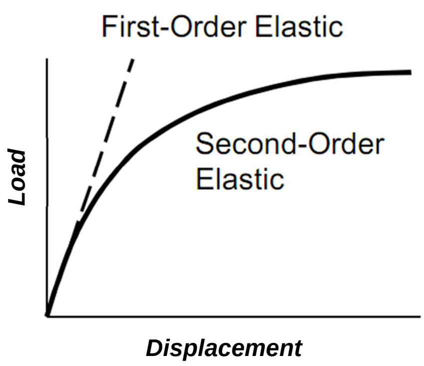

Figure 2: First-Order vs. Second-Order

2.3.1 Rigorous Second-Order Analysis Method

The rigorous second-order analysis method is a very accurate analysis method which directly accounts for the second-order effects. The second-order effects are mainly nonlinear where the superposition principles cannot be applicable for such analysis. Importantly, the only opportunity to model the actual behavior of the structure is by means of modifying the member stiffness terms in a method known as the direct stiffness method which is the most popular method coded in the commercial computer software programs such as SAP2000, ETABS, Staad Pro, RISA,…etc. The roots of nonlinearity are from the geometric nonlinearity (P-Δ and P-δ effects), material nonlinearity (Inelasticity, Cracking, Yielding,…), combined both geometrical and material effects, and large displacement. The stiffness matrix which considers all the effects of nonlinearity are the sum of all stiffness matrixes for each effect, it is given by:

$$\mathbf{k} = \mathbf{k}_{\mathbf{geometric}} + \mathbf{k}_{\mathbf{elastic}} + \mathbf{k}_{\mathbf{plastic}} \qquad \textbf{Eq. 1}$$

Through the direct stiffness method with the modified member stiffness, all nonlinear effects will be accounted for directly, however, it does require a large complicated numerical calculation and quite a considerate time to analysis the structures. Nevertheless, with the aids of the computer technology, we can either write our own algorithm using numerical programs such as Matlab, Mathcad, Mathematica, Visual Basic…etc. or using the commercial structural analysis programs available in the markets. The rigorous second-order analysis method is recommended by the specification for the accurate structural analysis when the moment amplification factor $\mathbf{B_1}$ is larger than **1.2** in the members that have a significant effect on the overall structural response.

2.3.2 Amplified First-Order Analysis Method

An amplified first-order analysis method is an approximate second-order analysis method which can be used as an alternative to a rigorous second-order analysis method under very limited application conditions. This method is restricted to the structures that are designed to support primarily the gravity loads by means of the vertical elements such as columns, walls, or frames. The goal of the amplified first-order analysis method is to develop a relationship between the first-order moment and the second-order moment that will simply amplify the results of a first-order analysis in order to get the results of a second-order analysis. It uses the first-order elastic analysis amplified by the factors $\mathbf{B_1}$ and $\mathbf{B_2}$ to the first-order internal forces and moments in order to get the estimated second-order internal forces and moments.

$$\mathbf{M_r = B_1 M_{nt} + B_2 M_{lt}} \qquad \textbf{Eq. 2}$$

$$\mathbf{P_r = P_{nt} + B_2 P_{lt}} \qquad \textbf{Eq. 3}$$

where

$\mathbf{B_1}$ = amplification factor to accounts for P-δ effects
$\mathbf{B_2}$ = amplification factor to accounts for P-Δ effects
$\mathbf{M_{lt}}$ = first-order moment due to lateral translation
$\mathbf{M_{nt}}$= first-order moment due to non-lateral translation
$\mathbf{M_r}$= required estimated second-order moment
$\mathbf{P_{lt}}$ = first-order axial force due to lateral translation
$\mathbf{P_{nt}}$= first-order axial force due to non-lateral translation
$\mathbf{P_r}$= required estimated second-order axial force

The principle of approximation technique used in this analysis method is that it considers the effects of P-Δ and P-δ effects separately through separate amplification factors $\mathbf{B_1}$and $\mathbf{B_2}$. Furthermore, the algebraic addition of the two terms of the amplified forces and moments using $\mathbf{B_1}$and $\mathbf{B_2}$ factors also gives quite reasonably accurate values of the second-order forces and moments.

2.3.2.1 Amplified Factor (B_1) for P-δ Effect

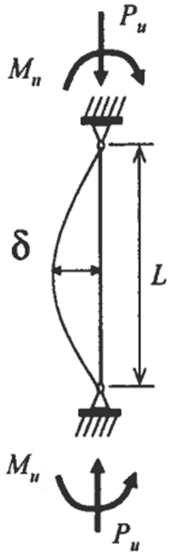

Figure 3: P-δ Effect

By writing the equilibrium equation at the mid-height, then:

$$\mathbf{M_{2nd} = M_u + P_u\delta} \qquad \textbf{Eq. 4}$$

Let's define the amplification factor as $\mathbf{B_1}$, thus:

$$\mathbf{B_{1*}M_u = M_{2nd} = M_u + P_u\delta} \qquad \textbf{Eq. 5}$$

Solve for $\mathbf{B_1}$:

$$\mathbf{B_1 = \frac{M_u + P_u\delta}{M_u}} \qquad \textbf{Eq. 6}$$

Add ($\mathbf{P_u\delta - P_u\delta}$) to the denominator and simplify, thus:

$$\mathbf{B_1 = \frac{M_u + P_u\delta}{M_u + P_u\delta - P_u\delta} = \frac{1}{1 - \frac{P_u\delta}{M_u + P_u\delta}}} \qquad \textbf{Eq. 7}$$

where

$$\boldsymbol{\delta} = \frac{\mathbf{M_u L^2}}{\mathbf{8EI}}$$

Eq. 8

Two approximation assumptions:

$$\frac{\mathbf{M_u}}{\boldsymbol{\delta}} = \frac{\mathbf{8EI}}{\mathbf{L^2}} \approx \frac{\boldsymbol{\pi}^2\mathbf{EI}}{\mathbf{L^2}} = \mathbf{P_e}$$

Eq. 9

$$\frac{\boldsymbol{\delta}}{\mathbf{M_u} + \mathbf{P_u}\boldsymbol{\delta}} \approx \frac{\boldsymbol{\delta}}{\mathbf{M_u}}$$

Eq. 10

Thus,

$$\boldsymbol{B_1} = \frac{\mathbf{1}}{\mathbf{1} - \frac{\boldsymbol{P_u}}{\boldsymbol{P_e}}}$$

Eq. 11

And the AISC 2010 specification determines this amplification factor by:

$$\mathbf{B_1} = \frac{\mathbf{C_m}}{\mathbf{1} - \frac{\boldsymbol{\alpha}\mathbf{P_u}}{\mathbf{P_e}}}$$

Eq. 12

where

- **α**(= 1 for LRFD and 1.6 for ASD) is used to make sure that the analysis can capture the nonlinearity at the ultimate strength.
- **C_m**is the coefficient assuming no lateral translation of the frame.
  It is given by:
  - For beam-columns not subject to transverse loading between supports in the plane of bending. **C_m** is determined by:

$$\mathbf{C_m = 0.6 - 0.4(M_1/M_2) \quad ; \quad M_1 < M_2}$$

Eq. 13

- For beam-columns subject to transverse loading between supports in the plane of bending, $\mathbf{C_m}$ is either obtained from the analysis or conservatively taken as 1 for all cases.

2.3.2.2 Amplification Factor (B_2) for P-Δ Effect

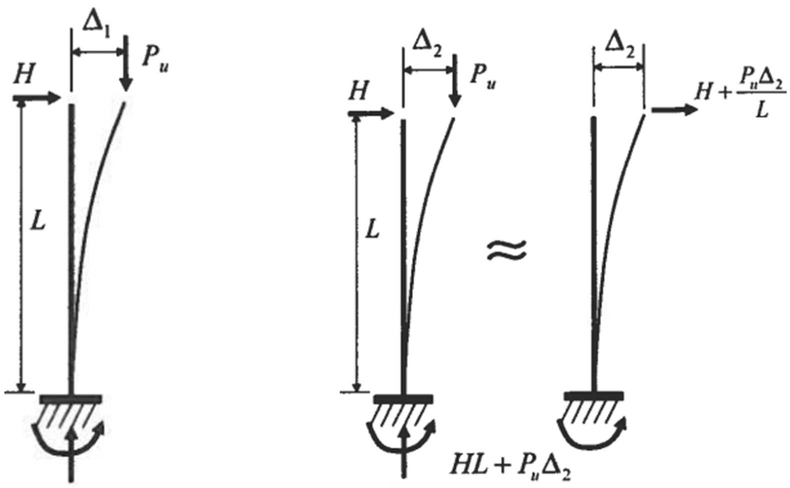

Figure 4: P-Δ Effect

From the first-order analysis, thus:

$$\mathbf{M = HL} \qquad \textbf{Eq. 14}$$

$$\Delta_1 = \frac{\mathbf{HL^3}}{\mathbf{3EI}} \qquad \textbf{Eq. 15}$$

It is assumed that the two models are equivalent, thus:

$$\Delta_2 = \frac{\left(\boldsymbol{H} + \frac{P_u \Delta_2}{L}\right) \mathbf{L^3}}{\mathbf{3EI}} \qquad \textbf{Eq. 16}$$

$$\Delta_2 = \frac{\mathbf{HL^3}}{\mathbf{3EI}} \left(\mathbf{1} + \frac{\mathbf{P_u \Delta_2}}{\mathbf{HL}}\right) \qquad \textbf{Eq. 17}$$

$$\Delta_2 = \Delta_1 + \frac{P_u \Delta_1 \Delta_2}{HL}$$

Eq. 18

Solve for Δ_2 :

$$\Delta_2 = \frac{\Delta_1}{\left(1 - \frac{P_u \Delta_1}{HL}\right)} = B_2 \Delta_1$$

Eq. 19

where the amplification factor is defined as:

$$B_2 = \frac{1}{1 - \frac{P_u \Delta_1}{HL}}$$

Eq. 20

And the amplification factor from the AISC 2010 specification is given by:

$$B_2 = \frac{1}{1 - \left(\frac{\alpha}{R_M}\right)\left(\frac{P_{story} \Delta_H}{HL}\right)}$$

Eq. 21

where

- **α**(= 1 for LRFD and 1.6 for ASD) is used to make sure that the analysis can capture the nonlinearity at the ultimate strength.
- **R_M**is used to account for the effects from the types of structural systems (equals to 0.85 for moment frames, and equals to 1 for braced frames)

2.4 Direct Analysis Method

The direct analysis method is a new efficient method that had been introduced in the appendix of the AISC 2005 specification as an alternative method. Furthermore, it has been moved to the main part of the AISC 2010 specification while the effective length method and the first-order analysis method have been shifted to the appendix as the alternative methods instead. The direct analysis method requires the performance of the second-order analysis; however, either the rigorous second order or the amplified first-order analysis is allowed to be used. Moreover, this method also accounts for the initial imperfectionsuch as out-of-plumbness and out-of-straightness by applying the notion lateral load at all levels. This lateral load plays a role as the additional load to the other lateral loads in every load combination. The value of this notional lateral load is given by:

$$\mathbf{N_i = 0.002\alpha P_i} \qquad \textbf{Eq. 22}$$

where

$\boldsymbol{\alpha}$= 1 for LRFD and 1.6 for ASD

$\mathbf{P_i}$ = the gravity load applied at level $\boldsymbol{i}$

Note that the coefficient of 0.002 is based on the assumption that the out-of-plumbness ratio is 1/500. If this assumption has been violated, an appropriate adjustment shall be made accordingly.

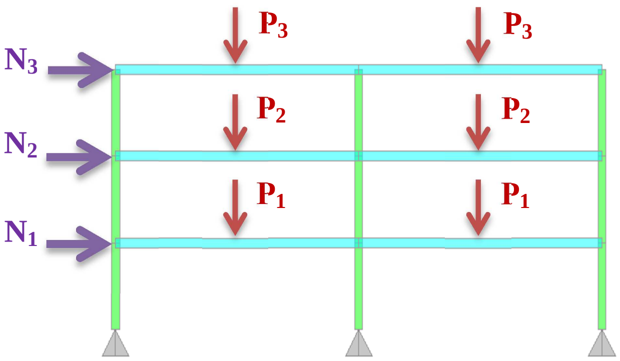

Figure 5: Notional Load

Figure 6: Out-of-plumbness

The direct analysis method uses the reduced flexural and axial stiffness to account for the inelasticity, which is the main assumption mentioned in the effective length method that all the columns behave purely elastic. The factor stiffness reduction can be a fixed value or a variable value depending on the ratio between the required axial compressive strength and the axial yield strength.

The expressions of the factor stiffness reduction in the case of variable value are given by:

$$\boldsymbol{\tau_b = 1.0 \quad \textit{if} \quad \alpha P_r/P_y \leq 0.5} \qquad \textbf{Eq. 23}$$

$$\boldsymbol{\tau_b = 4(\alpha P_r/P_y)[1-(\alpha P_r/P_y)] \quad \textit{if} \quad \alpha P_r/P_y > 0.5} \qquad \textbf{Eq. 24}$$

where

$\boldsymbol{\alpha}$= 1 for LRFD and 1.6 for ASD

$\mathbf{P_r}$ = the required axial compressive strength

$\mathbf{P_y}$ = the axial yield strength

And in the case where factor stiffness reduction is a fixed value of 1.0, the notional lateral load of $\boldsymbol{N_i = 0.001\alpha P_i}$must be used instead of that defined above.

Another important and handy feature used in the direct analysis method is the use of the effective length coefficient **K = 1** for every condition of every column. The mystery behind the use of **K = 1**is that a better consideration of the second-order effects P-Δ and P-δ effects, the geometric imperfections, and the effects of inelasticity has been accounted more efficiently than the effective length method. Using the unit effective length factor enables the engineers to carry out the calculation in a less time-consuming and at ease. And there is no limitation for the use of the direct analysis method. Furthermore, it becomes compulsory to use this method when the limitations of the effective length and first-order analysis method have been over-reached.

2.5 Effective Length Method

The effective length method is an approximate second-order analysis method which uses B_1 and B_2 moment magnification factors to amplify the first-order analysis force and bending moments. The concept of this method is based on the elastic or inelastic stability theory; it uses the effective length of column, which is great than the actual unbraced length, to include the effects of initial geometry imperfections and stiffness reductions due to the inelasticity and residual stress. So during the analysis, it is not required to account for the stiffness reduction again. This method uses the nominal member stiffness ***EI*** and ***EA*** for the columns and the girders. Moreover, it is required that in every gravity only load combinations the notional load of $\boldsymbol{0.002P_i}$ must be applied at all level in both orthogonal directions.

Since the effective length method is only the approximate and indirect second-order analysis method, it is subjected to some limitations. The structures should be used to support primarily the gravity loads through vertical elements such as columns, walls, and frames. The ratio between the maximum second-order drift and the maximum first-order drift in every story must be less than or equal to ***1.5***. And if this limitation is violated, it is required to carry out the analysis using the direct analysis method.

In order to use the effective length method, it is required to use the effective length factor, ***K***, in the design of all beam-columns. The most common and easy way to determine the ***K*** factor is by using the alignment charts. However, these charts are basically based on the assumptions of highly idealized conditions which seldom exist in the real world structures. First, it is assumed that all members must behave purely elastically. Second, all members must be prismatic, having constant cross section, i.e. tampered sections or cellular sections are not allowed to be used. Third, all joints must be rigid in spite of the fact that the real joints behavior more likely as semi-rigid joints while providing more economical results as well. Fourth, for columns in sway frames, the rotations at the ends of the girders are assumed to be equal in magnitude and opposite in direction which causes the columns to bend in a single curvature. Fifth, for columns in non-sway frames, the rotations at the ends of the girders are assumed to be equal in magnitude and direction which causes the reverse curvature bending. Sixth, the stiffness parameter $L\sqrt{(P/EI)}$ of all columns is equal. Seventh, joint restraint is distributed to the column above and below the joint in proportion to EI/L for the two columns. Eighth, the buckling of all columns takes place simultaneously within the same story. Ninth, the axial compression force to the girders is negligible. An important attention that the AISC Commentary draws is that it is important for the users to remember that the alignment charts are produced based on the highly idealized assumptions which seldom really exist in the real structures. Thus, adjustments are frequently required and take place in many different situations such as forcolumns with differing end conditions, girders with differing end conditions, girders with significant axial load, columns inelasticity, and connection flexibility. As we have seen the above assumptions and adjustments, it is impossible that the real-world structures could meet those assumptions and it is tedious to verify and adopt all the adjustment conditions for many columns and girders. Moreover, whenever we modify our model or run many analyses during the design process, we need to verify and adopt those adjustments again and again each time. Therefore, it is very time-consuming to adopt such method to real practical design projects.

The effective length method is suitable only for structures exhibiting small second-order effects since it is limited to structures that support primarily the gravity loads through vertical elements such as columns, walls, and frames.

2.6 First-Order Analysis Method

The first-order analysis is one of the alternative analysis methods given in the Appendix 7.3 of the AISC 2010 specification. It is a kind of structural analysis where the effects of the second-order such as P-Δ and P-δ effects are not taken into account. The specification allows the first-order analysis method to be used in a very limited way that is only when the ratio of maximum second-order drift to maximum first-order drift in all stories is equal to or less than ***1.5.*** And there is also anther condition where the required axial compression strengths of all members, whose flexural stiffnesses are considered to contribute to the lateral stability of the structure,are not greater than half of their yield strengths ($\alpha P_r \leq 0.5P_y$). If this condition limit are satisfied, it is permissible to use the effective length factor **K = 1**for the design of beam-columns. However, in the case of nonsway structures, the moment amplification factor $\mathbf{B_1}$ shall be applied to the total moments. This method does not account for the effects of inelasticity; it uses the unreduced flexural and axial stiffness with the gross cross-sectional areas for the columns and girders. To take care of the effects of initial imperfection, it uses the notional lateral load which is applied as an additional lateral load to the other loads at every level of the structure in every load combination. The notional lateral load is given by:

$$\mathbf{N_i = 2.1\alpha(\Delta/L)P_i \geq 0.0042P_i} \qquad \textbf{Eq. 25}$$

where

$\boldsymbol{\alpha}$= 1 for LRFD and 1.6 for ASD

$\mathbf{P_i}$ = the gravity load applied at level ***i***

Δ/L = the maximum ratio of **Δ** to **L** for all stories in the structure

Δ = the first-order inter-story drift due to LRFD/ASD load combination

L = the story height

The first-order analysis method is mainly intended to be used for only the structure that supports gravity loads primarily through nominally vertical columns, walls or frames.

2.7 Heuristic Optimization Algorithm

A heuristic optimization method is an effective effort-reducing method which simplifies process as well as eliminates the unrealistic possibilities from the large set of possible solutions in order to avoid the exhaustive search, but no guarantee of finding the solutions. The concept of this optimization algorithm is that it moves to the next search step based on the educated guess or experience-based data to speed up the searching process of the satisfactory solution in spite of the solutions guarantee. It basically works as the trial and error, however, with a good guess. Instead of trying all the possible search options, it will try to focus on the paths that likely to get closer to the objective solution. Generally, heuristics is well-known for its simplicity and efficiency to solve large complex problems or incomplete information. Specifically, in this study we will employ the heuristic algorithm for steel cross-section size selection.

Firstly, the initial cross-section sizes which pass the constraints are preliminary chosen, and then a new set of cross-section sizes will be created by randomly reducing the initial sizes two sizes down in terms of weight. If the new set of section sizes does not pass all the constraints, another new set of sections will be created by increasing the section size one size up in terms of weight. This kind of checking and modifying process will be repeated until steel cross-sections of the new set remain the same for three times, and it will be recorded as one of the three possible final solutions. Lastly, the minimum of those threerecorded solutions will be regarded as the optimum solutions of the problem.

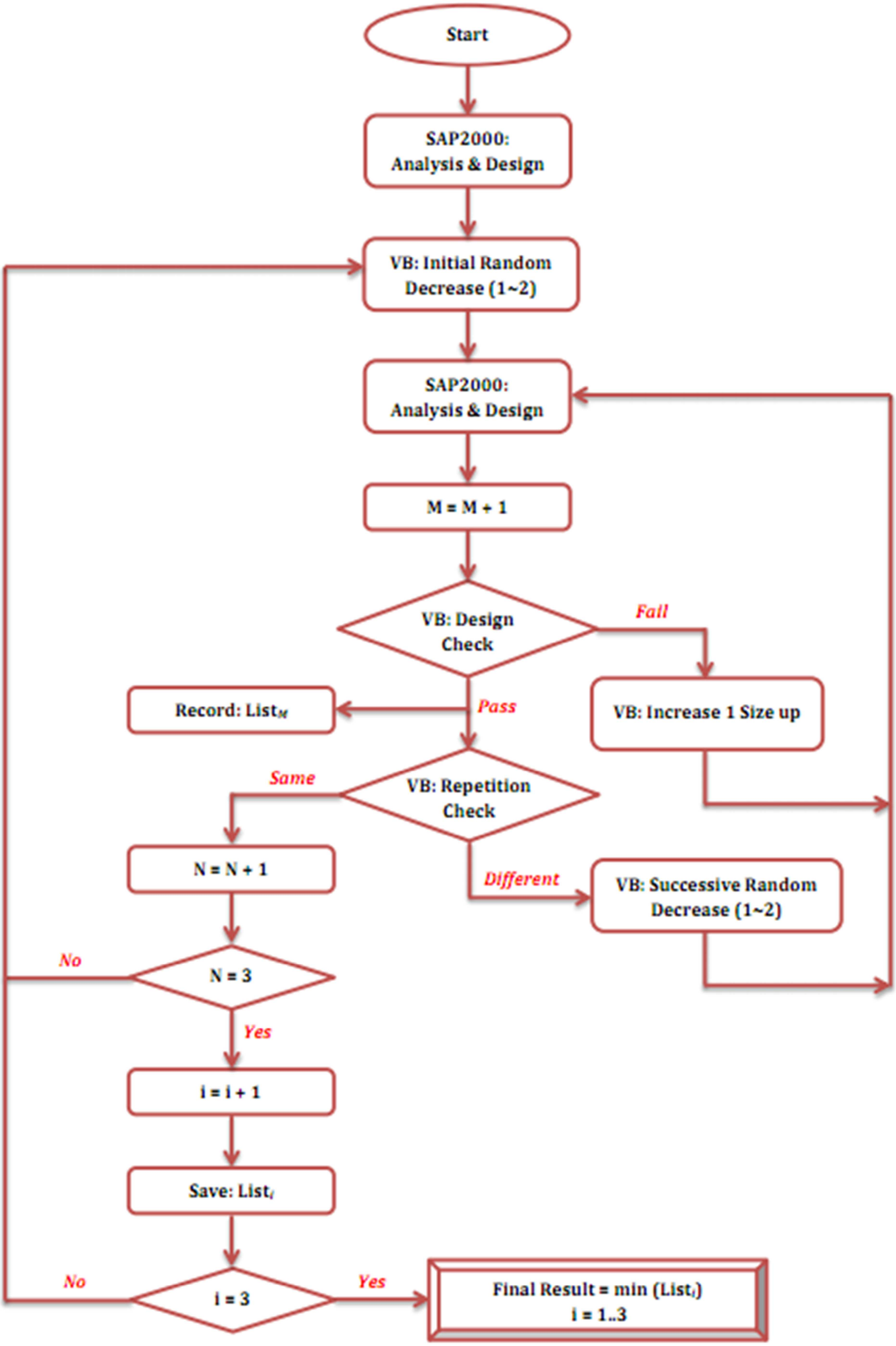

Figure 7: Flowchart of Heuristic Algorithm

2.8 Software CSi SAP2000

2.8.1 Introduction

The software CSi SAP2000 is a powerful commercial software for both analysis and design of various structural systems ranking from a simple small 2D static frame analysis to a large complex 3D nonlinear dynamic analysis. It has been used by many well-known design companies over 30 years up to now to analyze and design many iconic high-rise building projects including the world tallest building nowadays - Burj Dubai, United Arab Emirates.

SAP2000 offers many analysis options such as: Response spectrum analysis, Power spectral density, Steady state analysis with damping, Buckling analysis, Time history analysis, Tension and compression only springs, Large and small P-Delta analysis, Pushover analysis, Staged construction, Concrete shrinkage and time dependent creep analysis, Target force analysis, Model alive.

2.8.2 Design Method for Stability Using AISC 2010 Specification

For steel frame structural analysis and design, SAP2000 is capable of designing according to AISC 2005 specification using the three methods presented in the code which are effective-length method, first-order analysis method, and direct analysis method. For the effective-length and direct analysis methods, it provides two analysis methods either the rigorous second-order analysis or the amplified first-order analysis. Furthermore, using the direct analysis method, it gives us two more choices whether the stiffness reduction value is fixed or variable. The software SAP2000 is very suitable for using the direct analysis method in the AISC specification because it can capture the second-order P-Deltaeffects and can account for all deformations including axial deformation, shear deformation, and bending deformation.

However, the software does not automate everything, thus we need to find out its limitations and specify the additional conditions. In order to analyze and design the steel frame structure using the AISC specification, engineers need to apply the notional loads to account for the initial imperfection and also use the notional loads combinations which include lateral wind and earthquake load. But these notional loads and loads combinations need to be specified manually by the users. Furthermore, in order to tell the software SAP2000 to account for the second-order P-Delta effects, it is required to specify that a nonlinear P-Delta analysis be performed. And the last but not least important point to always keep in mind is that the software does not check the validity of the analysis method. Thus, the user must check the suitability of the chosen analysis method by the user before running the analysis. For example, check of the applicability of the first order analysis method and the effective length method by using the ratio of the second order displacements to the first order displacements.

The software CSi SAP2000 provides seven analysis options for design using AISC2005 specification: Direct analysis method-General second order elastic analysis/Amplified first order elastic analysis-Stiffness reduction is fixed/variable**,** Effective length method-General second order elastic analysis/Amplified first order elastic analysis**,** First order analysis.

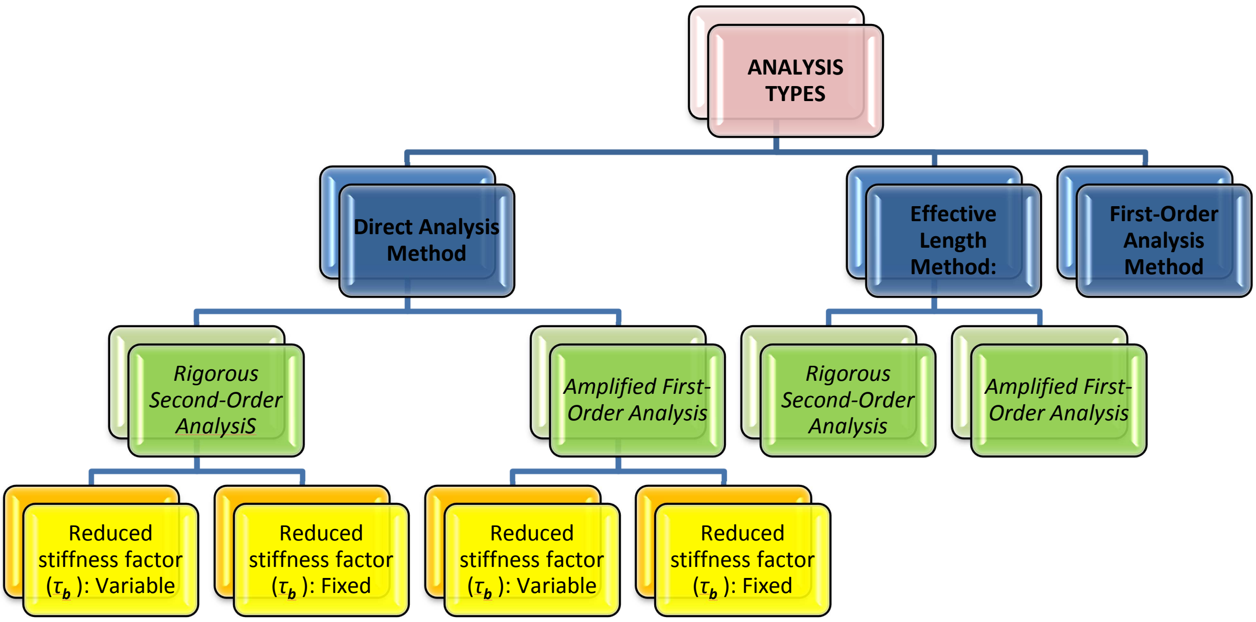

Figure 8: Flowchart of Analysis Types

When performing the amplified first order analysis, it is required to use the amplification factors B_1 and B_2. The B_1factor forP-δ effect is automatically calculated by the program, but $\boldsymbol{B_2}$ factor for P-Δ effect requires the user to input either using the overwrite options or turn on the nonlinear P-Δ analysis option.

2.8.3 Optimization Algorithm

The program SAP2000 is able to either check the adequacy of the sections or choose (i.e., design) the optimal sections in accordance with the requirements presented in the design code. It requires no preliminary design because it can automatically choose the member size. The optimization method used in the program is known as the virtual work based optimization for lateral deflections.

The program checks the adequacy of a section by verifying the demand/capacity ratios for every predefined load combination. It calculates the envelope of the demand/capacity ratios and compares with the demand/capacity ratioslimit which is by default equal to 0.95. However, the users can modify this value as their desire by the overwrite option. If the envelope of the demand/capacity ratiosis less than the demand/capacity ratioslimit as well as the other necessary requirements, the section is proved to be adequate. Otherwise, it is considered as inadequate. In order to do the optimization in SAP2000, it is required to firstly define the list of steel sections and assign to the frame elements. It is also possible to group the frame elements into different groups for optimal design, thus all the sections in the group will be same. For initial analysis, the program starts with the median section in terms of weight. After the initial analysis, the program will start with the smallest section in terms of weight to checkthe requirements for adequacy of a section. It will check each section in the predefined list until it finds the lightest weight of steel section that passes the design requirements. But if no sections in the predefined list that can pass the design check, the program will show the largest section in terms of weight with the notification of being overstressed.

2.9 Research Methodology

The necessary processes required to accomplish all of the objectives in this research are listed step by step as follows:

1. All structures are modeled using software CSi SAP2000
2. Run the analysis and design using the various options in the program
3. Export the results from SAP2000 to Microsoft Visual Basic (VB)
4. Use the program VB to do the optimization using the Heuristic Algorithm
5. Export the results from VB back to SAP2000
6. Use SAP2000 to re-run the analysis and design

After step 6, the process will go back to step 3 and continue to step 6. This cyclic process will keep running until the optimal resultsare obtained.

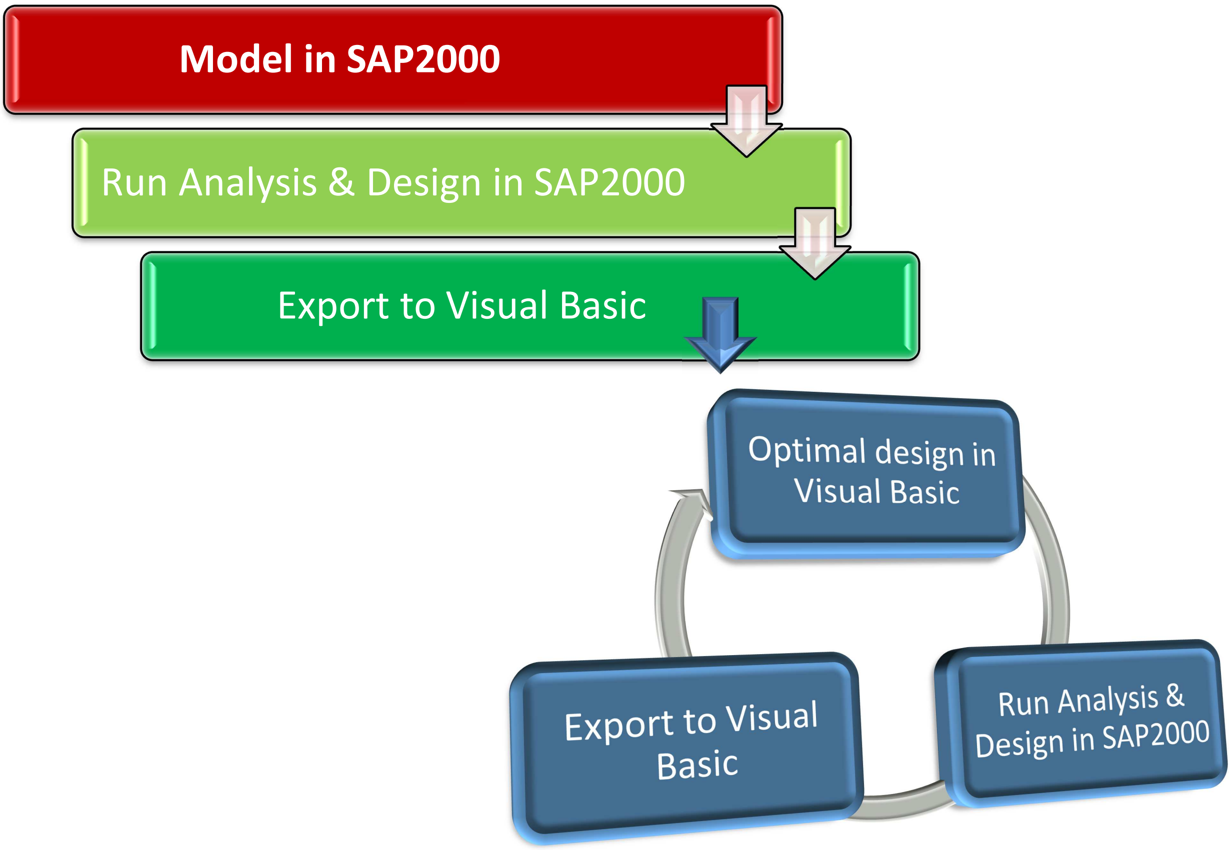

Figure 9: Flowchart of Research Methodology

CHAPTER III

RESULTS COMPARISON BETWEEN PREVIOUS STUDY – GENETIC, ANT COLONY, AND HARMONY SEARCH ALGORITHM WITH CSI SAP2000

3.1 Introduction

Three planar steel frame structures will be used to be the examples of this study. These three frames have already been optimized by using different algorithms such as genetic algorithm, ant colony optimization, and harmony search algorithm. And now those optimum results will be compared with the virtual work based optimization for lateral deflections which is encoded in SAP2000. Next, they will be designed and compared with different analysis methods for stability design presented in the AISC 2010 specification.

3.2 Optimal design results

3.2.1 Two-bay, three-story frame

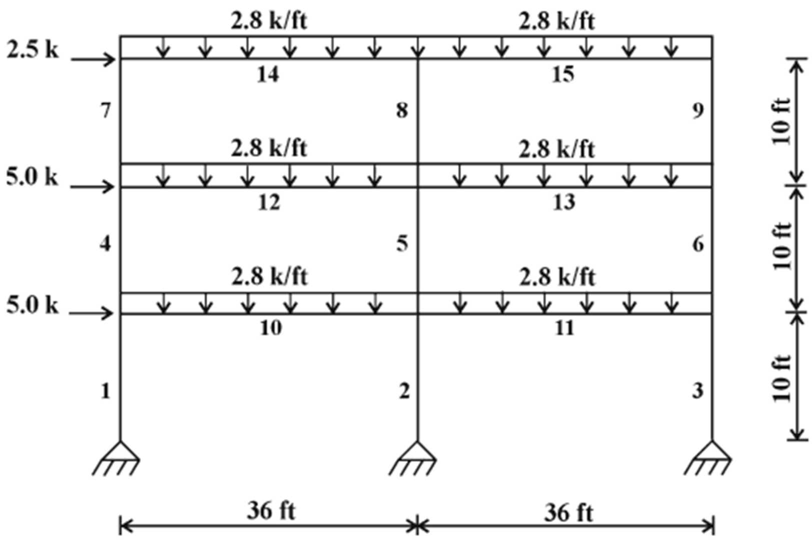

Figure 10: Two-bay, three-story frame

The two-bay, three-story frame under uniform gravity load and lateral load has the Young's modulus of $E = 29000\ ksi$ and the yield stress of $f_y = 36\ ksi$.The structural members have been grouped into two groups of columns and beams. This frame was optimally designed by Pezeshk et al. in 2000 using genetic algorithm, and later was designed by Camp et al. in 2005 using ant colony optimization, and then it was also designed by S. O. Degertekin in 2007 using harmony search algorithm. All of them used the first-order analysis method with AISC specification to design the structure.

Table 2: Design results for two-bay, three-story frame

Element Group	**GA** Pezeshk et al. (2000)	**ACO** Camp et al. (2005)	**HS** S. O. Degertekin (2007)	**SAP2000**
Beam	W 24 x 62	W 24 x 62	W 21 x 62	W 18 x 76
Column	W 10 x 60	W 10 x 60	W 10 x 54	W 14 x 53
Weight (lb)	18,792	18,792	18,292	21,168

The results have shown that the harmony search algorithm gives the lightest steel profile in this two-bay, three-story frame. However, it is interesting that the verification from the SAP2000 has found that there are six members from the GA, six members from the ACO, and seven members from the HS failed to satisfy the current AISC code of design.

3.2.2 One-bay, ten-story frame

The one-bay, ten-story frame under uniform gravity load and lateral load has the Young's modulus of $E = 29000\ ksi$ and the yield stress of $f_y = 36\ ksi$. The structural members have been grouped into nine groups. This frame was optimally designed by Pezeshk et al. in 2000 using genetic algorithm, and later was designed by Camp et al. in 2005 using ant colony optimization, and then it was also designed by S. O. Degertekin in 2007 using harmony search algorithm. All of them used the first-order analysis method with AISC specification to design the structure.

The results have shown that the Harmonic Search Algorithmstill gives the lightest steel profile in this one-bay, ten-story frame. However, the verification from the SAP2000 has found that there is one member from the GA, one member from the

ACO, and seven members from the HS failed to satisfy the current AISC code of design.

Table 3: Design results for one-bay, ten-story frame

Element Group	**GA** Pezeshk et al. (2000)	**ACO** Camp et al. (2005)	**HS** S. O. Degertekin (2007)	**SAP2000**
1	W14 x 233	W 14 x 233	W 14 x 211	W 14 x 233
2	W 14 x 176	W 14 x 176	W 14 x 176	W 4 x 176
3	W 14 x 159	W 14 x 145	W 14 x 145	W 14 x 132
4	W 14 x 99	W 14 x 99	W 14 x 90	W 14 x 99
5	W 12 x 79	W 12 x 65	W 14 x 61	W 14 x 68
6	W 33 x 118	W 30 x 108	W 33 x 118	W 30 x 108
7	W 30 x 90	W 30 x 90	W 30 x 99	W 30 x 90
8	W 27 x 84	W 27 x 84	W 24 x 76	W 24 x 84
9	W 24 x 55	W 21 x 44	W 18 x 46	W 14 x 61
Weight (lb)	65,136	62,610	61,864	62,589

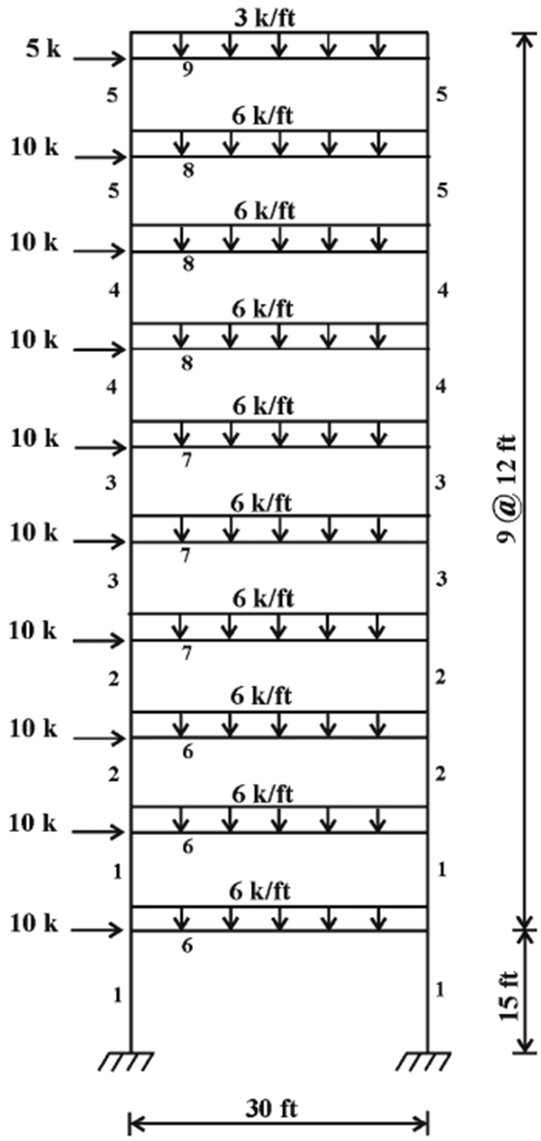

Figure 11: One-bay, ten-story frame

3.2.3 Three-bay, twenty four-story frame

The three-bay, twenty four-story frameunder uniform gravity load and lateral load has the Young's modulus of $E = 29732ksi$ and the yield stress of $f_y = 33.4ksi$. The applied loads are $W = 5{,}761.85\ lb$, $w_1 = 300\ lb/ft$, $w_2 = 436\ lb/ft$, $w_3 = 474\ lb/ft$ *and* $w_4 = 408\ lb/ft$. The structural members have been grouped into twenty groups. This frame was optimally designed by Camp et al. in 2005 using ant colony optimization, and then it was also designed by S. O. Degertekin in 2007 using harmony search algorithm. All of them used the first-order analysis method with AISC specification to design the structure.

The results have shown that the virtual work based optimization for lateral deflections which is encoded in SAP2000 gives the lightest steel profile in this three-bay, twenty four-story frame.

Table 4: Design results for three-bay, twenty four-story frame

Element Group	**ACO** Camp et al. (2005)	**HS** S. O. Degertekin (2007)	**SAP2000**
1	W 30 x 90	W 30 x 90	W 14 x 43
2	W 8 x 18	W 10 x 22	W 8 x 31
3	W 24 x 55	W 18 x 40	W 24 x 84
4	W 8 x 21	W 12 x 16	W 6 x 9
5	W 14 x 145	W 14 x 176	W 14 x 68
6	W 14 x 132	W 14 x 176	W 14 x 61
7	W 14 x 132	W 14 x 132	W 14 x 53
8	W 14 x 132	W 14 x 109	W 14 x 48
9	W 14 x 68	W 14 x 82	W 14 x 43
10	W 14 x 53	W 14 x 74	W 14 x 34
11	W 14 x 43	W 14 x 34	W 14 x 30
12	W 14 x 43	W 14 x 22	W 14 x 22
13	W 14 x 145	W 14 x 145	W 14 x 193
14	W 14 x 145	W 14 x 132	W 14 x 132
15	W 14 x 120	W 14 x 109	W 14 x 90
16	W 14 x 90	W 14 x 82	W 14 x 68

17	W 14 x 90	W 14 x 61	W 14 x 48
18	W 14 x 61	W 14 x 48	W 14 x 38
19	W 14 x 30	W 14 x 30	W 14 x 30
20	W 14 x 26	W 14 x 22	W 14 x 22
Weight (lb)	220,465	214,860	142,761

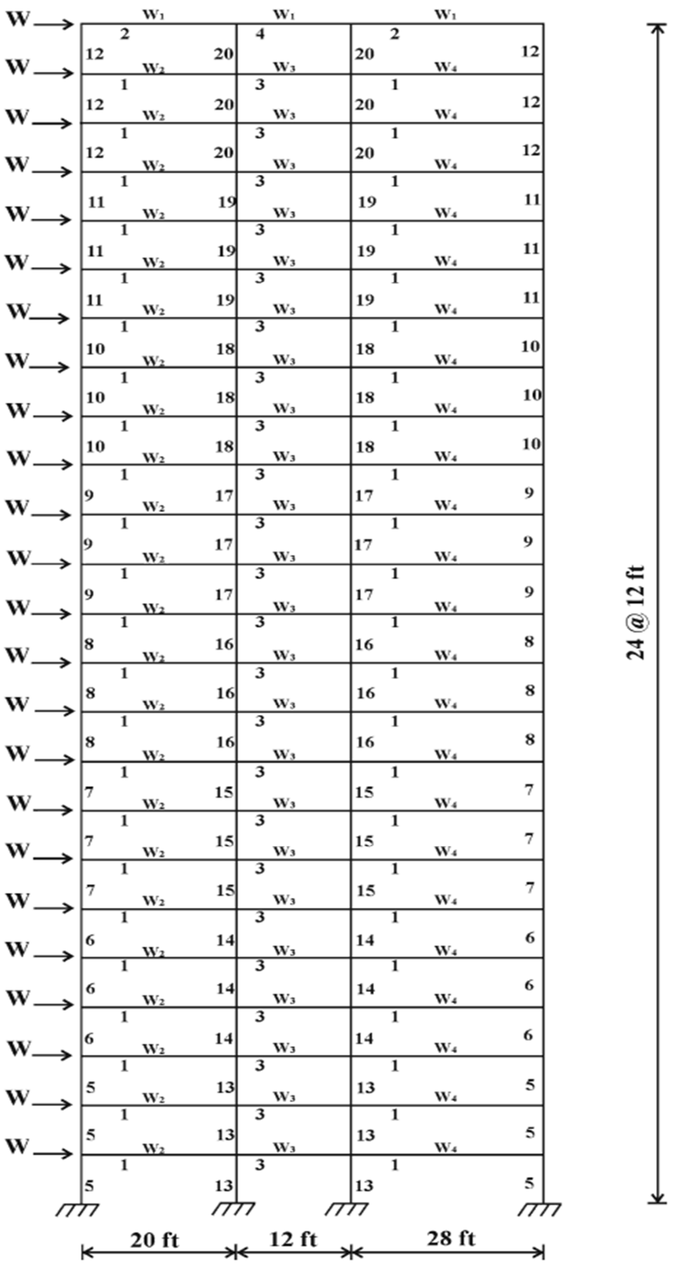

Figure 12: Three-bay, twenty four-story frame

3.3 Analysis methods for stability design results in SAP2000

All the previous three steel frames have now been analyzed and designed with the AISC 2010 specification using different analysis methods for stability design which are the first-order analysis method, effective-length method, and the direct analysis method. Also note that the limit of application of the first-order and the effective-length analysis method has been first verified that they are applicable according to the specification.

3.3.1 Two-bay, three-story frame

Table 5: Designs results from SAP2000 for two-bay, three-story frame

Element Group	FAM	ELM	DAM
Beam	W 18 x 76	W 18 x 76	W 18 x 76
Column	W 14 x 53	W 14 x 61	W 14 x 61
Weight (lb)	21,168	21,872	21,872

3.3.2 One-bay, ten-story frame

Table 6: Designs results from SAP2000 for one-bay, ten-story frame

Element Group	FAM	ELM	DAM
1	W 14 x 233	W 14 x 233	W 14 x 233
2	W 4 x 176	W 4 x 176	W 4 x 176
3	W 14 x 132	W 14 x 145	W 14 x 145
4	W 14 x 99	W 14 x 99	W 14 x 99
5	W 14 x 68	W 14 x 68	W 14 x 68
6	W 30 x 108	W 30 x 116	W 30 x 116
7	W 30 x 90	W 30 x 99	W 30 x 99

8	W 24 x 84	W 24 x 84	W 24 x 84
9	W 14 x 61	W 14 x 61	W 14 x 61
Weight (lb)	62,589	64,819	64,819

3.3.3 Three-bay, twenty four-story frame

Table 7: Designs results from SAP2000 for three-bay, twenty four-story frame

Element Group	FAM	ELM	DAM
1	W 14 x 43	W 18 x 60	W 18 x 60
2	W 8 x 31	W 8 x 31	W 8 x 31
3	W 24 x 84	W 24 x 62	W 24 x 62
4	W 6 x 9	W 6 x 9	W 6 x 9
5	W 14 x 68	W 14 x 90	W 14 x 90
6	W 14 x 61	W 14 x 68	W 14 x 74
7	W 14 x 53	W 14 x 61	W 14 x 61
8	W 14 x 48	W 14 x 61	W 14 x 61
9	W 14 x 43	W 14 x 48	W 14 x 48
10	W 14 x 34	W 14 x 38	W 14 x 38
11	W 14 x 30	W 14 x 30	W 14 x 30
12	W 14 x 22	W 14 x 22	W 14 x 22
13	W 14 x 193	W 14 x 145	W 14 x 145
14	W 14 x 132	W 14 x 99	W 14 x 99

15	W 14 x 90	W 14 x 74	W 14 x 74
16	W 14 x 68	W 14 x 61	W 14 x 61
17	W 14 x 48	W 14 x 43	W 14 x 43
18	W 14 x 38	W 14 x 34	W 14 x 34
19	W 14 x 30	W 14 x 26	W 14 x 30
20	W 14 x 22	W 14 x 22	W 14 x 22
Weight (lb)	142,761	151,260	151,985

The results have shown that the effective length and direct analysis methods yield the same results in terms of weight which is greater than that of the first-order analysis. The first-order analysis gives the lightest steel weight because it does not account for the second-order P-Deltas effects, while the other two methods use the rigorous second-order analysis to analysis and design the structure.

From the first simple low-rise structure to the third high-rise structure, the effects of P-Deltas keep increasing from 3% up to more than 6%. That is why the application of the first-order analysis method is very limited as specified in AISC specification. However, in these examples both the first-order and the effective-length method are applicable since their lateral loads are small enough.

CHAPTER IV
RESULTS COMPARISON BETWEEN CURRENT STUDY – HEURISTIC OPTIMIZATION ALGORITHM WITH SOFTWARECSI SAP2000

4.1 Introduction

Since the results obtained from the previous chapter have shown that SAP2000 is more efficient in optimizing steel frames than Genetic Algorithm, Ant Colony Optimization, and Harmony Search Algorithm; the current study using heuristic optimization algorithm will be compared to SAP2000's virtual work based optimization for lateral deflections. While comparing the optimization efficiency, this study also applies different analysis methods for stability design presented in the AISC 2010 specification to design and compare.

4.2 Optimal design results

4.2.1 Two-bay, three-story frame

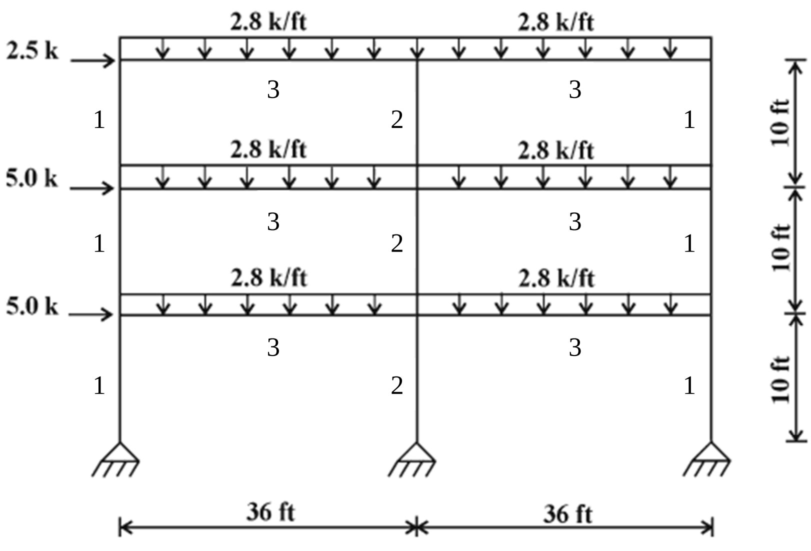

Figure 13: Two-bay, three-story frame

The two-bay, three-story frame under uniform gravity load and lateral load has the Young's modulus of $E = 29000$ *ksi* and the yield stress of $f_y = 36$ *ksi*. The structural members have been grouped into two groups of columns – inner columns and side columns, and one group of beams. This frame has been optimally designed by both the heuristic algorithm and SAP2000 using the first-order analysis method, effective length method, and direct analysis method. When using the effective length method and direct analysis method, the rigorous second-order analysis has been used for all optimization iterations.

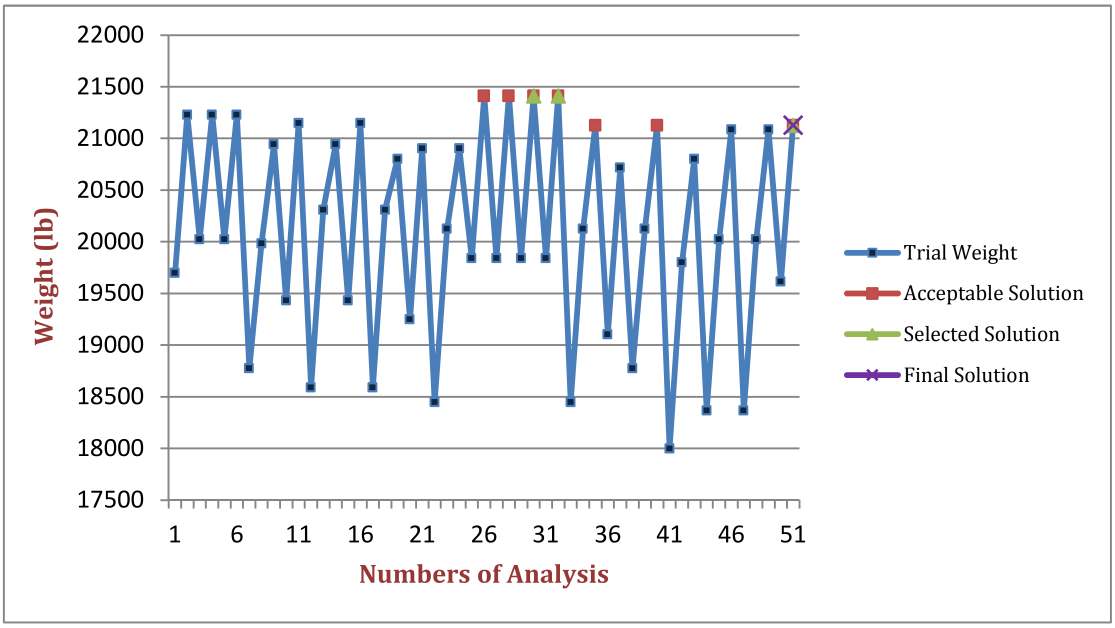

Figure 14: Numbers of Analysis vs. Weight for Two-bay, three-story frame

Table 8: Design results for two-bay, three-story frame

Analysis Methods	**Heuristic Algorithm (Current Study)**	**SAP2000**
First Order Analysis Method	Beam: W18x76 Side Column: W10x49 Inner Column: W10x60 Weight (lb): 21,127	Beam: W18x76 Side Column: W10x54 Inner Column: W10x60 Weight (lb): 21,413
Effective length Method	Beam: W18x76 Side Column: W10x54 Inner Column: W10x68 Weight (lb): 21,658	Beam: W18x76 Side Column: W10x54 Inner Column: W10x68 Weight (lb): 21,658
Direct Analysis Method	Beam: W18x76 Side Column: W10x49 Inner Column: W10x60 Weight (lb): 21,127	Beam: W18x76 Side Column: W10x49 Inner Column: W10x60 Weight (lb): 21,127

The optimization results have shown that the Heuristic optimization algorithm gives slightly lighter steel weight than the virtual work based optimization for lateral deflections which is encoded in software CSi SAP2000 for the case of the first-order analysis method, while giving the same results for the effective length and direct analysis methods.

4.2.2 One-bay, ten-story frame

The one-bay, ten-story frame under uniform gravity load and lateral load has the Young's modulus of $E = 29000\ ksi$ and the yield stress of $f_y = 36\ ksi$. The structural members have been grouped into two groups of columns – lower columns and higher columns, and one group of beams. The lower columns include the columns from the supports to the fifth floor, and the higher columns include the columns from the sixth floor to the top. This frame has been optimally designed by both the heuristic algorithm and SAP2000 using the first-order analysis method, effective length method, and direct analysis method. When using the effective length method and direct analysis method, the rigorous second-order analysis has been used for all optimization iterations.

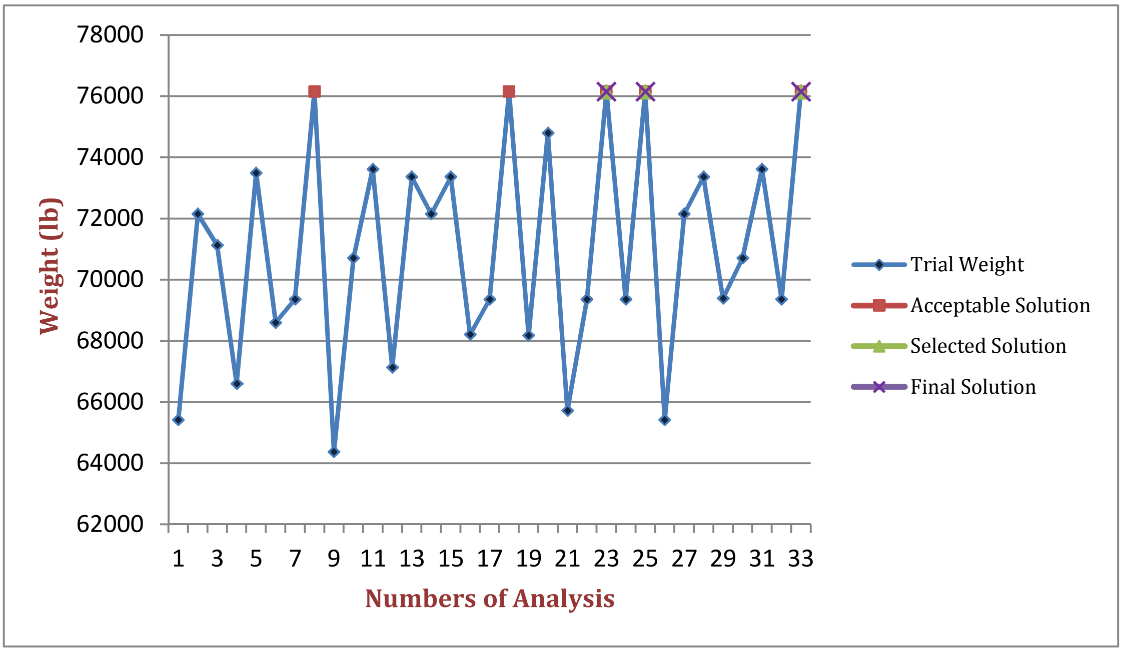

Figure 15: Numbers of Analysis vs. Weight for One-bay, ten-story frame

Table 9: Design results for one-bay, ten-story frame

Analysis Methods	**Heuristic Algorithm (Current Study)**	**SAP2000**
First Order Analysis Method	Beam: W30x108 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 76,144	Beam: W30x108 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 76,144
Effective length Method	Beam: W30x108 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 76,144	Beam: W30x108 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 76,144
Direct Analysis Method	Beam: W30x108 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 76,144	Beam: W30x116 Lower Column: W14x233 Higher Column: W14x120 Weight (lb): 78,696

The optimization results have shown that the Heuristic optimization algorithm gives slightly lighter steel weight than the virtual work based optimization for lateral deflections used in the software CSi SAP2000 for the case of the direct analysis method, while giving the same results for the effective length and the first-order analysis methods.

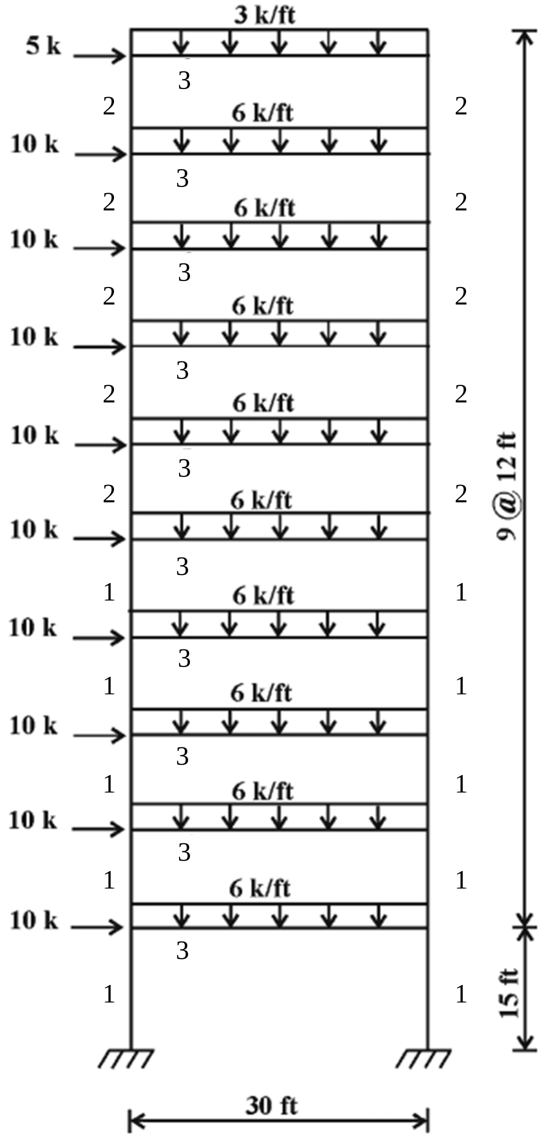

Figure 16: One-bay, ten-story frame

4.2.3 Three-bay, twenty four-story frame

The three-bay, twenty four-story frame under uniform gravity load and lateral load has the Young's modulus of $E = 29732ksi$ and the yield stress of $f_y = 33.4ksi$.The applied loads are $W = 5{,}761.85\ lb$, $w_1 = 300\ lb/ft$, $w_2 = 436\ lb/ft$, $w_3 = 474\ lb/ft$ *and* $w_4 = 408\ lb/ft$. The structural members have been grouped into two groups of columns – inner columns and side columns, and one group of beams. This frame has been optimally designed by both the heuristic algorithm and SAP2000 using the first-order analysis method, effective length method, and direct analysis method. When using the effective length method and direct analysis method, the rigorous second-order analysis has been used for all optimization iterations.

The optimization results have shown that the Heuristic optimization algorithm gives slightly lighter steel weight than the virtual work based optimization for lateral deflections which is encoded in software CSi SAP2000 for the case of the first-order analysis method, while giving the same results for the effective length and direct analysis methods.

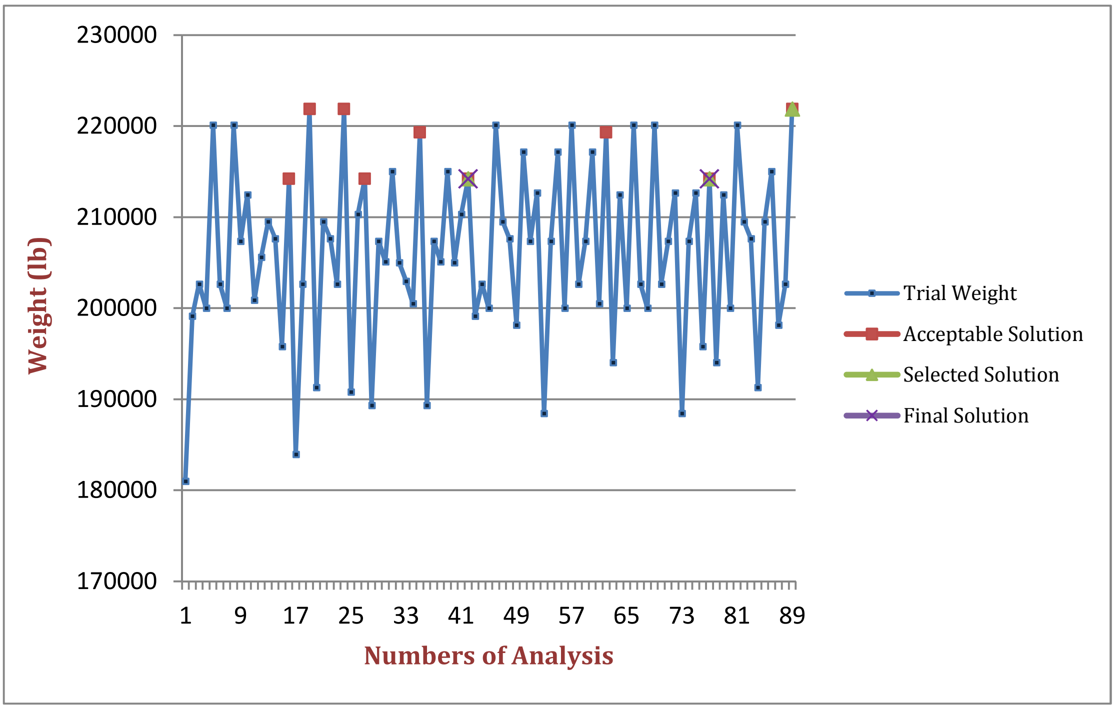

Figure 17: Numbers of Analysis vs. Weight for Three-bay, twenty four-story frame

Table 10: Design results for three-bay, twenty four-story frame

Analysis Methods	**Heuristic Algorithm (Current Study)**	**SAP2000**
First Order Analysis Method	Beam: W18x60 Side Column: W14x90 Inner Column: W14x132 Weight (lb): 214,228	Beam: W18x60 Side Column: W14x109 Inner Column: W14x120 Weight (lb): 218,148
Effective length Method	Beam: W18x60 Side Column: W14x99 Inner Column: W14x132 Weight (lb): 219,324	Beam: W18x60 Side Column: W14x99 Inner Column: W14x132 Weight (lb): 219,324
Direct Analysis Method	Beam: W18x60 Side Column: W14x99 Inner Column: W14x132 Weight (lb): 219,324	Beam: W18x60 Side Column: W14x99 Inner Column: W14x132 Weight (lb): 219,324

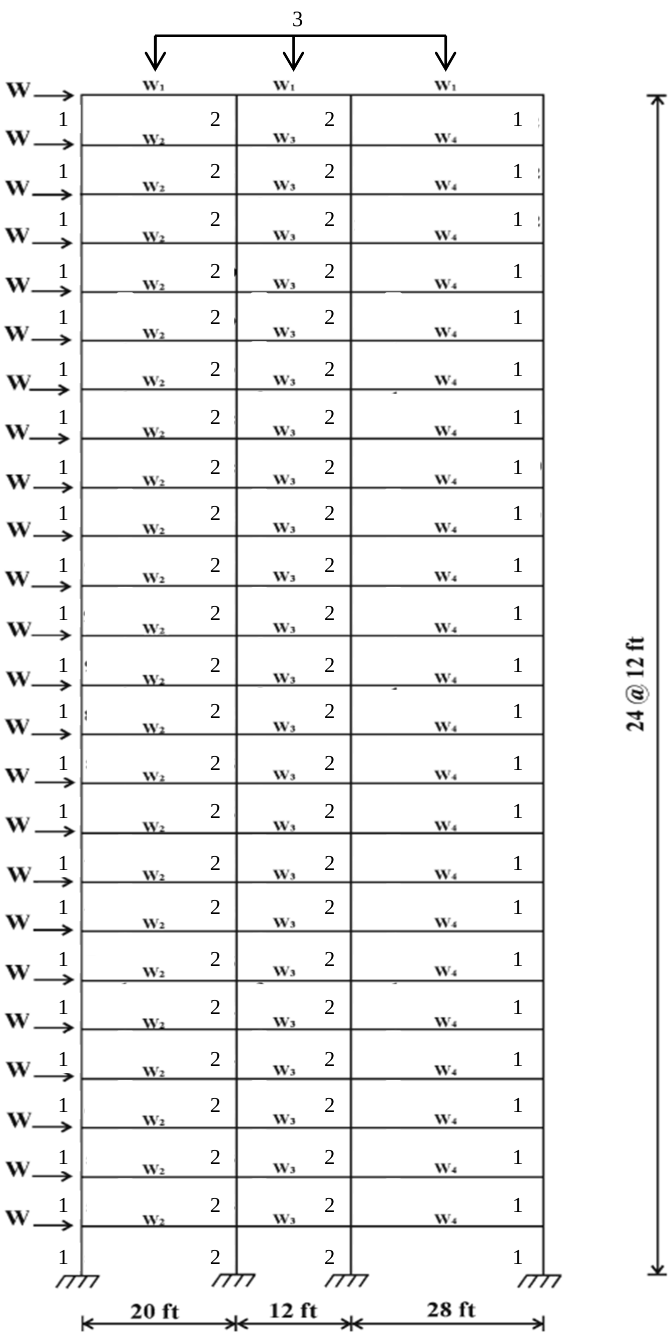

Figure 18: Three-bay, twenty four-story frame

CHAPTER V
CONCLUSION

From the current study results of the comparison between various optimization algorithms such as Genetic Optimization (GA), Ant Colony Optimization (ACO), Genetic, Harmony Search Algorithm (HS), Heuristic Algorithm (HA), and Virtual Work based Optimization for Lateral Deflections (CSi SAP2000), we can conclude as the followings:

1. The optimization algorithm encoded in the software CSi SAP2000 and the HA are more efficient than that of the GA, ACO, and HS by yielding lighter steel weight of the overall structure.
2. The Heuristic algorithm results at least the same or lighter steel weights than that from the Virtual Work based Optimization for Lateral Deflections of CSi SAP2000.
3. As observed from the number of iterations, the Heuristic algorithm search neglects the non-likely solutions by searching the likely path of the solutions at points of the final optimum solution. Thus, it reduces the number of iterations, and is heading towards the solution very quickly and effectively.
4. The Heuristic algorithm is powerful and less time-consuming for steel structures, especially for structures having not many groups of structural members.
5. The Heuristic algorithm is flexible in dealing with both simple to complex structures since it can vary the numbers of step for searching to work appropriately with the structures.
6. It is best to combine the HA with other optimization which is capable of finding the better likely path to converge, such as from SAP2000.

From the current study results of the comparison between various analysis methods presented in the AISC 2010 specification which are first-order analysis, effective length method, and direct analysis method, we can conclude as the followings:

1. Where applicable – the second-order effects are negligible, the first-order analysis method should be used in order to benefit the structural weight as well as the time-consuming for the analysis process.
2. The direct analysis method yields the results more or less the same as that from the effective length method.
3. However, the application of the direct analysis method is more convenient, more practical and has less potential of errors than the use of the effective length method. Thus, it is advisable to always use the direct analysis method when the second-order analysis is required.
4. The previous design of GA, ACO, and HS using the older code fail to satisfy the current design specification of AISC.

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APPENDIX

REPORTS FROM THE HEURISTIC OPTIMIZATION ALGORITHM

6.1 Two-bay, three-story frame – First-Order Analysis method

```
[m=0] [i=0]
 Increase Error Frame Section in Group:
  Inner W10X49 >-I-> W10X54
  Side W10X49 >-I-> W10X54
  Beams W18X71 >-I-> W18X76
 Decrease Non Error Frame Section in Group:

[m=1] [i=0]
 Increase Error Frame Section in Group:
  Inner W10X54 >-I-> W10X60
 Decrease Non Error Frame Section in Group:
  Side W10X54 >-D-> W10X49
  Beams W18X76 >-D-> W18X71

[m=2] [i=0]
 Increase Error Frame Section in Group:
  Side W10X49 >-I-> W10X54
  Beams W18X71 >-I-> W18X76
 Decrease Non Error Frame Section in Group:
  Inner W10X60 >-D-> W10X54

[m=3] [i=0]
 Increase Error Frame Section in Group:
  Inner W10X54 >-I-> W10X60
 Decrease Non Error Frame Section in Group:
  Side W10X54 >-D-> W10X49
  Beams W18X76 >-D-> W18X71

[m=4] [i=0]
 Increase Error Frame Section in Group:
  Side W10X49 >-I-> W10X54
  Beams W18X71 >-I-> W18X76
 Decrease Non Error Frame Section in Group:
  Inner W10X60 >-D-> W10X54

[m=5] [i=0]
 Increase Error Frame Section in Group:
  Inner W10X54 >-I-> W10X60
```

Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Beams W18X76 >-D-> W18X65

[m=6] [i=0]
Increase Error Frame Section in Group:
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X49

[m=7] [i=0]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49

[m=8] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X39
Beams W18X76 >-D-> W18X71

[m=9] [i=0]
Increase Error Frame Section in Group:
Inner W10X60 >-I-> W10X68
Side W10X39 >-I-> W10X45
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=10] [i=0]
Increase Error Frame Section in Group:
Side W10X45 >-I-> W10X49
Decrease Non Error Frame Section in Group:
Inner W10X68 >-D-> W10X54
Beams W18X76 >-D-> W18X65

[m=11] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71

Decrease Non Error Frame Section in Group:

[m=12] [i=0]
Increase Error Frame Section in Group:
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Inner W10X60 >-D-> W10X54

[m=13] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X39
Beams W18X76 >-D-> W18X71

[m=14] [i=0]
Increase Error Frame Section in Group:
Inner W10X60 >-I-> W10X68
Side W10X39 >-I-> W10X45
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=15] [i=0]
Increase Error Frame Section in Group:
Side W10X45 >-I-> W10X49
Decrease Non Error Frame Section in Group:
"Inner W10X68 >-D-> W10X54
Beams W18X76 >-D-> W18X65

[m=16] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=17] [i=0]
Increase Error Frame Section in Group:
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Inner W10X60 >-D-> W10X49

[m=18] [i=0]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Decrease Non Error Frame Section in Group:
"Side W10X49 >-D-> W10X39
Beams W18X76 >-D-> W18X71

[m=19] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X39 >-I-> W10X45
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=20] [i=0]
Increase Error Frame Section in Group:
Side W10X45 >-I-> W10X49
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X49
Beams W18X76 >-D-> W18X65

[m=21] [i=0]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=22] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X45

[m=23] [i=0]
Increase Error Frame Section in Group:
Side W10X45 >-I-> W10X49
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X54
Beams W18X76 >-D-> W18X71

[m=24] [i=0]
Increase Error Frame Section in Group:

Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=25] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Inner W10X60 >-D-> W10X54
Beams W18X76 >-D-> W18X71

[m=26] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=27] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Inner W10X60 >-D-> W10X54
Beams W18X76 >-D-> W18X71

[m=28] [i=0]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=29] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49
Inner W10X60 >-D-> W10X49
Beams W18X76 >-D-> W18X71

[m=30] [i=1]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X49 >-I-> W10X54

Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=31] [i=1]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X45
Inner W10X60 >-D-> W10X54
Beams W18X76 >-D-> W18X65

[m=32] [i=2]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=33] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49

[m=34] [i=2]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X39
Inner W10X60 >-D-> W10X49
Beams W18X76 >-D-> W18X71

[m=35] [i=2]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Side W10X39 >-I-> W10X45
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=36] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X45 >-I-> W10X49
Decrease Non Error Frame Section in Group:
Beams W18X76 >-D-> W18X65

[m=37] [i=2]
Increase Error Frame Section in Group:
Side W10X49 >-I-> W10X54
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X54

[m=38] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X49

[m=39] [i=2]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X39
Inner W10X60 >-D-> W10X54
Beams W18X76 >-D-> W18X65

[m=40] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X39 >-I-> W10X45
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=41] [i=2]
Increase Error Frame Section in Group:
Side W10X45 >-I-> W10X49
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X49

[m=42] [i=2]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X45
Beams W18X76 >-D-> W18X65

[m=43] [i=2]

Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X45 >-I-> W10X49
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=44] [i=2]
Increase Error Frame Section in Group:
Side W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X49

[m=45] [i=2]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X45
Beams W18X76 >-D-> W18X65

[m=46] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60
Side W10X45 >-I-> W10X49
Beams W18X65 >-I-> W18X71
Decrease Non Error Frame Section in Group:

[m=47] [i=2]
Increase Error Frame Section in Group:
Side W10X49 >-I-> W10X54
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:
Inner W10X60 >-D-> W10X49

[m=48] [i=2]
Increase Error Frame Section in Group:
Inner W10X49 >-I-> W10X54
Decrease Non Error Frame Section in Group:
Side W10X54 >-D-> W10X45
Beams W18X76 >-D-> W18X71

[m=49] [i=2]
Increase Error Frame Section in Group:
Inner W10X54 >-I-> W10X60

Side W10X45 >-I-> W10X49
Beams W18X71 >-I-> W18X76
Decrease Non Error Frame Section in Group:

[m=50] [i=2]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Side W10X49 >-D-> W10X45
Inner W10X60 >-D-> W10X49
Beams W18X76 >-D-> W18X71

6.2 One-bay, ten-story frame – First-Order Analysis method

[m=0] [i=0]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
Lower W14X211 >-I-> W14X233
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:

[m=1] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X193

[m=2] [i=0]
Increase Error Frame Section in Group:
Lower W14X193 >-I-> W14X211
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
HigherW14X120 >-D-> W14X109

[m=3] [i=0]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=4] [i=0]
Increase Error Frame Section in Group:

Beams W30X99 >-I-> W30X108
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X193
HigherW14X120 >-D-> W14X99

[m=5] [i=0]
Increase Error Frame Section in Group:
Lower W14X193 >-I-> W14X211
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X99

[m=6] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=7] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
Lower W14X233 >-D-> W14X193
HigherW14X120 >-D-> W14X109

[m=8] [i=0]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
Lower W14X193 >-I-> W14X211
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=9] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
Decrease Non Error Frame Section in Group:
HigherW14X120 >-D-> W14X99

[m=10] [i=0]
Increase Error Frame Section in Group:
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:

Beams W30X108 >-D-> W30X99
Lower W14X233 >-D-> W14X193

[m=11] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X193 >-I-> W14X211
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=12] [i=0]
Increase Error Frame Section in Group:
Lower W14X211 >-I-> W14X233
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X99
HigherW14X120 >-D-> W14X109

[m=13] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X211

[m=14] [i=0]
Increase Error Frame Section in Group:
Lower W14X211 >-I-> W14X233
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
HigherW14X120 >-D-> W14X99

[m=15] [i=0]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X211

[m=16] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=17] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X99
Lower W14X233 >-D-> W14X211
HigherW14X120 >-D-> W14X99

[m=18] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:

[m=19] [i=0]
Increase Error Frame Section in Group:
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
Lower W14X233 >-D-> W14X193

[m=20] [i=0]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
Lower W14X193 >-I-> W14X211
Decrease Non Error Frame Section in Group:
HigherW14X120 >-D-> W14X109

[m=21] [i=0]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=22] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
Lower W14X233 >-D-> W14X193
HigherW14X120 >-D-> W14X99

[m=23] [i=1]

Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=24] [i=1]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
Lower W14X233 >-D-> W14X211
HigherW14X120 >-D-> W14X109

[m=25] [i=2]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
Lower W14X211 >-I-> W14X233
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:

[m=26] [i=2]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X211

[m=27] [i=2]
Increase Error Frame Section in Group:
Lower W14X211 >-I-> W14X233
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X90
HigherW14X120 >-D-> W14X109

[m=28] [i=2]
Increase Error Frame Section in Group:
Beams W30X90 >-I-> W30X99
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Lower W14X233 >-D-> W14X211

[m=29] [i=2]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108

Lower W14X211 >-I-> W14X233
Decrease Non Error Frame Section in Group:
HigherW14X120 >-D-> W14X99

[m=30] [i=2]
Increase Error Frame Section in Group:
HigherW14X99 >-I-> W14X109
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X99
Lower W14X233 >-D-> W14X211

[m=31] [i=2]
Increase Error Frame Section in Group:
Beams W30X99 >-I-> W30X108
Lower W14X211 >-I-> W14X233
HigherW14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:

[m=32] [i=2]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W30X108 >-D-> W30X99
Lower W14X233 >-D-> W14X211
HigherW14X120 >-D-> W14X99

6.3 Three-bay, twenty four-story frame – First-Order Analysis method

[m=0] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X99 >-I-> W14X109
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=1] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82

[m=2] [i=0]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132

```
  Side W14X82 >-I-> W14X90
 Decrease Non Error Frame Section in Group:
  Beams W18X60 >-D-> W18X50

[m=3] [i=0]
 Increase Error Frame Section in Group:
  Beams W18X50 >-I-> W18X55
  Inner W14X132 >-I-> W14X145
  Side W14X90 >-I-> W14X99
 Decrease Non Error Frame Section in Group:

[m=4] [i=0]
 Increase Error Frame Section in Group:
  Beams W18X55 >-I-> W18X60
 Decrease Non Error Frame Section in Group:
  Side W14X99 >-D-> W14X82
  Inner W14X145 >-D-> W14X120

[m=5] [i=0]
 Increase Error Frame Section in Group:
  Inner W14X120 >-I-> W14X132
  Side W14X82 >-I-> W14X90
 Decrease Non Error Frame Section in Group:
  Beams W18X60 >-D-> W18X50

[m=6] [i=0]
 Increase Error Frame Section in Group:
  Beams W18X50 >-I-> W18X55
  Inner W14X132 >-I-> W14X145
  Side W14X90 >-I-> W14X99
 Decrease Non Error Frame Section in Group:

[m=7] [i=0]
 Increase Error Frame Section in Group:
  Beams W18X55 >-I-> W18X60
 Decrease Non Error Frame Section in Group:
  Side W14X99 >-D-> W14X90
  Inner W14X145 >-D-> W14X120

[m=8] [i=0]
 Increase Error Frame Section in Group:
  Inner W14X120 >-I-> W14X132
  Side W14X90 >-I-> W14X99
 Decrease Non Error Frame Section in Group:
```

Beams W18X60 >-D-> W18X55

[m=9] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X90
Inner W14X132 >-D-> W14X109

[m=10] [i=0]
Increase Error Frame Section in Group:
Inner W14X109 >-I-> W14X120
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=11] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82

[m=12] [i=0]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=13] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X82
Inner W14X145 >-D-> W14X120

[m=14] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=15] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Side W14X90 >-D-> W14X74
Inner W14X132 >-D-> W14X120

[m=16] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X120 >-I-> W14X132
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

[m=17] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=18] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X120

[m=19] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

[m=20] [i=0]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=21] [i=0]
Increase Error Frame Section in Group:

Beams W18X50 >-I-> W18X55
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X82
Inner W14X145 >-D-> W14X132

[m=22] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=23] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X132

[m=24] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

[m=25] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Inner W14X145 >-D-> W14X132

[m=26] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X90 >-D-> W14X82
Inner W14X132 >-D-> W14X109

[m=27] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120

Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=28] [i=0]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=29] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X90

[m=30] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X132

[m=31] [i=0]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=32] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Inner W14X145 >-D-> W14X120

[m=33] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=34] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X99 >-D-> W14X82
Inner W14X132 >-D-> W14X109

[m=35] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=36] [i=0]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=37] [i=0]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X90

[m=38] [i=0]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X132

[m=39] [i=0]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=40] [i=0]

Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Inner W14X145 >-D-> W14X132

[m=41] [i=0]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X90 >-D-> W14X82
Inner W14X132 >-D-> W14X120

[m=42] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82

[m=43] [i=1]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=44] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=45] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82
Inner W14X145 >-D-> W14X132

[m=46] [i=1]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145

Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=47] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X132

[m=48] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

[m=49] [i=1]
Increase Error Frame Section in Group:
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Inner W14X145 >-D-> W14X132

[m=50] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74

[m=51] [i=1]
Increase Error Frame Section in Group:
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Inner W14X145 >-D-> W14X120

[m=52] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90

Decrease Non Error Frame Section in Group:

[m=53] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X82

[m=54] [i=1]
Increase Error Frame Section in Group:
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Inner W14X145 >-D-> W14X132

[m=55] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=56] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82
Inner W14X145 >-D-> W14X120

[m=57] [i=1]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=58] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X82

[m=59] [i=1]
Increase Error Frame Section in Group:
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Inner W14X145 >-D-> W14X120

[m=60] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=61] [i=1]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X99 >-D-> W14X90
Inner W14X132 >-D-> W14X109

[m=62] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=63] [i=1]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Side W14X99 >-D-> W14X90

[m=64] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=65] [i=1]
Increase Error Frame Section in Group:

Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82
Inner W14X145 >-D-> W14X120

[m=66] [i=1]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=67] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=68] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82
Inner W14X145 >-D-> W14X120

[m=69] [i=1]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=70] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74

[m=71] [i=1]
Increase Error Frame Section in Group:
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

Beams W18X60 >-D-> W18X50
Inner W14X145 >-D-> W14X120

[m=72] [i=1]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=73] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74

[m=74] [i=1]
Increase Error Frame Section in Group:
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Inner W14X145 >-D-> W14X120

[m=75] [i=1]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=76] [i=1]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Side W14X90 >-D-> W14X74
Inner W14X132 >-D-> W14X120

[m=77] [i=2]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X109 >-I-> W14X120
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=78] [i=2]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50
Side W14X99 >-D-> W14X90

[m=79] [i=2]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Inner W14X132 >-I-> W14X145
Side W14X90 >-I-> W14X99
Decrease Non Error Frame Section in Group:

[m=80] [i=2]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X99 >-D-> W14X82
Inner W14X145 >-D-> W14X132

[m=81] [i=2]
Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X50

[m=82] [i=2]
Increase Error Frame Section in Group:
Beams W18X50 >-I-> W18X55
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X120

[m=83] [i=2]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X120 >-I-> W14X132
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:

[m=84] [i=2]

Increase Error Frame Section in Group:
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=85] [i=2]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Decrease Non Error Frame Section in Group:
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X120

[m=86] [i=2]
Increase Error Frame Section in Group:
Inner W14X120 >-I-> W14X132
Side W14X74 >-I-> W14X82
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55

[m=87] [i=2]
Increase Error Frame Section in Group:
Beams W18X55 >-I-> W18X60
Inner W14X132 >-I-> W14X145
Side W14X82 >-I-> W14X90
Decrease Non Error Frame Section in Group:

[m=88] [i=2]
Increase Error Frame Section in Group:
Decrease Non Error Frame Section in Group:
Beams W18X60 >-D-> W18X55
Side W14X90 >-D-> W14X74
Inner W14X145 >-D-> W14X132

BIOGRAPHY

Mr. Visoth Sambath KY was born on January 28th, 1987 in Battambang Province, Cambodia. He went to study at Preah Monivong high school and finished in 2005. After high school, he went to Phnom Penh City in the same year in order to continue his Bachelor degree. From 2005-2010, he conducted his study in Department of Civil Engineering at Institute of Technology of Cambodia (ITC). During the final year of study at ITC, he also worked as the assistant project manager of a Korean company for the project Gold Tower 42 in Phnom Penh. As soon as he graduated from ITC in a major of Civil Engineering, he became a lecturer in the Department of Civil Engineering at Norton University (NU) for one year. Then he was awarded the Thailand Scholarship for Neighboring Countries to pursue his Master's degree program in the field of Structural Engineering, Chulalongkorn University, Thailand.