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Article

Optimum Design of Steel Structures in Accordance with AISC 2010 Specification Using Heuristic Algorithm

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Abstract. This paper proposes a heuristic algorithm (HA) for the optimum design of steel structures in accordance with all three methods specified in the ANSI/AISC 360-10 "Specification for Structural Steel Buildings". These methods include the direct analysis method (DAM), and two alternative methods, namely, the first-order analysis method (FAM), and the effective length method (ELM). The objective of the design algorithm is to obtain the least weight for the designed steel sections. The optimum design combines the SAP2000 structural analysis program and the heuristic algorithm that is written in Microsoft Visual Basic program. The rigorous second-order analysis was performed in both DAM and ELM, while the first-order analysis was used in the FAM. Three design examples of planar steel frames are used to illustrate the application. Among the three design methods, the FAM results in lower bound solutions, while the EFM results in upper bound solutions.

Keywords: Optimization, heuristic algorithm, SAP2000, AISC 2010 specification, direct analysis method, first-order analysis method, effective length method, steel structures.

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1. Introduction

During the last four decades, mathematicians have developed programming methods for solving optimization problems [1]. However, there is no single method that has been proven to be efficient enough for the wide range of engineering optimization problems [2]. Nowadays, there are optimization techniques that have been used for the structural design of steel structures such as genetic optimization algorithm (GA), ant colony optimization (ACO), harmony search algorithm (HS).

The heuristic search algorithm was originally defined by Polya in 1945 [3]. 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 works. 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. In 1959, Gelernter [4] mentioned 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 works effectively by eliminating impractical options from the vast set of possibilities. In 1961, Minsky [5] employed heuristic in a vast problem space. Recently, the heuristic method has been developed and applied by researchers for various structural types such as reinforced concrete, prestressed concrete, and steel structures [e.g., 6–10].

The ANSI/AISC 360-10 "Specification for Structural Steel Buildings" [11], which hereafter is called the *specification*, has recently updated methods of design for stability. Previously, both the effective length method (ELM) and the first-order analysis method (FAM) were used for the design of steel frame structures for stability. Both methods are based on highly idealized assumptions which are reflected by several limitations of application. Consequently, the direct analysis method (DAM) was introduced. When the actual behavior of the structure falls outside the limitations of the above two methods, the *specification* requires that the DAM be used for the design for stability.

2. Design for Stability in Accordance with AISC Specification

Figure 1 shows the three design methods specified in the *specification*. The design procedure for each method is described in this section. The DAM is in the main part of the *specification* (Chapter C: Design for stability), while the FAM and ELM are in the appendix 7 as the alternative methods.

2.1. Direct Analysis Method (DAM)

The DAM requires that the second-order analysis, either the rigorous second order or amplified first-order analysis, be performed. The notional loads are used to represent the effects of initial imperfections consisting of out-of-plumbness and out-of-straightness. This lateral load is applied as an additional load to other lateral loads at all levels. The notional lateral load applied at level i, N_i, is given by

$$N_i = 0.002\alpha Y_i \tag{1}$$

where α = 1 for LRFD and 1.6 for ASD and Y_i = gravity load applied at level i. The coefficient 0.002 is based on the assumption that the out-of-plumbness ratio is 1/500. An appropriate adjustment shall be made if this assumption is violated. The method uses the reduced flexural and axial stiffness to account for inelasticity. A factor of 0.80 is applied to all stiffnesses in the structure. An additional factor, τ_b, is applied to the flexural stiffnesses of members which contribute to the stability of the structure. The value is given by

$$\tau_b = 1.0 \quad \text{for } \alpha P_r / P_y \le 0.5 \tag{2}$$

$$\tau_b = 4(\alpha P_r / P_y)[1-(\alpha P_r / P_y)] \quad \text{for } \alpha P_r / P_y > 0.5 \tag{3}$$

where P_r = required axial compressive strength and P_y = axial yield strength (= $F_y A_g$). However, the stiffness reduction factor of 1.0 can be used if the notional lateral load of $N_i = 0.001\alpha Y_i$ is applied to account for inelasticity. The effective length coefficient K = 1 for every condition of columns. 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 taken into account. There is no limitation for the DAM.

2.2. Effective Length Method (ELM)

The ELM requires that the second-order analysis, either the rigorous second order or amplified first-order analysis, be performed. The method is limited by two conditions (1) the structure supports gravity loads primarily through nominally vertical columns walls or frames and (2) the ratio of maximum second-order drift to maximum first-order drift (both determined for LRFD load combinations or 1.6 times ASD load combinations) in all stories is equal to or less than 1.5. If these limitations are violated, it is required that the DAM be used. The method is suitable for structures exhibiting limited second-order effects. The method is based on the elastic or inelastic stability theory. The effective length of column that is greater than the actual unbraced length (or K > 1 from a sidesway buckling analysis). Inelasticity is neglected in the analysis as the method uses the nominal member geometry and stiffness EI and EA for columns and beams. To account for imperfections, the notional load value of $0.002\alpha Y_i$ must be applied at all levels in both orthogonal directions only for gravity-only load combinations.

The most common way to determine the K factor is by using the alignment charts. However, these charts are based on the assumptions of highly idealized conditions most of which seldom exist in the real structures. First, it is assumed that all members behave purely elastically. Second, all members are prismatic, having constant cross section, i.e. tempered sections or cellular sections are not allowed. Third, all joints are rigid. 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. Fifth, for columns in non-sway frames, the rotations at the ends of the girders are assumed to be equal in magnitude and direction. 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 of the two columns. Eighth, the buckling of all columns within the same story takes place simultaneously. Ninth, the axial compression force in girders is negligible.

Adjustments are frequently required in situations such as for columns with differing end conditions, girders with differing end conditions, girders with significant axial load, columns inelasticity, and connection flexibility.

2.3. First-Order Analysis Method (FAM)

The FAM does not consider the second-order such as P-Δ and P-δ effects and inelasticity. The method is limited by three conditions. The first two conditions are same as those in the ELM. The third condition is that the required axial compressive strengths of all members, whose flexural stiffnesses are considered to contribute to the lateral stability of the structure, must be not greater than half of their yield strengths ($\alpha P_r < 0.5 P_y$). The required strengths are determined from the first-order analysis based on the unreduced member stiffness. The effects of initial imperfection are included by applying the notional load as an additional lateral load to other loads at each level of the structure in all load combinations. The value of notional lateral load is given by

$$N_i = 2.1\alpha(\Delta / L)Y_i \geq 0.0042Y_i \tag{4}$$

where Δ/L = the maximum ratio of the first-order story drift (Δ) to the story height (L) for all stories in the structure due to LRFD or ASD load combination. The nonsway amplification factor, B_1, specified in Appendix 8 of the *specification* shall be applied to the total member moments. The available strengths of members are calculated by using the effective length factor K = 1.

3. Heuristic Optimization Algorithm

Heuristics is well-known for its simplicity and efficiency to solve large complex problems or incomplete information. It eliminates the unrealistic possibilities from a large set of possible solutions, but no guarantee of finding the optimum solution. The concept of algorithm is that the next search step is based on the educated guess or experience-based data to speed up the searching process. The algorithm works basically as the trial and error, however, with a good guess. Instead of trying all possible search options, the algorithm focuses on the paths that likely to be closer to the objective solution.

In this study, the heuristic algorithm is used for steel cross-section size selection. The structures are first modeled and designed by SAP2000. The designed sections are then exported to Microsoft Visual Basic

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(VB) to perform the optimization using the heuristic algorithm. After the new set of sections is generated, it is exported back to SAP2000 to re-run the analysis and perform design check. Figure 1 shows the flowchart of the proposed algorithm. The preliminary cross-section sizes which pass the constraints are chosen as the initial set. Then a new set of cross-section sizes is created by randomly reducing the initial sizes one or two sizes down in terms of weight. If the new set does not pass all constraints, another new set is created by increasing the section size one size up. This process of checking and modification is repeated until steel cross-sections of the new set duplicates for three times. This set will be recorded as one of three possible final solutions. The minimum of three recorded solutions will be considered as the optimum solutions for the problem.

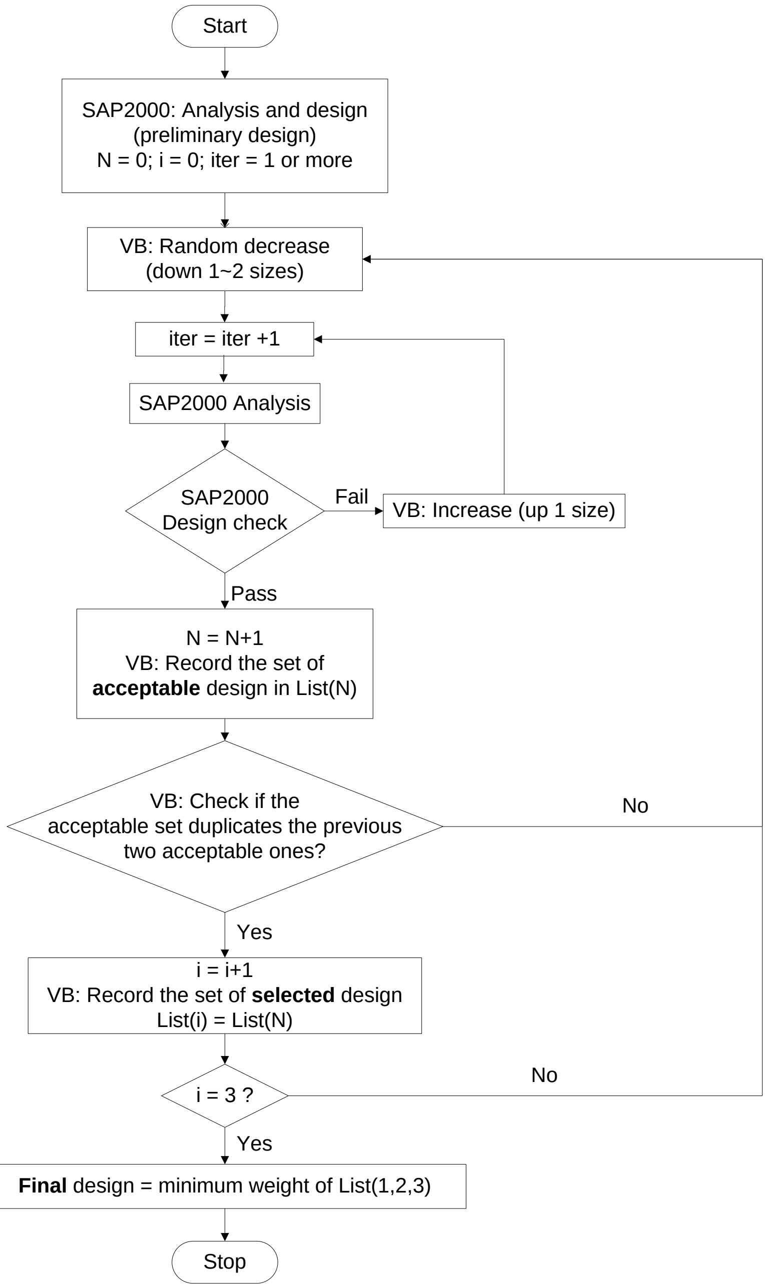

Fig. 1. Flowchart of proposed heuristic algorithm.

In the following section, three design examples of planar steel frames for which both FAM and ELM are applicable are used to illustrate the proposed design optimization. In both ELM and DAM where the second-order analysis is required, the rigorous analysis is performed by SAP2000. The beam sections are chosen from the entire W-shapes of AISC standard list [12], while the column sections are constrained to a particular depth. In the ELM, the in-plane effective length factors of the column members are calculated to be $K_x > 0$. Each column and beam is considered as non-braced along its length. The shear and axial deformations are considered.

4. Design Examples of Planar Steel Frames

4.1. Two-Bay, Three-Storey Frame

Figure 2 shows a two-bay, three-storey frame subjected to a single factored load combination. This problem has previously been studied by several previous researchers [13–19]. The values of factored uniform and lateral loads are appropriate for direct application of the strength/stability provisions of the AISC–LRFD specification [19]. Displacement constraints were not imposed for the design. The elastic modulus (E) and yield stress (F_y) values were 29000 and 36 ksi, respectively. The unit weight of steel was 0.284 lb/cu.in. The frame members were grouped into two groups of columns, namely, inner columns and outer columns, and one group of beams. The column members were limited to W10 sections for comparison purpose. Figure 3 shows a convergence history of the heuristic algorithm for the FAM.

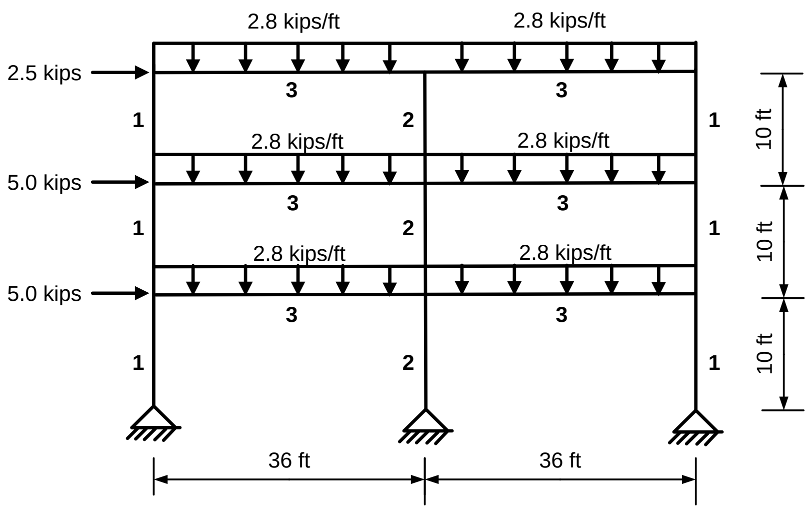

Fig. 2. A two-bay, three-storey frame subjected to factored loads.

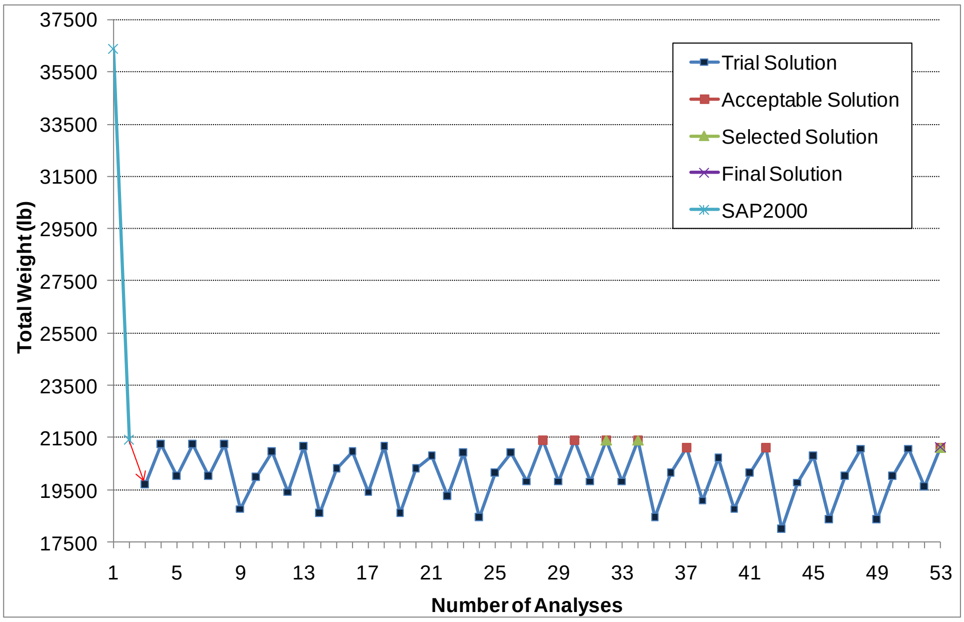

Fig. 3. A convergence history for a two-bay, three-storey frame.

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Table 1 shows the design optimization results using all design methods. Both FAM and DAM results are identical. The ELM results in the heaviest structure among the three methods. In comparison with the Virtual Work based Optimization for Lateral Deflections embedded in SAP2000, the proposed heuristic algorithm results in at least the same or lighter steel weights.

Table 1. Optimum design results of a two-bay, three-story frame (example 1).

Design Method	Heuristic Algorithm	SAP2000
First-Order Analysis Method (FAM)	Beams (3) : W18× 76 Outer columns (1) : W10× 49 Inner columns (2) : W10× 60 Total weight (lb) : 21,127	Beams (3) : W18× 76 Outer columns (1) : W10× 54 Inner columns (2) : W10× 60 Total weight (lb) : 21,413
Effective Length Method (ELM)	Beams (3) : W18× 76 Outer columns (1) : W10× 54 Inner columns (2) : W10× 68 Total weight (lb) : 21,658	Beams (3) : W18× 76 Outer columns (1) : W10× 54 Inner columns (2) : W10× 68 Total weight (lb) : 21,658
Direct Analysis Method (DAM)	Beams (3) : W18× 76 Outer columns (1) : W10× 49 Inner columns (2) : W10× 60 Total weight (lb) : 21,127	Beams (3) : W18× 76 Outer columns (1) : W10× 49 Inner columns (2) : W10× 60 Total weight (lb) : 21,127

4.2. One-Bay, Ten-Story Frame

Figure 4 shows a one-bay, ten-story frame subjected to a single factored load combination. This problem has previously been studied by several previous researchers [14–21]. The elastic modulus (E) and yield stress (F_y) values were 29000 and 36 ksi, respectively. The unit weight of steel was 0.284 lb/cu.in. The structural members have been grouped into two groups of columns – lower columns and upper 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. The column members were limited to W14 sections. Figure 5 shows a convergence history of the heuristic algorithm for the FAM.

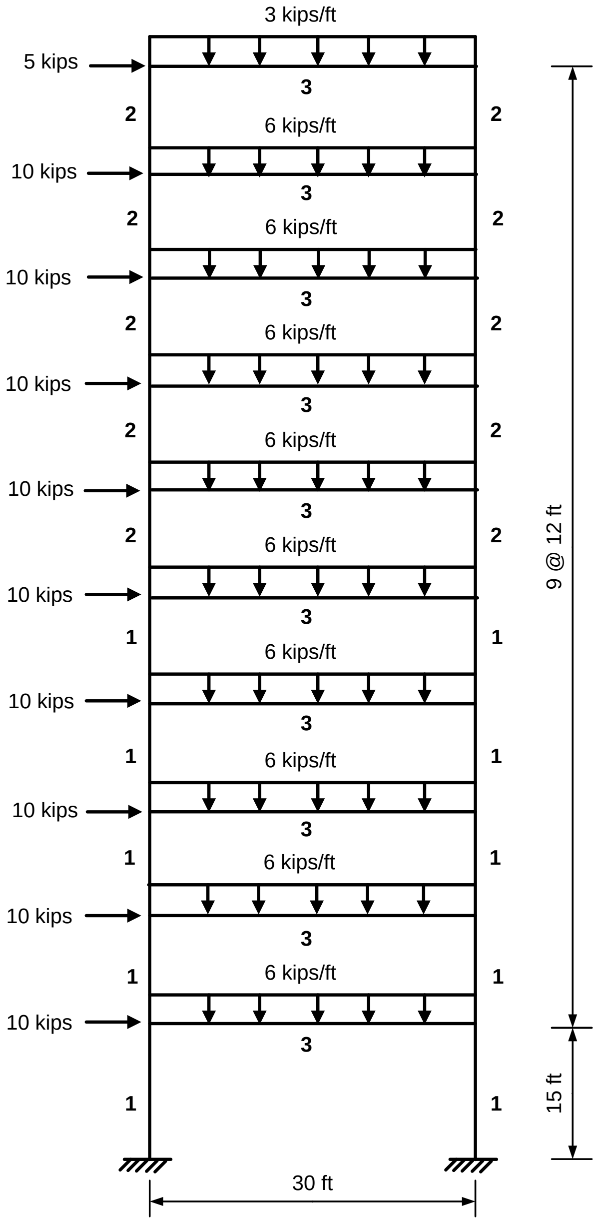

Fig. 4. A one-bay, ten-storey frame.

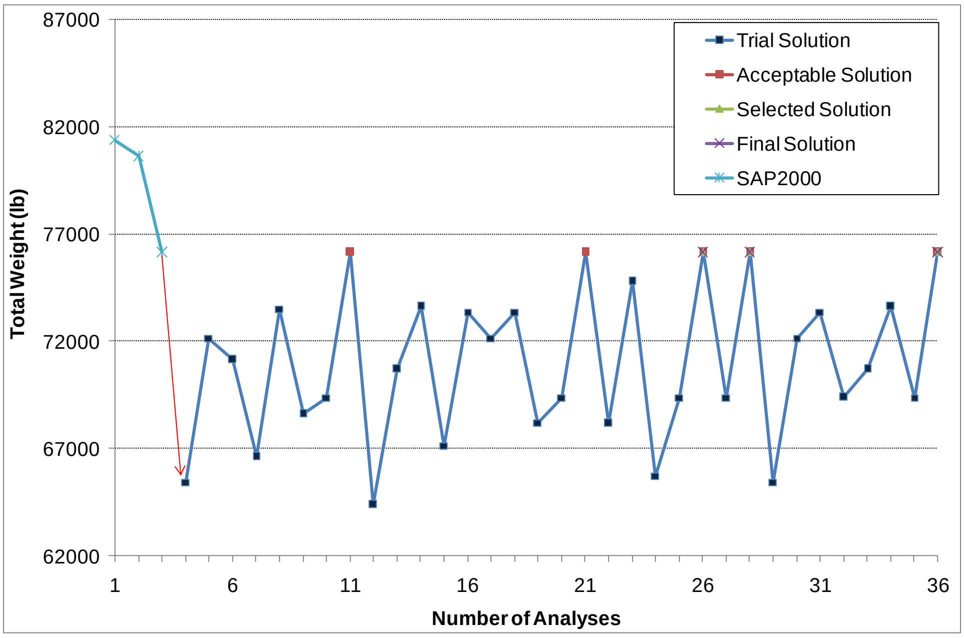

Fig. 5. A convergence history for a one-bay, ten-storey frame.

Table 2 shows the design optimization results using all design methods. All results are identical. In comparison with the Virtual Work based Optimization for Lateral Deflections embedded in SAP2000, the proposed heuristic algorithm results in the same or lighter structure.

Table 2. Optimum design results of a one-bay, ten-story frame (example 2).

Design Method	Heuristic Algorithm	SAP2000
First-Order Analysis Method (FAM)	Beams (3) : W30× 108 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 76,144	Beams (3) : W30× 108 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 76,144
Effective Length Method (ELM)	Beams (3) : W30× 108 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 76,144	Beams (3) : W30× 108 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 76,144
Direct Analysis Method (DAM)	Beams (3) : W30× 108 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 76,144	Beams (3) : W30× 116 Lower columns (1) : W14× 233 Upper columns (2) : W14× 120 Total weight (lb) : 78,696

4.3. Three-Bay, Twenty Four-Story Frame

Figure 6 shows a three-bay, twenty four-story frame subjected to a single factored load combination. This problem has previously been studied by several previous researchers [15–16, 19–20, 22–23]. The elastic modulus (E) and yield stress (F_y) values were 29732 and 33.4 ksi, respectively. The unit weight of steel was 0.284 lb/cu.in. The applied loads were W = 5,761.85 lb, w1 = 300 lb/ft, w2 = 436 lb/ft, w3 = 474 lb/ft and w4 = 408 lb/ft. The structural members were grouped into two groups of columns, namely, inner columns and outer columns, and one group of beams. The column members were limited to W14 sections. Figure 7 shows a convergence history of the heuristic algorithm for the FAM.

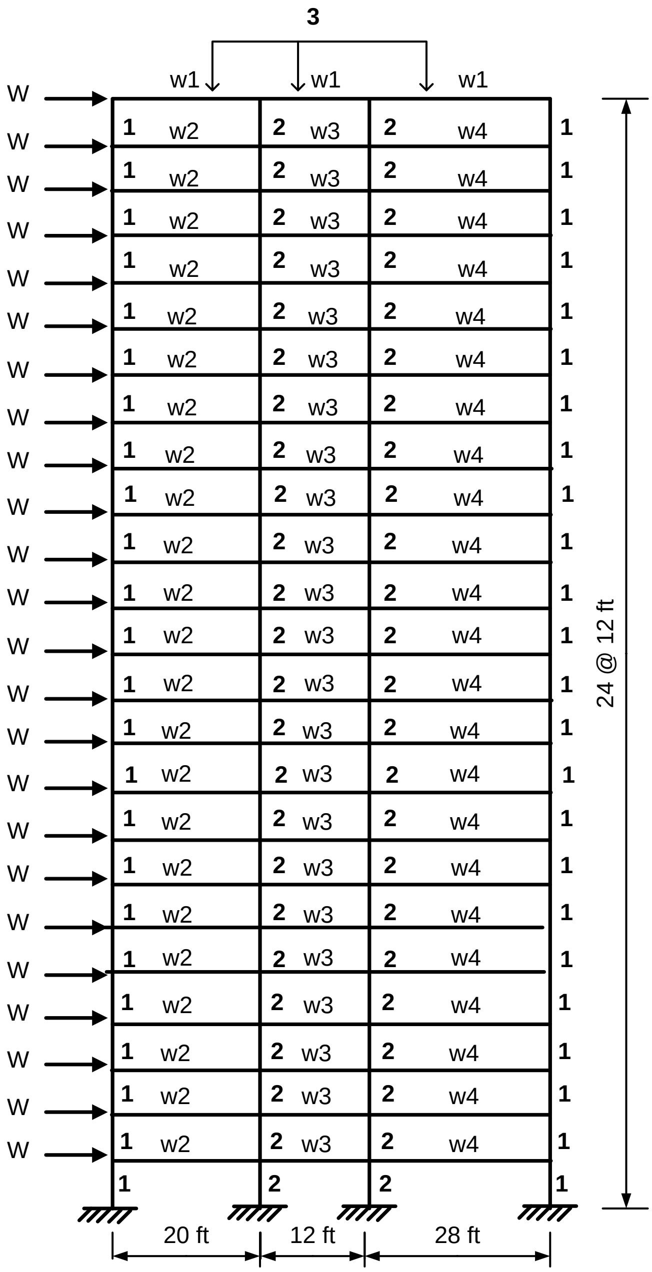

Fig. 6. A three-bay, twenty four-story frame.

Table 3 shows the design optimization results using all design methods. Both ELM and DAM results are identical. The FAM results in the lightest structure. In comparison with the Virtual Work based Optimization for Lateral Deflections embedded in SAP2000, the proposed heuristic algorithm results in the same or lighter steel weights.

Table 3. Optimum design results of a three-bay, twenty four-story frame (example 3).

Design Method	Heuristic Algorithm	SAP2000
First-Order Analysis Method (FAM)	Beams (3) : W18× 60 Outer columns (1) : W14× 90 Inner columns (2) : W14× 132 Total weight (lb) : 214,228	Beams (3) : W18× 60 Outer columns (1) : W14× 109 Inner columns (2) : W14× 120 Total weight (lb) : 218,148
Effective Length Method (ELM)	Beams (3) : W18× 60 Outer columns (1) : W14× 99 Inner columns (2) : W14× 132 Total weight (lb) : 219,324	Beams (3) : W18× 60 Outer columns (1) : W14× 99 Inner columns (2) : W14× 132 Total weight (lb) : 219,324
Direct Analysis Method (DAM)	Beams (3) : W18× 60 Outer columns (1) : W14× 99 Inner columns (2) : W14× 132 Total weight (lb) : 219,324	Beams (3) : W18× 60 Outer columns (1) : W14× 99 Inner columns (2) : W14× 132 Total weight (lb) : 219,324

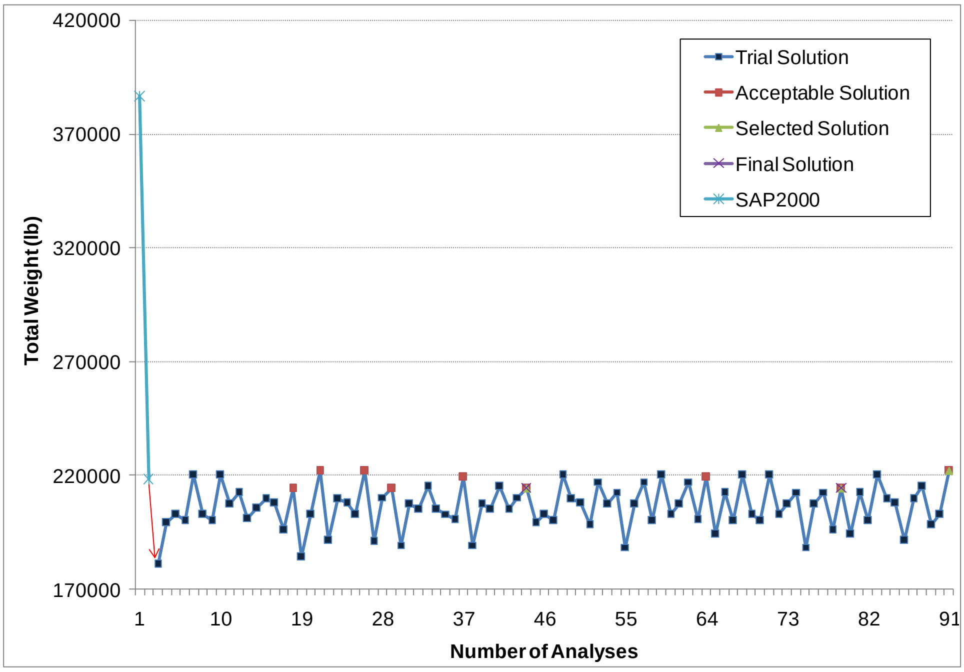

Fig. 7. A convergence history for a three-bay, twenty four-story frame.

5. Conclusions

An optimum design of steel structures in accordance with three design methods (DAM, ELF, and FAM) specified in the ANSI/AISC 360-10 "Specification for Structural Steel Buildings" is presented. The design combines the heuristic algorithm and the SAP2000 structural analysis program. Three design examples of planar steel frames are used to illustrate the application. Among the three design methods, the FAM results in lower bound solutions, while the EFM results in upper bound solutions.

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