Optimization of Placement of Braces for a Frame with Semi-rigid Joints by Scatter Search

Takao Hagishita[1], Makoto Ohsaki[2]

[1,2] Architecture and Architectural Engineering, Kyoto University,
Kyotodaigaku-Katsura, Nishikyo, Kyoto, Japan
E-mail: is.hagishita@archi.kyoto-u.ac.jp, ohsaki@archi.kyoto-u.ac.jp

1. Abstract

A population-based heuristic method called *Scatter Search* (SS) is used to optimize the placement of braces for a steel-frame with semi-rigid connections. The standard SS is modified such that the hierarchical clustering, which is a technique for data mining, is applied for the update of the diverse solutions of the reference set. We use the nonlinear structural analysis called refined plastic hinge method, which requires more computational cost than linear elastic analysis and conforms to conventional Load and Resistance Factor Design (LRFD), to obtain sufficient information on the optimized frame. The three design problems of minimizing the total structural weight of a steel-frame penalized by the costs for the semi-rigid connections are formulated according to the design variables: the types of semi-rigid connections, the types and locations of braces, and both of them simultaneously, where the cross-sectional properties of beams, columns and braces are also optimized in all of the three problems. We assume two loading cases for these problems which correspond to moderate and severe earthquakes, respectively. These problems are solved by SS to demonstrate the availability of the method for structural optimization which requires substantial computational cost. Tabu search is also applied for validation purpose. Finally, the characteristics of the optimal solutions are discussed based on the results of the nonlinear analyses.

2. Keywords: Scatter Search, Steel-Frame, Placement of Braces, Semi-Rigid Connections.

3. Introduction

The methods for structural optimization are classified into the mathematical programming approaches and heuristics. In this study, we use heuristics that are suitable for the problems formulated as combinatorial problems. The heuristic method applied in the present study is *Scatter Search* (SS) developed by Glover [6] which is preferable for the structural optimization problem that requires substantial computational cost for function evaluation. The nonlinear elasto-plastic analysis called refined plastic hinge method developed by Liew [1] is applied for the structural analysis. For simplicity, the nonlinear relations between rotations and bending moments of semi-rigid connections are modeled by the three-parameter models developed by Kishi and Chen [5].

There have been many papers on optimization of steel-frame structures with semi-rigid connections. Xu and Grierson [8] considered the rotational stiffness of semi-rigid connections of steel-frame as design variables, and performed the continuous-discrete optimization. However, the rotational stiffness of each connection is taken as continuous variables and the structural analysis is limited to linear elastic models. Therefore, the optimized types of connections are not guaranteed to be applicable for practical purpose. Hayalioglu and Degertekin [3] performed genetic optimization, which has also been performed by Kameshki and Saka [4], for steel-frame structures with/without semi-rigid connections. Although the rotational stiffness of all the semi-rigid connections of a steel-frame has been assumed to be same in their study, it is demonstrated that the use of semi-rigid connections for structural analysis can further reduce structural weight. It is possible to further reduce the total structural weight by adjusting the rotational stiffness of each semi-rigid connection, because the distributions of bending moment can be effectively improved.

Therefore, in this study, the type of semi-rigid connections for each beam is taken as discrete design variable. The types and locations of the braces can also be optimized to improve the load-carrying capacity of a frame. Takewaki et.al. [7] performed optimization for a frame with X-braces at the specific locations. In their study, the cross-sectional properties of beams, columns and braces are optimized. As far as authors' knowledge, there is no research for optimizing the types and locations of braces simultaneously.

It is well-known that the lateral drift of a frame can be drastically reduced by placing braces, and, accordingly, the total amount of material of the structure under design load is reduced. However, the stiffness and strength of the beams, columns and braces should be appropriately distributed to achieve the structural efficiency. For these reasons, the types and locations of braces as well as cross-sectional properties of beams, columns and braces are also considered as design variables in this study. The three design problems are formulated as combinatorial problems, which consider, as discrete design variables, the types of semi-rigid connections, the types and locations of braces, and both of them, respectively. Then, these are solved by SS in order to evaluate the performance of SS. Tabu search is also applied for validation purpose.

4. Heuristic Method

Genetic Algorithm (GA) is frequently used in structural optimization. In population-based heuristics, such as GA, intensification in local search and the diverse search over the design space are necessary to obtain an accurate and global optimal solution. GA uses the crossover and mutation operators to diversify the solution set, and the reproduction operator for intensification. However, these operators are implicitly defined. Hence, trials-and-errors of many steps are needed to reach the global optimal solution. GA also has some drawbacks as:

- The quality of optimal solution is influenced by the random seed and by the uniformity of the random numbers.
- The adjustment of parameters, such as probability of crossover, is needed.
- The population size should be large enough to maintain the diversity of the solutions.

The first fact suggests that the random seed needs to be changed several times to obtain an accurate solution. The second fact indicates that trials-and-errors are needed to reach a high-quality solution. The third fact indicates a large number of function evaluations. If we expect an accurate solution without trials-and-errors, which is often the case with optimization that demands large computational effort, GA is not preferable. Hence, in this study, SS is applied that resolves the shortcomings of GA. To reinforce the diversification aspect for candidate lists of design variables without appropriate ordering, the hierarchical clustering is applied.

4.1. Scatter Search

SS was originally proposed by Glover [6], as a heuristic method for the integer programming problems. SS is a population-based heuristic method like GA. However, the size of population is smaller than GA, and it has a few parameters to be set by trials-and-errors. SS also uses the rational restart mechanism to diversify the solution set. Therefore, SS is preferable for optimization that demands large computational cost for function evaluation. SS uses the reference set which is composed of the best solutions and the diverse solutions. Recently used SS is based on SS template, or algorithm, which is composed of five steps, in which the most typical features are systematic generation of the initial solution set, and rational update of the reference set, which are hereafter called *PSet* and *RefSet*, respectively. The overall structure of SS template is described as (see also Figure 1):

STEP 1. Create *PSet* by **Diversification Generation Method**, and improve each solution in the set by **Improvement Method**. Then, create *RefSet* by **Reference Set Update Method** from *PSet*.
STEP 2. Update *RefSet* by **Reference Set Update Method** from *combined solution set* comparing with former *RefSet*. Note that this step is ignored at first iteration.
STEP 3. Extract all subsets of *RefSet* by **Subset Generation Method**.
STEP 4. Combine solutions in each subset and generate *combined solution set* by **Combination Method**, and improve each solution in the set by **Improvement Method**.
STEP 5. Stop if the termination condition is satisfied, otherwise, go to **STEP 2**.

The five methods, which are written in bold letters in SS template, are described in detail in the following.

Diversification Generation Method

The Diversification Generation Method is used to systematically generate the diverse initial solution set, *PSet*, using two familiar strategies: the frequency-based memory, which is often used as long-term memory in TS, and the roulette strategy used in GA. First, each candidate list of the design variables is divided into several ranges. Suppose the list of the ith variable x_i is divided into some ranges. Let $\boldsymbol{X}_1, . ., \boldsymbol{X}_m$ denote the set of solutions. Count the number n_r of the solutions whose x_i's fall into the range r and allocate n_r to the frequency-based memory. The probability of the ith variable of the kth solution denoted by x_i^k, to have the value in the range r is determined to be proportional to ($\sum_s n_s - n_r$) in a similar manner as roulette strategy in GA. This process is repeated for all the design variables until *PSet* is filled.

Improvement Method (optional)

The Improvement Method is used for improving each solution in *PSet* or *combined solution set* generated by the simple local search without update to non-improving solution. However, the method is not typical for SS.

Reference Set Update Method

The Reference Set Update Method is considered as the main part of SS, because it improves both diversification and intensification aspects. The method generates *RefSet* from *combined solution set* generated by the Combination Method, where *RefSet* is composed of the best solutions and the diverse solutions. The best solutions are extracted from *combined solution set* according to their evaluation. In simple SS, the diversity is measured by the distance from best solutions and the most distant solutions are extracted from *combined solution set* as diverse solutions. However, in this study, the method is modified using the hierarchical clustering, which is explained in Section. 4.2.

Subset Generation Method

The Subset Generation Method extracts all subsets of a specific size from *RefSet* for the Combination Method. Each subset consists of the candidate solutions to be combined to generate new solutions. The size of subsets can be altered.

Combination Method

The Combination Method combines specific number of solutions in each subset which was generated by the Subset

Generation Method to generate the new solution set called *combined solution set*. As an example, consider a subset consisting of two solutions, **x'** and **x"**. These can be combined to solutions $\mathbf{x}_1$ and $\mathbf{x}_2$ by the linear combination as:

$$\mathbf{x}_1 = \mathbf{x}' - \mathbf{d}, \quad \mathbf{x}_2 = \mathbf{x}' + \mathbf{d}, \quad \mathbf{d} = r\frac{\mathbf{x}'' - \mathbf{x}'}{2}, \quad r = \mathrm{rand}[0,1) \tag{1}$$

where rand[0,1) is a uniform random number in the range [0,1).

If none of the best solutions in *RefSet* is improved, the algorithm replaces diverse solutions in the *RefSet* with the new diverse solutions generated by the Diversification Generation Method. Hence, there is no need to apply SS several times to obtain the global optimal solution.

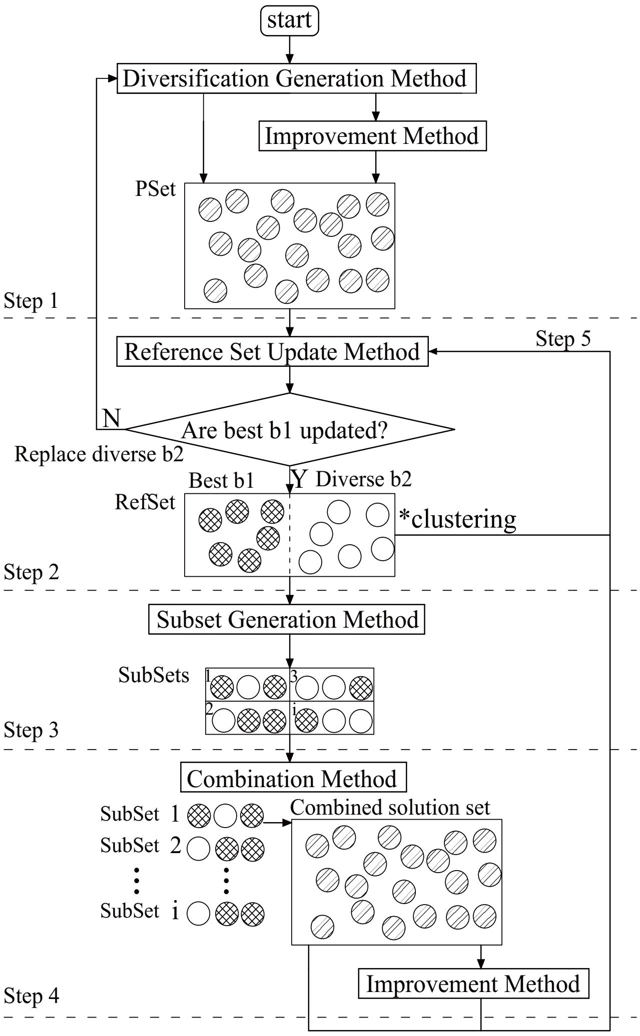


Figure 1. SS template

4.2. Clustering and Non-ordered List

In the standard SS, the most distant solutions from the best solutions are chosen as the diverse solutions in *RefSet*. However, the definition has obscure meaning for diversification of solution set. Therefore, we use the clustering, which is used for data mining, for explicitly diversifying the solution set (see; e.g., [2]). We use the hierarchical clustering, which is computationally inexpensive. The algorithm is briefly summarized as follows, where solution set is ($\mathbf{x}_1$, $\mathbf{x}_2$, . ., $\mathbf{x}_n$), $\boldsymbol{D}(C_i,C_j)$ denotes the distance between clusters C_i and C_j, and the target number of clusters is m.

Let { $C_i = \mathbf{x}_i$, for i=1, . ., n}

While (more than m clusters exist)

STEP 1. Calculate $\boldsymbol{D}(C_i,C_j)$ for all pairs (i , j).

STEP 2. Choose minimum $\boldsymbol{D}(C_k,C_l)$, and let $C_k = C_k \cup C_l$.

STEP 3. Remove cluster C_l

End While

The diverse solutions are extracted through the clustering for *PSet* and *combined solution set*, where the solution closest to the centroid of each cluster is chosen as the diverse solution. The clustering is effective to extract the diverse solutions from an ordered list. In the problems formulated in Section. 5, the candidate list of the design variables for beams and columns is ordered. Hence, the algorithm above can be applied (see Figure 5). However, the candidate list for braces is partially ordered for each type of braces. Therefore, the clustering is performed for each type of braces. The diverse solutions are composed of two kinds of solution sets of the same number, one solution set obtained from clustering of beams, columns and the other set from clustering of braces. Note that solution set obtained from brace clustering is further divided into three parts to be proportional to the frequency of each type of braces: the number of appearance of the type in the solution set.

4.3. Tabu search

Tabu Search (TS) is often used for structural optimization. TS uses short-term memory in order not to visit same solution within a specific period. There are at least two parameters to be adjusted for simple TS: length of short-term memory and the size of neighborhood solutions. The length of short-term memory and the size of neighborhood solutions have to be adjusted according to the performance of search. The neighborhood solutions are generated as:

$$x_i' = x_i + (2 \times \mathrm{rand}[0,1) - 1) \times \mathrm{g_i} \tag{2}$$

where, g_i is range of perturbation for the present solution, and rand [0,1) has same meanings as in eq.(1).

5. Formulation of problems

We use the nonlinear elasto-plastic analysis called refined plastic hinge method developed by Liew [2], which is confirmed to be equivalent to the Load and Resistance Factor Design (LRFD) practice, which is widely applied in U.S., by comparing the results of design by the analysis and the result of conventional LRFD design. We apply the analysis to reduce redundant codes and to obtain detailed information for the characteristic of the optimized frame. The nonlinear models for semi-rigid connections of the frame are modeled by the three-parameter model proposed by Kishi and Chen [6] is used as:

$$m = \frac{\theta}{(1+\theta^n)^{1/n}}, \qquad m = \frac{M}{M_u}, \qquad \theta = \frac{\theta_r}{\theta_0}, \qquad \theta_0 = \frac{M_u}{R_{ki}} \tag{3}$$

where M, θ_r, M_u, R_{ki} and n are the bending moment, the rotation, the ultimate moment capacity, the initial connection stiffness and shape parameter, respectively. Figure 2 shows the five types of semi-rigid connections considered in this study, where Types. 1 - 4 use the angles to connect beam and column. Note that these types of connections constitute the candidate list of the design variables for the semi-rigid connections. The three parameters of Types. 1 - 4 differ depending on the sizes of the angles. For Types. 3 and 4, the height of beam also affects the three parameters. Although the moment-rotation relation for each type is complicated, there exits a general property that Types. 1 - 5 are assigned in increasing order in view of stiffness and strength. Hence, to keep the order, we determine the three paremeters by assuming the angles of the same size for all connections, and the averaged height of candidate beams (see Table 1) for joint Types. 3 and 4. For Type 5, the three parameters are set far greater than the other types, because it is often classified as rigid joint. The moment-rotation relation for each joint is illustrated in Figure 3.

In order to demonstrate the performance of SS, three design problems that consider the types of semi-rigid connections (*Problem 1*), the types and locations of braces (*Problem 2*), and both of them (*Problem 3*), are formulated. Note that cross-sectional properties of beams, columns and braces are also considered as design variables for these problems. The steel-frame structure to be designed is the 6-bay 4-story frame simultaneously subjected to vertical and horizontal loads. The dimensions of the frame are illustrated in Figure 4. The two different loading cases are also illustrated in the figure. The magnitudes of vertical loads are assumed to be identical for the two loading cases, which correspond to 15 kN/m for all of the floors. The horizontal loads which are without and with parentheses in the figure are the values for two loading cases, hereafter called as *load 1* and *load 2*, respectively. Note that the conventional assumption of rigid floor is used; i.e., the horizontal displacement of the nodes in each floor have the same value. The base shear coefficients for *load 1* and *load 2* are 0.2 and 0.6, respectively, corresponding to the moderate and the severe earthquakes. The distribution of shear force is determined to be proportional to (1.00, 1.15, 1.35, 1.67) from the first to the fourth floor, according to the Japanese Building Standards Law. The modulus of elasticity: E=2.0×10^6 N/mm^2, and the yield stress: F_y=235 N/mm^2 are assumed for all members in the frame. Different requirements are set for the two loading cases. The upper bound for inter-story drift is 1/200 of each story height for *load 1*. Let Λ denote the load factor to be multiplied to the load pattern for load 2 in Figure 4. The factor for ultimate load, or collapse load, denoted as Λ_u, is required to be greater than, or equal to, the specified value, Λ_0=1. These constraints can be written as:

$$f_i = \frac{d_i}{\overline{d}_i} - 1.0 \leq 0 \qquad \text{for} \qquad i = 1, \ldots, 4 \tag{4}$$

$$g = 1.0 - \frac{\Lambda_u}{\Lambda_0} \leq 0 \tag{5}$$

where d_i is the inter-story drift of ith floor, and $\overline{d}_i$ is its upper bound.

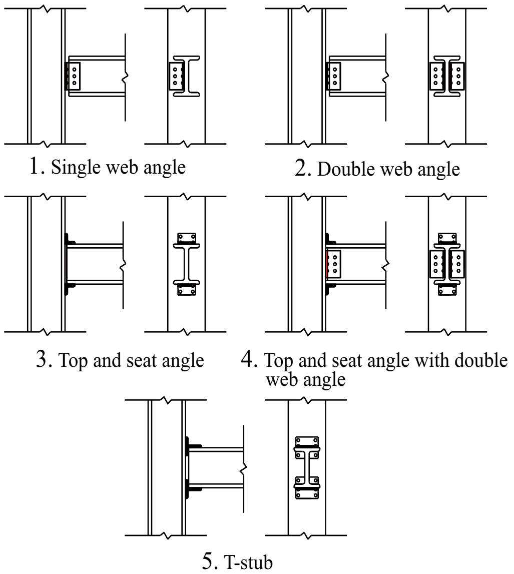


Figure 2. Types of semi-rigid connections

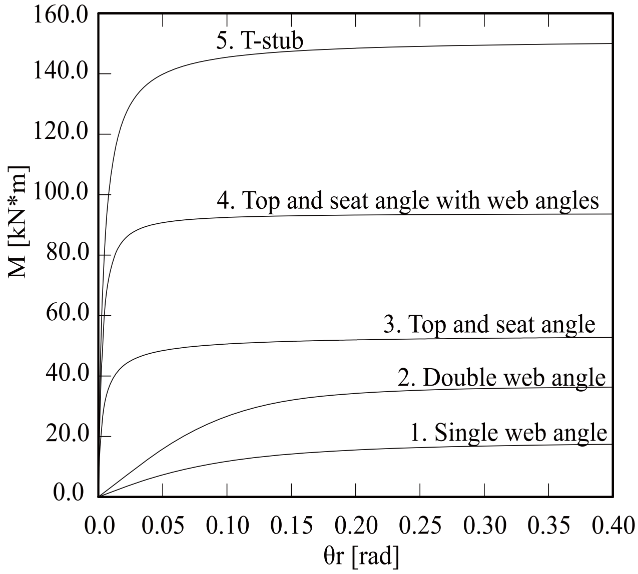
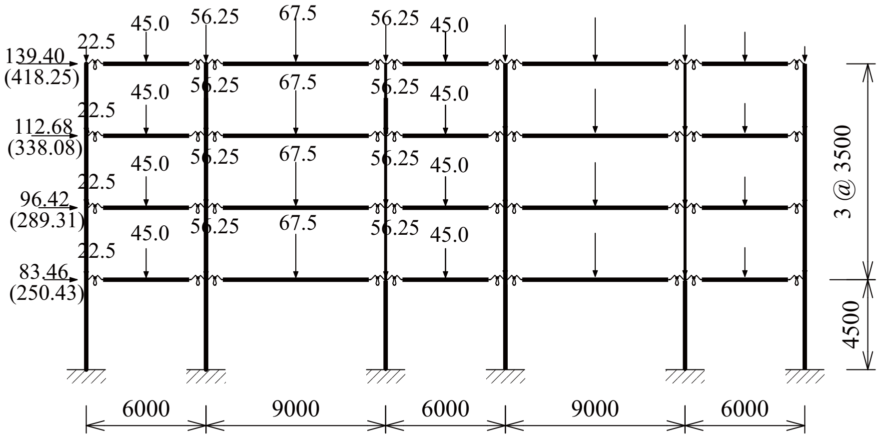


Figure 3. M-θ_r relation for each type of connection



* the dimensions in [mm] , the loads in [kN]

Figure 4. Dimensions of steel-frame and loading conditions.

Table 1. Candidate list for beams and columns.

Cross-section Type	*d* *(depth)* cm	*A* *(area)* cm^2	*I* *(inertia)* cm^4	Z_p*(plastic section module)* cm^3
1	15	26.4	1000	154
2	20	38.1	2630	301
3	25	55.5	6040	550
4	30	71.1	11100	842
5	35	99.5	21200	1380
6	40	133.2	37900	2140
7	45	153.9	54700	2760
8	50	159.2	68900	3130
9	60	187.2	114000	4350
10	70	231.5	197000	6340
11	80	263.5	286000	8100
12	90	305.8	404000	10300

Table 2. Candidate list for each kind of brace.

X-brace cross-section Type	*A* *(area)* cm^2	*I* *(inertia)* cm^4	K,V-brace cross-section Type	*A* *(area)* cm^2	*I* *(inertia)* cm^4
1	8.82	76	1	7.53	29
2	11.92	189	2	8.73	46
3	17.11	424	3	10.55	81
4	23.71	861	4	13.62	129
5	27.20	1380	5	18.76	258
6	31.33	1950	6	22.74	366
7	38.65	2490	7	29.21	627
8	44.07	4180	8	40.52	1170
9	48.57	6440	9	57.75	2180
10	69.39	14500	10	119.40	6950

The beams are divided into 12 groups according to the symmetry of the frame, and the columns in the same span are assumed to have the same cross-section. The design variables F-1 through F-15 for beams and columns are indicated in Figure 5 (a), and these variables are assumed in all of the three problems described in the following. The size of the candidate list of cross-sectional properties for these variables is 12 as is shown in Table 1 (see also Figure 6).

Problem 1 is to optimize the types of semi-rigid joints. The connections are divided into 12 groups according to the symmetry of the frame. The design variables C-1 through C-12 for semi-rigid connections are shown in Figure 5 (b). The size of the list for these variables is five, which corresponds to the number of types of the connections (see Figure 6).
Problem 2 is to optimize the types and locations of braces. The panels in the frame to which braces are assigned are

divided into 12 groups according to the symmetry of the frame. The design variables P-1 through P-12 for braces are shown in Figure 5 (c). The types of braces considered in this study are X-brace, K-brace and V-brace, and *no brace* is also included. 10 different cross-sections are considered for each type of braces (see Table 2). Therefore, the size of the list for these variables is 31 (see also Figure 6). We combine *Problems 1* and *2* to formulate *Problem 3*.

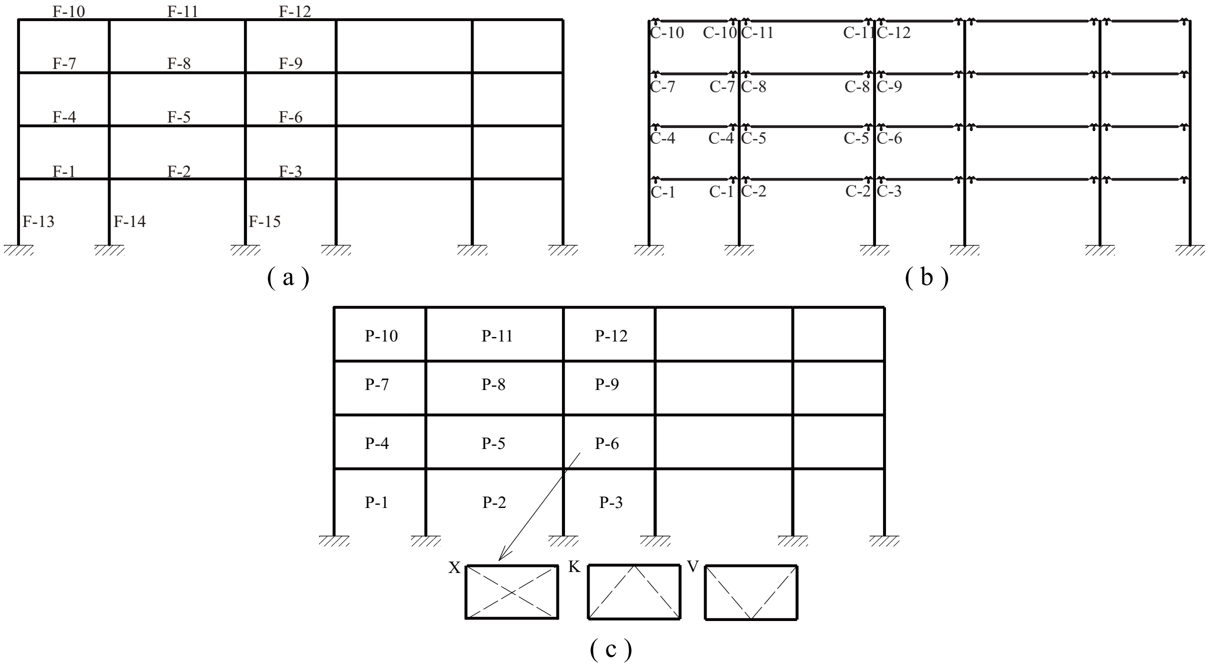


Figure 5. Design variables for beams, columns (a), for connections (b), for braces (c).

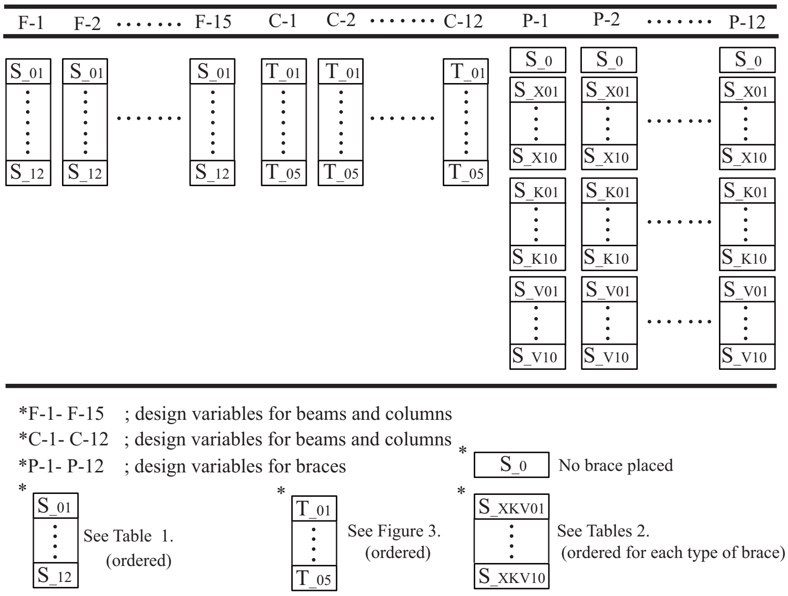


Figure 6. The summary of candidate lists for design variables.

The design variables to be considered are F-1 to F-15, C-1 to C-12 and P-1 to P-12. The summary of the candidate lists for all the design variables in *Problems 1 - 3* are illustrated in Figure 6, where the design variables for the braces are not considered in *Problem 1*, and the design variables for the semi-rigid connections are excluded in *Problem 2*. We consider penalized structural weight, *M'*, as objective functions for each problem, which includes the cost for the semi-rigid connections as:

$$M' = \sum_{i=1}^{n_f} m_f(\mathbf{X}_i) + \sum_{j=n_f+1}^{n_f+n_c} \beta(\mathbf{X}_j) m_f(\mathbf{X}_j) + \sum_{k=n_f+n_c+1}^{n_f+n_c+n_b} k_0 m_b(\mathbf{X}_k)$$

$$+ k_1 \max\{g\,,0\} + k_2 \sum_{l=1}^{4} \max\{f_l\,,0\} \tag{5}$$

where $\mathbf{X}_i$ (i=1, . ., $(n_f+n_c+n_b)$) is vector of design variables, corresponding to F-1 to F-15, C-1 to C-12 and P-1 to P-12 in Figure 6. n_f, n_c and n_b are the numbers of beams, columns, and the number of semi-rigid joints and braces, respectively. m_f and m_b are the functions which calculate weights of beams, columns and braces, respectively. k_0, k_1 and k_2 are the penalty coefficients for the structure not to forms stiff truss, for penalizing excessive inter-story drifts and for penalizing the shortage of ultimate load, respectively. β is function with respect to the types of the semi-rigid connections [9].

6. Optimization Results

The results of optimization by SS are presented for *Problems 1* to *3*. The sizes of *RefSet* in SS are assumed to be 28, 32 and 36 for *Problems 1*, *2* and *3*, respectively. The size of *PSet* is set to be the five times that of *RefSet*. The penalty coefficients are set to be k_0 = 5.0, k_1 = 200.0, k_2 = 50.0, respectively.

Problem 1

Figure 7 and Table 3 show the optimization results for *Problem 1*. Figure 6 (a) shows the history of the penalized weight, in which the weight gradually decreases to 283.1 kN as the optimization proceeds to 200 iterations. The inter-story drifts d_i and the ultimate load factor for the nearly optimal solution are shown in Table 3. Figure 6 (b) shows the nearly optimal solution for *Problem 1*, where the numbers near small hexagons indicate the types of semi-rigid connections, and the widths of beams and columns in the figure are proportional to the depths of the selected cross-sections, not in real scale. It is seen from the figure that the inner columns are stiffer than the outer columns which is a general property of the optimized non-braced frame. Figure 6 (c) shows the locations of the plastic hinges for *load 1*. As is seen, plastic hinges exits in nine beams, but no plastification occures along a column. Hence, the columns can be viewed as the cantilevers supported laterally by the elastic beams with no plastic hinge. In order to restrict the inter-story drifts to be within the allowable degrees, the upper part of the cantilevers, or columns, are supported by stiffer beams than lower parts. It is seen from the figure that the number of plastic hinges in beams increase from the first to fourth floor to restrict the inter-story drifts by adjusting the types of semi-rigid connections. Figure 6 (d) shows the locations of the plastic hinges for *load 2*. Plastic hinge denoted by *last* in the figure indicates the last plastic hinge formed which leads to the total collapse of the frame.

Table 3. d_i mm and Λ_u for the solution for *Problem 1*.

	d_i	$\bar{d}_i$
4th floor	17.1	17.5
3rd floor	17.4	17.5
2nd floor	15.3	17.5
1st floor	9.3	22.5
Λ_u / Λ_0	1.19	

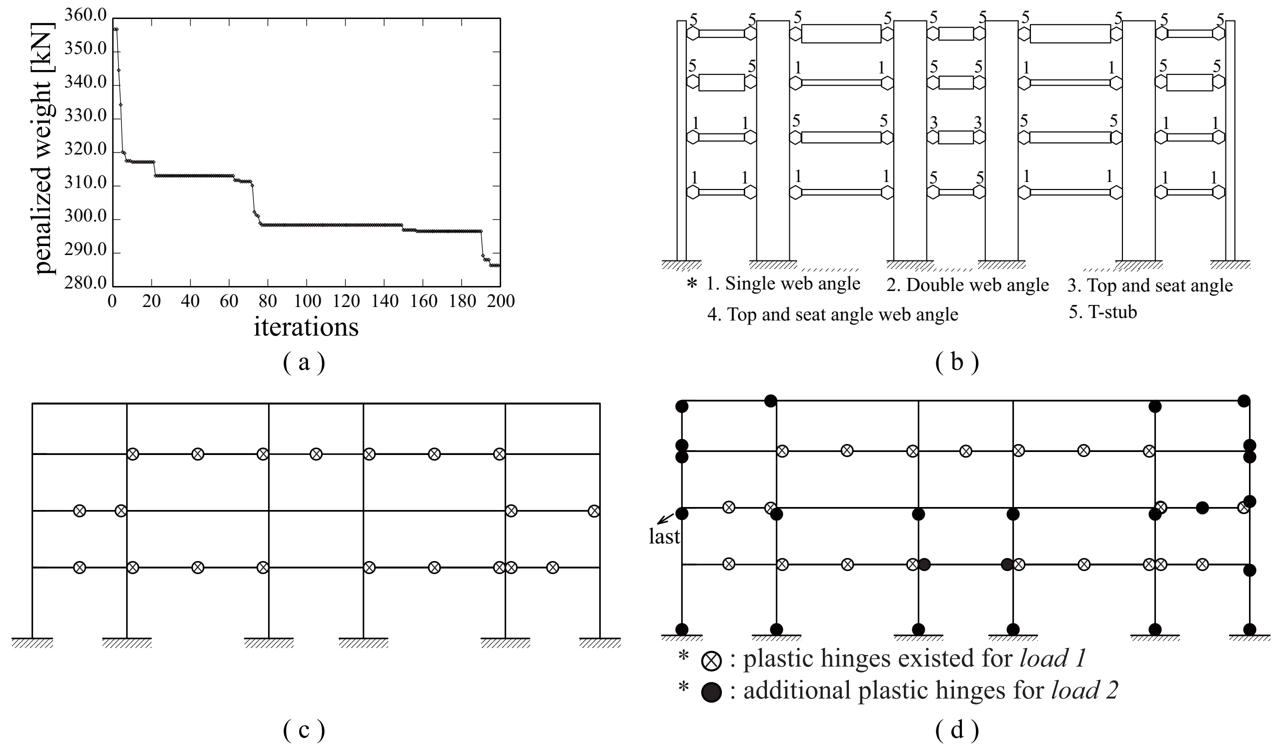


Figure 7. History (a) and optimal solution (b) for *Problem 1*. Locations of plastic hinges for *load 1* (c) and for *load 2* (d).

Problem 2

Figure 8 and Table 4 show the optimization results for *Problem 2*. Figure 8 (a) shows the history of the penalized weight, in which the weight gradually decreases to 202.2 kN as the optimization proceeds to 150 iterations. The inter-story drifts d_i and the ultimate load factor for the nearly optimal solutions are shown in Table 4. Figure 8 (b) shows the nearly optimal solution for *Problem 2*, where the widths of each brace are proportional to its cross-sectional area, not in real scales. It is seen from the figure that the type of braces chosen for the first floor is X-brace, which has greater lateral stiffness, and the types chosen for upper floor are K-brace or V-brace. Figure 8 (c) shows the locations of the plastic hinges and the buckled braces, indicated by dotted lines, for *load 1*. It is seen from the figure that the plastic hinges are formed along two columns, and six braces failed by buckling, while the plastic hinges are formed along ten beams, especially at the nodes connected by braces. Due to the existence of braces, the inter-story drifts are restricted far smaller than the allowable values. Hence, the design for the inter-story drifts is not critical. Figure 8 (d) shows the locations of the plastic hinges and the buckled braces for *load 2*. It is seen from the figure that the local failure due to the loss of rotational stiffness at the node, where four plastic hinges are formed, triggered the collapse of the frame, where the yielding of columns denoted by *yield* in the figure occurred simultaneously. It can be said that the braces resist lateral forces effectively, but, the local failure occurs, because the balance of the overall lateral stiffness becomes non-uniform by the presence of braces.

Table 4. d_i mm and Λ_u for the solution for *Problem 2*.

	d_i	$\bar{d}_i$
4th floor	3.4	17.5
3rd floor	9.1	17.5
2nd floor	15.3	17.5
1st floor	9.3	22.5
Λ_u/Λ_0	1.04	

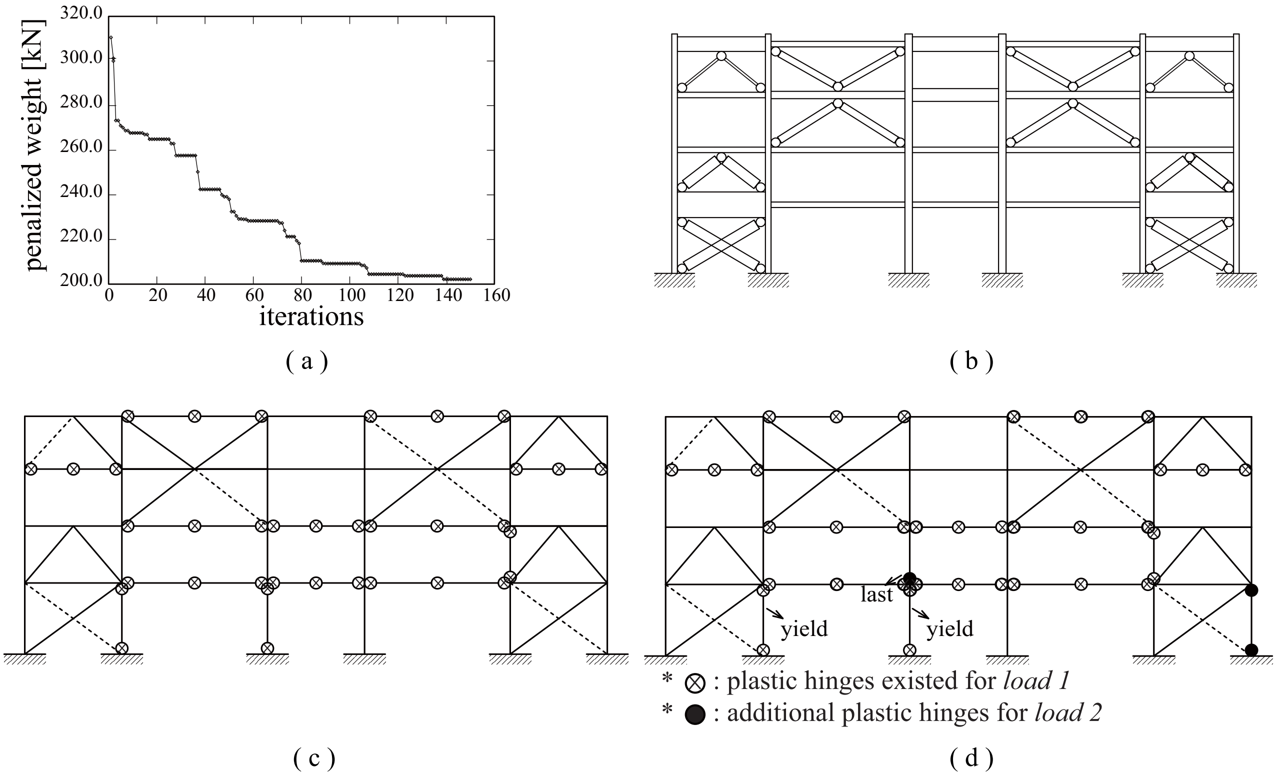


Figure 8. History (a) and optimal solution (b) for *Problem 2*. Locations of plastic hinges for *load 1* (c) and for *load 2* (d).

Problem 3

Figure 9 and Table 5 show the optimization results for *Problem 2*. Figure 9 (a) shows the history of the penalized weight, where the weight gradually decreases to 143.8 kN as the optimization proceeded to 150 iterations. The inter-story drifts d_i and the ultimate load factor for the nearly optimal solutions are shown in Table 5. Figure 9 (b) shows the nearly optimal solution for *Problem 3*, where the numbers near small hexagons indicate the types of semi-rigid connections. It is seen from the figure that the type of braces chosen for the first and second floors is X-brace, which has greater lateral stiffness, and the types chosen for upper floor are K-brace or V-brace, and the weaker types of semi-rigid connections are chosen for the stiffly braced panel. Figure 9 (c) shows the locations of the plastic hinges for *load 1*, where buckled braces are indicated by dotted lines. As is seen, the two braces buckled, and plastic hinges exit in 11 beams, especially at the nodes connected by braces. Due to the existence of braces, the inter-story drifts are restricted far smaller than the allowable values. Figure 9 (d) shows the location of the plastic hinges for *load 2*. It is seen from the figure that the local failure due to the loss of rotational stiffness at the node, where four plastic hinges are formed, triggered the collapse of the frame. stiffness becomes non-uniform by the presence of braces. It can be said that the braces resist lateral forces effectively, but, the local failure occurs, because the balance of the overall lateral stiffness becomes non-uniform by the presence of braces.

Table 5. d_i mm and Λ_u for the solution for *Problem 2*.

	d_i	$\overline{d_i}$
4th floor	1.2	17.5
3rd floor	4.7	17.5
2nd floor	7.7	17.5
1st floor	2.8	22.5
Λ_u/Λ_0	1.07	

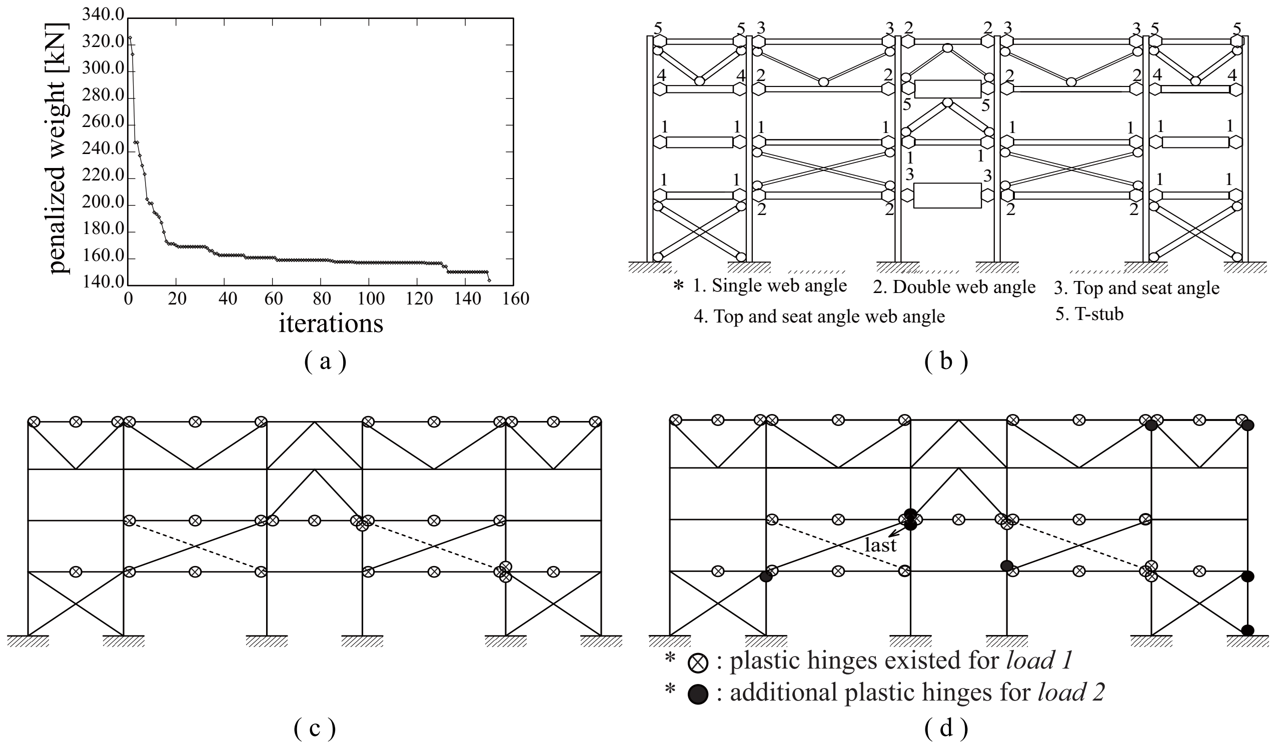


Figure 9. History (a) and optimal solution (b) for *Problem 3*. Locations of plastic hinges for *load 1* (c) and for *load 2* (d).

We also optimized the three problems mentioned above by Tabu search (TS). Figure 10 shows the history of the penalized weight. The penalized weights for *Problem 1* to *3* are 280.9 kN, 186.5 kN and 181.6 kN, respectively. These values are close to the values obtained by SS. Hence, the results obtained by SS are validated.

5. Summary and Conclusion

In this paper, we applied a heuristic method called Scatter Search (SS) for optimizing the types of semi-rigid joints, the types and locations of braces for steel frame structures. The three design problems for a frame have been formulated according to the design variables: the types of semi-rigid connections, the types and locations of braces, and both of them simultaneously, where the cross-sectional properties of beams, columns and braces of the structures are also optimized in all of the three problems. The nonlinear analysis called refined plastic hinge has been applied to obtain sufficient information on the properties of the optimized steel-frame.

These problems are solved to demonstrate the performance of SS. The characteristic of nearly optimal solutions are interpreted based on the results of nonlinear analyses. Finally, the optimization results through SS are validated by the optimization results obtained by Tabu search.

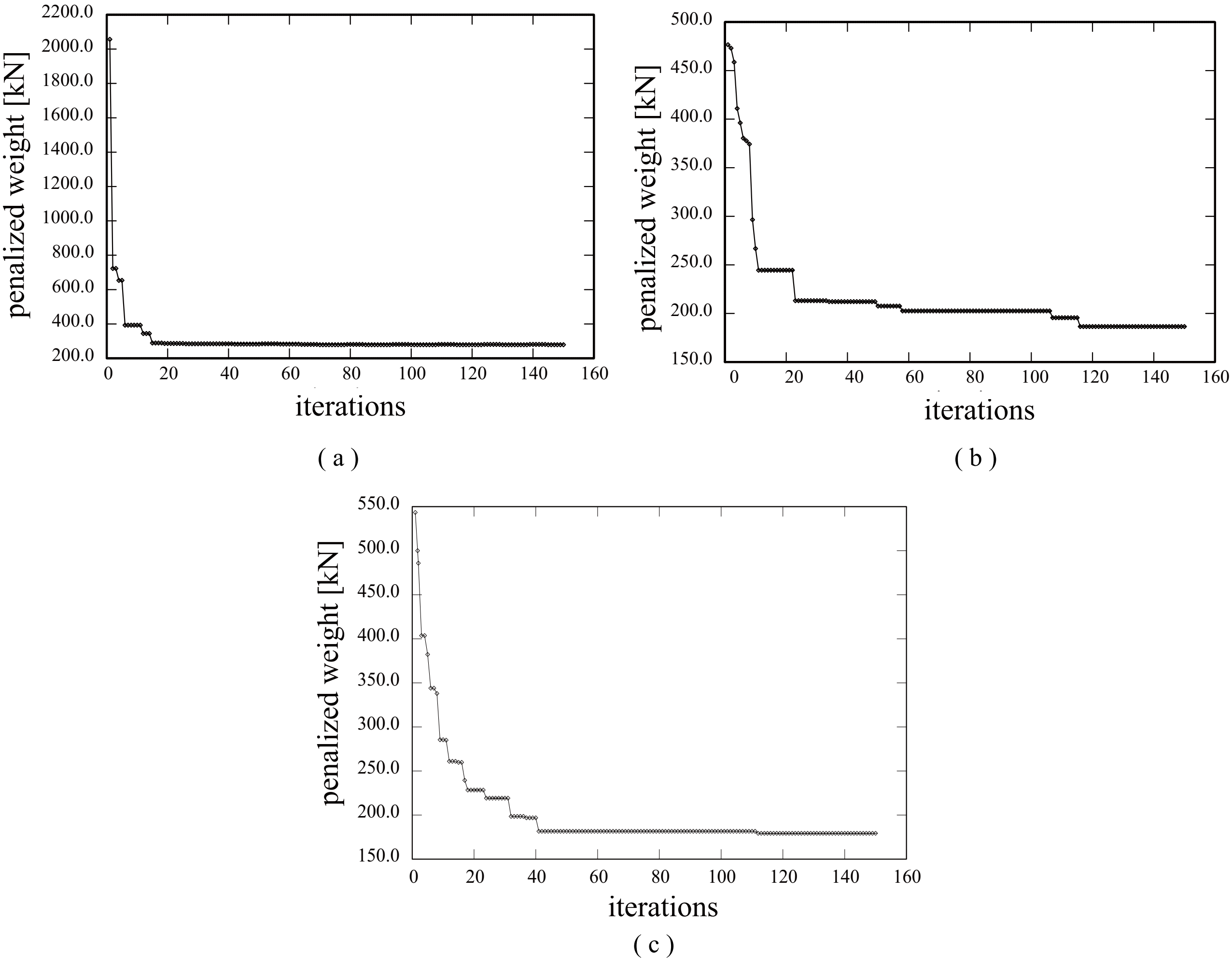


Figure 10. Optimization results by TS for *Problem1* (a), for *Problem2* (b), for *Problem3* (c).

Acknowledgement

Financial support by Grants-in-Aid for Scientific Research, Ministry of Education, Culture, Sports, Sciences and Technology of Japan (No. 17360270); and National Research Institute for Earth Science and Disaster Prevention are gratefully acknowledged.

7. References

1. Chen W.F, Kim S.E. 1997. LRFD steel design using advanced analysis. CRC Press.
2. Hand D, Mannila H, Smyth P. 2001. Principles of data mining. MIT Press, Massachusetts.
3. Hayalioglu M.S, Degertekin S.O. 2005. Minimum cost design of steel frames with semi-rigid connections and column bases via genetic optimization. Computers and Structures, Vol.83(21), pp.1849-1863.
4. Kameshki E.S, Saka M.P. 2001. Optimum design of nonlinear steel frames with semi-rigid connections using genetic algorithm. Computers and Structures, Vol.79(17), pp.1593-1604.
5. Kishi N, Chen W.F, 1990. Moment-rotation relations of semi-rigid connections with angles. Journal of Structural Engineering, ASCE, Vol.116, No.7, pp.1813-1834.
6. Laguna M, Marti R, 2003. Scatter search methodology and implementation in C. Kluwer Academic Publishers.
7. Takewaki I, Conte J.P, Mhin A, Pister K.S. 1990. Probablistic multi-objective optimal design of seismic-resistant braced steel frames using arma models. Computers and Structures, Vol.41(4), pp.687-707.
8. Xu L, Grierson D.E. 1993. Computer-Automated design of semirigid steel frameworks. Journal of Structural Engineering, ASCE, Vol.199, No.6, pp.1740-1759.