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Tabu search based optimum design of geometrically non-linear steel space frames

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Abstract. In this paper, two algorithms are presented for the optimum design of geometrically non-linear steel space frames using tabu search. The first algorithm utilizes the features of short-term memory (tabu list) facility and aspiration criteria and the other has long-term memory (back-tracking) facility in addition to the aforementioned features. The design algorithms obtain minimum weight frames by selecting suitable sections from a standard set of steel sections such as American Institute of Steel Construction (AISC) wide-flange (W) shapes. Stress constraints of AISC Allowable stress design (ASD) specification, maximum drift (lateral displacement) and interstorey drift constraints were imposed on the frames. The algorithms were applied to the optimum design of three space frame structures. The designs obtained using the two algorithms were compared to each other. The comparisons showed that the second algorithm resulted in lighter frames.

Keywords: optimum design; tabu search; steel space frames; non-linear analysis; allowable stress design.

1. Introduction

A large number of techniques and algorithms have been developed for the optimum design of structural systems in the last four decades. Most of the algorithms deal with continuous design variables and use mathematical programming techniques or optimality criteria. However, design variables are discrete in most practical design problems. This is due to the availability of standard sizes and their limitations for construction and manufacturing reasons.

A few articles deal with the optimum design of structures subjected to actual design constraints of code specifications (Chan and Grierson 1993, Soegiarso and Adeli 1994, 1997). Mathematical programming and optimality criteria methods with continuous design variables were used in all these articles.

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In recent years, some local search algorithms such as tabu search (TS) and simulated annealing (SA) have been used to solve many optimization problems. Local search is an emerging paradigm for combinatorial search which has recently been shown to be very effective for a large number of combinatorial problems. It is based on the idea of navigating the search space by iteratively stepping from one solution to one of its neighbours, which are obtained by applying a simple local change to it.

TS is based on the human memory process and uses an iterative neighbourhood search procedure in an attempt to avoid becoming trapped in local optima. TS was developed by Glover (1989, 1990) for solving combinatorial optimization problems. Since then, it has been applied to many different fields of engineering and technology recently (Chamberland and Sanso 2002, Sait and Zahra 2002, Abido 2002, Richards and Gunn 2003, Cunha and Riberio 2004, Jeon and Kim 2004, Aruga 2005, Peng *et al.* 2006, Sun 2006). An excellent theoretical aspect of TS is given by Glover and Laguna (1997).

TS was also applied to the structural optimization problems, However; the applications of it in this field were only about the optimal design of planar and space trusses which behave linear elastically (Dhingra and Bennage 1995, Bland 1995, Bennage and Dhingra 1995, Bland 1998a, 1998b, Manoharan and Shanmuganathan 1999). Rama Mohan Rao and Arvind (2007) put forward a simulated annealing algorithm in which TS is embedded in the algorithm in order to prevent recycling of recently visited solutions. They used this algorithm for optimal stacking sequence design of laminate composite structures.

Therefore, the present study aims to apply TS to the optimal design of a different structural system and structural behaviour, i.e., geometrically nonlinear steel space frames, under the actual design constraints of code specifications (AISC-ASD 1989). The actual design codes and loads were not also used in the aforementioned articles. Vertical and lateral loads were taken from actual standards and codes in this article (America Society of Civil Engineers 2000, Uniform Building Code 1997). Displacement constraints were also adopted in the optimal design of frames. Discrete design variable selected from the standard set of AISC wide-flange (W) shapes were also used. Two TS algorithms were developed in this study. The first one is similar to the algorithms given by Dhingra and Bennage (1995) which has short-term memory facility (tabu list). The second one is similar to the algorithm given by Bland (1998a, 1998b) which incorporates short and long-term memory (back-tracking) facilities. Optimum designs of three steel space frames were performed using the TS algorithms. The results obtained from two algorithms were compared to each other.

2. Tabu search

TS is an optimization method which finds optimum solution by neighbourhood search in the solution space. A constrained optimization problem consists of constraints to be satisfied and an objective function whose minimum value is searched. Objective function is composed of design variables. Design variables are selected from a list of discrete variables that each of them is represented by a sequence number in that list.

First an initial design is generated randomly. A variable of this design is also selected randomly and various designs are obtained by changing only that variable in the range of a predetermined neighbourhood depth. For example, if the neighbourhood depth is determined as ±2, four different designs are obtained by exchanging the selected variable with two upper and two lower variables in the sequence of the list. The best of the four designs is found (the best design is the one with the lowest objective function value even if it is not a feasible one). Meanwhile, the move (design variable) which determines the best design is recorded in a one-dimensional list called “tabu list”. The other design variables of the best design are also checked whether they are in the tabu list or not. This design is replaced with the current design even if a design variable of it is not in the tabu list and the process continues starting with the new current design. The other design variables are also selected randomly and the same process is applied to each of them. An iteration is completed when all design variables are considered. The best of the neighbourhood designs is recorded in a list with single member if it satisfies all the constraints. This list is called “aspiration list”. The aspiration list is updated throughout the iterations when a better feasible design is encountered. During the search process, even if all variables of a best neighbourhood design are in the tabu list, its tabu status is temporarily ignored providing that it is a better design than the one in the aspiration list and satisfies all the constraints. These two conditions are called “aspiration criteria”. This design is accepted as new current design and also put into the aspiration list. This design is rejected when its all variables are in the tabu list and it does not satisfy the aspiration criteria.

Tabu list is a one-dimensional array whose size is kept constant during the search process. For this reason, when the tabu list is filled the oldest move at the beginning of the list is dropped and a new move is put into the end of the list.

The above mentioned algorithm will be represented by TS-I in the present study. In this paper a second TS algorithm (TS-II) was also developed and designs obtained using this algorithm were compared to those of TS-I. In the second algorithm, behind the tabu list a back-track facility was also used which has long-term memory feature. In the long-term memory technique, after each set of a definite number of iterations the search returns to the best design of the set. The search process continues starting with that best design again. The overall process goes on for both algorithms until the end of a predetermined total number of iterations is reached. The design in the aspiration list at the end of the last iteration is accepted as the optimum design.

It is noted that the TS algorithm in the present study has been developed independently of Kargahi *et al*. (2006) in which they have also applied TS to the structural weight optimization of frames. The comparisons of the two studies from various aspects are given in the following:

As regards the TS algorithms; this study contains penalty function formulation, Eqs. (2)-(11), to deal with infeasible designs and aspiration mechanism which can temporarily ignore the tabu status of a move. This strategy was called tabu strategy III and proved to be the best in comparison with the others which do not include the aforementioned features (Dhingra and Bennage 1995). These merits increase the flexibility of the search which is restricted by using tabu list. However, the TS algorithm given by Kargahi *et al.* (2006) does not consider infeasible designs and the aspiration mechanism. These algorithms also differ in the implementation of the long-term memory. This type of memory was implemented by assigning a frequency penalty to previously chosen moves in the referring study. The length of the tabu list (tabu tenure), which acts as a short-term memory, was chosen as 8 at most in the referring study which seems quite short whereas it was taken as a certain times the number of design variables in this study. The drawbacks of using too short or too long tabu list are explained in the conclusions section. The neighbourhood depth was chosen as ± 1 in the referring article whereas the best value of it was determined from the computational experience gained in this study. Selecting the smallest value for the neighbourhood depth restricts the search area in the solution space.

As regards the configuration and behaviour of frames, design codes, loading and displacement restrictions ; this study considers space frames with geometrically non-linear behaviour subjected to the stress constraints of AISC-ASD (1989) and the displacement constraints specified by Ad Hoc Committee (1986). Wind loads are applied to the space frames as lateral loads which are calculated according to the specifications of Uniform Building Code (1997). However, the referring study considers plane frames extracted from the originally space frames with linear-elastic behaviour subjected to the stress constraints of AISC-ASD (1989) and the displacement constraints obtained from the 1994 edition of the Uniform Building Code. Static earthquake loads calculated and distributed according to the lateral force provisions of the 1994 Uniform Building Code are applied to the frames.

Consequently, exact comparison of this study with the one of Kargahi *et al.* (2006) is not possible because of differences in problem formulation and algorithmic implementation as well as in the configuration, behaviour, loading and displacement constraints of the structures.

3. Optimum design problem

The discrete optimum design problem of non-linear steel space frames where the minimum weight is considered as the objective can be stated of follows

$$\text{Minimize } W(x) = \sum_{k=1}^{ng} A_k \sum_{i=1}^{mk} \rho_i L_i \tag{1}$$

subjected to the stress constraints of AISC-ASD (1989), displacement constraints. In Eq.(1), mk is the total numbers of members in group k, ρ_i and L_i are density and length of member i, A_k is cross-sectional area of member group k, and ng is total numbers of groups in the frame.

All the constraints are given in normalized forms which is suitable for TS whose objective function can be arranged in an unconstrained manner.

The displacement constraints are

$$g_j(x) = \frac{\delta_j}{\delta_{ju}} - 1 \le 0, \qquad j = 1, \ldots, p \tag{2}$$

$$g_{ji}(x) = \frac{\Delta_{ji}}{\Delta_{ju}} - 1 \le 0, \qquad j = 1, \ldots, ns \quad i = 1, \ldots, nsc \tag{3}$$

where δ_j is the displacement of the j-th degree of freedom, δ_{ju} is its upper bound, p is the number of restricted displacements, Δ_{ji} is interstorey drift of i-th column in the j-th storey, Δ_{ju} is its limit, ns is the number of storeys in the frame, nsc is the number of columns in a storey.

The combined stress constraints taken from AISC-ASD (1989) are expressed in the following equations.

For members subjected to both axial compression and bending stresses,

$$g_i(x) = \left[\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{\left(1 - \frac{f_a}{F'_{ex}}\right) F_{bx}} + \frac{C_{my} f_{by}}{\left(1 - \frac{f_a}{F'_{ey}}\right) F_{by}}\right]_i - 1.0 \le 0, \qquad i = 1, \ldots, nc \tag{4}$$

$$g_i(x) = \left[\frac{f_a}{0.60 F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_i - 1.0 \le 0, \qquad i = 1, \ldots, nc \tag{5}$$

When $f_a/F_a \le 0.15$, Eq. (6) is permitted in lieu of (4) and (5)

$$g_i(x) = \left[\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_i - 1.0 \le 0, \qquad i = 1, \ldots, nc \tag{6}$$

For members subjected to both axial tension and bending stresses,

$$g_i(x) = \left[\frac{f_a}{F_t} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_i - 1.0 \le 0, \qquad i = 1, \ldots, nb \tag{7}$$

where nc is total number of members subjected to both axial compression and bending stresses and nb is total number of members subjected to both axial tension and bending stresses.

In Eqs. (4)-(7), the subscripts x and y, combined with subscripts b, m and e, indicate the axis of bending about which a particular stress or design property applies, and F_a = axial compressive stress that would be permitted if axial force alone existed, F_b = compressive bending stress that would be permitted if bending moment alone existed, F'_e = Euler stress divided by a factor of safety, f_a = computed axial stress, f_b = computed compressive bending stress at the point under consideration, C_m = a coefficient whose value is taken as 0.85 for compression members in frames subject to sidesway. In Eq. (7), f_b is the computed bending tensile stress, f_a is the computed axial tensile stress, F_b is the allowable bending stress and F_t is the governing allowable tensile stress. Allowable, $(0.6F_y)$ and Euler stresses are increased by 1/3 in accordance with the specification when produced by wind, acting alone or in combination with the design dead and live loads. Definitions of the allowable and Euler stresses and the other details are given AISC-ASD (1989) specifications and therefore will not be repeated here.

The effective length factor K is required to determine the permitted compressive stress F_a and Euler stress F'_e in the design of members. The K-factor for unbraced frames was calculated from the following equation (Dumonteil 1992)

$$K = \sqrt{\frac{1.6G_AG_B + 4.0(G_A + G_B) + 7.50}{G_A + G_B + 7.50}} \tag{8}$$

where G_A and G_B are relative stiffness factors at A-th and B-th ends of column.

The unconstrained objective function $\varphi(x)$ is then written as

$$\varphi(x) = W(x)\left(1 + C\sum_{i=1}^{m} \nu_i\right) \tag{9}$$

where C as a penalty constant which was taken as 0.9 in the design examples. m is the total number of constraints and ν_i are violation coefficients which are calculated as

$$\begin{aligned}
&\text{if} \quad g_j(x) > 0 \quad \text{then} \quad \nu_j = g_j(x)\\
&\text{if} \quad g_j(x) \le 0 \quad \text{then} \quad \nu_j = 0\\[1ex]
&\text{if} \quad g_{ji}(x) > 0 \quad \text{then} \quad \nu_{ji} = g_{ji}(x)\\
&\text{if} \quad g_{ji}(x) \le 0 \quad \text{then} \quad \nu_{ji} = 0\\[1ex]
&\text{if} \quad g_i(x) > 0 \quad \text{then} \quad \nu_i = g_i(x)\\
&\text{if} \quad g_i(x) \le 0 \quad \text{then} \quad \nu_i = 0
\end{aligned} \tag{10}$$

The minimum of the constrained function $\varphi(x)$ will be searched by TS. It is clear that computation of $\varphi(x)$ requires the values of displacements and stresses in the frame. This is achieved by carrying out the non-linear analysis of space frames.

4. Non-linear analysis of space frames

In this study, an algorithm and its programming code were used developed by Spillers (1990) and Levy and Spillers (1994) for the analysis of geometrically non-linear space frames. A frame becomes geometrically non-linear mainly due to the presence of large deformations. The ultimate load is reached by incremental loads and at each load increment incremental displacements are obtained by solving the equilibrium equations of the frame systems which are written in the incremental form of load and displacements. The member stiffness matrices are composed of linear elastic and geometric stiffness matrices. The iterations at each load increment continue until the unbalanced joint forces become quite small. The equilibrium equations are linearized and written for the deformed frame systems at each iteration. The solutions for all load increments are added up to acquire a total non-linear response.

5. Optimum design algorithm using tabu search

Design variables which form the objective function are discrete ones and they are the members of the steel section list with selected length. The optimum design algorithm for non-linear steel space frames using TS-I consists of the following steps:

1. Construct the initial design randomly. Assign this design as current design. Carry out the non-linear analysis and obtain the response of the frame. Calculate the value of unconstrained objective function $\varphi(x)$ using Eqs. (1)-(10)
2. Randomly select a variable (a member group of frame) of this design and obtain new designs by changing the variable along the neighbourhood depth. Carry out non-linear analysis for each new design and select the one with lowest objective function value (the best design) even though it does not satisfy all the constraints. Record the move (sequence number of the member group in the steel section list) which determines the best design in the tabu list. Put the best design into the aspiration list if it satisfies all the constraints.
3. Select again randomly a variable among the remaining ones of the best design and apply the process in the previous step to this design. Put the best neighbourhood design into the aspiration list if it satisfies the aspiration criteria, otherwise reject it.
4. Assign the best neighbourhood design as the current design and repeat steps 2 to 4 until the same process is completed for the last variable. This is the end of an iteration.
5. Start the next iteration with the current design obtained at the end of the previous iteration. If TS-II algorithm is considered, use the back-tracking after a definite number of iterations. If TS-I algorithm is considered do not use back-tracking and continue the process. Repeat steps 2 to 5 until the end of the total number of iterations is reached. Define the existing design in the aspiration list at the end of the last iteration as the optimum design.

6. Design examples

The algorithms were applied to the optimum designs of three space frame structures. A36 steel grade with a modulus of elasticity of 200 GPa and shear modulus of 83 GPa was used in the examples. The yield stress and unit weight of material are 248.2 MPa and 7850 kg/m^3, respectively. Three types of loads were employed: dead load (D), live load (L) and wind load (W). A load combination is considered, per AISC ASD specification: (D+L+W). The values of 2.88 kPa for dead load (D), 2.39 kPa for live load (L) were considered in the three design examples. Wind loading was obtained from Uniform Building Code (1997) using the equation $p = C_e C_q q_s I_w$, where p is design wind pressure; C_e is combined height, exposure and gust factor coefficient; C_q is pressure coefficient; q_s is wind stagnation pressure; and I_w is wind importance factor. Exposure C was assumed and the values for C_e were selected depending on the frame height and exposure type. The C_q values were assigned as 0.8 and 0.5 for inward and outward faces. The value of q_s was selected as 0.785 kPa assuming a basic wind speed of 129 km/h (80 mph) and the wind importance factor was assumed to be one.

The maximum drift of top storey was restricted to $H/400$ (Ad Hoc Committee 1986), where H is the total height of the structure. The interstorey drift was also limited to $h_c/300$ (Ad Hoc Committee 1986), where h_c is the height of the considered storey.

Two discrete design sets comprised 64 W sections each were used in the examples. The first one is beam section list taken from AISC-ASD (1989)-Part 2, “Beam and Girder Design”- Allowable stress design selection table for shapes used as beams. The second one is column section list taken from the same code, Part 3, “Column Design”- Column W shapes tables.

The maximum iteration number was taken as 200 for both algorithms which divided into four equal parts for back-tracking in TS-II.

6.1 Design of 5-storey 40-member space frame

The five-storey 40-member frame shown in Fig. 1 is the first example. The members of the frame were divided into six groups. The groups were organized as follows: 1-st group: the beams in x-direction at 5-th and 4-th storeys, 2-nd group: the beams in x-direction at 3-rd, 2-nd and 1-st storeys, 3-rd group: the beams in y-direction at 5-th and 4-th storeys, 4-th group: the beams in y-direction at 3-rd, 2-nd and 1-st storeys, 5-th group: all the columns of 5-th and 4-th storeys, 6-th group: all the columns of 3-rd, 2-nd and 1-st storeys.

The horizontal loads due to wind act in the y-direction at each node on the sides AB and CD. The maximum drift of top storey was restricted to 3.75 cm in the y-direction and interstorey drift was also limited to 1 cm. The length of tabu list was taken as 30. The optimum design sections and design results for TS-I are given in Table 1 and Table 2 using different neighbourhood depths.

The lightest frame was obtained for the neighbourhood depth ±3 and in this case, stress constraints were active in columns and passive in beams. Computing time was 57 minutes for this case using a personal computer with Intel Pentium 4 , 3.2 GHz microprocessor.

The optimum design sections and design results for TS-II are given in Table 3 and Table 4.

The lightest frame was obtained for the neighbourhood depth of ±3 again and stress constraints were active in the columns of 1-st and 2-nd storeys. 10.5% lighter frame was obtained by TS-II when compared to the one obtained using TS-I.

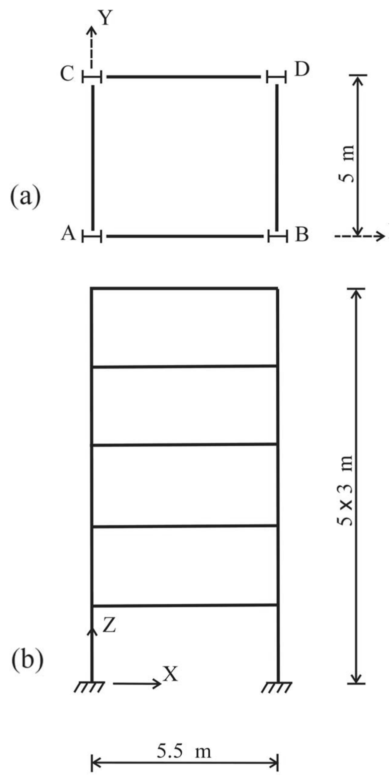

Fig. 1 Five-storey 40-member space frame: (a) plan, (b) side view

Table 1 Optimum design sections of 5-storey 40-member space frame using TS-I

Group no.	Neighbourhood depth			
	1	2	3	4
1	W27×84	W24×55	W24×55	W21×44
2	W27×84	W33×118	W24×55	W21×44
3	W24×55	W21×44	W14×34	W21×44
4	W30×90	W30×90	W27×84	W33×118
5	W12×40	W8×31	W10×33	W10×39
6	W12×53	W12×53	W14×61	W14×61

Table 2 Optimum design results of 5-storey 40-member space frame using TS-I

Neighbourhood depth	Weight (kg)	Top storey drift (cm)	Max. interstorey drift (cm)
1	16839	2.78	0.79
2	16886	2.80	0.79
3	13737	2.93	0.73
4	14872	2.55	0.70

Table 3 Optimum design sections of 5-storey 40-member space frame using TS-II

Group no.	Neighbourhood depth			
	1	2	3	4
1	W18×35	W18×35	W14×34	W18×35
2	W24×55	W18×40	W24×55	W18×40
3	W21×44	W21×44	W21×44	W21×50
4	W27×84	W30×99	W24×55	W30×99
5	W10×39	W10×39	W12×40	W10×33
6	W14×61	W14×68	W14×61	W14×61

Table 4 Optimum design results of 5-storey 40-member space frame using TS-II

Neighbourhood depth	Weight (kg)	Top storey drift (cm)	Max. interstorey drift (cm)
1	13602	2.62	0.72
2	13902	2.25	0.60
3	12298	2.77	0.74
4	13474	2.67	0.73

6.2 Design of 4-storey 52-member space frame

The second example is the 4-storey space frame with a rectangular plan and side view shown in Fig. 2. The structure has 52 members divided into 8 groups. The groups were organized as follows:

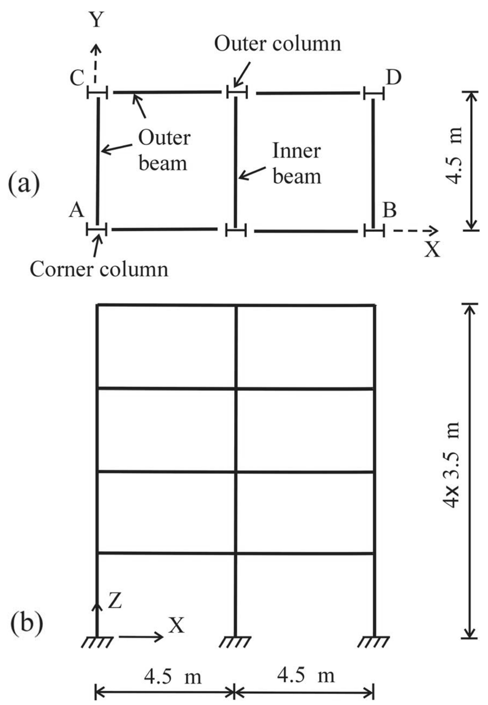

Fig. 2 Four-storey 52-member space frame: (a) plan, (b) side view

1-st group: outer beams of 4-th and 3-rd storeys, 2-nd group: outer beams of 2-nd and 1-st storeys, 3-rd group: inner beams of 4-th and 3-rd storeys, 4-th group: inner beams of 2-nd and 1-st storeys, 5-th group: corner columns of 4-th and 3-rd storeys, 6-th group: corner columns 2-nd and 1-st storeys, 7-th group: outer columns of 4-th and 3-rd storeys, 8-th group: outer columns of 2-nd and 1-st storeys.

The wind loads act in the y-direction at each node on the sides AB and CD. The top storey drift was restricted to 3.5 cm in the y-direction while interstorey drift was limited to 1.17 cm. The length of tabu list was taken as 40. The optimum design sections and design results for TS-I are given in Table 5 and Table 6 for various neighbourhood depths.

The lightest frame was obtained for the neighbourhood depth of ±3 and stress constraints were passive and interstorey drift constraint was active for this case. Computing time was 2 hours and 5 minutes.

Table 5 Optimum design sections of 4-storey 52-member space frame using TS-I

Group no.	Neighbourhood depth			
	1	2	3	4
1	W21×44	W21×44	W16×31	W24×55
2	W27×84	W33×118	W21×44	W24×76
3	W21×44	W14×34	W33×130	W33×130
4	W18×50	W18×40	W36×135	W24×131
5	W8×40	W8×35	W8×31	W10×45
6	W12×170	W10×49	W14×61	W14×61
7	W12×45	W12×53	W10×54	W10×45
8	W14×48	W12×72	W14×145	W14×61

Table 6 Optimum design results of 4-storey 52-member space frame using TS-I

Neighbourhood depth	Weight (kg)	Top storey drift (cm)	Max. interstorey drift (cm)
1	22286	2.96	1.17
2	20144	2.75	1.14
3	17593	2.26	1.14
4	20694	3.50	1.17

Table 7 Optimum design sections of 4-storey 52-member space frame using TS-II

Group no.	Neighbourhood depth			
	1	2	3	4
1	W27×84	W24×55	W14×34	W21×44
2	W21×93	W21×57	W18×35	W16×57
3	W21×50	W14×34	W21×44	W16×31
4	W16×57	W33×130	W36×135	W30×108
5	W8×48	W8×31	W8×31	W10×33
6	W14×90	W12×40	W14×90	W14×68
7	W14×43	W14×61	W10×49	W10×49
8	W14×43	W14×90	W14×132	W14×132

Table 8 Optimum design results of 4-storey 52-member space frame using TS-II

Neighbourhood depth	Weight (kg)	Top storey drift (cm)	Max. interstorey drift (cm)
1	23228	2.94	1.05
2	17343	2.90	1.00
3	16778	2.27	1.17
4	17995	2.52	0.97

The optimum design sections and design results for TS-II are given in Table 7 and Table 8. The lightest frame was obtained for the neighbourhood depth of ±3 again. The stress constraints were active in the corner columns of the 1-st storey while interstorey drift constraint was active in this case. 4.6% lighter frame was obtained by TS-II than the one obtained using TS-I.

6.3 Design of 3-storey 63-member space frame

The last example is the 3-storey space frame with a square plan and side view shown in Fig. 3. The structure consists of 63 members divided into 5 groups. The groups were organized as follows:

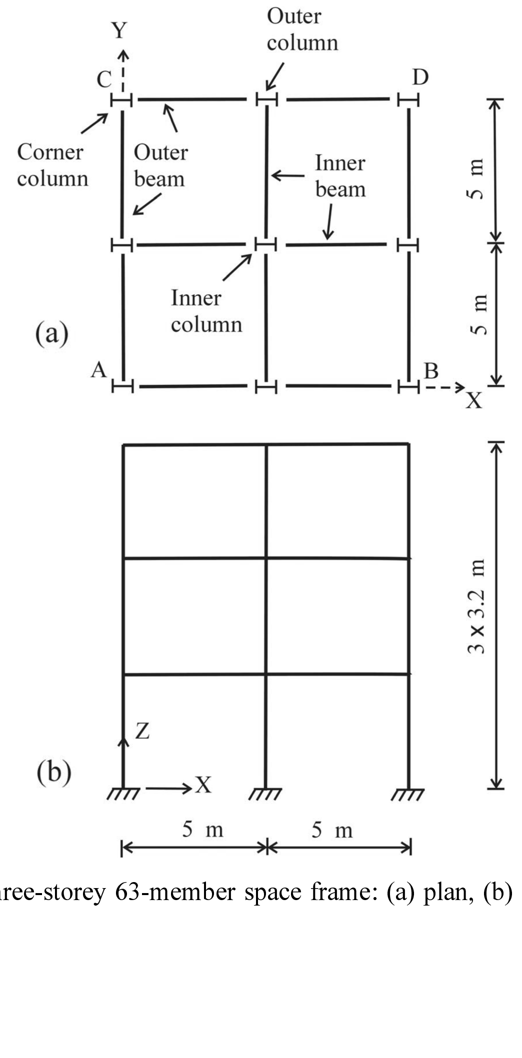

Fig. 3 Three-storey 63-member space frame: (a) plan, (b) side view

Table 9 Optimum design sections of 3-storey 63-member space frame using TS-I and TS-II

Group no.	TS-I	TS-II
1	W24×55	W14×34
2	W16×31	W21×44
3	W8×31	W8×35
4	W10×33	W14×53
5	W14×159	W12×87

Table 10 Optimum design results of 3-storey 63-member space frame using TS-I and TS-II

Method	Weight (kg)	Top storey drift (cm)	Max. interstorey drift (cm)
TS-I	18540	1.52	0.91
TS-II	16310	1.42	0.90

1-st group: outer beams of 3-rd, 2-nd and 1-st storeys, 2-nd group: inner beams of 3-rd, 2-nd and 1-st storeys, 3-rd group: corner columns of 3-rd, 2-nd and 1-st storeys, 4-th group: outer columns of 3-rd, 2-nd and 1-st storeys, 5-th group: inner columns of 3-rd, 2-nd and 1-st storeys.

The wind loads act in the y-direction at each node on the sides AB and CD. The top storey drift and interstorey drift were restricted to 2.4 cm and 1.07 cm in the y-direction respectively. The lengh of the tabu list was taken as 25. The optimum design sections and design results for TS-I and TS-II are given in Table 9 and Table 10 using a neighbourhood depth of ±3.

12% lighter frame was obtained by TS-II when compared to the one obtained by TS-I. Computing time was 2 hours and 20 minutes. In TS-II, the stress constraints of the 1-st storey columns were found to be active while the drift constraints were passive at the optima.

7. Conclusions

The following conclusions are drawn from the design examples considered when using tabu search for the optimum design of non-linear steel space frames:

1. A value of ±3 was found suitable for neighbourhood depth in all design examples presented in this paper. The lightest frames were obtained with this value.
2. It was observed that TS-II with back-tracking feature yielded better designs when compared to TS-I. This showed that the use of back-tracking strengthened the search process. 4.6 %- 12 % lighter frames were obtained by TS-II when compared to the designs obtained by TS-I.
3. In TS-II, behind the short-term memory (tabu list) a long-term memory (back-tracking) was also used. After each set of 50 iterations, the search returns to the best design of the set and the search starts with this design again. The number of sets is quite important in TS-II. It was selected as 4 herein. The search turned around local optima when fewer iterations and greater number of sets were selected. The values of 200 and 4 were found suitable as the number of iterations and sets respectively in the examples presented.
4. It is quite important to assign an adequate value to the length of the tabu list. The length should

be neither so short nor so long. The short tabu list caused the search to turn around the old and the same designs while the long list restricted the search to a small area because most of the moves were in the tabu list. Five times the number of member groups in the frames was found suitable for the length of the tabu list as a result of computational experience.

5. Computing time is quite long and it increases depending on the increase in the dimensions of the frames. Most of the time is spent in the non-linear analyses of frames in the optimization process. Computations increase enormously on account of feature of the non-linear analysis. This due to the fact that each load increment requires 4-10 more iterations to satisfy the equilibrium equations, and many load increments are necessary to reach the ultimate load. For these reasons, faster computers and faster analysis techniques are needed in the solution of this kind of problem.

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