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Genetic Algorithm Optimization of Space Frame

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ABSTRACT

Structural design of space frames requires appropriate form for a structure so that it can carry the imposed loads safely and economically. Traditional approaches towards the task of finding such forms for structures have been by the use of experimental models or by intuition and experience. The main objective of this paper is to develop and use reliable, creative and efficient computational tools for the linearly elastic analysis and optimum design of space frame structures under static loads.

The use of SAP2000 can assist greatly in achieving a safe design. However, commercially available programs are not designed as optimization tools. In this study for optimization of multistory structures, home written MATLAB code interface program is designed to connect SAP2000 which is known as a commercial nonlinear finite element program and genetic algorithm optimization program.

The design algorithm obtains minimum weight frames by selecting suitable sections from specified group list, with consideration actual design constraints like, strength, lateral displacement, inter story drift according to Load and Resistance Factor Design (LRFD). The improved method is tested on different two dimensional multi story moment resisting frames. It is concluded that this method can be used as a useful tool in engineering design and optimization.

Keywords: *Optimum design, Genetic algorithm, Steel structure, SAP2000, OAPI*

INTRODUCTION

The development and validation of methods for obtaining optimal steel frame designs has merited significant attention for several decades. The objective of steel frame optimization is the minimization of the cost of frame design, subject typically to strength and serviceability constraints. The wide-flange shapes provided in the AISC steel construction manual constitute the variable space in steel optimizations. As steel shapes do not exist on a continuous scale of cross-sectional area, moment of inertia, or any other section parameter, frame optimization problems are typically conducted on discrete spaces, rendering deterministic gradient-based methods impractical. Also, as structural system response is the result of complicated interaction between various members, steel frame optimizations are also highly nonlinear. Despite these inherent difficulties, the development of innovative stochastic algorithms and increase in computing capability has enabled optimal designs for large, discrete structural optimization problems with various constraints to be obtained within reasonable computational expense.

Genetic Algorithm (GA), interfaced with a SAP2000 commercial package program, is utilized to produce the optimal solutions. SAP2000 structure analysis program is a well-known integrated Finite Element (FE) structural analysis tool which already used for modelling and designing structures according to different design codes. The Open Application Programming Interface (OAPI) in SAP2000 is a free service in some versions of it, to export and import data files from and to SAP2000. In SAP2000 after input file being opened, SAP2000 will analyse, save result and design all members. From one of output files, any required data's, like element stress and joint displacements can be found to check strength and serviceability constraints [1].

Genetic Algorithm

In this paper Genetic Algorithm (GA) is used so detailed explanation is given for this method. There are fascinating algorithms. The name came from the way in which they loosely mimic the process of evolution of organisms, where a problem solution stands in for organism's genetic string [2]. Features include a survival of the fittest mechanism in which potential solutions in a population are pitted against each other, as well as recombination of solutions in mating process and random variations.

The GA is used to solve the following problem.

To minimize $F(\mathbf{s})$

Subjected to $g_j(s) \leq 0 \qquad j = 1,......., m$

$$s_i^l < s_i < s_i^u, \quad i = 1, 2, \ldots, n$$

Where, $\mathbf{s}$ is the vector of design variables, and $F(\mathbf{s})$ is the objective function to be minimized. s_i^l and s_i^u are the lower and upper bounds on a typical design variable s_i, $g_{j(s)}$ are the behavioural constraints.

Optimization by Using GA- SAP2000 OAPI

SAP2000 structure analysis program is a well-known integrated (FE) structural analysis tool which already used for analysing, modelling and design of structures according to different design codes.

In this paper GA, interfaced with a SAP2000 commercial package program, is utilized to produce the optimal solutions.SAP2000 could export or import analysis and design data with extension data base file, Microsoft excel, text file and Microsoft access. The interaction with it occurs through the input (*$2k) and output files (*out).

The Open Application Programming Interface (OAPI) in SAP2000 is a free service in some versions of SAP2000, to export and import data files from and to SAP2000,which aims to offer efficient access to the analysis and design technology of the SAP2000 structural analysis software.[3]

In SAP2000 after input file being opened, SAP2000 will analyse, save result and design all members. From one of output files, any required data’s, like element stress and joint displacements can be found to check strength and serviceability constraints [4] Figure 1.

However most of available commercially structural analysis programs are not designed for optimization [5], but it will be able to achieve this task with preparing open optimization designed code in any code have ability to interact with it and interfacing them together. The SAP2000 API offers a broad range of programming languages that it can be used which cover the vast majority of the modern software development options including Visual Basic.NET, Visual Basic for Applications (VBA), Visual C#, Visual C++, Visual Fortran and Matlab. [3].

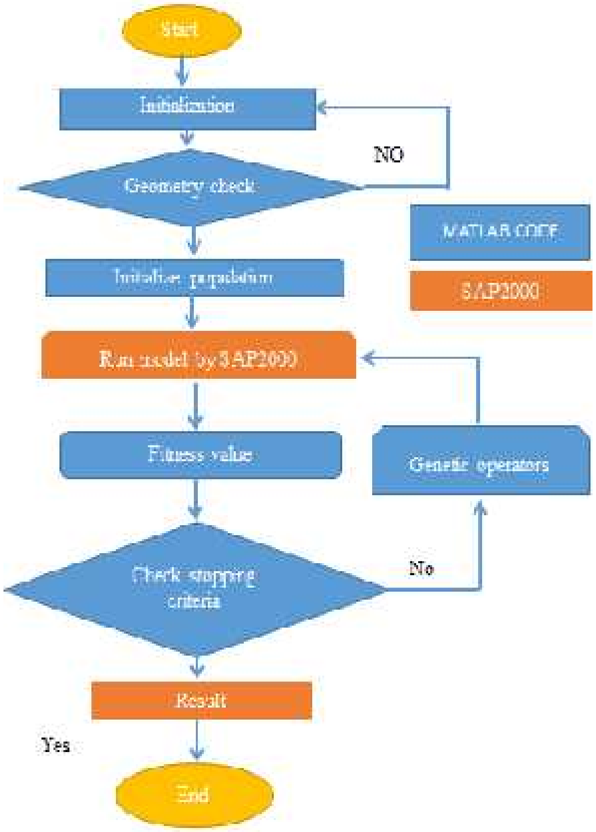

Figure 1. Interfacing flowchart between sap2000 and GA

Constraints in Structural Optimization

The introduction of the large-scale digital computers allowed the adaptation of classic optimization algorithms to realistic engineering problems, as well as the advancement of new and more powerful techniques to obtain the optimum design of structural systems. Most of them deal continuous design variables with simple constraints. Only a few of these papers deal with the discrete design variables and actual design constraints according to different structural design code [6, 7, and 8], most of them used optimality criteria methods and mathematical programming techniques with continuous design variables as an optimization tool [9].

The AISC-LRFD specification combines strength, stability and displacement requirements. Displacement constraints are the allowable interstory drift. These constraints are implicit constraints because structural responses like stresses, strains, and displacements are functions of design variables [10].

Stress constraints according to LRFD

According to (AISC-LRFD) specification the allowable stress for members subject to bending and axial force are [11].

$$\text{For} \quad \frac{P_u}{\varphi\ P_n} \geq 0.2 \tag{1}$$

$$\frac{P_u}{\phi P_n} + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right) \leq 1.0 \tag{2}$$

$$\text{For} \quad \frac{P_u}{\varphi P_n} < 0.2 \tag{3}$$

$$\frac{P_u}{2\phi P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right) \leq 1.0 \tag{4}$$

In equation 2 and 4 if the axial force is in compression or in tension the terms in above equations are P_u is the required axial strength (tension or compression); P_n nominal axial strength (tension or compression), M_{ux} is the required flexural strength about the minor axis, M_{uy} is the required flexural strength about the minor axis, M_{nx} is the nominal flexural strength about the major axis, M_{ny} is nominal flexural strength about the minor axis,

(for 2D structures, M_{uy} is equal to zero); $\phi = \phi_t$ resistance factor for tension (equal to 0.90)

$\phi = \phi_c$ compression resistance factor and ϕ_b = flexural resistance reduction factor =0.9.

The nominal compressive strength of a member is computed as

$$P_n = A_g . F_{cr} \tag{5}$$

$$F_{cr} = \left(0.658\ \lambda c^2\right) . F_y \tag{6}$$

Where $\lambda c \leq 1.5$

$$F_{cr} = \left(\frac{0.877}{\lambda c^2}\right) . F_y \tag{7}$$

For $\lambda c > 1.5$

$$\lambda_c = \frac{KL}{r\pi}\sqrt{\frac{F_y}{E}} \tag{8}$$

In which A_g is the gross cross-sectional area of a member, K = Effective length factor for braced and unbraced member [12].

E =modulus of elasticity of a member, r = radius of gyration, L = length of member, and F_y = yield stress of steel.

Serviceability limit states (displacement constraints)

The increasing use and reliance on probability based limit states design methods, such as the recently adopted AISC- LRFD Specification [11], has concentrated new attention on the serviceability problems in steel buildings. These methods, along with the development of higher-strength building materials and the use of lighter and less rigid building materials, have led to more flexible and lightly damped structures than ever before, making serviceability problems more prevalent.

Lateral frame movement or deflection is usually evaluated for the building as a whole, where the applicable parameter is total building drift, which is equal to (D/ H) where D is total top-story drift and H is the total structure height, and for each floor of building which is known as inter-story drift, and can be defined as the lateral deflection of a floor relative to the one immediately below it divided by the distance between floors ((dn–(dn–1)/ h) [13]).

Where dn is the drift of specified floor and h is equal to height of that floor.

According to the ASCE report [14], normally allowable accepted ranges for lateral displacements are restricted between 1/750–1/250 times the building heights with a typical value of H/400 and the normally accepted limits on the inter-story drift is 1/500–1/200 times the story height with a typical value h/300; where h is the height of an story.

Fabrication constraints

The fabrication constraint is that, structure elements are available in the form of discrete sections; otherwise the algorithm would not have any practical application.

The standard available steel sections are treated as design variables and the stress and displacement constraints are taken from the design codes [15]. Traditionally, in design of space moment frames, frame members (column and beams) are usually selected W-sections, so a file with different section property is prepared, for beams and columns. For example, consider a framed structure, where the structure is subjected to design stress, displacement and fabrication constraints the equation of optimization problem may be expressed as

$$\text{Minimize} \qquad W = \sum_{i=1}^{N} \rho_i l i A_i(\eta_i) \tag{9}$$

$$\text{Subjected to} \quad (\sigma^u) \geq (\sigma) \geq (\sigma^l) \tag{10}$$

$$(d^u) \geq (d) \geq (d^l) \tag{11}$$

$$(A^u) \geq (A) \geq (A^l) \tag{12}$$

Where σ, d, A are stress, displacement and cross sectional area and subscripts *u* and *l* refer to prescribed upper and lower boundaries of each constraints.

η_i Index number according to fabrication code

$A_i(\eta_i)$ Is the cross sectional area of element *i*.

NUMERICAL EXAMPLES

5.1 Space Frame Examples

In this part 3D moment frame examples are optimized under static loads. The objective function is weight minimization under stress and displacement constraints according to AISC-LRFD specifications, with the 4 load combinations as shown in Table 1.

Table 1 Load combination case

Load case	Combinations
Comb1	$1.4D_l$
Comb2	$1.2D_l+1.6L_l+0.5R_l$
Comb3	$1.2D_l+0.5L_l+1.6R_l$
Comb4	$1.2D_l+1.3\ W_l+0.5L_l+0.5R_l$

5.1.2 Four story space moment frame

This example deals with four-story space moment frame, which is optimized previously by Tabu-search (TS) [15] and Simulated Annealing (AS) [16], the frame members are divided in to 10 groups. The groups were organized as follows: 1-st group: outer beams of 4-th storey, 2-nd group: outer beams of 3-rd, 2-nd and 1-st storeys, 3-rd group: inner beams of 4-th storey, 4-th group: inner beams of 3-rd, 2-nd and 1-st storeys, 5-th group: corner columns of 4-th storey, 6-st group: corner columns of 3-rd, 2-nd and 1-st storeys, 7-th group: outer columns of 4-th storey, 8-th group: outer columns of 3-rd, 2-nd and 1-st storeys, 9-th group: inner columns of 4-th storey, 10-th group: inner columns of 3-rd, 2-nd and 1-st storeys. The height and span lengths of the structure are as shown in Figure 2 and 3.

The structure subjected to live load (Ll= 2.39 kpa) , dead load (Dl=2.78 kpa), roof live load (R_l= 2.39) kpa and wind pressure (*p*) = $c_e c_q q_s i$. where *p* is design wind pressure; c_e is combined height, exposure and gust factor coefficient, c_q is pressure coefficient is equal to 0.8 and 0.5 for both windward and leeward faces of the structure respectively, q_s is wind stagnation pressure is equal to 0.785 kpa, and the importance factor i=1. wind loads acted on the x-direction for both wind ward and leeward sides. The example is optimized under LRFD stress constraints and 4.55 cm and 1.52 cm for top and inter-storey drift constraints respectively. Material properties for the frame are: young's modulus $E = 200 \times 10^6$ kN/m^2, material density $\rho = 7850$ kg/m^3, minimum yield stress *fy*=248.2 Mpa and modulus of rigidity *g*=83 Gpa

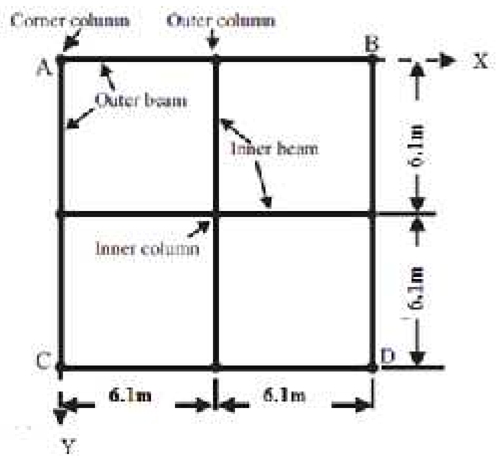

Figure 2 *Beams and columns of four story moment frame*

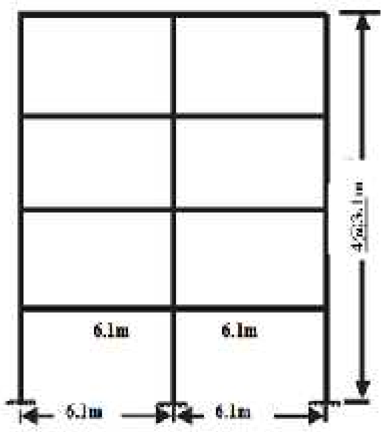

Figure 3 *Side view, of four story space frame*

The maximum inter-story drift is 0.22 cm which is less than maximum allowable drift =1.52 cm, and maximum total story drifts =1.4 cm which is less than the maximum allowable top-story drift = 5.54 cm as recommended by reference [15]and [16].

Table 2 Optimum design variable of four story space frame

Group no.	**Design variables**		
	Degertekin [16]	**Degertekin et al**	**Present Work**
1	W 16×31	W 18×35	W 12×26
2	W 16×31	W 18×35	W 16×36
3	W 18×40	W 18×35	W 18×76
4	W 18×35	W 18×35	W 18×35
5	W 8×35	W 8×31	W 12×30
6	W 14×53	W 12×40	W 16×26

7	W 8×31	W 10×39	W 12×53
8	W 8×35	W 12×45	W 14×43
9	W 8×31	W 8×28	W 6×20
10	W 14×68	W 12×58	W 14×61
Weight(kg)	22405	23105	22961.2

10 story space moment frame

This example deals with 10-storey space moment frame with rectangular plane as shown in Figure 4[9]. The structure is divided in to 9 groups. The groups are organized as follows: 1-st group: outer beams of top storey, 2-nd group: inner beam of top storey, 3-rd group: outer beams of storeys from 1 to 9, 4-th group: inner beams of storeys from 1 to 9, 5-th group: outer and corner columns of 10-th and 9-th storeys, 6-th group: outer and corner columns of 8-th and 7-th storeys, 7-th group: outer and corner columns of 6-th and 5-th storeys, 8-th group: outer and corner columns of 4-th and 3-rd storeys, 9-th group: outer and corner columns of 2-nd and 1-st storeys.. The structure is subjected to the same design loads and load combinations of previous example. The value of qs is 0.622 kPa with wind load in x-direction, assuming a basic wind speed of 113 km/h (70mph) and the importance factor is assumed to be one. The maximum allowable drift is restricted to 18.7 cm. The material is steel with a modulus of elasticity of 200 000MPa and shear modulus of elasticity of 77 000MPa. The yield stress and the unit weight of material are 344.8MPa and 7850 kg/m3, respectively.

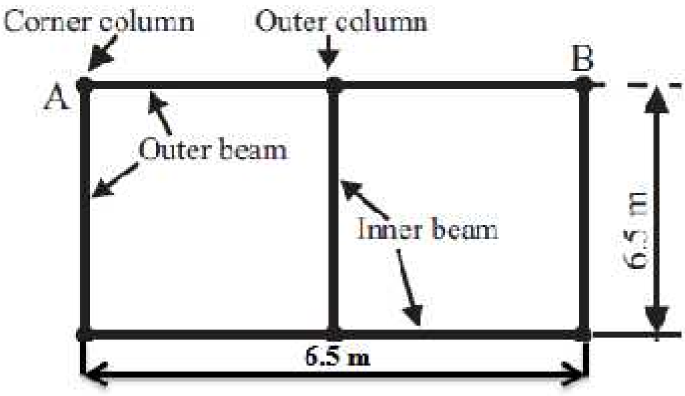

Figure 4 *plane of 10 story space moment frame*

The results are compared with the other references [9] as shown in table 5.7 which is more close to them. The maximum displacement is equal to 15.5 cm which is less than the maximum allowable top story drift = 18.7 cm.

Table 3 Optimum design variable of 10 story space moment frame

Group no.	**Design variables**

	Hayalioglu [9]	**Present Work**
1	W14×26	W 14×30
2	W12×40	W 14×34
3	W12×35	W 14×34
4	W12×35	W 14×38
5	W10×22	W 14×53
6	W12×35	W14×48
7	W14×68	W 12×53
8	W14×68	W 12×53
9	W14×82	W14×74
Max. Displ. (cm)	18.1	15.5
Weight(kg)	40976.3	39970

Conclusion

The use of nonlinear finite element SAP2000 commercial program can assist greatly in achieving a safe design and is used to check if the applied inner force, member groups and elected sections are corresponded specified code and constraints or not.

However most of the commercial packages have been developed to be used as verification rather than the optimization tool, but it is possible to do it by designing an optimization code in an open file to achieve this task and interfaced with them.

Continued research is allowed for combining with other FEM programs and optimization methods.

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