GENETIC ALGORITHM SEARCH FOR OPTIMAL BRACE POSITIONS IN STEEL FRAMES

D. Safari[1] and Mahmoud R. Maheri[2, *]

[1]*PhD Candidate, Department of Civil Engineering, Shiraz University, Shiraz, Iran.*
[2] *Professor of Civil Engineering, Faculty of Engineering, Shiraz University,*
P O Box 71345/1676, Shiraz, Iran, Tel: +98-711-6287505, Fax: +98-711-6286619
**(Corresponding author : E-mail: maheri@shirazu.ac.ir and mmaheri@hotmail.com)*

Received: 9 April 2005; Revised: 7 May 2006; Accepted: 9 May 2006

ABSTRACT: In steel structures, steel bracing is often used to resist the seismic or wind-induced lateral forces. The optimum positions of the braces are generally determined by trial and error or through previous experiences, usually with the objective that the distance between floor centres of mass and stiffness are reduced to a minimum and that a viable load path is provided throughout the lateral resisting system. This process is cumbersome and the trial and error optimization is usually incomplete. In this paper, topology optimization of steel braces in 2D steel frames is carried out using a simple Genetic Algorithm. To improve the GA optimization of the brace-frame system, theory of graphs is also utilized as a heuristic operator. The objective is minimization of the weight of the steel frame subject to strength and drift constraints. Other independent constraints adopted include; architectural constraints and the number of braced panels. It is shown that the GA can be used effectively to optimize the topology of bracings in steel structures. Also, it is shown that utilizing the graph theory as a heuristic operator, greatly improves the convergence rate of the optimization.

Keywords: Bracing, topology optimization, genetic algorithm, theory of graphs, seismic design, steel structures.

1. INTRODUCTION

In design of steel structures for lateral loading, steel braces are considered more suitable than other lateral load resisting elements including the concrete shear walls. The relative low cost and weight of the resisting system together with the speed and ease of construction, make steel bracing attractive not only in steel structures but also in concrete structures (Maheri et al. [1]). Some of the main tasks facing a designer when using steel bracing include; selecting the number of braced panels in a frame, the cross-sectional size of the braces and particularly the positions of the panels to be braced. The number and size of the braces are generally functions of the applied loading and/or the lateral drift limitations imposed by codes of practice, whereas, the optimum positions of the braced panels in the frame are dictated not only by the strength and serviceability requirements, but also by the architectural layout of the building. Architectural limitations are generally outlined by the architect prior to the engineering design. The designer should take these limitations into consideration.

Structural optimization may be divided into four main categories. These include; size optimization, shape optimization, material optimization and topology optimization. In size optimization, the size of the structural members is the main problem variable. In shape optimization, the nodal coordinates are the variables which may include changes in the size of the structural elements, whereas in topology optimization, the position of structural elements may also vary. A review of the earlier classical optimization solutions carried out on these types of problems was given by Topping [2] and later by Suzuki and Kikuchi [3].

The earlier works conducted on structural optimization using a genetic algorithm (GA) concentrated on truss structures. Rajeev and Krishnamoorthy [4] used a simple GA to optimize the size of a space truss. They however did not use a mutation operator and found the solution to be very slow. Adeli and Cheng [5] used concurrent genetic algorithms to improve the optimization process of large structures. They also investigated the effects of the GA population size on the convergence rate of optimization. Later, Adeli and Kumar [6] adopted a distributed genetic algorithm for optimization of large space structures on a cluster of workstations connected via a local area network.

The first application of GA to size optimization of frame structures is attributed to Camp et al. [7]. They investigated the effects of different penalty functions as well as the GA operators including selection, crossover and mutation on the accuracy and rate of convergence of the optimization process. They also compared the results of GA optimization of frames and trusses with those of an optimality criteria optimization method and concluded favourable results. Mahfouz et al. [8] and Torpov et al. [9] also studied the influence of different GA parameters on the solution performance. They adopted a modified GA to treat optimization of 2D and 3D steel framed structures. In their modified GA, an intelligent initialization procedure was used to increase the rate of solution convergence. In another study, Erbature et al. [10] introduced a multi level optimization to reduce the solution time. In this method, after the first global design process, the frame is divided into a number of sub-structures so that the optimal search could be carried out in smaller search spaces. The only GA optimization of bracing design reported in the literature was carried out by Kameshki and Saka [11]. They searched for the optimal type of bracing from amongst the common types to account for both the serviceability and strength constraints in tall 2D frames. They found the X-bracing to be more suitable than some other types of bracing.

Topology optimization of framed structures has also attracted some attention in recent years. Mijar et al [12] carried out a continuum topology optimization for 2D braced frames. They modelled the spaces between the discrete frame members as variable continuums with fixed thickness, shape of which could change for an optimized solution of the frame. They found that the optimal shape of these continuums represented partial or global bracing of the frame by X-bracing. Fernandes et al. [13] also presented a computational model for the continuum topology optimization of a 3D linear elastic structure. In another study, Ellis et al. [14] searched for optimal brace types and positions in latticed structures. The objective functions in the study were minimization of structural weight and maximization of energy absorption. They found that a diamond type bracing configuration produced the most favourable result for the type of structures under consideration.

All the above studies on topology optimization had followed formal mathematical programming techniques. Steven et al. [15], on the other hand, used a heuristic, evolutionary algorithm for the size and topology optimization of discrete structures. They, however, did not directly address the topology of braces in the frames. They concluded that their evolutionary structural optimization could be suitable for a full range of structural situations. In the present paper, a different heuristic approach, in the form of a simple genetic algorithm, is used to directly explore the optimal positions of X-braces in 2D steel frames. The GA optimization process is helped by the added heuristic operator of graph connectivity.

2. OPTIMIZATION PROCEDURE

The main procedure adopted for GA topology optimization of braces in steel frames, follows the simple genetic algorithm. The choices for necessary functions and operators are however different for the problem at hand. These are discussed below.

2.1 Objective Function, Constraints and Penalty Function

In topology optimization of bracing in steel frames, the objective function may be considered as the minimization of the weight, W, of the frame-brace system, subject to problem constraints.

$$\text{Minimize}: W = f(x) \tag{1}$$

The dependent problem constraints for this class of problems may include; the total drift of the frame (δ), column uplift force (T), the number of braced panels (N) and the architectural limitations. i.e.

$$\begin{gathered} \delta(x) \leq \delta_{allow} \\ T(x) \leq T_{allow} \\ N_L \leq N \leq N_U \end{gathered} \tag{2}$$

In Eqn. 2, δ_{allow} and T_{allow} are the allowable drift and uplift, respectively and N_L and N_U are the lower and upper limits of the number of braced panels.

Since most optimization methods, including the GA optimization, are only capable of solving unconstrained problems, the problem should first be unconstrained. An external penalty function method is here used to un-constrain the problem. In this method, an appropriate penalty, proportional to the violation of each constraint, is added to the objective function. The unconstrained objective function (Q) considered for this study, is therefore of the following form;

$$Q = W + r_p \sum_{i=1}^{n} (\max\{0, (\frac{g_i}{g_{i\ allow}} - 1)\})^2 \tag{3}$$

in which, g_i are the constrained problem variables, $g_{i_{allow}}$ are the allowable limits of the constraints and r_p is the penalty coefficient. A value of 0.1 is assigned for the penalty coefficient throughout this study. The number of braced panels, as an independent constraint, is imposed separately on the problem. In this study, it is assumed that at least one panel in each storey of the frame will be braced. No upper limits are however imposed on the number of braced panels. Also, an architectural constraint is imposed on the problem. The architectural constraint simply allows the user to specify the panels that, for architectural reasons, can not be braced.

2.2 Initialisation and Coding

To initiate the optimization procedure, an initial population is selected. The population can be selected randomly. Alternatively, a more intelligent selection can be carried out. In this study, the initial population consists of frames that in each storey one, randomly selected panel is braced. The problem variables are stored in binary format in a GA string. Identical number of bits is used to represent each variable. Each bit represents one panel of the frame; therefore, the length of the GA string equals the number of panels in the frame.

2.3 Analysis and Design

After generating the members of the initial population, each member is decoded and the corresponding braced frame recreated. Initial member sections are then assigned to the decoded frame and analyzed. The frame is then designed for the specified applied loads according to a specific code of practice and the new sections are used for the re-analysis of the frame. Considering that in this study the object is the topology optimization of the braces and not the section size optimization, three iterations are assumed to be sufficient for the required convergence. Also, the SAP-90 general-purpose structural analysis program was used for linear analysis of the frames and the AISC-ASD89 code of practice [16] was utilized for design of the frames.

2.4 Fitness, Selection, Crossover and Mutation

Using the results from the analysis of the final designed sections for each population member, the weight (W) and the dependent problem constraints (δ and T) are calculated and the fitness value of the member is determined. After evaluating the fitness values for all the members, selection of the parents for creating the next generation is carried out using the tournament selection procedure. The selected parents are then placed in the mating pool and the GA operators such as crossover and mutation are applied to the population of the pool. The first of these operators is the crossover which in turn works on two randomly selected members of the pool. In this work, 1 to 5 points crossover operators are used. After the creation of two new members from the selected parents, mutation is applied to a selected small fraction of the new members.

2.5 Heuristic Graph Operator

To increase the convergence rate of the GA optimization, in this study a heuristic operator is applied using the 'Graph Theory'. Graph theory is a branch of applied mathematics with applications in optimization problems (Kaveh [17]). According to the connectivity theorem in graphs, a grid consisting of linear members joined at pin nodes in rectangular forms can only be rigid if its corresponding graph is connected. Previous works on 2D braced frames have shown that if the bracing pattern in the frame follows the corresponding connected graph for that frame, that frame-brace system will be stiffer than most frames having other bracing patterns (Kaveh [18], Narsingh [19]). In this study, the graph theory is used as a heuristic operator with a small probability of 1% to 10%. This operator controls the corresponding graph for the given frame-brace system and if the graph is not connected carries out minimal necessary changes to make the graph connected. This operator, in effect, works as an 'intelligent' mutation operator.

The above process is repeated on the new generation and the generations after that until the algorithm converges to an optimum solution. The convergence criterion adopted for this study is the satisfaction of one of the following three conditions; (i) the number of generations reaches a user specified value, (ii) the best member of the population remain unchanged in a user specified number of generations and (iii) the fitness value of the best member of the population has a small, specified variation compared to the average fitness values of the members of that population.

3. OPTIMIZATION EXAMPLES

To verify the ability of the GA optimization procedure outlined above to optimize the brace topology in frames a total of six, 2D frames of different heights and widths were selected. The frames, which fall in the category of short to medium height, include; 4-storey, 8-storey and 12-storey frames having 3 bays and 6 bays. All the six frames have identical frame panel dimensions of 3m x 4m. The brace topologies of the frames were first optimised without imposing any architectural limitations on the frames. Two, 4-storey, 3-bay and 4-storey, 8-bay frames were then optimised considering certain architectural limitations. A discussion on the results of these optimization examples follows.

3.1 Optimization Without Architectural Limitations

The history of GA optimization for the 4-storey, 3-bay frame during 18 generations is shown, along with the optimal brace topology, in Figure 1. The figure indicates the convergence of the optimization solution after 16 generations. This convergence corresponds to a heuristic graph operator of 8%. In order that the effect of the graph theory as a heuristic operator on the rate of convergence of the optimization could be studied, this frame was also optimized with the heuristic operator assuming values of 0% (without the operator), 3% and 5%. The solution converged after 31 generations, 24 generations and 16 generations, respectively. These results indicate the efficiency of the operator in increasing the convergence rate of optimization. The optimal weight of the frame after 18 generations and the corresponding total drift for the optimum brace topology are given in Figure 2. Also shown in this figure for comparison are the weight and total drift calculated for two conventional bracing patterns. This figure indicates that over 5% reduction in weight and 8% reduction in drift are achieved by GA topology optimization when compared with the best conventional brace topology.

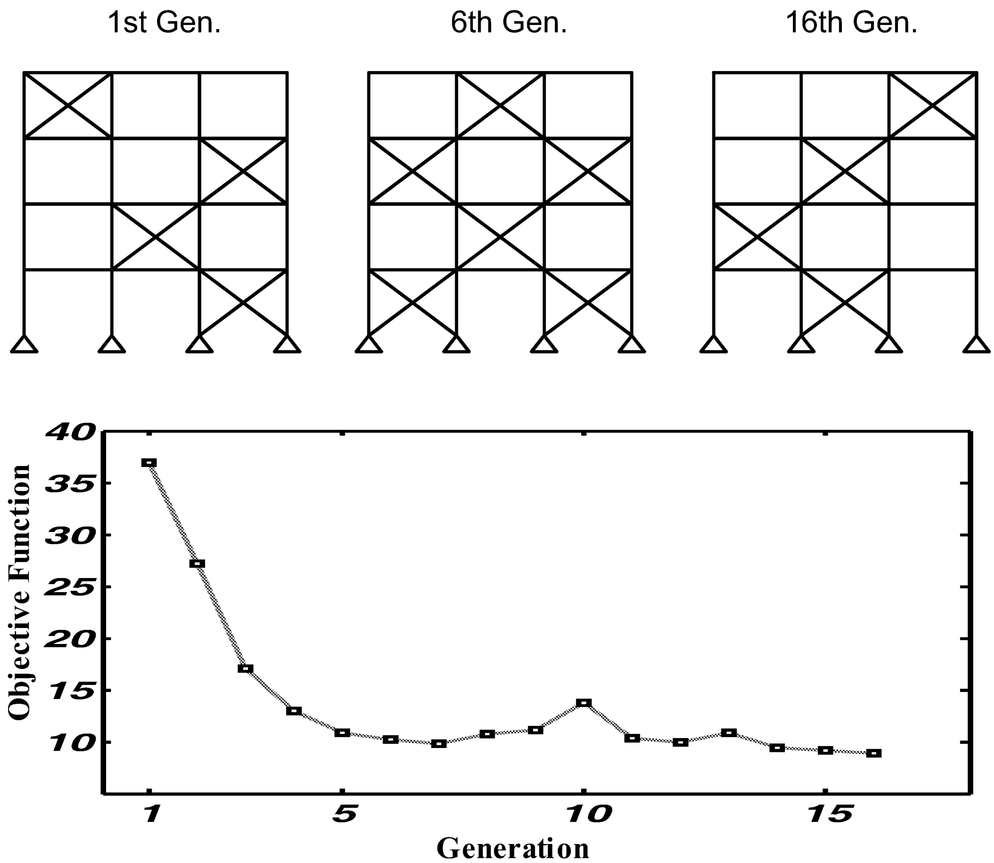

Figure 1. GA Optimization Trend and the Optimal Brace Topology for the 4-storey, 3-bay Frame

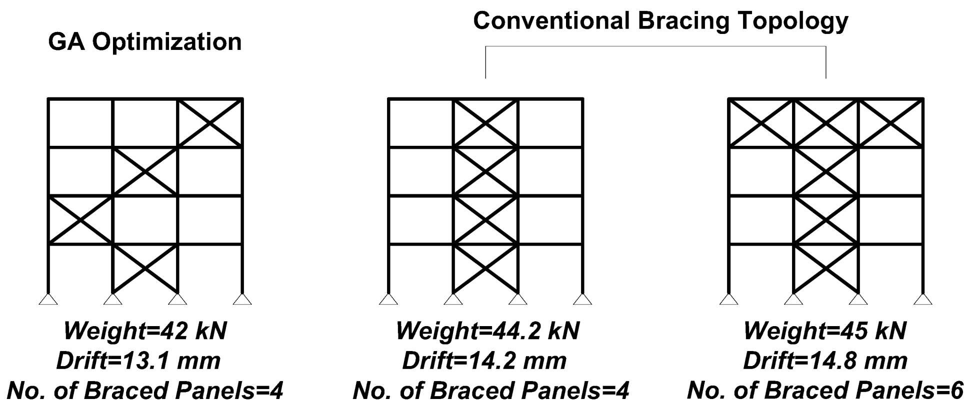

Figure 2. Comparison between Results of GA Optimization for
the 4-storey, 3-bay Frame and Two Conventional Brace Topologies

In Figure 3, the history of optimization for the 4-storey, 6-bay frame through 30 generations is presented. A good rate of convergence may be noted for this example. When considering the results of GA optimization for this frame, it is noted that only 4 braced panels produce a frame with 10% less weight compared with a typical conventional brace topology, having 8 panels braced.

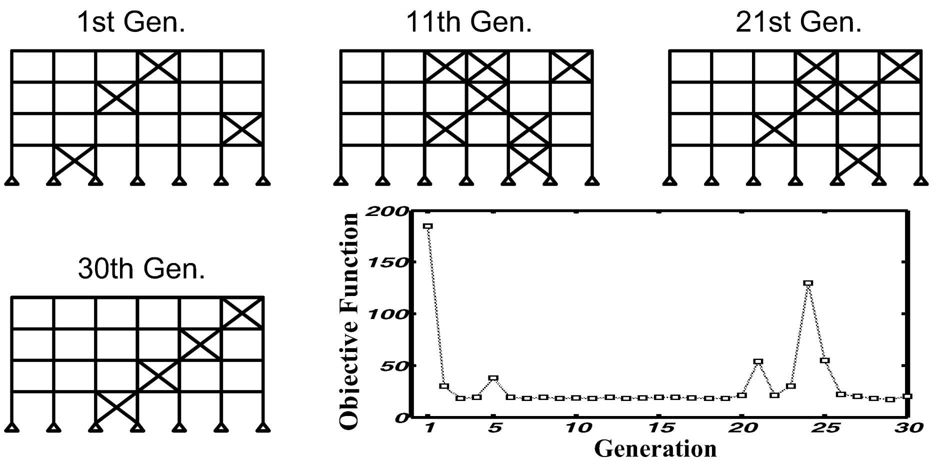

Figure 3. GA Optimization History and the Optimal Brace Topology for the 4-storey, 6-bay Frame

The optimization trend for the 8-storey, 3-bay frame was also evaluated and is presented in Figure 4. A fast rate of convergence is also achieved for this frame. Comparing the results of the GA optimal brace topology with those of a typical conventional topology for this frame having the same number of braced panels, show a 16.5% reduction in weight and 54% reduction in the total drift of the frame. A fast rate of optimization convergence was also noted for the 8-storey, 6-bay frame. In Figure 5, the results of GA brace topology optimization for this frame are compared with the results obtained from two conventional brace topologies for the same frame. The ability of the GA to reach for optimal brace topology is evident in this comparison. By using only half the number of braced panels in a GA optimization solution, 17% reduction in weight of the frame and 87% reduction in drift are achieved.

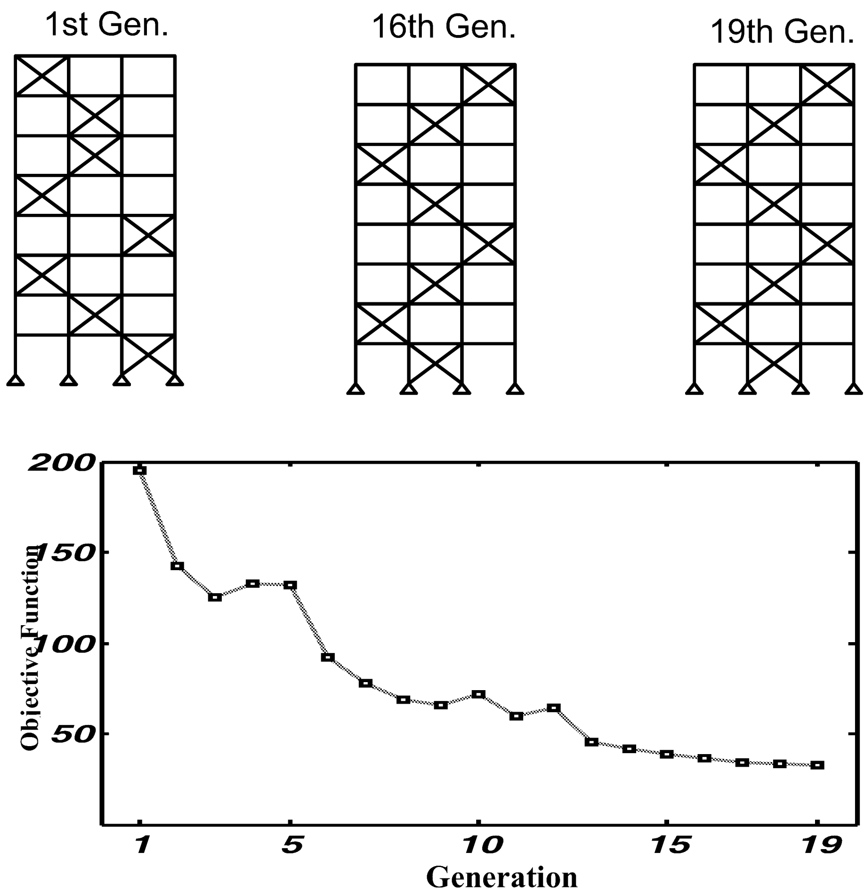

Figure 4. GA Optimization Trend and the Optimal Brace Topology for the 8-storey, 3-bay Frame

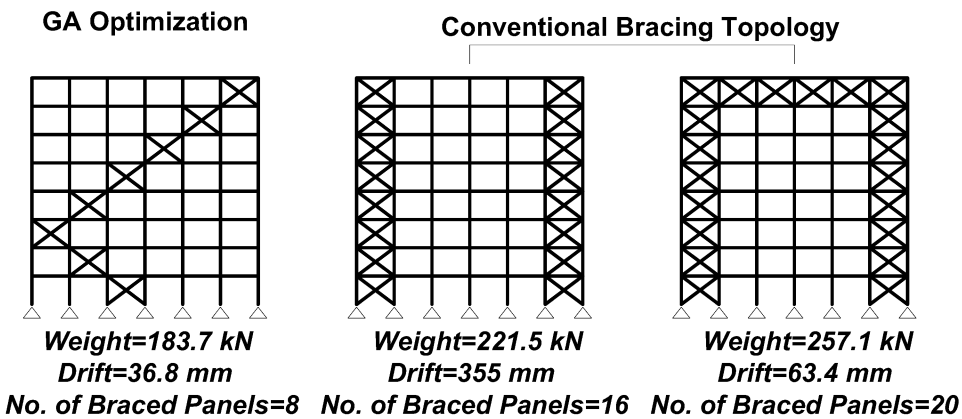

Figure 5. Comparison between Results of GA Optimization for
the 8-storey, 6-bay Frame and Two Conventional Brace Topologies

For the 12-storey, 3-bay frame, the optimal brace topology is obtained after 25 generations. The optimised topology and the history of optimization through 40 generations are shown in Figure 6. The weight and the total drift of the GA optimised frame show, respectively, over 20% and about

60% reductions when compared with a conventional brace topology, having the same number of braced panels, located in a central bay.

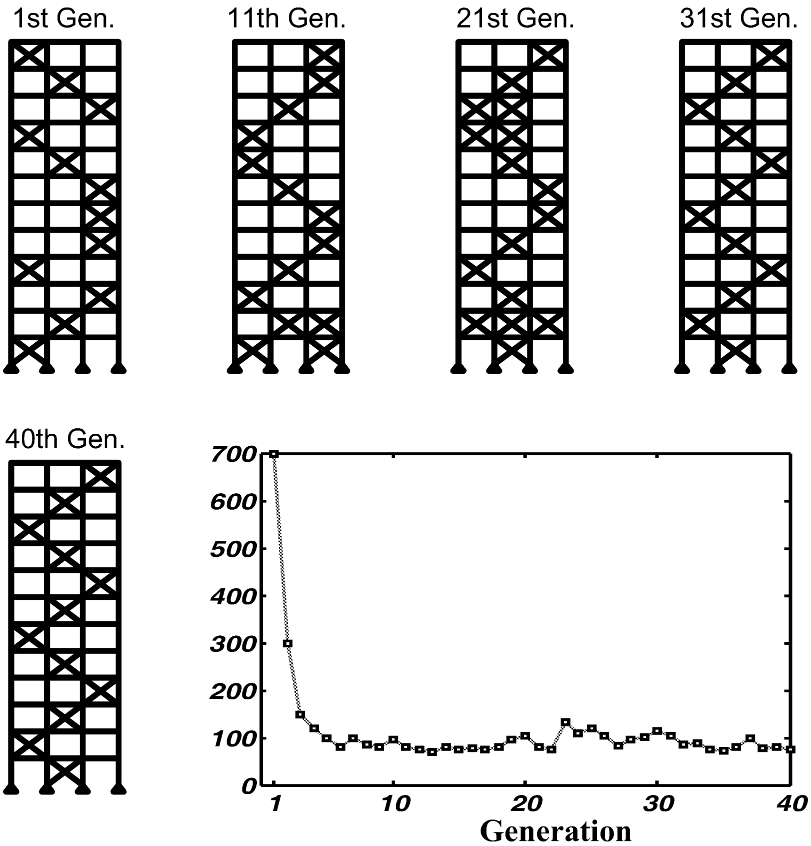

Figure 6. The GA Optimised Topology and the Optimization Trend for the 12-storey, 3-bay Frame

Finally, the brace topology in the 12-storey, 6-bay frame was optimised without considering any architectural limitations. Figure 7 shows the optimised topology together with the weight and maximum drift of the frame, compared with three conventional brace topologies for this frame. The GA optimised topology resulted in a lighter and stiffer frame with a smaller number of braced panels than all the conventional topologies considered. A notable reduction of 18.3% in weight and a larger reduction of 50% in drift are obtained when comparing the GA topology with the best conventional topology. It would be interesting to note that these reductions are achieved using only 18 braced panels in the GA topology as compared to 48 braced panels in the conventional topology.

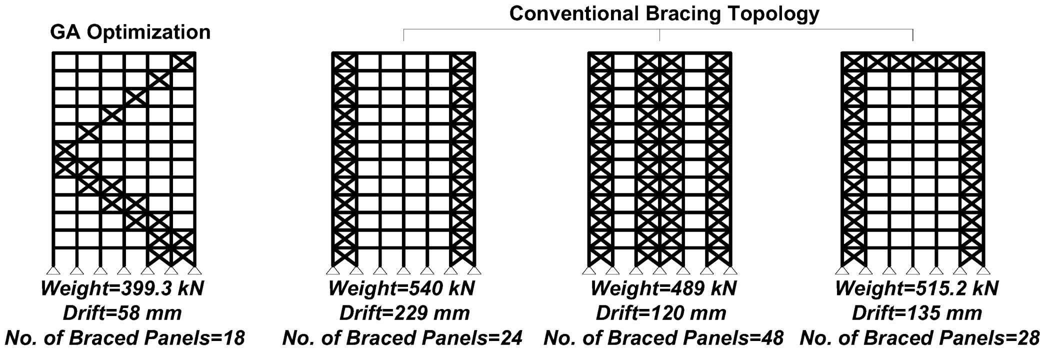

Figure 7. Comparison between Results of GA Optimization for the 12-storey, 6-bay Frame and Three Conventional Brace Topologies

The results of the above six examples of GA brace topology optimization, without architectural limitations are summarised in Table 1. The results clearly show the ability of the algorithm to produce optimal solutions with limited computational effort. In this respect, the use of graph theory as a heuristic operator has greatly enhanced the rate of solution convergence. It is also worth noting that the optimal GA solutions tend to favour continuous, diagonal, patterns of bracing as opposed to the accepted norms of column or capped-column patterns.

Table 1. Comparison between Results of GA Optimization and the Conventional Bracing Topology for Frames without Architectural Limitations.

Parameter	Method	Frame 1 (4 storey 3 bays)	Frame 2 (8 storey 3 bays)	Frame 3 (12 storey 3 bays)	Frame 4 (4 storey 6 bays)	Frame 5 (8 storey 6 bays)	Frame 6 (12 storey 6 bays)
Weight (kN)	GA	42.0	121.6	217.6	80.6	183.7	399.3
	Conventional	44.2	145.6	273.6	89.4	221.5	540.0
Drift (mm)	GA	13.1	44.8	85.0	15.6	36.8	58.0
	Conventional	14.2	97.4	210	25.0	355	229

3.2 Optimization with Architectural Limitations

One of the independent problem constraints considered for the GA brace topology optimization is the architectural limitation. The architectural constraint, specified as panels that for architectural reasons can not be braced, are often encountered in design of framed structures. To verify the ability of the GA optimization to accommodate this constraint, two frames, each assuming two different forms of architectural constraints, were optimised. The frames included the 4-storey, 3-bay frame of previous examples and a new 4-storey, 8-bay frame having similar frame panel dimensions of 3m x 4m. For the 3-bay frame, the first type of architectural constraint consisted of limiting the panels allowed to be braced to the two right hand bays. The GA optimization history through 30 generations and the optimal brace topology are shown in Figure 8. As expected, the solution convergence for this example appeared slower than for the same frame without the architectural convergence. It however produced an optimum solution within the 30 generations.

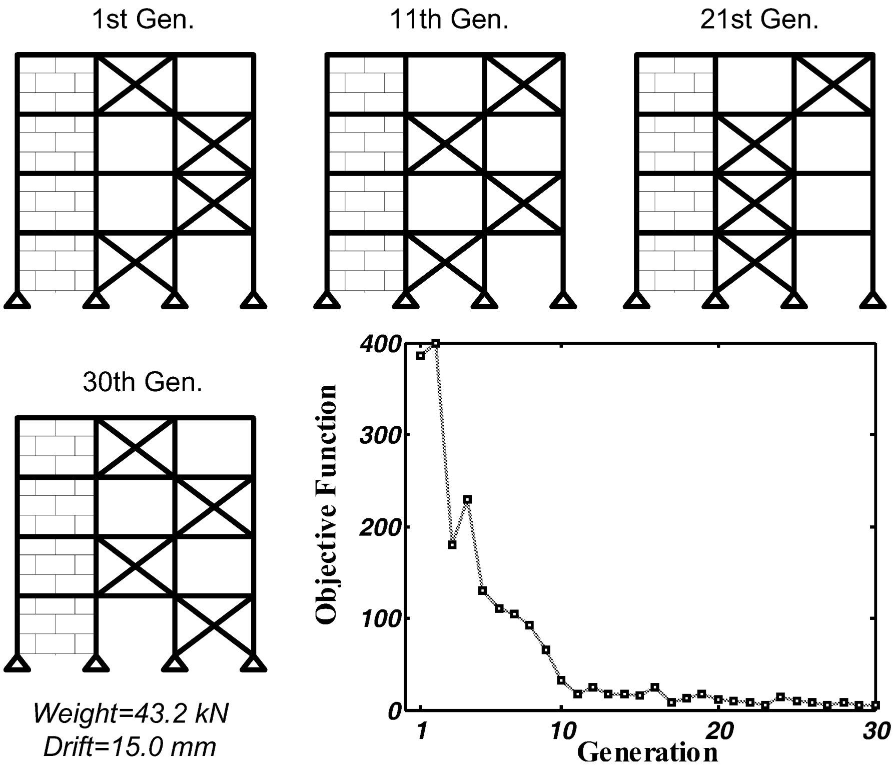

Figure 8. GA Optimization Trend and the Optimal Brace Topology for the 4-storey, 3-bay Frame with Type 1 Architectural Limitation

In the second type of the architectural constraint, the panels in the outer bays were allowed to be braced. Figure 9 shows that the optimal brace position for this example is reached after the 21^{st} generation. In Figure 10, the optimal results of the 4-storey, 3-bay frame with the two types of architectural constraints outlined above are compared with the results of the GA optimised brace topology and a conventional topology without architectural constraints. It can be seen in this figure that even with the imposition of the architectural limitation, the genetic algorithm is capable of producing brace topologies more favourable than the conventional brace topologies.

To verify further the ability of GA to produce optimal brace topologies for frames with architectural limitations, a 4-storey, 8-bay frame was also investigated assuming two different types of architectural constraints. The first type of constraint is shown in Figure 11 to be an outer bay. This figure also shows the optimization trend through 50 generations for this example. The optimal brace topology does not appear to be affected by this architectural limitation as it is similar to the brace topology obtained for the frame without limitation. Figure 12, shows the optimization history for the 4-storey, 8-bay frame having the second type of architectural constraint. As expected, the imposition of the constraints in a central bay has produced a slightly heavier and more flexible optimal solution compared with the first type of constraint. The results of the optimization of the above four frames with architectural limitations are also presented in Table 2.

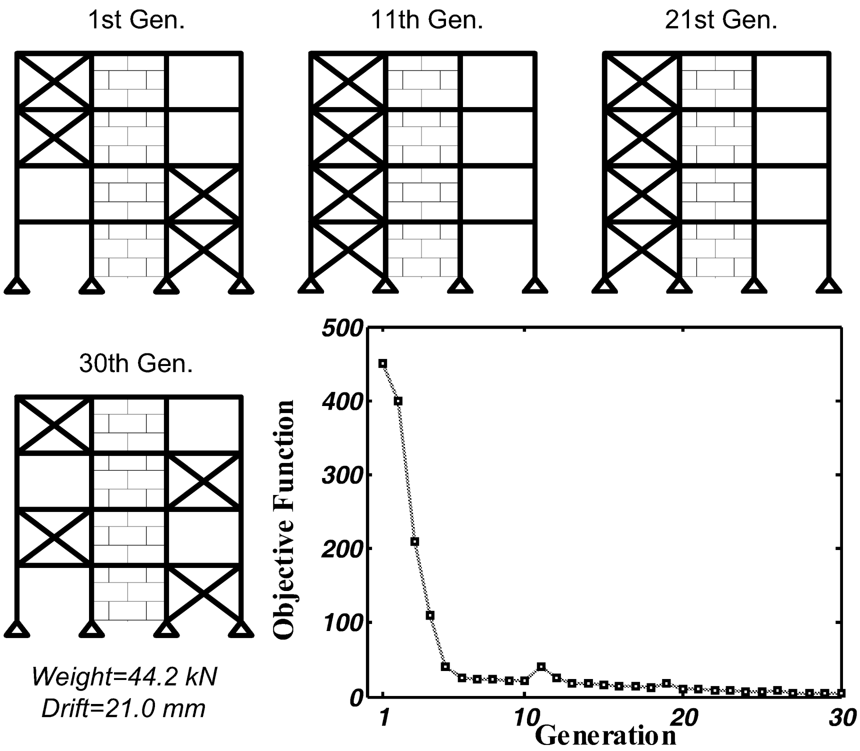

Figure 9. The Optimal Brace Topology and the Optimization History for the 4-storey, 3-bay Frame with Type 2 Architectural Limitation

Table 2. Results of the Optimised GA Brace Topology for Frames with Architectural Limitations

Frame	Weight (kN)	Drift (mm)
4-storey, 3-bay, (Arch. limit. type 1)	43.2	15.0
4-storey, 3-bay, (Arch. limit. type 2)	44.2	21.0
4-storey, 8-bay, (Arch. limit. type 1)	94.6	13.0
4-storey, 8-bay, (Arch. limit. type 2)	95.7	13.7

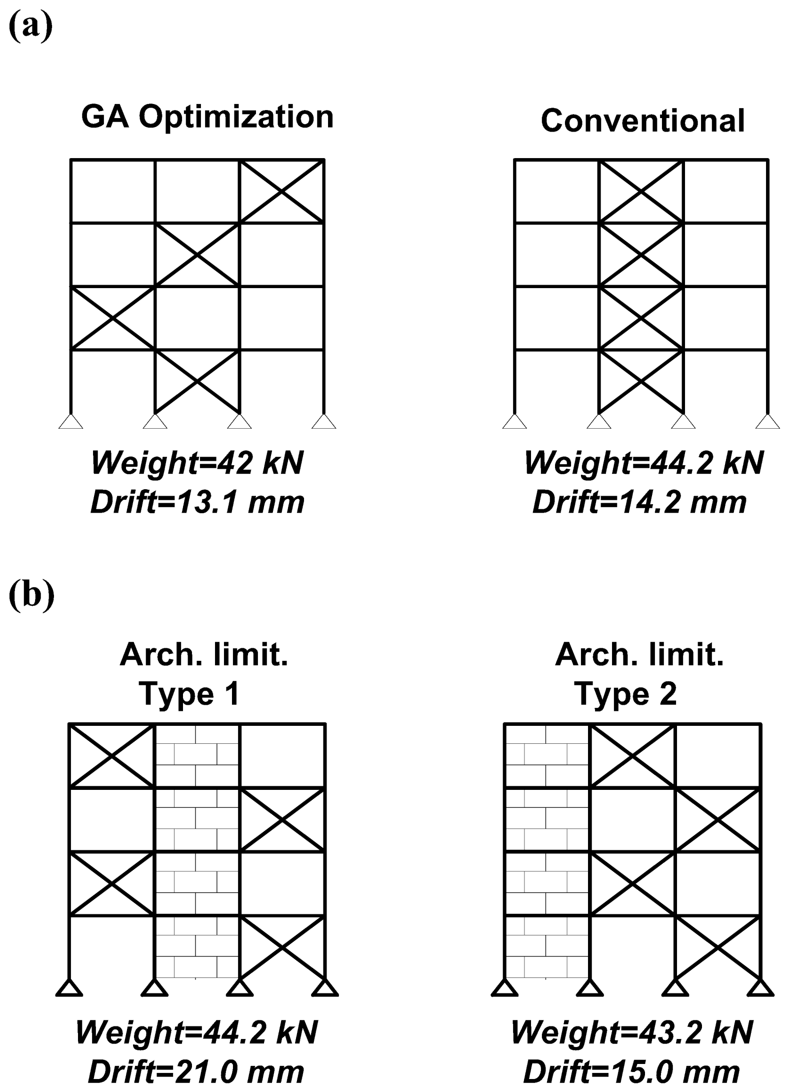

Figure 10. Comparison between Results of the 4-storey, 3-bay Frames
(a) Without Architectural Limitations and (b) With Architectural Limitations

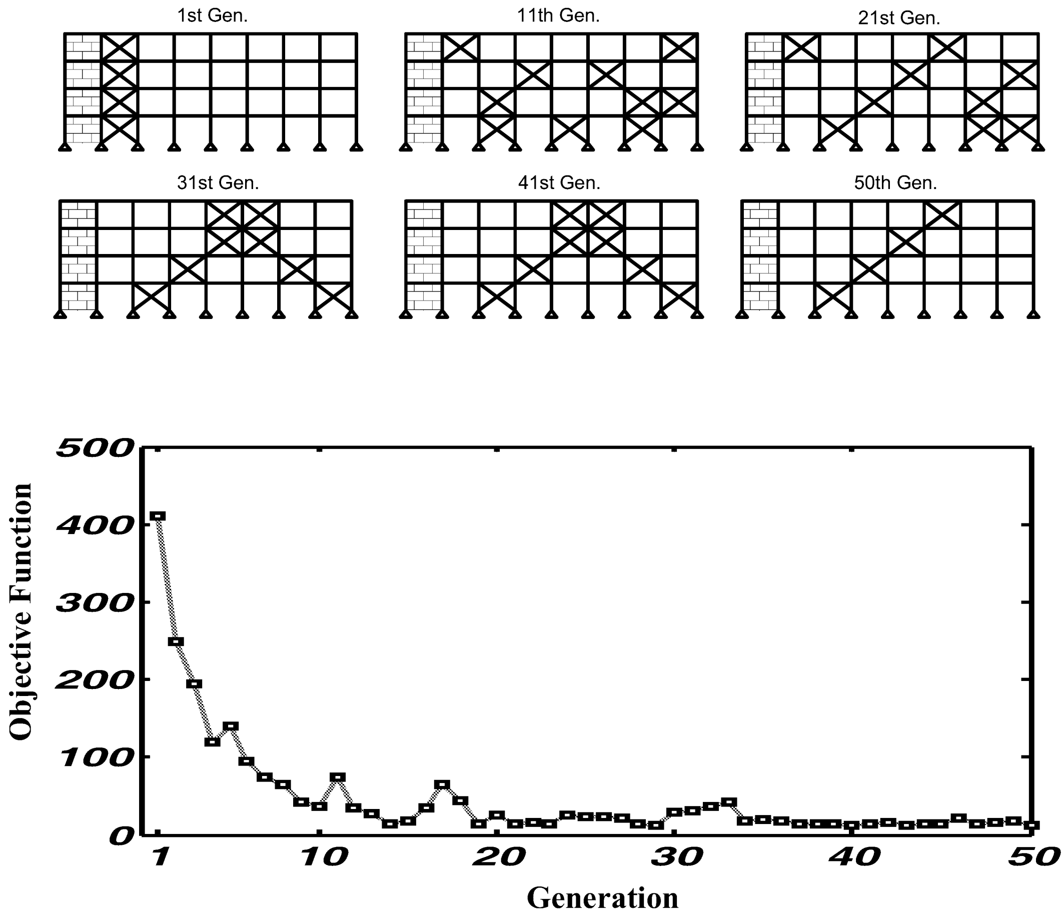

Figure 11. GA Optimization History and the Optimal Brace Topology for the 4-storey, 8-bay Frame with Type 1 Architectural Limitation

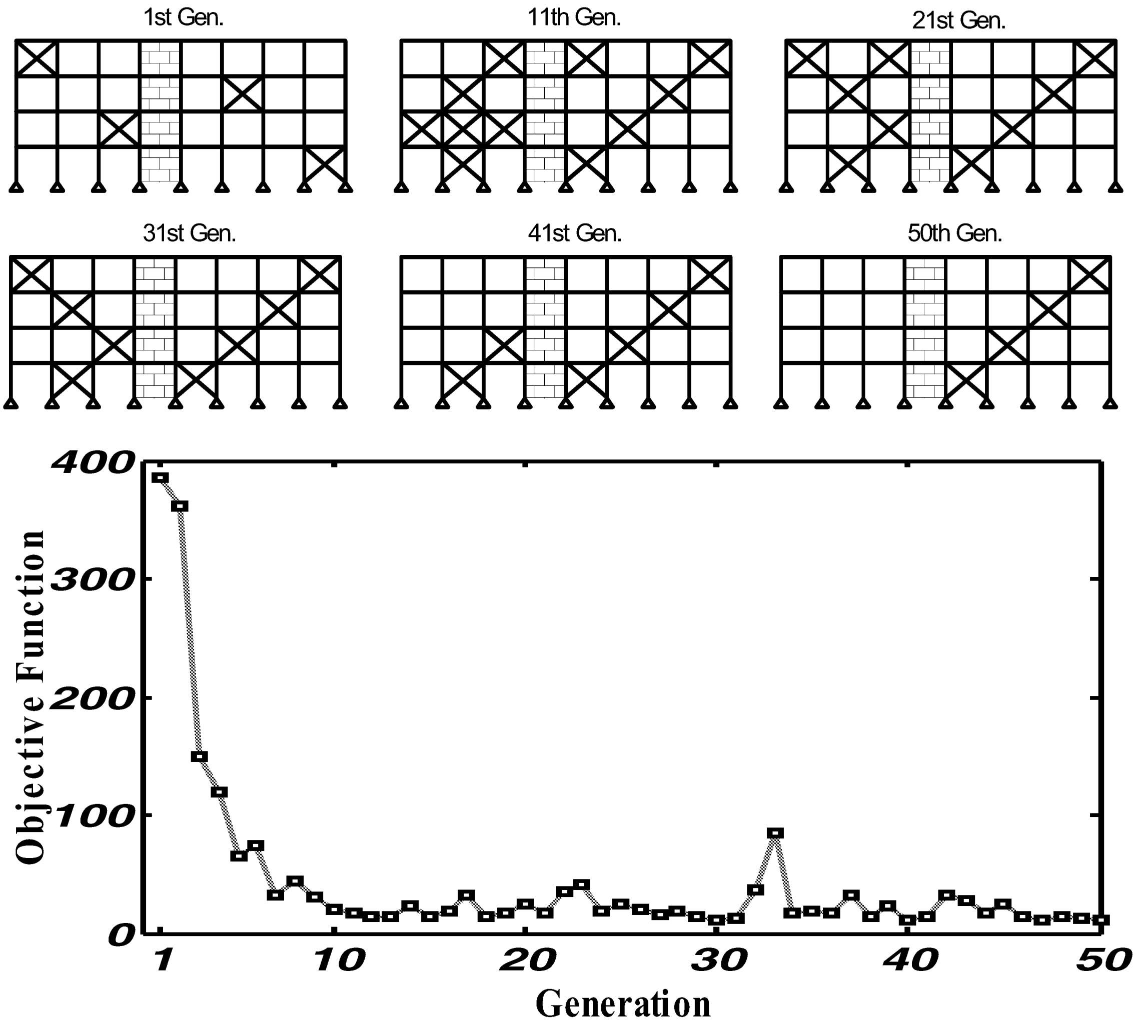

Figure 12. The Optimal Brace Topology and the Optimization Trend for the 4-storey, 8-bay Frame with Type 2 Architectural Limitation

4. CONCLUSIONS

A genetic algorithm with the aid of graph theory was successfully applied to obtain optimum brace topology for a number of 2D steel frames with and without architectural constraints. Conclusions drawn from this study are summarized as follows;

1. The use of graph theory as a heuristic operator greatly increases the rate of convergence of the brace topology optimization.

2. Large reductions in weight of the frame and its maximum drift may be achieved by using brace topologies produced by the GA optimization process presented in this paper. GA optimized brace topologies with limited number of braced panels invariably produced frames having considerably less weight and lateral drift compared to similar frames with conventional bracing topologies and larger numbers of braced panels. This was noted to be also true when certain

architectural limitations were imposed on the problem.

3. For all the frames analysed, a connected diagonal topology for the braces appears to be more suitable than the conventional column or capped-column patterns..

REFERENCES

[1] Maheri, M.R., Kousari, R. and Razazan, M., "Pushover Tests on Steel X-braced and Knee Braced RC Frames", Engineering Structures, 2003, 25, pp. 1697-1705.

[2] Topping, B.H.V., "Shape Optimization of Skeletal Structures: A Review", J. Struct. Engineering, ASCE, 1983, 109(8), pp. 1933-1955.

[3] Suzuki, K. and Kikuchi, N., "A homogenization Method for Shape and Topology Optimization", Comp. Methods in Appl. Mech. and Engrg., 1991, 93, pp. 291-318.

[4] Rajeev, S. and Krishnamoorthy, C.S., "Discrete Optimization of Structures Using Genetic Algorithms", J. Struct. Engineering, ASCE, 1992, 118(5), pp. 1233-1250.

[5] Adeli H. and Cheng N.T., "Concurrent Genetic Algorithm for Optimization of Large Structures" J. Aerospace Engineering, ASCE, 1994, 7(3).

[6] Adeli, H. and Kumar, S., "Distributed Genetic Algorithm for Structural Optimization", J. Aerosp. Engrg., 1995, 8(3), pp. 156-163.

[7] Camp, C., Pezeshk, S. and Cao, G.., "Optimized Design of Two-dimentional Structures Using a Genetic Algorithm", J. of Structural Engineering, 1998, ASCE, 124(5), pp. 551-559.

[8] Mahfouz, S.Y., Toropov, V.V. and Westbrook, R.K., "Modification, Tuning and Testing of a GA for Structural Optimization Problems", Proc. 1st AMSO UK/ISSMO Conf. on Engrg. Design Optimization, 1999, pp. 271-278.

[9] Torpov, V.V., Mahfouz, S.Y. and Westbrook, R.K., "Discrete Design Optimization of 3-dimensional Steel Structures Using a Genetic Algorithm", Proc. 3rd World Congress of Structural and Multidisciplinary Optimization Techniques for Engineering Design, Buffalo, NY., 1999.

[10] Erbatur, F., Hasancebi, O. Tutuncu, I. and Kilic H., "Optimal Design of Planar and Space Structures with Genetic Algorithms", Computers and Structures, 2000, 75, pp. 209-224.

[11] Kameshki, E.S. and Saka, M.P., "Genetic Algorithm Based Optimum Bracing Design of Non-swaying Tall Plane Frames", J. of Constructional Steel Research, 2001, 57, pp.1081-1097.

[12] Mijar, A.R., Swan, C.C., Arora, J.S. and Kosaka, I., "Continuum Topology Optimization for Concept Design of Frame Bracing Systems", J. Structural Engineering, ASCE, 1998, 124(5), pp. 541-550.

[13] Fernandes, P., Guedes, J.M. and Rodrigues, H., "Topology Optimization of Three-dimensional Linear Elastic Structures with a Constraint on Perimeter", Computers and Structure, 1999, 73, pp. 583-594.

[14] Ellis, J.S., Shyu, C.T. and Quenneville, J.H.P., "Latticed Mast Structures", J. Structural Engineering, ASCE, 1998, 124(2), pp. 203-206.

[15] Steven, G., Querin O. and Xie, M., "Evolutionary Structural Optimization (ESO) for Combined Topology and Size Optimization of Discrete Structures", Com. Methods in Appl. Mech. and Engrg., 2000, 188, pp. 743-754.

[16] "Manual of Steel Construction – Allowable Stress Design", American Institute of Steel Construction, Chicago, 1989.

[17] Kaveh A., "Structural Mechanics: Graph and Matrix Methods", Research Studies Press (John Wiley), Exeter, UK, 1992.

[18] Kaveh A., "Optimal Structural Analysis", Research Studies Press (John Wiley), Exeter, UK, 1997.

[19] Narsingh, D., “Graph Theory with Application to Engineering and Computer Science”, Prentice Hall. Englewood Cliffs, NJ, 1974.