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Towards Optimal Design of Steel - Concrete Composite Plane Frames using a Soft Computing Tool

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ABSTRACT

The use of steel – concrete composite elements in a multistoried building increases the speed of construction and reduces the overall cost. The optimum design of composite elements such as slabs, beams and columns can further reduce the cost of the building frame. In the present study, therefore, Genetic Algorithm (GA) based design optimization of steel concrete composite plane frame is addressed with the aim of minimizing the overall cost of the frame. The design is carried out based on the limit state method using recommendations of IS 11834, EC 4 and BS 5950 codes and Indian and UK design tables. The analysis is carried out using computer - oriented direct stiffness method. A GA based optimization software, with pre- and post-processing capabilities, has been developed in Visual Basic.Net environment. To validate the implementation, examples of 2 × 3 and 2 × 5 composite plane frames are included here along with parametric study.

Keywords - Composite plane frame, Genetic algorithm, Optimization, Soft computing

1. INTRODUCTION

The term "composite construction" is normally understood in the context of buildings and other civil engineering structures to imply the use of steel and concrete formed together into a component in such a way that the resulting arrangement functions as a single unit [1]. Such structural components have an ideal combination of strengths with the concrete being efficient in compression and the steel being efficient in tension.

A steel – concrete composite building may be considered as group of plane frames supporting composite slab with or without profile sheets. In columns of composite plane frames either Steel Reinforced Concrete (SRC) column, where a steel section is encased in concrete, or a Concrete Filled Tube (CFT) is generally used. Composite floor may consist of steel beams supporting concrete slab with or without profile sheets.

Cheng and Chan [2] have addressed the optimal lateral stiffness design of composite steel and concrete tall frameworks subjected to drift constraint and overall member sizing constraint. Genetic algorithm based optimum design method for multi-storey non-swaying steel frames with serviceability and strength constraints has been reported by [3]. Minimum cost design of steel frames with semi-rigid connections and column bases via genetic algorithm considering displacement, stress and member size constraints has been studied [4]. The main aim in the above reported applications has been to find the best solution to derive the maximum benefit from the available limited resources. The best design could be in terms of minimum cost, minimum weight or maximum performance or a combination of these.

Among the various available techniques, Genetic Algorithm [5] technique, which is based on the concept of the survival of the fittest, is the most adaptive technique to solve search and optimization problems. The availability of various options in composite structural components makes it lucrative to find the optimum shape and size of steel beam and composite column in steel concrete composite plane frame.

This paper is, therefore, devoted to the development of GA based optimization software for finding the optimum size of steel - concrete composite elements of a frame system. VB.NET environment is selected because it facilitates better user interface over the web, simplified deployment, a variety of language support and an extendable platform for the future portability of compiled application. In the optimum design of the composite plane frame, composite column section and beam section are considered as sizing variables and hence number of design variables equals to number of members in the plane frame geometry. One solution string of GA, thus contains section properties of all the beams and columns. The objective is to find the best possible combination of section properties of members so as to minimize the cost of the composite frame subjected to moment, shear, lateral torsional buckling and axial compression constraints.

Concrete encased UK and Indian steel sections and concrete filled hot finished hollow sections are used in the optimum design process in the present study. Analysis of composite plane frame has been carried out by stiffness member approach while the design has been carried out according to provisions of Euro code 4 [6] and IS: 11384 [7] code employing the limit state method of design. To validate the suggested concepts and implementation part of the software, it is used to find optimum cross sectional properties of members by trying varieties of available composite cross – sections stored in the database. The optimum design solutions provided by the software are compared with the results provided [8] for a two bay three-storey plane frame. Also, results of a parametric study carried on a 2 x 5 frame are presented followed by suitable recommendations for the practicing engineers.

2. Algorithm for a Composite Frame

The problem of size optimization of a composite plane frame can be defined as follows:

Find, (x)

To minimize, $C_T(x) = C_S + C_C$

Subject to, $gi(x) \leq 0$ … (1)

where, $C_T(x)$ is the total cost of composite frame, C_S is the cost of steel used in plane frame, C_C is the cost of concrete slab, x is the vector of design variables and gi(x) is the ith constraint function.

Genetic algorithm based optimum design algorithm [9] for steel concrete composite frames consists of the following steps:

(a) Initial population of trial design solutions is constructed randomly and the solutions are generated in binary coding form.

(b) The binary codes for the design variables of each individual solution are decoded to find the integer number which is assigned as an index to a composite section in the available design table list. The analysis by computer – oriented direct stiffness approach is carried out by extracting section properties of members of steel concrete composite frame, which represents an individual in the population. The analysis results are used for design and to evaluate constraint functions.

(c) The fitness value for each individual is calculated using

$$F(X) = 1/(1+Op(x)) \quad \dots (2)$$

with the penalized objective function Op(x) given by

$$Op(x) = (1+K^* C) O(x) \quad \dots (3)$$

where O(x) is the objective function which is the total cost of the frame, K is the penalty factor, and C is the cumulative value of constraint violation. The fitness thus obtained are scaled to get scaled fitness.

(d) Depending on scaled fitness, individuals are copied into the mating pool.

(e) The individuals are coupled randomly and the reproduction operator is applied. Using one- or two-point crossover, off springs are generated and the new population is obtained.

(f) Mutation is applied to the new population with a probability value between 0.01 and 0.07.

(g) vii. The initial population is replaced by the new population and steps (i) to (vi) are repeated until a pre-determined number of generations are reached or until the same individual dominates the new population. The fittest design among generations is considered to be the near-optimum design.

To ensure that the best individual of each generation is not destroyed from one design cycle to another, an 'elitist' strategy is followed in the design algorithm. At each generation, among the individuals which satisfy all the design constraints, the one with minimum weight is stored and compared with a similar individual of the next generation. If the new one is heavier than the old one then there is a loss of good genetic material. This situation is rectified by replacing the individual having the lowest fitness of the current generation with the fittest individual of previous generation. In this way the loss of good individuals during the development of new generations is prevented [3].

3. Design Variables and Constrains

A design variable is used for the composite beam which contains the details of steel section properties such as width of flange, depth of section, area of cross section etc. Another design variable is used for composite columns which represents column size and steel section details. A variable when decoded gives a unique integer number which helps in extracting the section properties from SQL server database.

In structural optimization problems, constraints are formed by setting relationship between function of design variables with the resource values, and constraints in the optimization process prevent the search to enter the infeasible region

3.1 Constraints imposed on composite beam

(a) Moment constraint: In ultimate limit state design the moment capacity of the composite beams should exceed the total factored applied moment (Narayanan et al. 2001) which can be written as

$$M_n \leq M_{pn} \quad \dots (4)$$

$$M_p \leq M_{pp} \quad \dots (5)$$

$$M_{pn} = P_y \times Z_{px} + \frac{A_s f_{sk}}{\gamma_s}\left(\frac{D}{2} + a\right) - \left(\frac{A_s f_{sk}}{\gamma_s}\right)^2 / 4 t_w f_y / \gamma_a \quad \dots (6)$$

$$M_{pp} = \frac{A_a f_y}{\gamma_a}\left(\frac{D}{2} + h_c - \frac{X_u}{2}\right) \quad \dots (7)$$

where M_{pn} and are negative and positive plastic moment of resistance of the section of the composite beam respectively, Mn is factored design negative moment and Mp is factored design positive moment. Corresponding functions for this constraint are:

$$g_1(x) = \text{Max}((M_n / M_{Pn} - 1), 0) \quad \dots (8)$$

$$g2(x) = \text{Max}((M_p / M_{Pp} - 1), 0) \quad \dots (9)$$

(b) Shear force constraint: This constraint ensures that the shear capacity of the frame member is more than the actual load induced in the member. The constraint for member is considered as,

$V \le V_P$ … (10)

$V_p = 0.6 \times D \times t \times \frac{f_y}{\gamma_a}$ … (11)

where V is the factored shear force and Vp is the plastic shear capacity of beam. The associated constraint function is given by,

$g_3(\mathbf{x}) = \mathrm{Max}\left((V / V_p - 1), 0\right)$ … (12)

(c) Lateral torsional buckling constraint: This constraint ensures that the capacity of frame member is more than the actual torsion moment induced in the member and is written as,

$M \le M_b$ … (13)

$M_b = x_{LT} \beta_W Z_{px} \frac{f_y}{\gamma_m}$ … (14)

where M is the negative moment at construction stage and M_b is the design buckling resistance moment of a laterally unrestrained beam. The associated constraint function is has the form,

$g_4(\mathbf{x}) = M_{ax}\left((M / M_b - 1), 0\right)$ …(15)

3.2

onstraints imposed on composite column

(a) Axial compression constraint: In ultimate limit state design the compression capacity of a composite column should exceed the total factored applied axial compression force. The corresponding constraint function is written as,

$P < \chi$ Pp … (16)

$P_p = A_a{*}f_y / \gamma_a + \alpha_c {*}A_c {*}(f_{ck})_{cy} / \gamma_c + A_s {*} f_{sk} / \gamma_s$ …(17)

where P is the axial force, χ is a reduction factor for column buckling and Pp is a plastic resistance to compression of the cross section. The constraint function can be written as,

$g_1(\mathbf{x}) = M_{ax}\left((P / (\chi P_p) - 1), 0\right)$ …(18)

(b) Moment constraint: In ultimate limit state design the moment capacity of the composite column should exceed the total factored applied moment and thus the constraint is written as follows:

$M \le 0.9\,\mu\, M_p$ …(19)

$M_p = p_y\,(Z_{pa} - Z_{pan}) + 0.5\, p_{ck}\,(Z_{pc} - Z_{pcn}) + p_{sk}\,(Z_{ps} - Z_{psn})$ …(20)

where μ = moment resistance ratio, M is the design bending moment and M_p is a plastic moment resistance of composite column. The design against combined compression and uni-axial bending is adequate if Eq. (19) is satisfied.

The constraint function for GA based search can be written as follows:

$g_2(\mathbf{x}) = M_{ax}\left((M / (0.9\,\mu\, M_p) - 1), 0\right)$ …(21)

4. Design Example Of A 2 X 3 Storey Composite Frame

A problem of two-bay, three-storey composite portal frame with fixed support is under taken. The gravity loads at construction stage and composite stage are as shown in Figs. 1 and 2 respectively. The design and GA data are listed below followed by the output given by GA based optimization program.

Geometry data

- Number of bays in horizontal direction = 2
- Number of Storeys = 3
- Storey height = 3 m
- Span of beam = 6.6 m
- Slab thickness = 130 mm

Material data

- Grade of concrete = M 30
- Grade of steel = Fe 275
- Grade of reinforcement = Fe 415

Load data at serviceability limit state

- Dead load on the beam = 35.16 kN/m
- Live load on the beam = 14.84 kN /m

Load data at ultimate limit state

- Dead load on the beam = 49.224 kN /m
- Live load on the beam = 23.744 kN /m

Unit cost data

C Unit cost of steel = 32 Rs./ kg.
- Unit cost of concrete = 3000 Rs./ cum.

GA data

- String Length = 9
- Population size = 50
- Generation = 50
- Type of crossover = Single Point Crossover
- Crossover probability = 0.90
- Selection scheme = Roulette Wheel Scheme
- Mutation Probability = 0.07 with variable mutation.

Objective Function

Total cost of composite frame = Cost of beam + Cost of connector + Cost of column.

Output

Figure 3 shows the optimum design results obtained through GA based program.

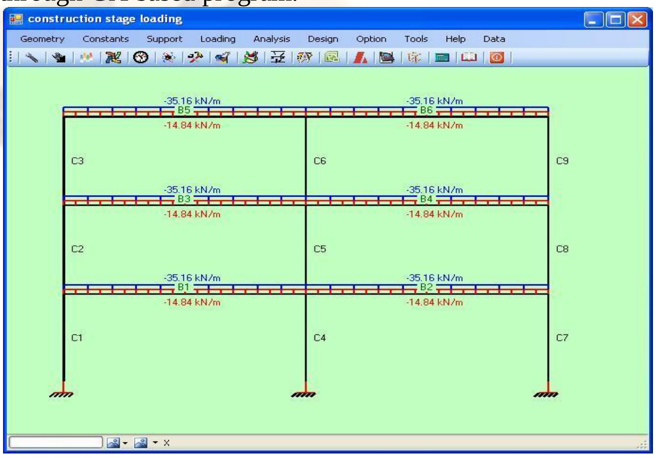

Fig. 1 Composite frame loading at construction stage

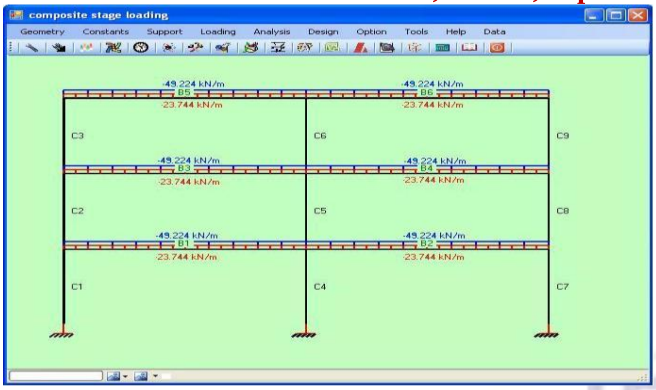

Fig. 2 Composite frame under loading at composite stage

Summary of the results obtained is as follows:

i. **Type of beam:** Structural steel beam with headed stud shear connector.
ii. **Size of beam :** All beam are of size 305 (depth) x 102 (flange width) mm x 33 kg/m.
iii. **Type of shear connector**– Headed stud of 12 mm diameter x 100 mm height.
iv. **Type of column:** Partial encased composite column.

Size of column: All columns are of size 203 x 203 mm concrete casing with 203 × 203 mm × 33 kg/m rolled steel I section.

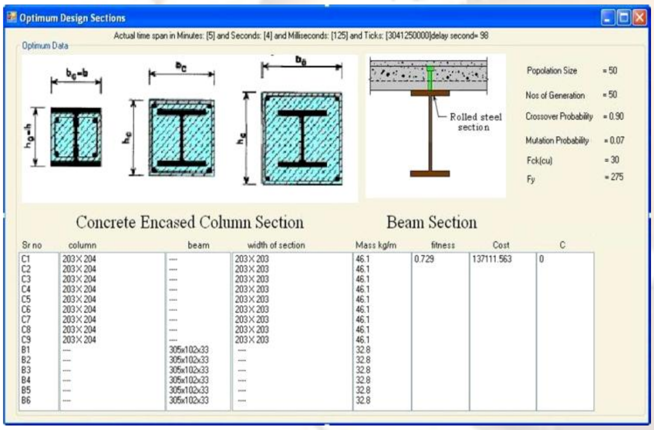

Fig. 3 Final results for a 2 bay × 3 storey frame

The final solution is obtained after 9 GA runs. The convergence of GA towards optimum solution is indicated by the graphs of generation versus fitness and generation versus cost as shown in **Figs. 4** and **5** respectively

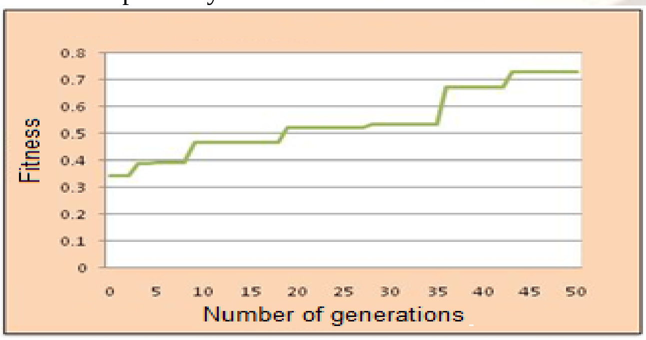

Fig. 4 Generation versus fitness grpah

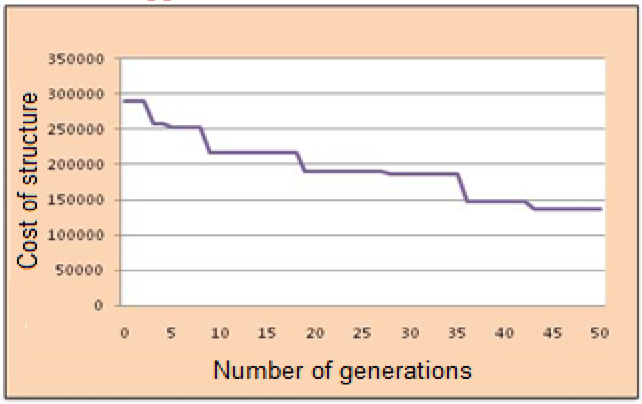

Fig. 5 Generation versus cost graph

The obtained results are compared in **Table 1** with those provided by [10].

Table 1 Comparison of Results for A 2 × 3 Storey Frame

Storey	Member	Composite Frame Section (Wang and Li 2000)	Composite Frame Section (Present Work)	% Saving in Weight
3rd	Beam	HN300x150x6.5x9 @ 36 kg/m	305 x 102 @ 32.8 kg/m	8.89
	Column	HW 250x250x9x14 @70.63 kg/m	203 x 203 @ 46.1 kg/m	34.73
2nd	Beam	HN300x150x6.5x9 @ 36 kg/m	305 x 102 @ 32.8 kg/m	8.89
	Column	HW 250x250x9x14 @ 70.63 kg/m	203 x 203 @ 46.1 kg/m	34.73
1st	Beam	HN300x150x6.5x9 @ 36 kg/m	305 x 102 @ 32.8 kg/m	8.89
	Column	HW 250x250x9x14 @ 70.63 kg/m	203 x 203 @ 46.1 kg/m	34.73

5. Design Example of a 2 x 5 Storey Composite Frame

A two-bay five-storey, fixed footed composite portal frame is selected here. Gravity loads acting on the frame at construction stage and composite stage are as shown in **Figs. 6** and **7** respectively. The optimum design of this frame is carried out five times by selecting different type of section every time. The following five sections are considered for optimum design:

- Fully encased Indian steel column section.
- Partially encased Indian steel column section.
- Square tubular section filled with concrete.
- Rectangular tubular section filled with concrete.
- Circular tubular section filled with concrete.

Geometry data
- Number of bays in horizontal direction = 2
- Number of storeys = 5
- Storey height = 3 m
- Span of beam = 7 m
- Slab thickness = 130 mm
- c/c distance between beams = 7 m

Load data
- Imposed load = 3.5 kN/m2
- Partition load = 1.0 kN/m2
- Floor finishing load = 0.5 kN/m2
- Construction load = 0. 5 kN/m2

Unit cost data
- Unit cost of steel = 32 Rs./kg
- Unit cost of concrete = 3000 Rs./cum

GA data
- String length = 9
- Population size = 50
- Generation = 50
- Type of crossover = Single point crossover
- Crossover probability = 0.90
- Selection scheme = Roulette wheel scheme
- Mutation probability = 0.07 with variable mutation

Material data
- Grade of concrete = M 30
- Grade of steel = Fe 250
- Grade of reinforcement = Fe 415

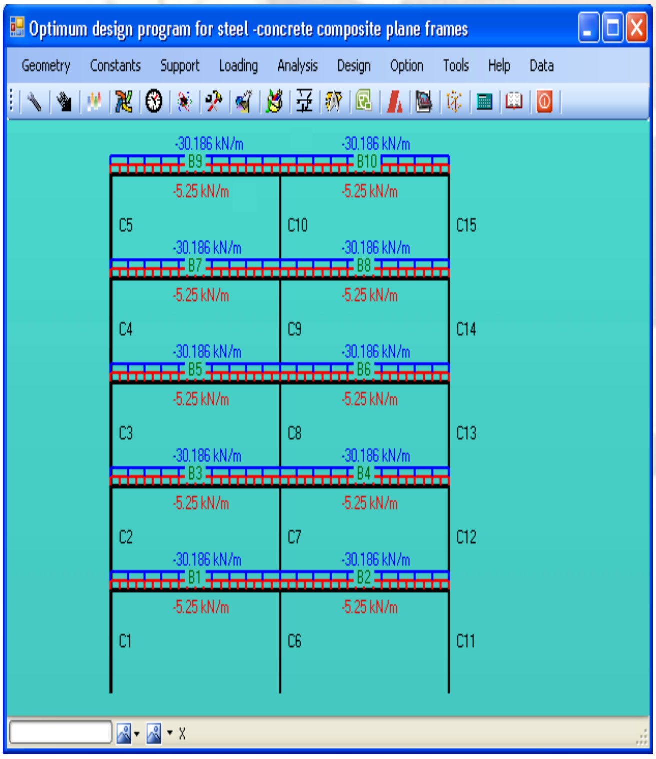

Fig. 6 Composite frame under loading at construction stage

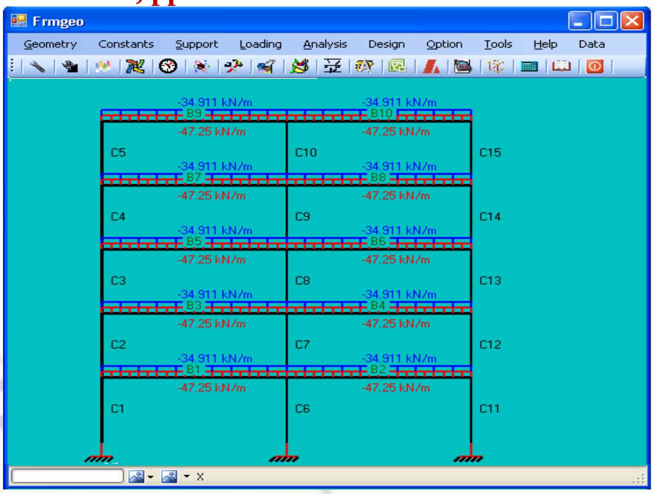

Fig. 7 Composite frame under loading at composite stage

Output

Figure 8 shows the output obtained by selecting fully encased Indian sections. The results derived from the program by selecting partially encased Indian sections are depicted in Fig. 9. The optimum concrete infilled hollow square, circular and rectangular sections obtained through the program are displayed in Figs. 10, 11 and 12 respectively.

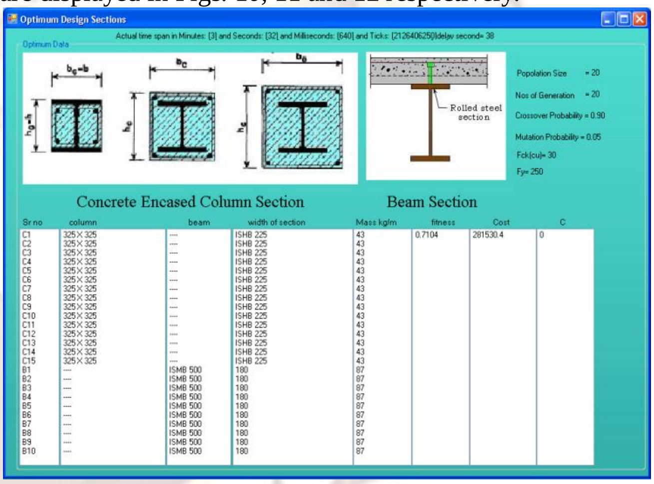

Fig. 8 Output for Fully Encased Sections

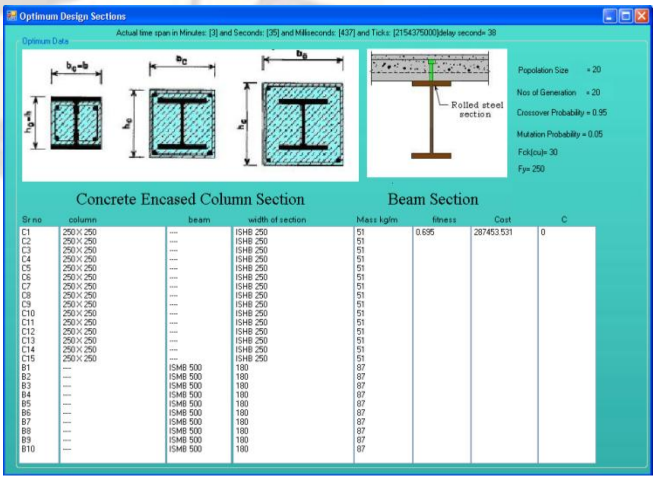

Fig. 9 Output for partially encased sections

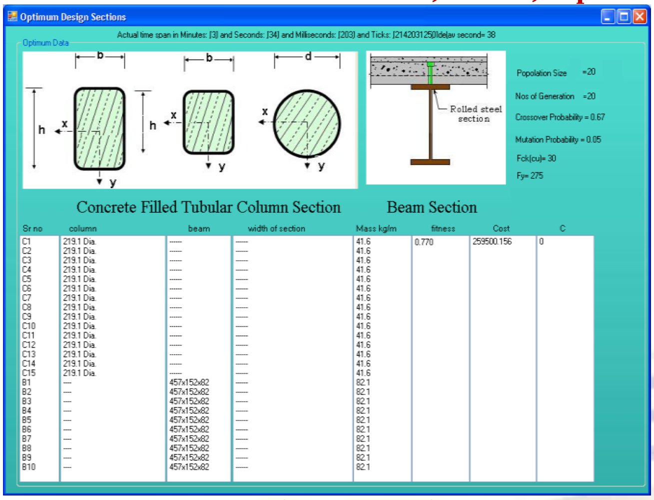

Fig. 11 Output for concrete filled hollow circular sections

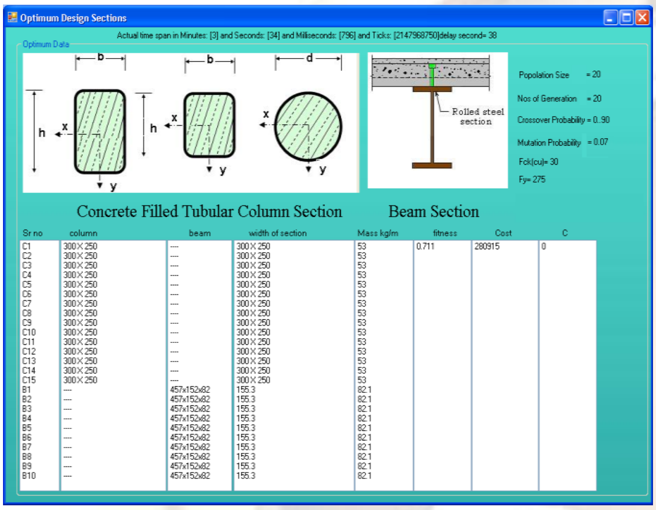

Fig. 12 Output for concrete filled hollow rect. sections

In optimization process, genetic parameters such as population size, number of generations, crossover probability and mutation probability play an important role. The final solutions are obtained after 4 to 8 GA runs for various composite sections. The relation between number of generations and time taken in optimization process is depicted in Fig. 13.

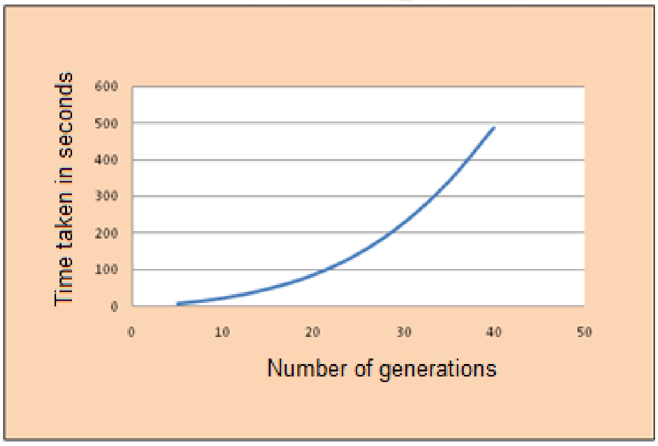

Fig. 13 Time taken in optimization process graph

Results of the parametric study are summarized here in TABLE 2 wherein total structural weight and overall cost (in Indian currency) for each type of section are mentioned.

Table 2 Weight and Cost Comparison of Composite Frame

Case	**Type**	**Steel (Kg)**	**Cost** (Rs.)
Case 1	Square concrete filled tubular column and beam section	7912	272035
Case 2	Circular concrete filled tubular column and beam section	7619	259500
Case 3	Rectangular concrete filled tubular column and beam section	8132	280915
Case 4	Fully encased Indian column and beam section	8025	281530
Case 5	Partially encased Indian column and beam section	8385	287454

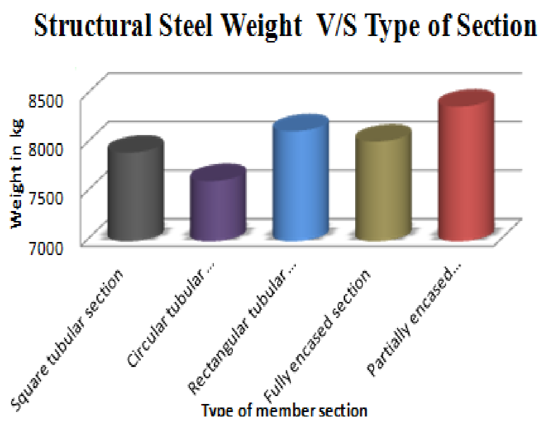

Fig. 14 Comparison of weight between types of sections

The comparison of structural steel weight versus type of section is shown in Fig. 14. It can be observed that the fully encased Indian steel section performs better than the partially encased one. In case of concrete filled tubular sections, concrete filled hollow circular section performed the best with steel weight of 7619 kg which is the minimum among the five types of sections considered here.

6. CONCLUSIONS

- Most classical methods do not have the global perspective and often get converged to a locally optimal solution whereas GA based soft computing tool is a global optimization method which can find new innovative designs instead of traditional designs corresponding to local minima. In the present work this soft computing tool has been used in conjunction with computer-oriented direct stiffness method for the development of GUI based software which is found to be quite attractive and effective. The first example of 2 x 3 frame has clearly indicated the benefits of using the present GA based optimization software in the design of composite building frames.
- Suitable selection of crossover and mutation probabilities in optimization problem is necessary to obtain new generation with better solution. After a number of trials, it is found that the crossover probability of 0.72 to 0.90 and mutation probability of 0.03 to 0.07 give quite satisfactory results.
- The developed menu-driven software is capable of finding the optimum solution for various types of composite plane frame problems and provides the generation history report automatically along with the optimum section details including the overall cost of structure. The software can be used for both symmetrical as well as unsymmetrical composite frames.
- From the parametric study, it is clear that the circular concrete filled tubular column section is more economical compared to other type of column shapes such as square concrete filled tubular section, rectangular concrete filled tubular section and fully as well as partially concrete encased sections. It is also found that the circular concrete filled in tubular column section is 4.60% more economical compared to the concrete filled square tubular column section. The circular concrete filled in tubular column section is found 7.62%, 7.82% and 9.72% more economical than the concrete filled in rectangular tubular column section, fully concrete encased section and partially concrete encased section respectively.

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