Investigating the Optimum Design of Steel Portal Frame Using Genetic Algorithms

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Abstract:
This paper presents a structural optimisation based on modified distributed genetic algorithm (DGA) as a family of parallel genetic algorithm. The technique is developed to deal with discrete optimisation of steel portal frame. In order to have a realistic design and imitate the displacement and strength limitations, the DGA has been linked to BS5950 code of practice. Although the appearance of steel portal frames is simple, many complicated limitations and different structural criteria which are considered in complex structures must be taken into account. As the behaviour of steel portal frames necessitates using universal beam for both column and rafter, the algorithm selects the universal beam cross-sections from a standard table given in code of practice. In addition, it determines the minimum length and depth of haunch satisfying the limitations in order to reduce the weight and reach the most cost-effective form. Formulation of the design is based on elastic method. The objective function is in terms of total weight of frame as it gives a reasonable accurate cost of frame. A pitched roof steel portal frame has been designed to check its practicability.

Keywords:
Steel Portal Frames, Optimisation, Distributed Genetic Algorithm

1. Introduction

Single storey buildings are widely used in the UK; it is estimated that 50% of the single storey steel work buildings are constructed by portal frames (Salter et al, 2004). Because of its economy and versatility for large spans in construction of pitched roofs like shopping centres, warehouses, retail shops, pools, factories, etc, the steel portal frame has become the most often used structure within this sector. Furthermore, those aforementioned places need to have a large span without using intermediate columns and therefore it necessitates using steel portal frames whereas the steel yields economical solution for large spans (Saka, 2003). A number of steel portal frames are commonly available of which the pitched roof type is more popular. The design of steel portal frames can be carried out using either elastic or plastic methods.
Any structural designer attempts to conduct an economical design. This can be achieved by formulating a design problem as an optimisation problem and solving by a systematic way of optimisation and considering the limitations of a code of practice to control the safety of the structure (Toropov and Mahfouz, 2001). However, due to large number of iterations in implementing the optimisation technique, it cannot be achieved by using the designer's experiences and intuition. Optimisation is a mathematical way to seek the minimum and

maximum of a certain function. As the major cost of structural steelwork is its own weight, it has been endeavoured to minimise the weight using a systematic way of optimisation. In general, optimisation technique in structural engineering can be categorised into three different approaches: 1) Mathematical programming, 2) Optimality criteria methods and 3) Heuristic search technique (Camp et al. 1998). During the past decades, the attempts have been made to use any of the three aforementioned methods, see for example the work of Rizzi (1976); Arora (1980); Allwood and Chung (1984); Lin and Liu (1989); Krisch (1991); Saka (1991); Chang (1992) and Rozvany & Zhou (1993). Heuristic search method became the best option for dealing with discrete design variables, (Camp et al. 1998). Genetic algorithm as a sort of heuristic search method has been added to the optimisation technique. Genetic algorithm is the strategy that models a genetic evolution (Holland, 1975; Goldberg, 1989). Its core characteristic is based on the simulation of Darwinian 'Survival of the Fittest' theory and adaptation. A remarkable advantage of genetic algorithm appears when it does not require an explicit relation between objective function and constraints while this relation has to be defined using the mathematical programming and optimality criteria method. Genetic algorithm has been successfully implemented in structural optimum design by many researchers during the earlier past decades including the work of Rajeev and Krishnamorthy (1992); Adeli and Cheng (1993, 1994); Adeli and Kumar (1995); Camp et al. (1998); Mahfouz (1999); Pezeshk et al. (2000); Kameshki and Saka (2001); Toporov and Mahfouz (2001); Foley and Schinler (2003); Balling et al. (2006) and Liu et al. (2007).

Genetic algorithm (GA) as a robust and efficient technique can achieve the aforementioned requirements. The simple genetic algorithm, however, has quite low speed process. Therefore, the author has attempted to modify the simple GA in order to accelerate its operation. In this paper a Distributed Genetic Algorithm (DGA) has been chosen to minimise the weight of the pitched roof steel portal frame satisfying the limitations given in BS 5950 code of practice. As the genetic algorithm is used for unconstraint problems, therefore a penalty is used to bring a constraint problem into unconstraint one.

The basic mechanics of the GA is based on randomised procedures of selecting and reproduction of the population of individuals and copying the fittest individuals into the next generation. A basic GA consists of three main operators; reproduction, crossover and mutation. In the reproduction stage, a set of population are selected for mating depending on their fitness value which represent the objective function including the penalty function for any violation of constraints.

2. Distributed Genetic Algorithm

In DGA, the performance of conventional GA is improved by some minor modifications in its main algorithm that leads to quicker convergence and higher searching capability compared to conventional GA (Starkweather et al. 1990; Mühlenbein et al. 1991).

The DGA adopted in this paper can be described according to the following steps:

1) The parameters of DGA are specified.
2) The initial population are randomly selected for each group of population.

3) The objective function of each individual design is calculated. This is achieved by analysing the frame using the selected design variables (area of the section) and checking the feasibility of each individual with the constraints. For any violation of the constraint, a penalty is imposed. The penalised objective function is calculated (PF_i).
4) The smallest and largest penalised objective function (PF_{min} & PF_{max}) are specified.
5) The fitness function is evaluated for each individual design applying the formula

$$FF_i = PF_{min} + PF_{max} - PF_i \qquad \text{Eq. 1(a)}$$

6) The average fitness value is calculated

$$PF_{av} = \frac{\sum_{i=1}^{PopNo} FF_i}{PopNo} \qquad \text{Eq. 1(b)}$$

7) The individuals whose fitness values are below the average one are killed.
8) For the survived population new largest value of the penalised objective function is found which is slightly above the average fitness value and the new fitness values are evaluated.

$$PF_i^{new} = PF_{smal} + PF_{l\arg e}^{new} - PF_i \qquad \text{Eq. 1(c)}$$

9) The probability of all the survived individuals are calculated using

$$P_i^{Surv} = \frac{FF_i^{new}}{\sum_{j=1}^{SurvNo} FF_j^{new}} \qquad \text{Eq. 1(d)}$$

10) Using the percentage of elitism, find the best individuals among the survived population of each group.
11) The rest of the population are undergoing the crossover operation whereas the increment rate is specified the number of offspring produced by crossover operation for each group of population.
12) For each defined interval of the generation, the migration is taken place. Relying on the rate of migration, the best individuals of the groups (except that group 1) are migrating to the first group.
13) The termination conditions are checked. In this study, three termination conditions are used and if any one of them is satisfied then the process terminates.
    a. If during the 30 successive generations the fittest individual are not changed or the difference between their fitness values are very small, then the termination will take place. The formula below shows the explicit relationship between the fittest individual, F^{GenNo} and a range of small value R^{GenNo}.

    $$\frac{F^{GenNo} - F^{GenNo-30}}{F^{GenNo}} \le R^{GenNo} \qquad \text{Eq. 1(e)}$$

    b. While the genetic process proceeds, the best individuals are about to be selected. That causes the average of the fitness value to converge the best fitness value. Therefore, it necessitates defining another termination condition in terms of average fitness value so that the difference ratio between the average fitness value and the best individual's fitness value is limited as R^{avg}.

    $$\frac{F^{GenNo} - F^{avg}}{F^{avg}} \le R^{avg} \qquad \text{Eq. 1(f)}$$

    c. When the maximum allowable number of generation is reached.

14) Each gen of the strings is mutated depending on the adopted probability.

$$P_m^{N_{Gen}} = P_m^{\min} + \frac{GenNo - N_{Gen}}{GenNo}(P_m^{\max} - P_m^{\min}) \qquad \text{Eq. 1(g)}$$

15) The step 3 to step 14 must be repeated until one of the termination condition achieves.

3. Analysis

The elastic analysis of the pitched roof steel portal frame was conducted using two different stiffness matrices. A conventional stiffness matrix was applied for the prismatic member and a derived stiffness matrix for non-prismatic member whereby the haunched rafter was analysed. The non-prismatic stiffness matrix was derived using the virtual work method and column analogous (Ghali et al. 2003). Virtual work was implemented to derive the axial stiffness coefficient. Whereas, column analogy was employed to derive the non-prismatic stiffness matrix for bending and shear effect. Accordingly, the axial stiffness coefficient is:

$$K = \frac{E}{2L}(A_1 + A_2) \qquad \text{Eq. 2}$$

while the stiffness matrix for shear and bending is (*EI* changes in terms of *x*):

$$[S] = \begin{bmatrix} \frac{E}{2L}(A_1+A_2) & 0 & 0 & -\frac{E}{2L}(A_1+A_2) & 0 & 0 \\ 0 & \frac{1}{\int \frac{x^2}{EI}dx} & \frac{L_1}{\int \frac{x^2}{EI}dx} & 0 & -\frac{1}{\int \frac{x^2}{EI}dx} & \frac{L_2}{\int \frac{x^2}{EI}dx} \\ 0 & \frac{L_1}{\int \frac{x^2}{EI}dx} & \left(\frac{1}{\int \frac{1}{EI}dx} + \frac{L_1^2}{\int \frac{x^2}{EI}dx}\right) & 0 & -\frac{L_1}{\int \frac{x^2}{EI}dx} & \left(-\frac{1}{\int \frac{1}{EI}dx} + \frac{L_1 L_2}{\int \frac{x^2}{EI}dx}\right) \\ -\frac{E}{2L}(A_1+A_2) & 0 & 0 & \frac{E}{2L}(A_1+A_2) & 0 & 0 \\ 0 & -\frac{1}{\int \frac{x^2}{EI}dx} & -\frac{L_1}{\int \frac{x^2}{EI}dx} & 0 & \frac{1}{\int \frac{x^2}{EI}dx} & -\frac{L_2}{\int \frac{x^2}{EI}dx} \\ 0 & \frac{L_2}{\int \frac{x^2}{EI}dx} & \left(-\frac{1}{\int \frac{1}{EI}dx} + \frac{L_1 L_2}{\int \frac{x^2}{EI}dx}\right) & 0 & -\frac{L_2}{\int \frac{x^2}{EI}dx} & \left(\frac{1}{\int \frac{1}{EI}dx} + \frac{L_2^2}{\int \frac{x^2}{EI}dx}\right) \end{bmatrix} \qquad \text{Eq. 3}$$

In the special case, when *EI* is constant, $L_1 = L_2$ and $A_1 = A_2$ then the stiffness matrix degenerate to what is used for the prismatic members.

4. Design to BS5950

BS 5950 states that when an elastic analysis is used for the design of steel framework such as the one shown in Fig. 1, the capacity and buckling resistance should be calculated. It is required to use the effective length equal to that between two intermediate restraints.

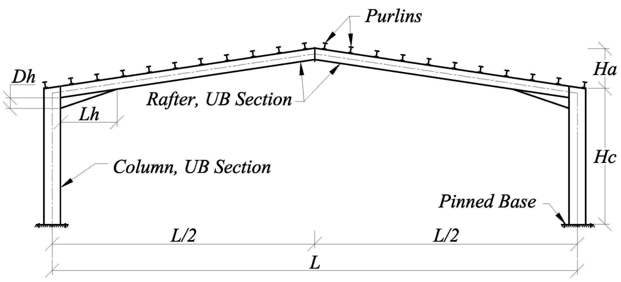

Fig. 1. Typical pitched roof steel portal

The members or portion of members restrained should satisfy the conditions to ensure the stability between two effective torsional restraints. For the prismatic members the following requirement should be satisfied:

$$\frac{F}{P_c}+\frac{mM_A}{M_b}\leq 1 \qquad \text{Eq. 4(a)}$$

and for the haunch part (i.e. non-prismatic member):

$$\frac{F}{A}+\frac{M}{S_x}\leq p_b \qquad \text{Eq. 4(b)}$$

5. Optimum Design

In the design of pitched roof steel portal frames, it is common to have the same universal beam section for the both rafters and a different universal beam sections for the columns. For the reason of economy, the same section of rafter is used to produce the haunch. Fig. 2 shows more details of the haunched rafter section. Therefore, the optimum design of the pitched roof steel portal frame necessitates using two design variables; one for rafter and its haunch and another for the columns. However, if it is necessary to use different section for the haunched section, the number of design variables increases to three. Moreover, due to the complexity of the design constraints in the formulation of the design problem only vertical gravity load is considered at this stage.

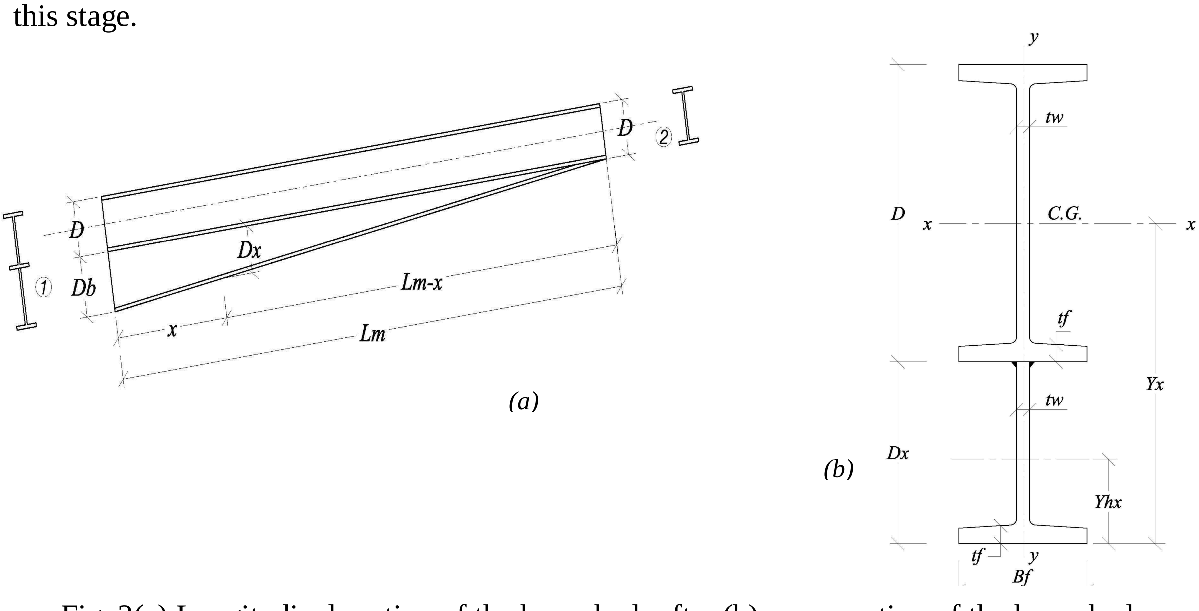

Fig. 2(a) Longitudinal section of the haunched rafter (b) cross section of the haunched rafter at the distance *x* from the near end (1) of the member

The design of pitched roof steel portal frame with haunched eaves when the objective is obtaining minimum weight and the constraints are implemented according to BS 5950 has the following form of formula:

Minimise $w = w_m + w_h = \sum_{i=1}^{GrNo} G_m \sum_{j=1}^{MemNo} L_w + \sum_{k=1}^{HauNo} H_w$ Eq. 5 (a)

Subjected to:

$\delta_i \le \delta_{iu}$ *i=1, 2, 3 …., JointNo* Eq. 5 (b)

$\frac{F_j}{A_{gj} p_y} + \frac{M_{xj}}{M_{cxj}} \le 1$ *j=1, . . . , MemNo* Eq. 5 (c)

$\frac{F_j}{A_{gj} p_{cj}} + \frac{m_j M_{xj}}{M_{bj}} \le 1$ *j=1, . . . , MemNo* Eq. 5 (d)

$\frac{F_k}{A_k} + \frac{M_k}{S_{xk}} \le p_b$ *k=1, 2, . . . , TapMNo* Eq. 5 (e)

$\frac{F_n}{P_{cn}} + \frac{\overline{M}_d}{M_{bn}} \le 1$ *n=1,2, … , UniMNo* Eq. 5 (f)

Eq. (5b) checks the displacement of the joints. BS 5950 has limited the horizontal displacement of the joints to column/300 and the upper limit of the beam deflection is span/360. Inequality (5c) defines the load capacity check for beam-column with semi-compact or slender cross section. Inequality (5d) is the simplified approach of the overall buckling check for beam-column. Inequalities (5e) and (5f) define the stability constraints for rafters and columns respectively where the compression flange is unrestrained.

The solution of the optimum design problem is given in Eq. (5a) necessitates selecting universal beam section from the table of standard section for rafters, columns and haunched section. This manipulates using the discrete design variables. Implementing mathematical programming on the discrete problems require discretising the problems which does not give an efficient solution and is somewhat cumbersome. Alternatively, genetic algorithm can handle with discrete design variable and can give the efficient optimum solution.

6. Solution by Distributed Genetic Algorithm

The optimisation of the pitched roof steel portal frame is based on distributed genetic algorithms. The individuals (design variables) are the area of the standard steel sections table. The author has decided to formulate the mutation probability (Eq. 1(g)) to check its suitability and effect on the convergence of the solution. The mutation probability was used as constant by researchers Adeli and Cheng (1993, 1994), Pezeshk et al. (2000) and Saka (2003, 2007). In addition, a probability has been given to produce the greater offspring than the usual by the same parents (Fig. 3, increment rate of population) to increase the number of population and likely get the best individuals in the earlier stage of the solution. As the DGA can only handle unconstraint objective function, a penalty function has to be introduced to include the constraints in calculations. There are different types of the penalty function which can be used in GA such as linear double segment, linear multiple segment and quadratic penalty functions (Adeli and Cheng, 1994). In this paper the transformation of the constraints given in Eq. 5 is based on the violation of the normalised constraints according to following rearrangement (Rajeev and Krishnamoorthy, 1992).

$$g_i = \frac{\delta_i}{\delta_{iu}} - 1 \le 0 \qquad i=1, 2, 3 \ldots., JointNo \qquad \text{Eq. 6(a)}$$

$$g_j = \begin{cases} (\frac{F_j}{A_{gj} p_y} + \frac{M_{xj}}{M_{cxj}}) - 1 \le 0 \\ or \\ (\frac{F_j}{A_{gj} p_{cj}} + \frac{m_j M_{xj}}{M_{bj}}) - 1 \le 0 \end{cases} \qquad j=1, \ldots, MemNo \qquad \text{Eq. 6(b)}$$

$$g_k = \frac{\frac{F_k}{A_k} + \frac{M_k}{S_{xk}}}{p_b} - 1 \le 0 \qquad k=1, 2, \ldots, TapMNo \qquad \text{Eq. 6(c)}$$

$$g_n = (\frac{F_n}{P_{cn}} + \frac{\overline{M}_d}{M_{bn}}) - 1 \le 0 \qquad n=1,2, \ldots, UniMNo \qquad \text{Eq. 6(d)}$$

The unconstraint function P is then constructed by adding the normalised constraints to the objective function as in the following

$$P = W\left(1 + C\sum_{m=1}^{ConNo} Z_m\right) \qquad \text{Eq. 7}$$

Where W is the objective function given in Eq. 5(a), C is a constant to be selected depending on the problem under consideration which for this study it is taken as 10 and Z_m is the violation coefficient determined as

$$\text{If } g_m > 0 \text{ then } Z_m = g_m \qquad \text{Eq. 8}$$
$$\text{If } g_m \le 0 \text{ then } Z_m = 0$$

Saka (2003) has designated C as 10 after several trials he carried out. The unconstraint function (Eq. 7) is used to obtain the fitness value of individuals according to the Eq. 1 (c). The chosen number of population for each group was found after several trials to be 30. The adopted number of group is 2.

For the purpose of implementing the DGA, software was developed by the author known as Optimum Design of Steel Portal Frames (ODSPF). Visual Basic Language was employed to code ODSPF. A part of software is depicted in Fig. 3 which shows up the input genetic parameters.

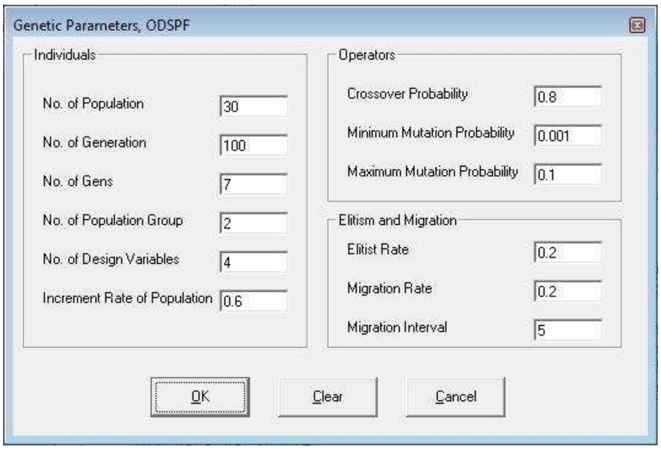

Fig. 3. The genetic parameters which have been input for this study into one of ODSPF

7. Design Example

A typical pitched roof steel portal frame with pinned supports was selected to test the efficiency of the developed DGA. The relevant data and diagram of the structure are presented in Table 1 and Fig 4 respectively. The problem has already been solved by Saka (2003) using simple GA. Unlike the example designed by Saka (2003), the frame is not subdivided into a large number of elements of relatively small lengths. Instead, the overall numbers of the frame members was taken as six: two for columns, two for rafters and the rest for haunched part of the rafter. This outperforms the operation speed of the algorithm as the less number of members, the more speed of the analysis of the frame will be, hence the convergence will dramatically be improved. Eighty steel sections from the standard steel tables given in Steel work Design Guide to BS 5950 are employed as design variables while Saka (2003) used 64 sections to have 2^6 upper limit. The final optimum design is shown in Fig. 5. This achieved after 10 re-designs running of the pitched roof steel portal frame with varied seeds as presented in Table 2. Initially running the program took place 50 times, but later it was found out that the optimum design obtained with 10 runs revealed the same result as 50 runs. Therefore for saving the time of calculation, it was adopted to re-design the frame in 10 times.

Table1: The required data for design of the pitched roof steel portal frame

Span, m	Column, m	Purlin Space, m	P, kN	Modulus of Elasticity, E, kN/m^2	Haunch Depth Range & increment, cm	Haunch Length Range & Increment, m
20	5	1.25	5	200	10 – 74, & 2	0.5 – 5, & 0.25

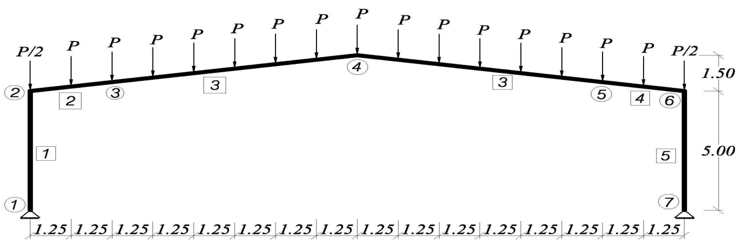

Fig. 4. The pitched roof steel portal frame of the example

It is observed from Table 2 that, whatever the number of generation increases, the likelihood of getting the optimum or near optimum solution is raised. Due to inputting a smaller value for the max mutation probability and consequently premature convergence of Run 6, the optimum result has been booked as heaviest. This was achieved after 36 generations. The design carried out for different applied load values and the best output is collected into Table 3 with the associated frame weight. It is clear that whatever the applied load increases the weight of the frame turns to be heavier and the depth of the haunch turned to be smaller, because the heavier member necessitates having smaller depth of haunch. Furthermore, the obtained designed is compared with what was done by Saka (2003) using simple genetic algorithms. The implemented DGA increased the speed of the operation and the convergence took place after 63 generations which took 204 seconds of physical time (using Pentium 4, 2.40 GHz CPU, with 512 MB RAM). Also the obtained depth of the haunch for each seed is less than that designed using simple genetic algorithms. The reason refers to the reduction in number of considered members for design and using the derived non-prismatic stiffness matrix. The depth of the haunch is required to be less than the section depth of the rafter. However, some of the design run reveals that the depth of the haunch exceed that of the rafter. It therefore, raises the requirement for adding another constraint which will restrict any exceeds in the depth of the haunch. This constraint could be defined as $D_h < (D - t_f - r)$. This makes it possible to use the same section of the rafter for the haunch. By making a comparison between Fig. 5 and Fig. 6, it can be realised that adding the aforementioned constraints resulted in a heavier frame which caused an increasing in the weight by 20.02%.

Fig. 7 shows the convergence of the problem into optimum solution. After reaching the 63rd generation, the best individual dominated consistently in the population. This refers to the application of elitism and migration strategy which caused a convergence within a few generations. As a consequence, it saved the time consuming for checking the constraints and performing the analysis accordingly. Fig. 8 depicted the percentage of domination the best individual after certain number of generation.

Table 2: Result of the optimum solution from different Run for P=5kN

Run	Section Designation		Depth of Haunch, m	Length of Haunch, m	Generation No. for Optimum Design	Weight, kg
	Column	Rafter				
1	457x191x89 UB	356x127x33 UB	0.38	3.00	59	1562.3
2	457x191x74 UB	356x127x39 UB	0.40	3.25	71	1530.3
3	457x191x89 UB	356x171x45 UB	0.36	2.75	46	1902.7
4	457x191x74 UB	356x127x33 UB	0.40	3.25	63	1515.9
5	457x191x74 UB	356x171x45 UB	0.38	3.50	49	1774.8
6	457x191x98 UB	356x171x67 UB	0.32	1.50	36	2415.8
7	457x191x74 UB	356x127x33 UB	0.42	3.50	64	1528.6
8	457x191x74 UB	356x127x33 UB	0.42	3.25	67	1520.3
9	457x191x82 UB	356x171x67 UB	0.30	2.0	41	2124.2
10	457x191x98 UB	356x127x33 UB	0.28	1.75	48	1694.6

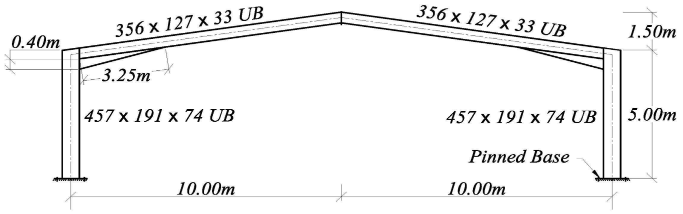

Fig. 5. The best optimum design from 10

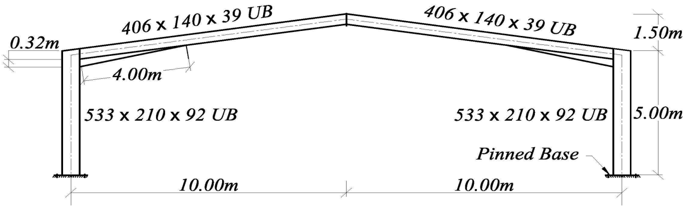

Fig. 6. The best optimum design accounting the haunch depth

Table 3: Optimum design parameters for different load values

Load P, kN	Section Designation		Depth of Haunch, m	Length of Haunch, m	Weight, kg	Weight, kg By Saka (2003)
	Column	Rafter				
5.0	457x191x74 UB	356x127x33 UB	0.40	3.25	1515.9	1521.4
7.5	610x229x101 UB	406x140x39 UB	0.36	3.00	1893.6	1903.7
10.0	610x229x101 UB	406x178x54 UB	0.26	3.00	2202.9	2260.0
20.0	610x229x140 UB	533x210x92 UB	0.14	2.25	3334.3	3224.0
30.0	914x305x210 UB	610x229x101 UB	0.12	2.75	4141.8	4197.7

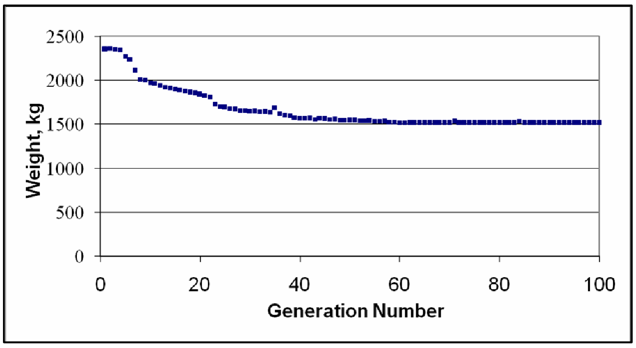

Fig. 7. Converging of the design to Optimum Solution when P=5kN

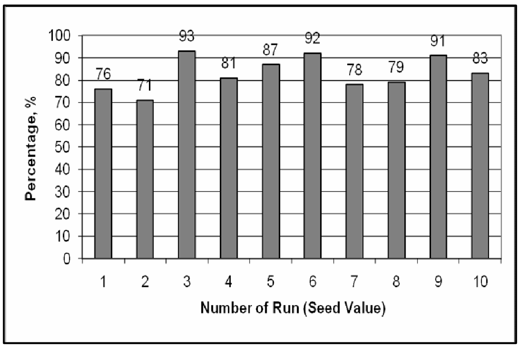

Fig. 8. Percentage of domination of best individual in each run

8. Conclusion

The distributed genetic algorithm was presented to investigate the optimum design of the pitched roof steel portal frame. The algorithm was linked to a data base containing the standard universal beam sections table. The performance of the algorithm was checked by comparing it with the simple genetic algorithm. The design obtained by using the DGA was slightly lighter than the design obtained by simple genetic algorithms. In addition, the optimum design was achieved after a small number of the generation. This shows the great capability of the DGA to converge into the optimum or near-optimum solution rapidly. The derived stiffness matrix for non-prismatic member played the great role to reduce the depth of the haunch and consequently the total weight of the structure. In fact, it could handle the analysis of the frames with tapered members. Using the seed, representing the number of design running increased the likelihood of getting the best design among different runs. This improves the possibility to cover more domains of the design spaces. As a result, it potentially eliminates any entrapment into local optimum. The developed software ODSPF uses DGA, the derived stiffness matrix and formula of the mutation to reach the optimum solution of steel portal frame within a certain number of generations. By gradually decreasing the mutation probability as the generation increases, the premature convergence of the solution (which could lead to a non-optimal solution) can be avoided. Producing more offspring raised the likelihood of having the best individuals in earlier stages of the solution.

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Notations:

A_1 and A_2 : The areas of member ends
A_{gj} : Gross cross sectional area of the member *j*
ConNo : Total number of the constraints
D_h Depth of the flange
E : Modulus of Elasticity
F^{avg} Average fitness value of the population
FF Fitness value of individuals
F^{GenNo} Fitness value of the current generation
F_j : Applied axial force at the critical region of the member *j*
GenNo : Number of generation
G_m : Group of member from the table of standard sections
GrpNo : Number of population group
H_w : Weight of the haunched eaves
I : Moment of the inertia
JointNo Total number of frame joints
K : Stiffness Coefficient
L : Length of the member
L_w : Member weight
m : Equivalent uniform moment factor
M Equivalent uniform moment
M_b buckling resistance
M_{bj} : Buckling resistance moment capacity for member *j* about its major axis (Clause 4.3.7 of BS5950)
M_{cxj} : Moment capacity of the member about the major axis
M_k Applied moment in member k
M_{xj} : Bending moment around the major axis at the critical region of the member *j*
MemNo : Total number of the members
N_{Gen} : Current generation
p_b Bending strength
P_c Compression resistance
P_c : Crossover probability
p_{cj} : Compression strength obtained from the solution of the quadratic Perry–Robertson formula
P_{en} : Increment rate of population
P_E : Elitism rate
P_i Survival probability of the individual *i*
P_m : Mutation probability
$P_m^{\max}$: Maximum range of mutation probability
$P_m^{\min}$: Minimum range of mutation probability
$P_m^{N_{Gen}}$: Mutation probability in current generation
P_{mig} : Migration rate
p_y : Bending strength
PF Penalised fitness value of the individuals
PF_{max} Maximum penalised fitness value of the current population
PF_{min} Minimum penalised fitness value of the current population
PopNo : Number of population in each group
r root radius of the universal beam section
S_x plastic modulus of a section about x–x axis
TapMNo : Number of tapered members
t_f Thickness of the flange
UniMNo : Number of the uniform member
δ_i : Displacement at joint *i*
δ_{iu} : Upper limit displacement of the joints