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Design Optimization of Single Span Fixed-Feet Portal Frame Using Generalised Reduced Gradient Method

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Abstract

The design of single span fixed-feet portal frames was optimized using MSExcel solver, a multi-disciplinary optimizing ad-in in MSExcel spreadsheet formulated using Generalised Reduced Gradient (GRG2) method of optimization. Portal frames of different geometries with two sets of different loading arrangements were designed using structural design software - PROKON (version W2.0.11) and the resulting design sections were mass-optimized based on the area of member cross section, using Excel solver. In the optimization exercise, the objective function (area of cross section) was minimized subject to the satisfaction of the constraints in accordance with the relevant British Standard. After the optimization process, the portal frame structural members (two vertical members and one horizontal member) for the first set of loading were 21.86%, 19.65% and 27.22% lighter than their initial sections thereby giving an average of 22.91% lighter section, and the second set of loading results show that the optimized sections were 30.31%, 31.27% and 30.29% lighter than their initial sections giving an average of 30.62% lighter section.

Keywords: optimization, excel solver, generalised reduced gradient, portal frame.

1. Introduction

1.1 Background

A good structural design must minimize material resources by ensuring that just the required amount and dimensions of structural elements are provided after worst loading condition has been considered. This is referred to as design optimization. According to Querin (1997), optimization is the procedure through which the best possible values of decision variables are obtained under the given set of constraints and in accordance to a selected optimization objective. The best design could be in terms of minimum cost, minimum weight, maximum performance or a combination of these (Iyengar, 2002).

The objective of this research is to develop an algorithm for minimum mass design of flat-roof fixed-feet steel portal frames in accordance with the provisions of BS 5950-1(2000), using Generalised Reduced Gradient method of optimization.

2. Literature Review

2.1 Gradient Based Optimization Methods

Different methods are available for the successful determination of the optimum set of design variables that can provide the minimum or maximum value for a specific function. One of such methods is gradient based method – an optimization technique based on the differentials of the objective function. Optimization problems may or may not have constraints. For problems without constraints, ordinary differential calculus method provides the best means of achieving an optimum solution. However, most practical structural optimization problems have limitations or constraints on some of the design variables or algebraic relationships in terms of these design variables (Haftka and Gurdal, 1992). Problems with constraints can be solved using either differential calculus methods (Lagrangean and Kuhn-Tucker) or search methods (Linear Programming and Integer-Linear Programming).

2.1.1 Generalised Reduced Gradient Method (GRG2)

This procedure belongs to a class of techniques called reduced-gradient methods. They are based on extending methods for linear constraints to apply to non-linear constraints (Gill *et al*. 1981). They adjust the variables so the active constraints continue to be satisfied as the procedure moves from one point to another. According to Faluyi and Arum (2012), the ideas for these algorithms were devised by Wilde and Beightler in 1967 using the name *constrained derivatives* and extended by Abadie_and Carpenter in 1969 using the name *general reduced gradient.* If the economic model and constraints are linear this procedure is the simplest method of linear programming and if no constraints are present it is gradient search.

The GRG2 method is based on the idea of elimination of variables using the equality constraints. The idea of generalised reduced gradient is to convert the constrained problem into an unconstrained one by using direct substitution. The method uses an approach which is to find an improved direction for the economic model and also to satisfy the constraint equations.

Microsoft Excel Solver uses the Generalised Reduced Gradient (GRG2) Algorithm for optimizing problems. The solver combines the functions of a graphical user inter-phase (GUI) and algebraic modelling language for linear, nonlinear and integer programs. Each of these functions is integrated into the host spreadsheet program as closely as possible (Daniel *et al*. 1998).

2.2 Steel sections optimization works

Simoes (1996) describes a computer-based method for the optimum design of steel frameworks accounting for the behaviour of semi-rigid connections. The procedure explicitly accounts for both connections and members by taking connection stiffnesses and member sizes as continuous-valued and discrete-valued design variables, respectively. The optimization algorithm minimizes the cost of the connections and members of the structure subjected to constraints on stresses and displacements under specified design loads

Deb and Gulati (2001) simultaneously optimized the size, topology, and configuration of 2-D and 3-D truss structures through a GA to obtain the minimum total weight while complying with stress and deflection limitations. The design variables considered were continuous and were assigned real-number values. A ground truss-structure was also optimized using discrete values for the member areas, and this solution was compared to the continuous solution. A loaded and fully connected ground structure was first assumed containing all nodes of the truss. Truss members were removed from the initial ground structure in order to search for better solutions. Members that were assigned very small cross-sectional areas were removed, thus changing the topology of the truss structure. The nodes that carried loads or were at support points were termed *basic* nodes, whereas other nodes that could more efficiently distribute loads between members were considered *non-basic* nodes. When basic nodes were eliminated through optimization, a large penalty constant was applied to the objective function which inhibited further optimization of that particular solution. The population size chosen for the GA was dependent upon the number of members used in the ground structure. GA proved to find better solutions to problems that had previously been solved in literature using other optimization techniques.

Hayalioglu and Degertekin (2005) presented an optimum design method for the minimum cost of non-linear steel frames with semi-rigid connections and column bases through GA while satisfying stress, deflection, and size constraints.

3. Methodology

This research work was carried out in three stages as follows.

i. A design for two sets of portal frame members with different loading conditions and spans was carried out using software, PROKON (Version W2.0.11). Two sets of loading conditions were considered so as to establish the consistency of optimization process. The two loading conditions considered are shown in figures 1 and 2.
ii. The PROKON design sections obtained in (i) were mass-optimized using Excel solver, an optimizing ad-in in MSExcel spreadsheet which is based on the Generalised Reduced Gradient method of optimization.
iii. Comparisons were made between initial designs in (i) and optimized design in (ii) to evaluate the results.

The flow chart of the optimization process is shown in Figure 1.

The loading arrangements considered are presented in figures 2 and 3.

3.1 Design and Optimization Assumptions

The following assumptions were made.

a. Each of the structural members has a uniform cross-section throughout its length.

b. The structural elements are made of universal sections (UB or UC).

c. The structural sections are class 1(plastic) or class 2(compact) sections

d. Web and flanges are made of the same steel material.

3.2 Optimization Process

The optimization problem was modeled in Micro-Soft Excel spreadsheet using Generalized Reduced Gradient Algorithm (GRG2). The Excel solver has three primary components which are:

i. Target Cell: This is the cell that represents the goal or objective of the problem expressed in mathematical formulation. The objective of design optimization is to achieve reduced structural member sections.

Considering universal beam/column sections only, the optimization function, **Z** (which is the area of the cross section), is as given in equation **(1).**

$$\mathbf{Z = 2(b_f \times T) + (d \times t)} \qquad \mathbf{(1)}$$

The parameters b_f, T, d and t are as shown in Fig.4.

The optimization objective is to minimize **Z**, subject to design constraints as given in equations **(2)** to **(12)**

ii. Variable Cells: These are cells that can be modified to arrive at the desired outcome. In this research work, the variable cells are depth of sections (**D**), web thickness (**t**), flange thickness (**T**) and flange width (**b_f**).

The initial sectional sizes inputted in the variable cells are the design outputs obtained using PROKON software for corresponding loadings.

iii. Constraints: These are restrictions or limitations to what solver can do while solving the problem. In this research work, the constraint functions were based on the provisions of BS 5950-1(2000) on cross section classifications, moment and axial force resistance, shear capacity as well as slenderness considerations.

The constraints considered based on the provisions of the code are presented in equations **(2)** to **(7)**.

Other than the provisions of the code, some constraints were set to ensure that the optimization outputs are realizable in practice.
Considering plastic and compact sections only;

$b/T \leq 10\epsilon_f$ **(2)** Table 11 (BSI 2000)

Considering cross-section not susceptible to shear buckling;

$d/t \leq 62\epsilon_w$ **(3)** clause 4.4.4.1 (BSI 2000)

Cross-section capacity not affected by shear ;

$F_v \leq 0.6P_v$ **(4)** clause 4.2.3 (BSI 2000)

Moment Capacity;

$M_{cx} \geq M_x$ **(5)** clause 4.2.5.2 (BSI 2000)

Compression members with moment;

$$\frac{F_c}{A_g P_y} + \frac{M_x}{M_{cx}} \leq 1$$ **(6)** clause 4.8.3.2 (BSI 2000)

Member buckling resistance;

$$\frac{F_c}{P_{cy}} + \frac{m_{LT} M_x}{M_b} \leq 1$$ **(7)** clause 4.8.3.3 (BSI 2000)

Slenderness consideration;

$\lambda_y \leq 200$ **(8)**

Other than the provisions of the code, some constraints are set to ensure practicability of optimization results. These constraints are presented in equations **(9)** to **(12).**

$310mm \geq b_f \geq 75mm$ **(9)**

$55mm \geq T \geq 7mm$ **(10)**

$1000mm \geq D \geq 110mm$ **(11)**

$30mm \geq t \geq 4mm$ **(12)**

where;
b_f is section flange width

T is section flange thickness
d is depth of web
D is depth of section
t is web thickness
P_y is steel design strength
A_g is gross sectional area
F_v is design shear force
F_c is design axial compression
M_b is buckling resistance moment
P_b is buckling strength
P_V is shear strength
M_x is maximum major axis moment in the segment length L_x governing P_{cx}
M_{LT} is maximum major axis moment in the segment length L governing M_b
P_{cy} is compression resistance considering buckling about minor axis only
λ_y is slenderness ratio about the minor axis.

3.3 Optimizer (Excel Solver) Settings

The solver was set to a maximum of 100 iterations, though solution is usually found before the specified number of iterations. A linear estimate with tolerance of 1% and convergence of 0.0001 was set. Newton search using forward derivative with automatic scaling was also set.

4. Results and Discussions

4.1 Results

The PROKON (initial) design sections and optimized sections for loading arrangement 1 are presented in Tables 1 to 3.

The PROKON (initial) design sections and optimized sections for loading arrangement 2 are presented in Tables 4 to 6.

4.2 Discussions

In loading arrangement 1, the difference between the areas of the initial and optimized design section for member 1 is 433.32mm^2 (21.86%), for member 2 is 995.16mm^2 (19.65%) and for member 3 is 856.81mm^2 (27.22%) giving an average section area reduction of 761.76mm^2 (22.91%). Since steel members are valued in terms of their mass (tonnes or kg) and given that the unit weight of steel is 7850kg/m^3, the average reduction in mass is 5.98kg/m and for a frame having overall length of 16m, the average mass reduction is 95.68kg. Extending this reduction in mass over the entire portal framework of a building, there will be a significant saving in material which will normally lead to savings in cost.

In loading arrangement 2, the difference between the areas of the initial and optimized design for member 1 is 954.04mm^2 (30.31%), for member 2 is 4299.68mm^2 (31.27%) and for member 3 is 953.43mm^2 (30.29%) giving an average section area reduction of 2069.05mm^2 (30.62%). Analogous to the case of the loading arrangement 1, the average reduction in mass in this case is 16.24kg/m and for a frame having overall length of 20m, the average mass reduction is 324.84kg. Extending this reduction in mass over the entire portal framework of a building, there will be a significant saving in material which will normally lead to savings in cost.

The difference in PROKON section and the optimized section is majorly as a result of the fact that PROKON software is restricted to picking design steel section from standard sections. When a particular standard section does not satisfy the entire constraints requirement, the software selects the next heavier section that satisfies all the constraints and in most cases, the selected section has excessive strength reserve. The excess strength reserve is not an advantage economically to the design engineer in this case because, in limit state design especially, both the design load and structural material strength have been factored by a factor of safety already. Therefore, there is no need to further provide excess structural section in addition to what is actually required since the code requirement has already been satisfied by the results obtained using the optimizer. There are emerging steel structures construction companies that treat every project uniquely by providing structural sections as required by each project using prefabricated steel rather than based on the standard sections especially when massive construction is involved. For massive projects, a design engineer that does not restrict himself to standard sections as provided by software will give a better cost effective design than a design engineer that restricts himself to standard sections.

Generally, the validity of the optimization process is established by the fact that the optimized sections are lighter than the initial design sections while at the same time satisfying all the constraints as required by the provisions of BS 5950-1(2000). The consistency of the optimization process is also established by having similar results (i.e. lighter sections) for two different loadings and member lengths.

5. Conclusions

Loading arrangement 1 results show that optimized section of member 1 is 21.86% lighter than the initial (PROKON software-aided design) section while that of members 2 and 3 are 19.65% and 27.22% lighter respectively giving an average of 22.91% lighter section, and loading arrangement 2 results show that the optimized section of member 1 is 30.31% lighter than the initial (PROKON software-aided design) section while that of members 2 and 3 are 31.27% and 30.29% lighter respectively giving an average of 30.62% lighter section.

The work has provided a simple algorithm for optimizing the design of fixed-feet steel portal frames by minimizing the cross sectional area of frame members.

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Table 1. Initial and optimized design results for member 1 of loading arrangement 1

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	88.7	83.2	5.47	6.17
T (mm)	7.7	7.0	0.7	9.09
D (mm)	152.4	110.0	42.4	27.82
T (mm)	4.5	4.0	0.5	11.11
Area of Section (mm^2)	1982.48	1549.16	433.32	21.86

Table 2. Initial and optimized design results for member 2 of loading arrangement 1

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	165	174.8	-9.82	-5.95
T (mm)	10.2	8.9	1.28	12.54
D (mm)	303.4	255.3	48.12	15.86
T (mm)	6	4.0	2	33.33
Area of Section (mm^2)	5064	4068.84	995.16	19.65

Table 3. Initial and optimized design results for member 3 of loading arrangement 1

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	133.2	136.2	-2.97	-2.23
T (mm)	7.8	7.0	0.80	10.26
D (mm)	203.2	110.0	93.20	45.87
T (mm)	5.7	4.0	1.7	29.82
Area of Section(mm^2)	3147.24	2290.43	856.81	27.22

Table 4. Initial and optimized design results for member 1 of loading arrangement 2

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	133.2	129.2	3.97	2.98
T (mm)	7.8	7.0	0.80	10.26
D (mm)	203.2	110.0	93.20	45.87
T (mm)	5.7	4.0	1.70	29.82
Area of Section (mm^2)	3147.24	2193.20	954.04	30.31

Table 5. Initial and optimized design results for member 2 of loading arrangement 2

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	210.8	275.8	-64.99	-30.83
T (mm)	18.8	14.1	4.68	24.87
D (mm)	539.5	342.0	197.50	36.61
T (mm)	11.6	5.3	6.32	54.45
Area of Section (mm^2)	13748.12	9448.44	4299.68	31.27

Table 6. Initial and optimized design results for member 3 of loading arrangement 2

	Initial Size	Optimized Size	Difference	% Difference
b_f (mm)	133.2	129.3	3.93	2.95
T (mm)	7.8	7.0	0.80	10.26
D (mm)	203.2	110.0	93.20	45.87
T (mm)	5.7	4.0	1.70	29.82
Area of Section (mm^2)	3147.24	2193.81	953.43	30.29

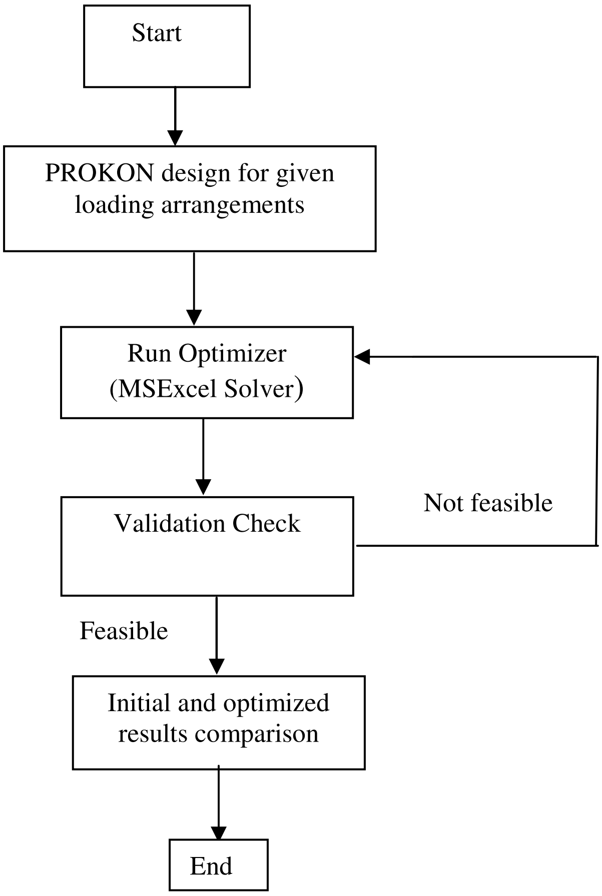

Figure 1. Optimization Process

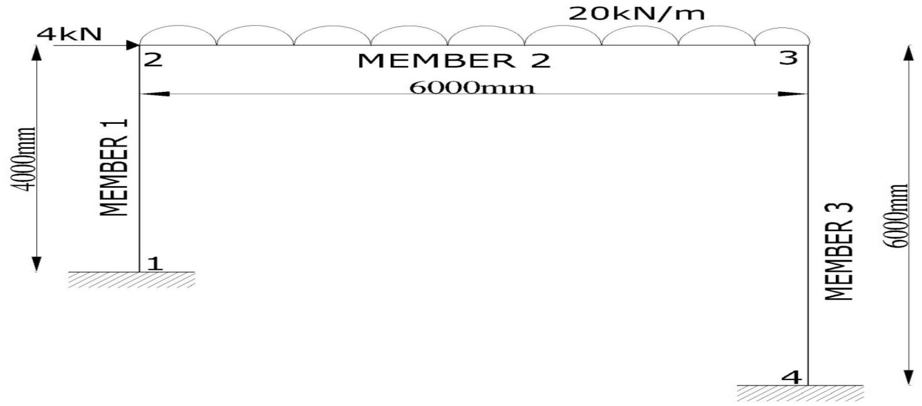

Figure 2. Portal Frame Loading Arrangement 1

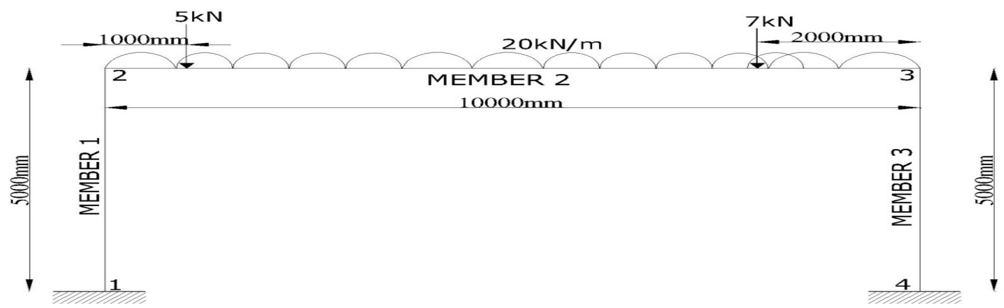

Figure 3. Portal Frame Loading Arrangement 2

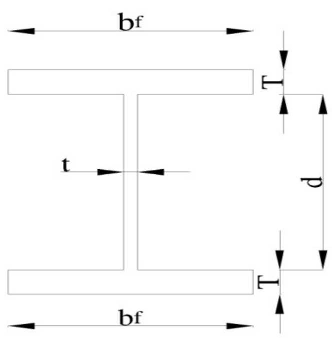

Figure 4. Typical universal beam section