

Parametric Study and Design of Steel Portal Frames according to Egyptian Standards based on Genetic Algorithms

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Abstract: In this paper, a Genetic Algorithm-based parametric study is carried out to present a robust design optimization approach for steel portal frames according to Egyptian standards. The privilege of such an approach is that it can help structural engineers obtain optimal topology and sizing of a steel portal frame without referring to traditional experience-based procedures. The main parameters assessed in this study are frame's span, column's height, spacing of frames, roof slope and imposed loads. A new software tool, which combines Finite Elements and Genetic Algorithms, is utilized in this study to produce design tables and charts for a typical single bay pitched-roof steel portal frame subjected to a general case of loading defined by the Egyptian Code of Practice. Hot rolled standard steel sections are adopted for frame's columns and rafters while frame's rafters are assumed to be provided with built-up haunches at eaves and apex. Reliability of the present approach is investigated by comparing the obtained designs against their counterparts of traditional procedures as well as other optimization methods. The results indicate achieving considerable savings in steel hardware. Furthermore, the contribution of rafters' haunched parts in maximizing frame's structural efficiency is studied. The developed design aids can put structural optimization results into common practice.

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1. Introduction

Numerous researches have been carried out in the past years to optimize design of portal steel frames using mathematical programming or stochastic search techniques, e.g. [1-6]. However, there is a reluctance to use optimization techniques in common practice because of their complexity [7]. Upon adopting a mathematical gradient based programming method, a set of equations handling different design situations have to be formulated and derivatives have to be obtained which is a cumbersome task.

On the other hand, if a stochastic search technique is adopted, obstacles such as pre-mature convergence, computation costs and processing time issues have to be overcome in order to efficiently reach an optimal or a quasi-optimal solution. This is very true when the assessed problems have complex search spaces with many local optima.

In this research work, an attempt is made to bridge the gap between progress of optimization techniques and their implementation in common practice. A new software tool (GA-STRAP), which combines a Finite Elements structural analysis program (STRAP) [8] with a hybrid Genetic Algorithms (GA_s) optimization code, is developed to produce optimal design tables and charts of steel portal frames according to Egyptian standards. From the authors' point of view, such developed design aids can help

implement structural optimization process in design firms.

GA-STRAP selects the optimal sections for columns and rafters of a typical steel portal frame from standard steel sections tables. Also, it determines the optimal haunch length and depth at the eaves and apex. Furthermore, GA-STRAP determines the optimal apex height or pitched-roof slope required for reaching the least weight frame, while satisfying strength, stability and serviceability constraints defined by the Egyptian Code of Practice (ECP 205-2001) [9].

GA_s simplicity and robustness lie in their fundamental nature of using minimal a priori knowledge as they do not need specific information to guide the search, and require only an evaluation of the objective function value for each decision variable set in order to proceed [10-13]. If hybridized with a local search technique, GA_s can reach an optimal or a quasi-optimal solution in a computationally efficient manner.

To this end, the rest of this article is structured as follows: First, the design optimization problem is formulated and the computation procedure is illustrated. Next, the obtained results are compared with those available in the literature. Then, tables which present the optimal solutions for different values of governing design parameters are produced. After that, charts which illustrate the role of rafters' haunched parts in maximizing frame's structural

efficiency are developed. Finally, conclusions are drawn.

2. Optimization Problem Statement and Computation Procedure

The design optimization problem addressed herein is to find out the optimal topology and sizing of a typical single bay pitched-roof steel portal frame, illustrated in Figure 1. So, a frame with a minimum weight is obtained. Hence the objective function can be stated as:

Find $X \in R_k$ to minimize $f(X)$

Subject to $g_i(X) \leq 0$, $i=1, 2, \dots, n$ and

$X_j^L \leq X \leq X_j^U$, $j=1, 2, \dots, k$

where X is the vector of design variables; $f(X)$ is the objective function; $g_i(X)$ are the performance constraints; X_j^L and X_j^U refer to the lower and upper bounds on the design variables respectively. The objective function here is the total weight of the frame and can be expressed as:

$$\text{minimize } W = \rho \sum_{i=1}^m A_{j(i)} L_i + \sum_{h=1}^{nh} W_h, \quad j(i)=1, 2, \dots, n \quad (1)$$

where ρ is the steel density; m is the number of frame members; $A_{j(i)}$ is the cross sectional area of different members taken from n trial sections available in a standard steel sections table; $L_{(i)}$ is the length of different members; W_h represents the weight of a single haunch and nh is the total number of haunches in the frame.

The performance constraints, e.g., strength, serviceability and stability constraints, are implemented according to ECP 205-2001 as follows:

$$g_{1i} = |\sigma_i| - \sigma_{all} \leq 0, \quad i = 1, 2, \dots, m \quad (2-a)$$

$$\frac{f_{ca(i)}}{F_{c(i)}} + \frac{f_{bc(i)}}{F_{bc(i)}} A_1 + \frac{f_{bcy(i)}}{F_{bcy(i)}} A_2 \leq 1.0, \quad i = 1, 2, \dots, m \quad (2-b)$$

$$g_{2i} = |\Delta_j| - \Delta_{all} \leq 0, \quad j = 1, 2, \dots, k \quad (3)$$

$$g_{3i} = |\sigma_{c(i)}| - F_{ltb} \leq 0, \quad i = 1, 2, \dots, m \quad (4)$$

Equations (2-a) and (2-b) define the strength constraint, where σ_i is the maximum induced stress in member i and σ_{all} is the allowable stress. Stresses at any section shall satisfy the interaction equation as illustrated in Clause 2.6.7.1 of ECP 205-2001 [13]. Equation (3) defines the serviceability constraint as illustrated by Table (9.1) of ECP 205-2001 [9], where Δ_j is the induced displacement at joint j and Δ_{all} is the allowable displacement. Equation (4) defines the lateral torsional stability constraint, where $\sigma_{c(i)}$ is the maximum induced compressive stress in member i and F_{ltb} is the lateral torsional buckling resistance calculated as illustrated in Clause 2.6.5.5 of ECP 205-2001 [9]. Also, local and shear buckling are prevented by satisfying conditions defined in Tables (2.1a), (2.1c) and Clause 2.6.3 of ECP 205-2001 respectively [9].

Seven design variables, listed hereinafter, are to be determined: column section; rafter section; roof slope; eave haunch length; eave haunch depth; apex haunch length and apex haunch depth. Columns and rafters' sections are to be selected from hot rolled steel sections tables of Egyptian standards. The hot rolled rafter is provided with built-up haunches. The haunch lengths are selected from a range of 1.0m to 4.75m while haunch maximum depths are selected from a range of 10cm to 72cm. The haunch web thickness, flange width and thickness are assumed to be the same as those of the hot rolled rafter's section as illustrated in Figures 1-b and 1-c. The roof slope, expressed as a percentage, ranges from 5% to 22.5%.

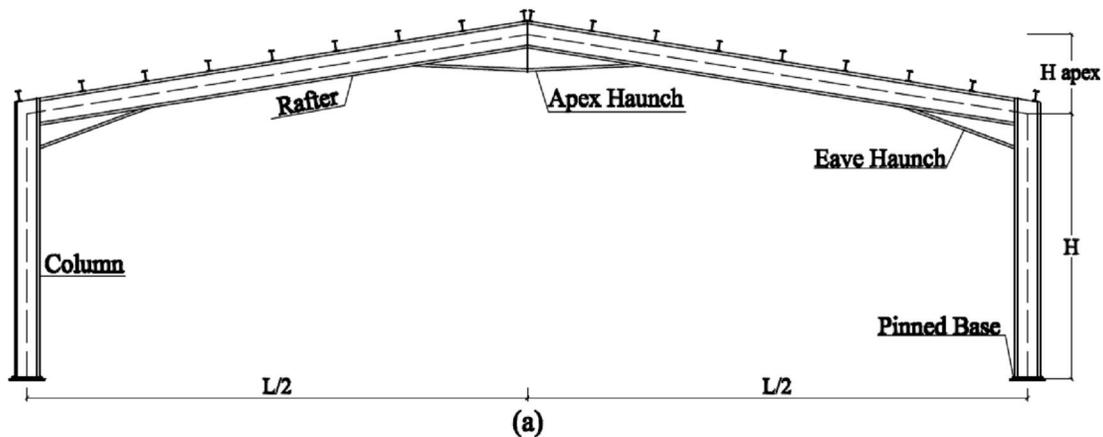


Figure 1. A single bay pitched-roof steel portal frame. (a) Frame's Layout.

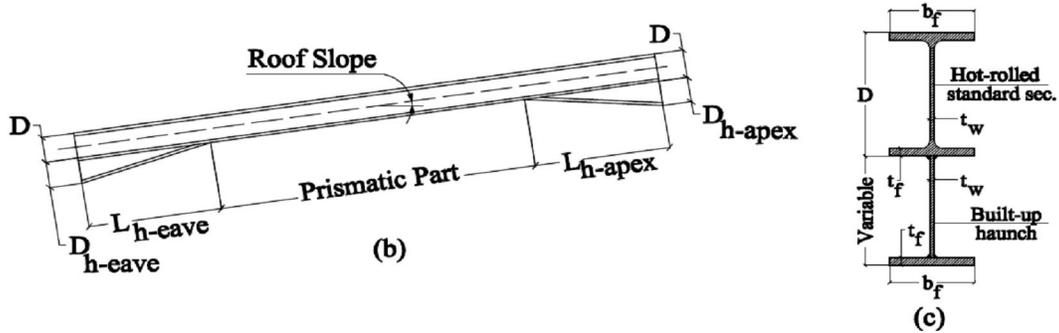


Figure 1. A single bay pitched-roof steel portal frame. (b) Rafter is provided with built-up haunches. (c) Cross section of a haunched rafter – haunch depth may exceed its rafter counterpart.

The adopted computation procedure is illustrated in Figure 2. In order to enhance the ability of the algorithm to reach a unique optimal solution, GA-STRAP is hybridized with a local search technique at

the final generations to exploit the local information and reach the global optimum. GA-STRAP is terminated upon achieving stability of the values of design variables after final convergence.

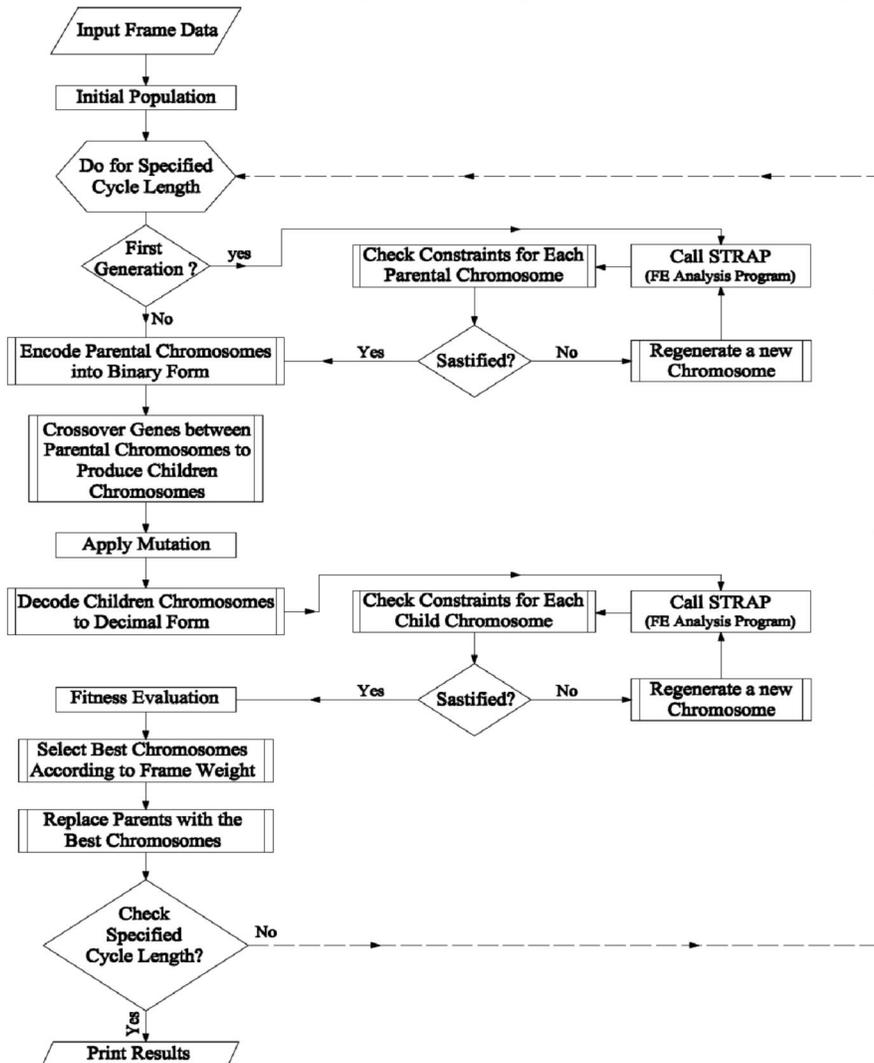


Figure 2. GA-STRAP flowchart

3. Is the Present Approach Reliable?

Reliability of the present approach is investigated by comparing the obtained designs against their counterparts of traditional procedures as well as mathematical programming methods. A design example given in [14] is studied. The span of the frame is 22m, the column height is 6m and the roof slope is 10%. In [14], prismatic hot rolled sections are adopted for columns and rafters.

GA-STRAP is applied to solve the problem in four different cases listed as follows:

Case (1): Prismatic hot rolled rafters with a roof slope equals 10% (roof slope isn't a design variable in this case); Case (2): Prismatic hot rolled rafters with roof slope as a design variable; Case (3): Haunched rafters at the eaves with a roof slope equals 10% (roof slope isn't a design variable in this case); Case (4): Haunched rafters at the eaves and apex with roof slope as a design variable. The obtained results and their counterparts of traditional design procedures [14] are illustrated in Table 1.

Table 1. Optimal Design for Different Cases vs. Traditional Experience-based Approach.

Design Variables	Case (1)	Case (2)	Case (3)	Case (4)	Reference [14]
Column's Section	I.P.E. 400	I.P.E. 400	I.P.E. 450	I.P.E. 400	B.F.I.B. 260
Rafter's Section	I.P.E. 400	I.P.E. 360	I.P.E. 270	I.P.E. 200	B.F.I.B. 280
Eave Haunch (Length x Depth) cm	-----	-----	(400 x 68)	(425 x 60)	-----
Apex Haunch (Length x Depth) cm	-----	-----	-----	(400 x 42)	-----
Roof Slope	10.0 %	22.5 %	10.0 %	22.5 %	10.0 %
Weight (kg)	2269.50	2188.30	1959.43	1596.0	3393.30

It is noticed that the pitched-roof slope has reached its upper bound in Cases (2) and (4). A minimum weight of 1596 kg is reached in Case (4) with a reduction of more than 50% compared to the design given in [14]. Convergence progression towards the optimal design in the studied four cases is shown in Figure 3. In [1], the same example has been solved using a mathematical programming technique. The Modified Method of Feasible Directions (MMFD) has been adopted and the frame has been assumed to be

composed of prismatic built-up sections. A minimum weight of 1910 kg has been reached [1].

Upon providing built-up haunches at eaves and apex alongside with an optimized roof slope, GA-STRAP has obtained a lighter frame than its counterparts achieving considerable savings in steel hardware, which demonstrates the robustness of the present approach. The optimal design of Case (4) is illustrated in Figure 4. The results are summarized in Figure 5.

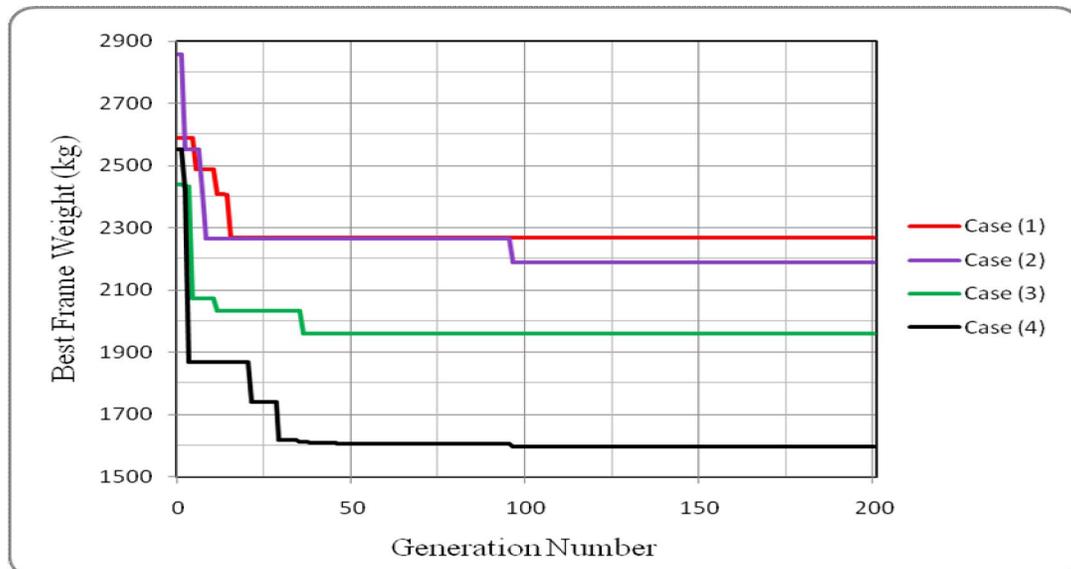


Figure 3. Convergence progression towards the optimal design in the studied four cases.

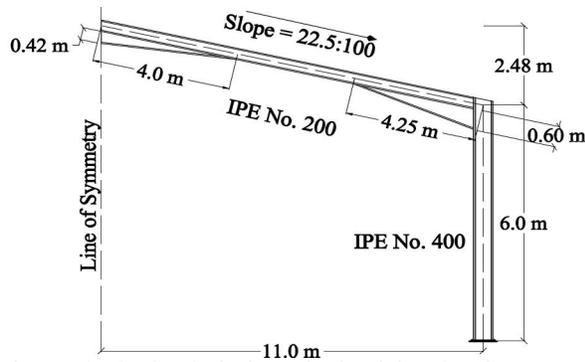


Figure 4. Optimal design obtained by GA-STRAP – Case (4).

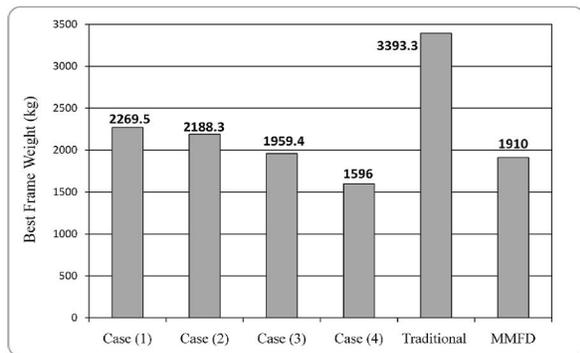


Figure 5. GA-STRAP (Cases 1, 2, 3 and 4) vs. traditional design procedure [14] and MMFD [1].

4. Parametric Study and Design

A typical pitched-roof steel portal frame, illustrated in Figure 6, subjected to a combination of dead, live and wind loads is analyzed and designed using GA-STRAP. The roof covering loads including weight of purlins \square 14 kg/m²; imposed live loads \square 53 kg/m²; wind load intensity = 70 kg/m².

Frame’s columns are assumed to be laterally supported at mid-height. So, buckling length in out of plane direction equals half of column’s height. Rafters’ compression flanges are laterally braced effectively by

a knee bracing which connects them with the purlins; i.e. the laterally unsupported length of the rafter equals to the spacing between purlins. Steel of grade 44 (St 44) is used.

It should be noted that GA-STRAP calculates straining actions due to imposed loads and carries-out the necessary combinations so that the most critical load combinations are accounted for. It is worthwhile to mention that the frame’s topology and own weight are changed at every call for the Finite Elements analysis module (STRAP) according to the variations of generated chromosomes. This is carried out by changing the frame’s descriptive geometry and sections’ properties.

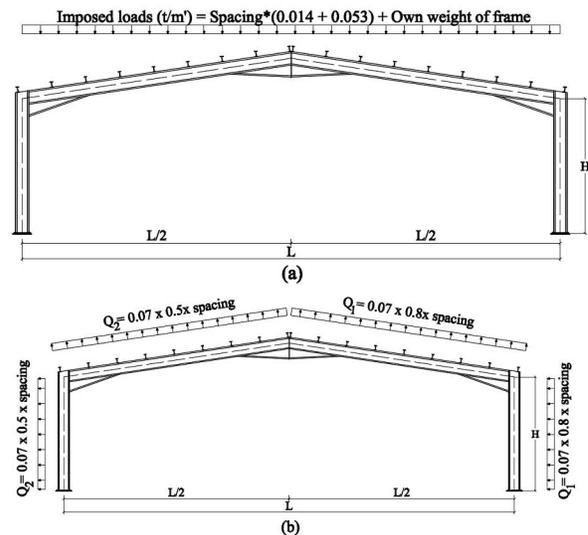


Figure 6. A frame adopted for parametric study, the main parameters assessed are Span, column height and spacing of frames. (a) Dead and live loads. (b) Wind loads from right to left.

Table 2. Optimal values of cross sections’ sizes of columns and rafters - (H=5m).

Spacing (m)	Span (m)	Column Section	Rafter Section	Roof Slope	Weight (kg)
4	15	I.P.E. No. 270	I.P.E. No. 160	10.0 %	735.00
4	20	I.P.E. No. 300	I.P.E. No. 160	22.5 %	1005.96
4	25	I.P.E. No. 360	I.P.E. No. 200	22.5 %	1494.23
4	30	I.P.E. No. 450	I.P.E. No. 270	22.5 %	2178.48
5	15	I.P.E. No. 270	I.P.E. No. 160	22.5 %	751.66
5	20	I.P.E. No. 330	I.P.E. No. 160	20.0 %	1093.15
5	25	I.P.E. No. 400	I.P.E. No. 220	22.5 %	1693.70
5	30	I.P.E. No. 450	I.P.E. No. 270	22.5 %	2332.17
6	15	I.P.E. No. 300	I.P.E. No. 160	22.5 %	816.67
6	20	I.P.E. No. 360	I.P.E. No. 200	22.5 %	1283.20
6	25	I.P.E. No. 400	I.P.E. No. 270	22.5 %	1925.83
6	30	I.P.E. No. 500	I.P.E. No. 300	22.5 %	2583.84

Table 3. Optimal values of haunch length and depth - (**H=5m**).

Spacing (m)	Span (m)	Eave Haunch		Apex Haunch	
		Length (m)	Depth (m)	Length (m)	Depth (m)
4	15	2.25	0.42	3.50	0.32
4	20	3.50	0.70	4.25	0.54
4	25	4.50	0.60	4.50	0.56
4	30	4.75	0.64	1.00	0.20
5	15	2.25	0.36	3.75	0.40
5	20	4.00	0.66	4.75	0.50
5	25	4.50	0.54	4.50	0.50
5	30	4.75	0.68	4.75	0.30
6	15	2.50	0.46	3.50	0.36
6	20	4.25	0.66	2.50	0.36
6	25	4.25	0.60	2.75	0.38
6	30	4.75	0.72	1.50	0.36

The assessed parameters are Span, column height and spacing of frames. The frame's span is assigned to (15, 20, 25, 30) m; column's height is assigned to (5, 6, 7) m; spacing of frames is assigned to (4, 5, 6) m. The optimal design corresponding to each of these parameters is obtained by GA-STRAP as listed in Tables 2 - 7.

It is interesting to notice that roof slope has reached its upper bound in the majority of the optimal solutions. This demonstrates the influence of roof topology optimization on maximizing frame's structural efficiency. Such a result can be related to the arch action mobilized in the structure.

Table 4. Optimal values of cross sections' sizes of columns and rafters - (**H=6m**).

Spacing (m)	Span (m)	Column Section	Rafter Section	Roof Slope	Weight (kg)
4	15	I.P.E. No. 240	I.P.E. No. 200	17.5 %	843.93
4	20	I.P.E. No. 330	I.P.E. No. 180	22.5 %	1220.75
4	25	I.P.E. No. 400	I.P.E. No. 240	22.5 %	1861.72
4	30	I.P.E. No. 450	I.P.E. No. 270	22.5 %	2465.30
5	15	I.P.E. No. 270	I.P.E. No. 220	22.5 %	955.00
5	20	I.P.E. No. 360	I.P.E. No. 200	22.5 %	1392.19
5	25	I.P.E. No. 400	I.P.E. No. 300	22.5 %	2145.72
5	30	I.P.E. No. 450	I.P.E. No. 300	22.5 %	2712.79
6	15	I.P.E. No. 300	I.P.E. No. 180	15.0 %	970.00
6	20	I.P.E. No. 360	I.P.E. No. 200	22.5 %	1438.32
6	25	I.P.E. No. 450	I.P.E. No. 300	22.5 %	2286.53
6	30	I.P.E. No. 500	I.P.E. No. 360	22.5 %	3153.70

Table 5. Optimal values of haunch length and depth - (**H=6m**).

Spacing (m)	Span (m)	Eave Haunch		Apex Haunch	
		Length (m)	Depth (m)	Length (m)	Depth (m)
4	15	1.00	0.40	3.75	0.32
4	20	3.50	0.66	3.50	0.48
4	25	4.75	0.64	1.50	0.22
4	30	4.75	0.60	3.50	0.54
5	15	1.00	0.20	3.25	0.28
5	20	3.50	0.66	3.75	0.30
5	25	3.75	0.50	1.75	0.26
5	30	4.75	0.64	3.75	0.48
6	15	2.75	0.46	3.00	0.48
6	20	3.50	0.60	4.50	0.48
6	25	3.75	0.68	1.00	0.20
6	30	3.50	0.68	1.00	0.10

Table 6. Optimal values of cross sections' sizes of columns and rafters - ($H=7m$).

Spacing (m)	Span (m)	Column Section	Rafter Section	Roof Slope	Weight (kg)
4	15	I.P.E. No. 270	I.P.E. No. 200	20.0 %	969.17
4	20	I.P.E. No. 330	I.P.E. No. 200	12.5 %	1416.57
4	25	I.P.E. No. 400	I.P.E. No. 240	22.5 %	2058.27
4	30	I.P.E. No. 450	I.P.E. No. 300	17.5 %	2860.92
5	15	I.P.E. No. 300	I.P.E. No. 200	22.5 %	1071.52
5	20	I.P.E. No. 360	I.P.E. No. 220	22.5 %	1594.55
5	25	I.P.E. No. 450	I.P.E. No. 270	22.5 %	2337.87
5	30	I.P.E. No. 500	I.P.E. No. 330	22.5 %	3166.33
6	15	I.P.E. No. 300	I.P.E. No. 240	20.0 %	1185.06
6	20	I.P.E. No. 360	I.P.E. No. 240	22.5 %	1719.66
6	25	I.P.E. No. 450	I.P.E. No. 300	20.0 %	2554.30
6	30	I.P.E. No. 500	I.P.E. No. 330	22.5 %	3315.87

Table 7. Optimal values of haunch length and depth - ($H=7m$).

Spacing (m)	Span (m)	Eave Haunch		Apex Haunch	
		Length (m)	Depth (m)	Length (m)	Depth (m)
4	15	1.50	0.22	3.50	0.26
4	20	2.50	0.58	4.75	0.56
4	25	4.00	0.60	4.25	0.36
4	30	4.75	0.66	3.75	0.48
5	15	2.50	0.32	2.25	0.38
5	20	2.75	0.50	4.50	0.38
5	25	3.75	0.64	3.25	0.30
5	30	4.75	0.60	1.50	0.42
6	15	1.25	0.34	2.50	0.28
6	20	2.25	0.42	4.75	0.50
6	25	3.75	0.60	2.75	0.66
6	30	4.75	0.66	3.75	0.48

GA-STRAP results have been compared to their counterparts of a recently published paper [15]. In this paper, a software program has been developed to analyze and design pitched-roof steel portal frames. According to the authors of [15], the program has intelligent criteria to find the optimum design under different conditions. It also achieves immediately the most economic design of a typical pitched-roof steel portal frame subjected to the popular case of loading according to Egyptian standards.

In [15], haunches are used at eaves and apex connections. It has been assumed that haunches are made from the same sections of beams with a height that equals the depth of frame's beam and length equal 10% of frame's span. From comparison, it has been found out that GA-STRAP has converged to better solutions or lighter frames than their counterparts in [15], which proves GA-STRAP efficiency. Table 8 shows GA-STRAP vs. literature results.

Table 8. GA-STRAP vs. literature [15].

Spacing (m)	Height (m)	Span (m)	Literature [15] Weight (kg)	GA-STRAP Weight (kg)	Weight Reduction (%)
4	5	20	1288.4	1005.96	21.9
5	5	20	1503.8	1093.15	27.3
6	5	20	1749.4	1283.20	26.7
4	6	20	1455.6	1220.75	16.1
5	6	20	1602.0	1392.19	13.1
6	6	20	1863.6	1438.32	22.8
4	7	20	1553.8	1416.57	8.80
5	7	20	1812.2	1594.55	12.0
6	7	20	1977.8	1719.66	13.0

5. Contribution of Haunches in Maximizing Frame's Structural Efficiency

In order to investigate the role of haunches at eaves and apex in maximizing frame's structural efficiency, the haunch length to span ratio has been plotted against frame span for different values of column's height and spacing of frames. Also the product of haunch depth and haunch length to span ratio is plotted against frame span, as illustrated in Figures 7 - 9. All dimensions presented in these Figures are given in (m). These Figures can be utilized in the design process so as to help structural engineers obtain optimal sizing of haunched parts of steel portal frames without referring to the traditional experience based approach.

An investigation of Figures 7 - 9 reveals that the experience based value of haunch length which equals 10% of frame's span is far from the optimal solution. It would be better to determine haunch length and depth on a case by case basis using an efficient optimization technique. The length to span ratio of haunches at eaves commonly reaches a peak value for spans from 15 to 25 m, then it deteriorates. So, the role of eave haunches is substantial in this region. Such a role becomes less effective for relatively small or large

spans whose design is most likely governed by strength constraints. In the same line, the length to span ratio of apex haunch commonly decreases for large spans, as the design of portal frames is more governed by strength constraints which indicates the role of haunches in displacement control rather than stress resistance.

6. Effect of Displacement Constraint

In order to further investigate the contribution of rafters' haunched parts, another example which is given in [16] is solved using GA-STRAP. Design data are as follows: frame span = 20 m; column's height = 8 m; spacing of frames = 5 m; roof covering loads including weight of purlins \square 10 kg/m²; imposed live loads \square 53 kg/m². Total imposed dead and live loads \square 0.32 t/m, in addition to the own weight of the frame. Wind load intensity = 70 kg/m². Steel of grade 37 is used. In this example, the effect of displacement constraint on the optimal solution is investigated. The problem is solved twice, once upon releasing displacement constraint and the other is upon applying this constraint. The best frames corresponding to these two cases are illustrated in Figures 10-11.

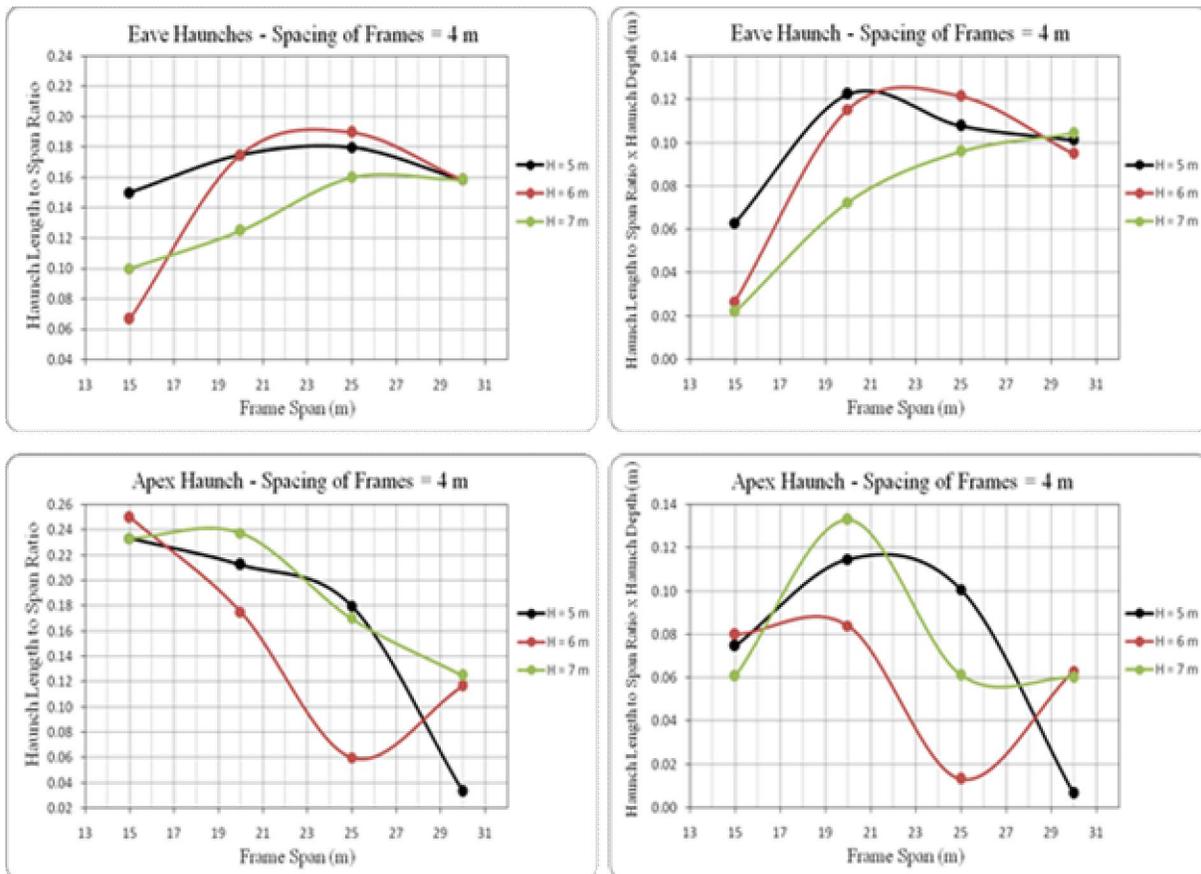


Figure 7. Relationship between frame span and haunch length to span ratio - Spacing = 4m.

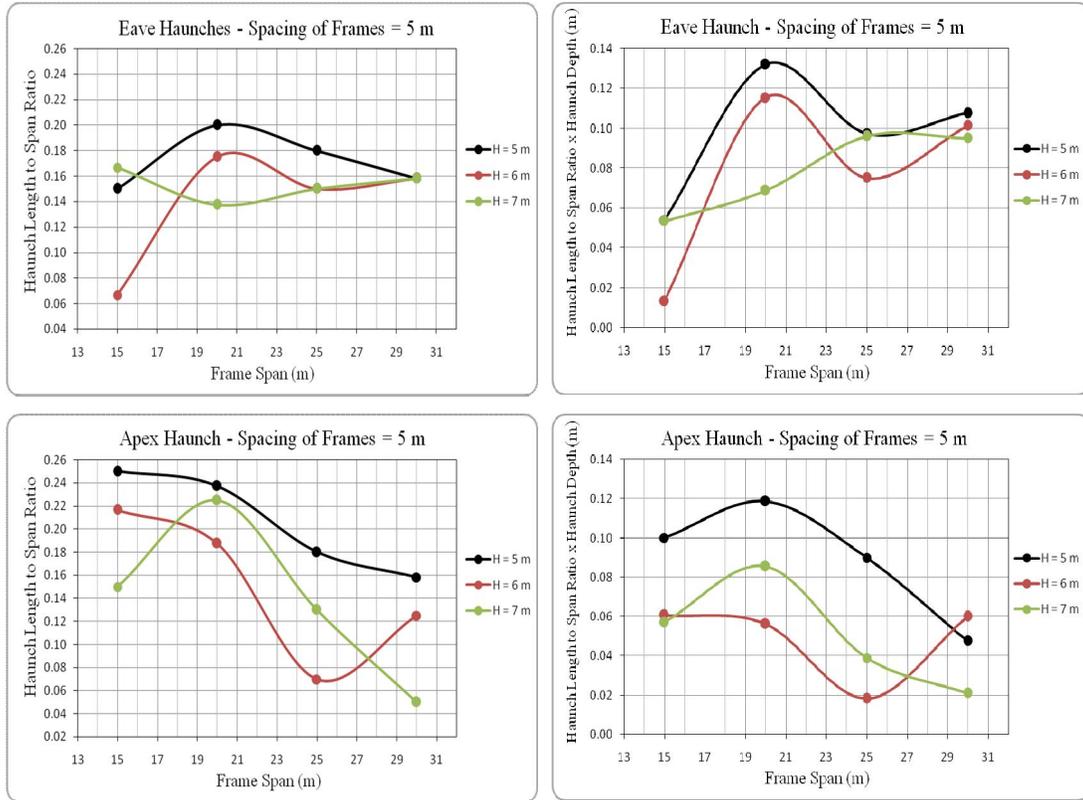


Figure 8. Relationship between frame span and haunch length to span ratio - Spacing = 5m.

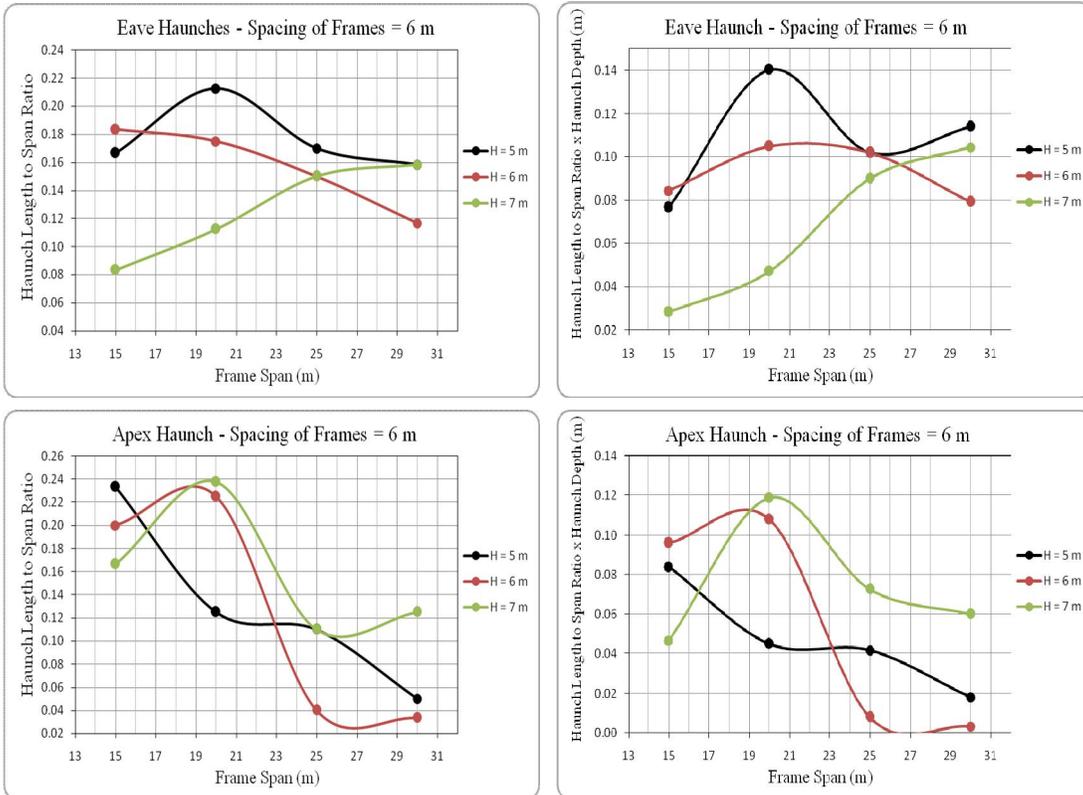


Figure 9. Relationship between frame span and haunch length to span ratio - Spacing = 6m.

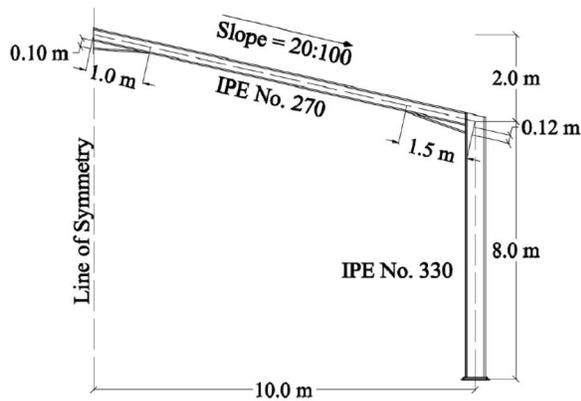


Figure 10. The best frame in case of releasing displacement constraint; Weight = 1590 kg.

Upon releasing displacement constraint, the best frame's weight equals 1590 kg which represents a reduction of 5.75% compared to the obtained weight upon applying this constraint. Also, it is interesting to notice that haunches' dimensions at eaves and apex, in case of releasing displacement constraint, are obviously smaller than their counterparts in case of displacement constraint application. Such a result suggests that haunches are typically needed to resist displacements rather than stresses. It is worthwhile noting that the cross-sections used for this example in [16] do not satisfy ECP 205-2001 displacement constraints.

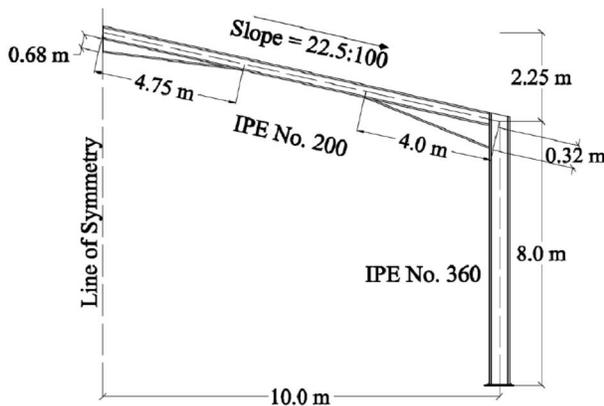


Figure 11. The best frame in case of applying displacement constraint; Weight = 1687 kg.

7. Conclusion

The design optimization of steel portal frames according to Egyptian standards can be put into practice utilizing tables and charts developed in the present work. Such design aids are produced using a Genetic Algorithm-based parametric study. Parameters assessed in this study are frame's span, column's height, spacing of frames, roof slope and imposed loads. Hot rolled standard steel sections are adopted for

frame's columns and rafters while frame's rafters are assumed to be provided with built-up haunches at eaves and apex. The objective is to obtain an economic design with the least weight. Considerable weight savings are achieved compared to traditional design procedure as well as other optimization methods. The contribution of rafters' haunched parts in optimizing the design is investigated. It has been shown that haunches are typically needed to resist displacements rather than stresses, especially in case of moderate spans with relatively light imposed loads.

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