FACTA UNIVERSITATIS
Series: **Architecture and Civil Engineering** Vol. 17, N° 4, 2019, pp. 359-376
https://doi.org/10.2298/FUACE190610021O

OPTIMIZATION OF SINGLE-SPAN SINGLE-STOREY PORTAL FRAME BUILDINGS

UDC 72.012.26
624.072.336
004.43Visual Basic

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Abstract. *Many structural designs are done without comprehensive consideration for achieving optimum design. To achieve minimum mass optimization, a mathematical model was developed in this study and subjected to British Standard (BS 5950) code requirements for structural integrity as constraints. Visual basic application (VBA) codes were written into a spreadsheet environment to implement the model. The developed optimization model was validated using different sample shed structures of same volume (729m³) but of different height to span to length (H: b: L) ratios which were obtained using the Ratio method and the Step size method. The best parameter ratio of height to length to breadth obtained was 1:1:1 which is similar to what was obtained by other authors. Parametric design case study analysis was also performed for three different design situations with a given span b, heights H and h and frame spacing S. The minimum masses of steel for a fixed plan area of the buildings were obtained for each of the three scenarios. It is recommended that design engineers should consider varying major frame parameters such as frame spacing and heights at pre-design stages in order to obtain optimal values of parameters which will ensure economical structures.*

Key words: *optimization, steel structures, portal frames, Visual basic, single-story*

1. INTRODUCTION

Single storey buildings form the largest sector of the steel construction market in the United Kingdom. These buildings are used mainly for workshops, factories, warehouses, stores and recreation. Traditionally they are called 'sheds'. The size of the sheds varies from small workshops with a few thousand square meters to warehouses with more than one million square meters. The increasing specialization of steel workers and other

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members of the supply chain has led to significant improvements in the quality, cost and delivery of single-story steel buildings. These improvements have been made possible by the increasingly effective use of the portal frame structures. Portal frames for industrial buildings have been extensively studied because of their wide spread use [1-6].

Earlier, before the advent of computer, an important goal of the structural design process was to find a calculation method that was elegant, simple and reasonably accurate. Once the efficacy of the design process is established, it was recorded as a convenient method to solve repetitive structural design problems. The approach which is referred to as the quick 'Rule of Thumb' became an essential resource for structural engineers. However, as computer software evolved and advanced the 'Rule of Thumb' and approximate method became less important. Quick computational speed and ease of application of computer methods made the initial 'Rule of Thumb' approach less relevant. The computer-based approaches allow for quicker computation of design alternatives with great ability to improve structural integrity and reduce cost. The need to reduce cost of construction and shorten the implementation period necessitated a new design trend [7-9]. This new design approach uses analysis and design software to evaluate possible design options replacing the conventional design methods. Optimization is the process of modifying a system to make the system work more efficiently or use fewer resources. It involves studying the problems in which one seeks to minimize resources and maximize the benefits or profit by systematically choosing the values of real or integer variables from within an allowed set [10, 11].

To obtain efficient frame designs, researchers have introduced various optimization techniques ranging from mathematic programming to stochastic search technique [12]. The complexity of these techniques made many researchers reluctant to use them in common practice [13]. The mathematical gradient based programming method requires formulating a set of equations and obtaining derivatives to handle different design situation. This was argued to be a cumbersome task [11]. On the other hand, Stochastic search technique required overcoming obstacles such as pre-convergence, computation costs and processing time issues to reach an optimal solution. The limitations became more complicated when the assessed problems had a complex search space [13].

Researchers have also experimented with evolutionary computing methods, including genetic algorithms [14-20] and simulated annealing [21] and Generalized Reduced Gradient (GRG) algorithm [22]. Grierson and Khajehpour [23] developed methods involving multi-objective genetic algorithms (MOGAs) and Pareto optimization to investigate trade-offs for high-rise structures

2. Objectives of Investigation

In the face of increase in price of materials, economic recession and increase in competition, civil engineers and manufacturers are forced to reduce cost of construction and shorten the implementation period [22]. As a result, removal of excesses is a priority. Optimization is a sure means of achieving removal of excesses. This research work aimed at optimizing frame parameters of single span single storey steel open frame utility building. The specific objectives of the research work are to:

i. develop a minimum mass optimization model for fixed and pinned feet single span single storey portal steel frame utility building, and
ii. establish the relationships between frame parameters and the mass of frame work steel.

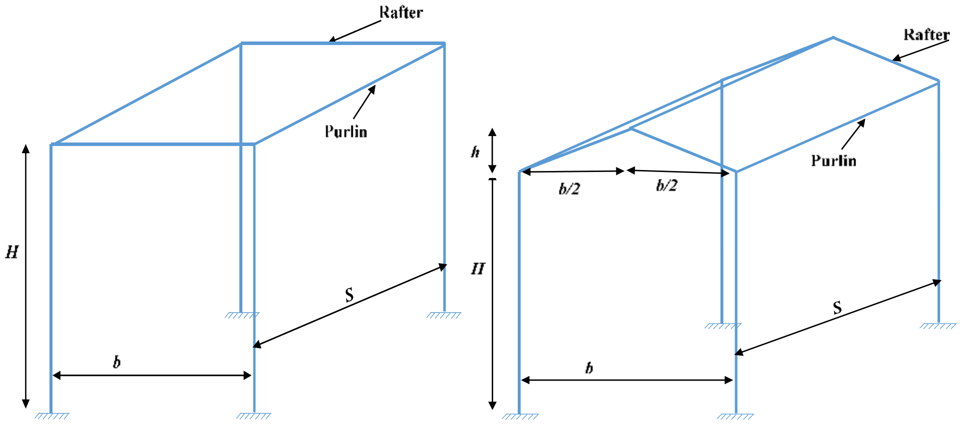
The developed optimization model will be verified using twenty-five sample shed structures of the same volume (729m³) but of different height to span to length *(H: b: L)* ratios. Visual Basic Application (VBA) codes will be written in Microsoft Excel 2010 environment to implement the model for three case studies. The usefulness of this work derives from the fact that optimization helps in the production of minimum mass designs and promotes reduction of construction weight with attendant improvement in the ease of construction of portal steel frames. The study is unique in the flexible ability of the program written and combination of tables and charts to present optimization process results.

3. Research Methodology

3.1. Development of minimum mass optimization model

The following were considered in order to obtain the overall mass of the portal frame structure:

i. The structure was divided into frames whose number was determined based on its length
ii. The frames are far apart at a constant distance (or frame spacing)
iii. The structure consists of a minimum of two portal frames
iv. Each frame consists of two stanchions, two rafters for pitched roof (Fig. 1a) and one rafter for flat roof (Fig. 1b)



(a) Pitch frame structure (b) Non-pitch steel frame structure

Fig. 1 Typical sections of pitch and non-pitch fixed feet open frame

i. Open steel frame pitched single span single storey building [Fig. 1(a)]

Two stanchions are required for each frame in a typical pitched portal frame building (Fig. 1(a)). Therefore, for n number of portal frame in a building, the mass of stanchion for the entire structure (M_T) is expressed in Equation 1.

$$M_T = 2nM_s \tag{1}$$

Similarly, two rafters whose lengths on plan are 1/2 of the breadth of the building are required in a typical pitched portal frame (Fig. 1). Therefore, for *n* number of portal frames in a building, the total mass of rafter M_R is expressed in Equation 2.

$$M_R = \frac{1}{2} \cdot 2nM_r = nM_r \quad (2)$$

Purlins are usually spaced at 1.2m for long span corrugated aluminum roofing sheets ideal for shed structures. Hence, purlin is assumed to be spaced at 1.2*m*. Hence, the total mass of purlin, M_{Pt} is expressed in Equation 3.

$$M_{Pt} = \frac{b}{1.2} M_p \cdot S \cdot (n-1) \quad (3)$$

The total mass of steel for the building frame is expressed in Equation 4.

$$Z = M_T + M_R + M_{Pt} = n(2M_s + M_r) + \frac{b}{1.2} \cdot M_p \cdot S \cdot (n-1) \quad (4)$$

where M_s is the mass of stanchion
M_r is the mass of rafter
M_R is the total mass of rafter
M_p is the mass of purlin per unit length
M_{Pt} is the total mass of purlin
M_s is the mass of one stanchion
M_t is the mass of two stanchions of a portal
M_T is the total mass of stanchion for the entire building structure
L_p is the length of purlin
N_p is the number of purlins
S is the frame spacing
b is the breadth of building (or frame span); and
Z is the total mass of steel for the building frame.

ii. Open steel frame of non-pitch portal frame [Fig. 1(b)]

Two stanchions are also required per each frame in a typical non-pitch portal frame. However, just one rafter is required. The total mass of steel mathematical model is similar for both pitch and flat roofed portal frame considered.

iii. Design Objective

The objective is to obtain the minimum mass of the structural steel that adequately satisfy the design constraints.

Therefore, the Objective function is expressed in Equation 5.

$$Z = n(2M_s + M_r) + \frac{b}{1.2} \cdot M_p \cdot S \cdot (n-1) \quad (5)$$

Minimize Z subject to the following constraints (BS 5950-1:2000)

a. Moment resistance M
b. Design steel stress P_y
c. Overall Buckling P_b
d. Section Classification
e. Serviceability, using the criterion of minimum web thickness, t_w
f. Shear Strength check.
g. Compression Resistance P_c
h. Equivalent Slenderness λ_{LT}
i. Minimum web thickness t

Accordingly, the constraints are expressed below

Minimize Equation 5 subject to Equation 6 to 14

a. **Moment resistance *M***

$$C_1 = M \leq Mb / m_{LT} \quad (6)$$

b. **Design steel stress P_y**

$$C_2 = P_y (275N / mmA?) \quad (7)$$

c. **Overall buckling P_b**

$$C_3 = V / P_c + M_x / M_b + M_y / P_y Z_y \leq 1.0 \quad (8)$$

d. **Section classification**

$$C_4 = IF\ \frac{b}{T} < 9 \in \text{ and } \frac{d}{s} < 80 \in \text{ then the section is plastic} \quad (9)$$

e. **Serviceability, using the criterion of minimum web thickness, t_w**

$$C_5 = T \text{ and } C_{web} < P_{bw} = (b_1 + n_1 k) \cdot t_w \cdot P_{yw} \quad (10)$$

f. **Shear strength check**

$$C_6 = F_V \leq P_V \text{ where } P_V = 0.6 P_y A_V \quad (11)$$

g. **Compression resistance P_c**

$$C_7 = P_c = A_g P_c,\ p_c = \frac{P_E P_y}{\Phi + \sqrt{(\Phi^2 + P_E P_y)}} \text{ where } P_E = \pi^2 E / \lambda^2 \quad (12)$$

h. **Equivalent slenderness λ_{LT}**

$$C_8 = \lambda_{LT} = UV\lambda \sqrt{^{\beta} w} \quad \lambda = L_E / \gamma_y \quad (13)$$

i. **Minimum web thickness *t***

$$C_9 = t \geq d / 250 \quad (14)$$

where M_b is the buckling resistance moment
m_{LT} is the equivalent uniform moment factor for lateral torsional buckling
V is the compressive force due to axial force
P_c is the compression resistance
M_x is the nominal moment about the major axis
M_y is the nominal moment about the minor axis
P_y is the steel design strength
Z_y is the section modulus about the minor axis;
b is the flange length

T is the flange thickness
d is the web length
s is the web thickness
C_{web} is the web compressive force
r is the root radius
P_{bw} is the web bearing capacity
b_1 is the stiff bearing length
P_{yw} is web design strength
λ is the slenderness
p_c is the compressive strength
A_g is the gross sectional area

iv. Variables

The design variables of the research work are

- Height to eaves: Ranging from 2.5m to 11.5m at a step size of 0.5m
- Height from eaves to apex: Ranging 0 to 17.3m (slope 0 to 60^0) at a step size of 3^0
- Frame Spacing: Ranging from 2m to 8m at a step size of 0.1m

3.2. Optimization Procedure

The optimization procedure is illustrated in Fig 2

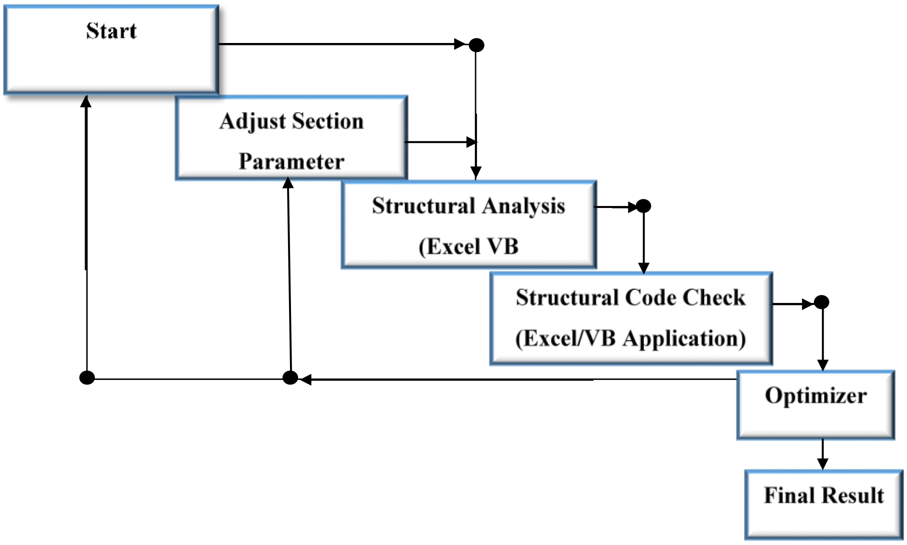


Fig. 2 Structural design, analysis and optimization process

3.3. Validation of model

Sample test of the already established parametric relationships of single span single storey open framed buildings were run on the program and similar results were obtained.

3.3.1. *Ratio method*

Using the ratio method, the ratio between the length, breadth and height of the structure was made in a modulus of 3. This was computed by the use of the tree diagram illustrated in Fig. 3. The re-occurring ratios which are 2:2:2 and 3:3:3 were removed and the 25 possible ratios of length, breadth and height are used to model 25 different portal frames of same volume (729m³). Each of the models was designed for structural integrity using the Excel program produced by using basic Excel functions to implement design formula and satisfy design requirements. The masses of steel sections adequate for the purlins, rafters and stanchions of each of the 25 ratios of the same volume were optimized using the objective functions.

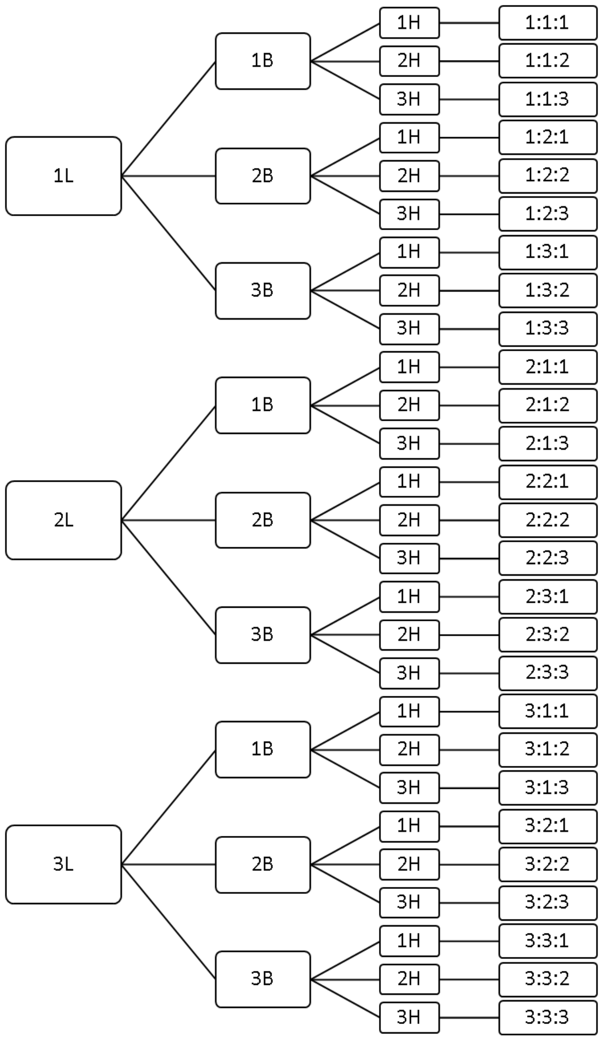


Fig. 3 A tree diagram for computation of possible combinations of the dimensions in mod3

3.3.2. *Step size method*

For same volume (729 m^3) of shed structure, the breadth (or span, *b*) and height (*H*) were kept at same ratio while the length (*L*) was varied at step size of 10cm to obtain optimum length for this volume (729 m^3). Similarly, the span and length were kept at same ratio and the height was varied at step size of 10cm to obtain optimum height for the same volume (729 m^3). Also, the length and height were kept at same ratio while the span was varied at step size of 10cm to obtain optimum span of the volume (729 m^3).

3.3.3. *Case study analysis*

Parametric design case study analysis was also performed for three different design situations with a given span b, heights H and h and frame spacing S. The design cases include:

A. Given a span *b*, frame spacing *S* and height from eaves to apex *h*, the height from ground to eaves *H* was varied and corresponding masses of steel for purlin, rafter and stanchion were estimated.
B. Given a span *b*, heights *H* and *h*, the frame spacing *S* was varied, and corresponding masses of purlin, rafter and stanchion were determined and
C. Given height to eaves *H*, height from eaves to apex *h* and optimal spacing *S* of 6.1m, span *b* was varied, and corresponding masses of purlin, rafter and stanchion were determined

3.4. Data analysis using VBA enabled spreadsheet

To obtain the mass of structure of each combination of dimensions, a VBA enabled spreadsheet is developed to calculate the number of frames, the mass of purlin, mass of rafter and the mass of stanchion. The conventional method of programming the spreadsheet to select the section of steel was used according to the British Standard codes (BS5950) for the stipulated dimensions. Relevant functions were defined using Visual Basic for Applications in the supplied Visual Basic editor, and such functions were automatically accessible on the worksheet. Programs were written that pull information from the worksheet, perform required calculations, and report the results back to the worksheet.

4. Results and Discussions

4.1. Results and discussion of the Ratio method

Masses of steel sections which satisfy design requirements were optimized by the use of the objective functions. The results displayed in Table 1 serves as guide for validity of the objective functions. The objective of the structural optimization process was to minimize the cost of steel frame while satisfying structural safety criteria for strength design. From Table 1 and Fig. 4, the minimum resultant steel mass of 1,755.80kg was obtained when the length: breath: height was ratio at 1:1:1. The result is in agreement with the results from other researchers [14, 16, 20]. The most expensive parametric combination was l: b: 3h with a huge resultant mass of 13,288.29kg. The results revealed the possibility of wasting (or saving) more mass of steel by simple parameter adjustment. Huge savings can be made when parameters are adequately combined while careless combination of shed dimensions can cause significant increase in cost.

Table 1 The resultant mass of steel involved in the computation of the data generated by the ratio method

Ratio	Length(m)	n=l/4	mr(kg)	ms(kg)	Ms(kg)	Mr(kg)	Mp(kg)	Z (kg)
l.b.h	**9.00**	**2**	**32.80**	**23.10**	**207.90**	**417.48**	**11.90**	**1755.80**
l.b.2h	7.14	2	25.20	45.00	642.90	254.57	11.90	3151.58
l.b.3h	**5.83**	**2**	**23.10**	**149.20**	**3197.34**	**190.54**	**11.90**	**13228.29**
l.2b.h	7.14	2	60.10	19.00	135.72	1214.28	11.90	3113.13
l.2b.2h	5.67	2	45.00	40.30	456.97	721.63	11.90	3383.60
l.3b.h	6.24	2	89.30	16.00	99.84	2364.23	11.90	5313.48
2l.b.h	14.29	4	25.20	19.00	135.72	254.57	11.90	2316.59
2l.b.2h	11.34	3	23.10	37.00	419.55	185.22	11.90	3185.42
2l.b.3h	10.43	3	19.00	45.00	651.67	129.71	11.90	4394.91
2l.2b.h	11.34	3	45.00	16.00	90.71	721.63	11.90	2934.07
2l.2b.3h	7.86	2	31.10	40.30	475.27	345.80	11.90	2670.65
2l.3b.h	10.43	3	59.80	13.00	62.75	1224.71	11.90	4337.88
2l.3b.2h	7.86	2	46.00	19.00	149.38	767.20	11.90	2248.88
2l.3b.3h	6.87	2	39.10	31.10	320.41	569.68	11.90	2523.15
3l.b.h	18.72	5	23.10	16.00	99.84	203.86	11.90	2265.26
3l.b.2h	14.48	4	19.00	25.20	262.79	129.71	11.90	2764.78
3l.b.3h	12.98	3	16.00	40.30	523.10	97.90	11.90	3518.15
3l.2b.h	14.48	4	39.10	13.00	62.75	576.64	11.90	3118.83
3l.2b.2h	11.79	3	31.10	19.00	149.38	345.80	11.90	2089.62
3l.2b.3h	10.30	3	25.10	31.10	320.41	243.80	11.90	2790.06
3l.3b.h	12.98	3	54.10	13.00	56.25	993.11	11.90	3574.24
3l.3b.2h	10.30	3	39.10	19.00	130.50	569.68	11.90	2696.36

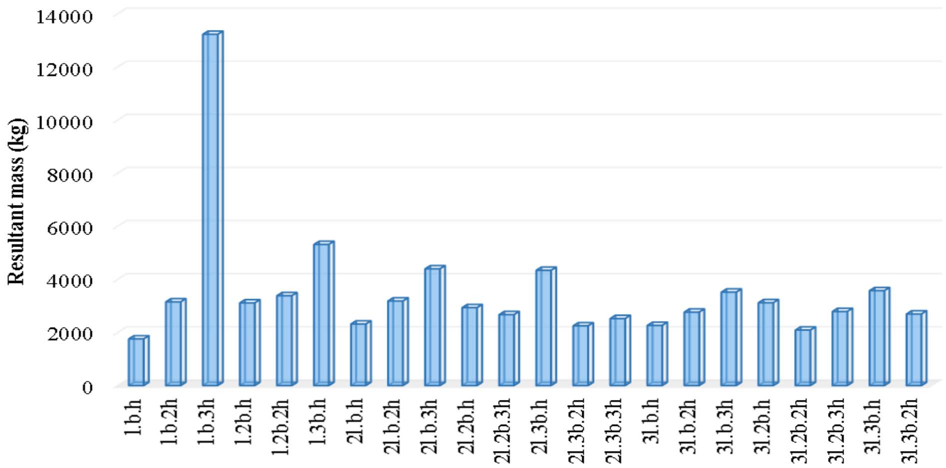


Fig. 4 Chart of the resultant mass of steel versus the ratio of dimension

4.2. Results and discussion of the Step size method

Masses of sections of purlin, rafter and stanchion obtained by the step size adjustment of the frames parameters were computed for the optimum masses of steel using the objective function. The results are displayed in Table 2 to Table 4.

The step size method results in Table 2 show the optimum parameters of length 9.1m, breadth 8.95m and height 8.95m (1.017l: b:h) with resultant steel mass of 1,746.13kg. In Table 3 minimum resultant mass of steel of 1739.21kg is achieved at 9.15m length, 8.7m breadth and 9.15m height (1.05l: b: 1.05h). Table 4 revealed the minimum resultant mass of 1,755.80kg at 9m length, 9m breadth and 9m height (l: b: h). From table 4.5, optimum resultant steel mass of 1,743.84kg is obtained at 9.1m length, 8.6m breadth and 9.21m height (1.06l: b : 1.07h).These results are equivalent and similar to the result obtained by ratio method in table 4.1 and complement previous works [24] on parametric optimization of single span single storey structures.

Table 2 The resultant mass of steel of fixed portal frame for a varying length (Length >7.0m) keeping height and breadth the same on a fixed volume

Length(m)	Breadth(m)	Height(m)	n=l/4	mr(kg)	ms(kg)	Ms(kg)	Mr(kg)	Mp(kg)	Z(kg)
7.8	9.67	9.67	2	37	25.1	242.66	505.86	11.90	2078.22
7.9	9.61	9.61	2	37	25.1	241.11	502.65	11.90	2065.02
8	9.55	9.55	2	37	25.1	239.60	499.50	11.90	2052.08
8.1	9.49	9.49	2	37	25.1	238.12	496.41	11.90	2039.37
8.2	9.43	9.43	2	37	25.1	236.66	493.37	11.90	2026.90
8.3	9.37	9.37	2	37	25.1	235.23	490.39	11.90	2014.65
8.4	9.32	9.32	2	37	23.1	215.20	487.46	11.90	1928.09
8.5	9.26	9.26	2	37	23.1	213.93	484.59	11.90	1916.72
8.6	9.21	9.21	2	37	23.1	212.68	481.76	11.90	1905.54
8.7	9.15	9.15	2	37	23.1	211.45	478.98	11.90	1894.56
8.8	9.10	9.10	2	37	23.1	210.25	476.25	11.90	1883.76
8.9	9.05	9.05	2	37	23.1	209.06	473.57	11.90	1873.15
9	9.00	9.00	2	32.8	23.1	207.90	417.48	11.90	1755.80
9.1	**8.95**	**8.95**	**2**	**32.8**	**23.1**	**206.75**	**415.18**	**11.90**	**1746.13**
9.2	8.90	8.90	3	32.8	23.1	205.63	412.91	11.90	2649.06
9.3	8.85	8.85	3	32.8	23.1	204.52	410.69	11.90	2634.77
9.4	8.81	8.81	3	32.8	23.1	203.43	408.50	11.90	2620.72
9.5	8.76	8.76	3	32.8	23.1	202.36	406.34	11.90	2606.89
9.6	8.71	8.71	3	32.8	23.1	201.30	404.22	11.90	2593.28
9.7	8.67	8.67	3	32.8	23.1	200.26	402.13	11.90	2579.88
9.8	8.62	8.62	3	32.8	23.1	199.23	400.07	11.90	2566.68
9.9	8.58	8.58	3	32.8	23.1	198.22	398.05	11.90	2553.69
10	8.54	8.54	3	32.8	23.1	197.23	396.05	11.90	2540.88

Table 3 The resultant mass of steel of portal frame for a varying breadth (breadth >9.0m) keeping height and length the same on a fixed volume

Length(m)	Height(m)	Breadth(m)	n=l/4	mr(kg)	ms(kg)	Ms(kg)	Mr(kg)	Mp(kg)	Z (kg)
9.55	9.55	8.00	3.00	28.20	25.10	239.60	319.05	11.90	2553.43
9.49	9.49	8.10	3.00	28.20	25.10	238.12	323.03	11.90	2558.47
9.43	9.43	8.20	3.00	32.80	25.10	236.66	380.37	11.90	2723.71
9.37	9.37	8.30	3.00	32.80	25.10	235.23	385.01	11.90	2731.03
9.32	9.32	8.40	3.00	32.80	23.10	215.20	389.64	11.90	2626.71
9.26	9.26	8.50	3.00	32.80	23.10	213.93	394.28	11.90	2635.00
9.21	9.21	8.60	3.00	32.80	23.10	212.68	398.92	11.90	2643.41
9.15	**9.15**	**8.70**	**2.00**	**32.80**	**23.10**	**211.45**	**403.56**	**11.90**	**1739.21**
9.10	9.10	8.80	2.00	32.80	23.10	210.25	408.20	11.90	1744.66
9.05	9.05	8.90	2.00	32.80	23.10	209.06	412.84	11.90	1750.19
9.00	9.00	9.00	2.00	32.80	23.10	207.90	417.48	11.90	1755.80
8.95	8.95	9.10	2.00	37.00	23.10	206.75	476.17	11.90	1869.59
8.90	8.90	9.20	2.00	37.00	23.10	205.63	481.40	11.90	1876.54
8.85	8.85	9.30	2.00	37.00	23.10	204.52	486.63	11.90	1883.56
8.81	8.81	9.40	2.00	37.00	23.10	203.43	491.86	11.90	1890.66
8.76	8.76	9.50	2.00	37.00	23.10	202.36	497.10	11.90	1897.82
8.71	8.71	9.60	2.00	37.00	23.10	201.30	502.33	11.90	1905.05
8.67	8.67	9.70	2.00	37.00	23.10	200.26	507.56	11.90	1912.35
8.62	8.62	9.80	2.00	37.00	23.10	199.23	512.79	11.90	1919.71
8.58	8.58	9.90	2.00	37.00	23.10	198.22	518.03	11.90	1927.13
8.54	8.54	10.00	2.00	37.00	23.10	197.23	523.26	11.90	1934.61

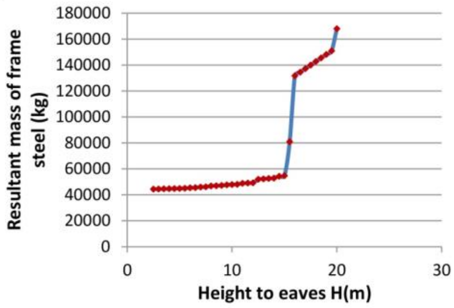
Table 4 The resultant mass of steel of portal frame for a varying height (height>8.0) keeping length and breadth the same on a fixed volume

Length(m)	Breadth(m)	Height(m)	n=l/4	mr(kg)	ms(kg)	Ms(kg)	Mr(kg)	Mp(kg)	Z (kg)
9.49	9.49	8.10	3	37	23.10	187.11	496.41	11.90	2800.04
9.43	9.43	8.20	3	37	23.10	189.42	493.37	11.90	2803.64
9.37	9.37	8.30	3	37	23.10	191.73	490.39	11.90	2807.42
9.32	9.32	8.40	3	37	23.10	194.04	487.46	11.90	2811.39
9.26	9.26	8.50	3	37	23.10	196.35	484.59	11.90	2815.53
9.21	9.21	8.60	3	37	23.10	198.66	481.76	11.90	2819.85
9.15	9.15	8.70	2	37	23.10	200.97	478.98	11.90	1852.62
9.10	9.10	8.80	2	37	23.10	203.28	476.25	11.90	1855.89
9.05	9.05	8.90	2	37	23.10	205.59	473.57	11.90	1859.25
9.00	**9.00**	**9.00**	**2**	**33**	**23.10**	**207.90**	**417.48**	**11.90**	**1755.80**
8.95	8.95	9.10	2	33	23.10	210.21	415.18	11.90	1759.95
8.90	8.90	9.20	2	33	23.10	212.52	412.91	11.90	1764.18
8.85	8.85	9.30	2	33	23.10	214.83	410.69	11.90	1768.49
8.81	8.81	9.40	2	33	25.10	235.94	408.50	11.90	1848.08
8.76	8.76	9.50	2	33	25.10	238.45	406.34	11.90	1853.35
8.71	8.71	9.60	2	33	25.10	240.96	404.22	11.90	1858.69
8.67	8.67	9.70	2	33	25.10	243.47	402.13	11.90	1864.11
8.62	8.62	9.80	2	33	25.10	245.98	400.07	11.90	1869.60
8.58	8.58	9.90	2	33	31.10	307.89	398.05	11.90	2112.75
8.54	8.54	10.00	2	33	31.10	311.00	396.05	11.90	2120.77

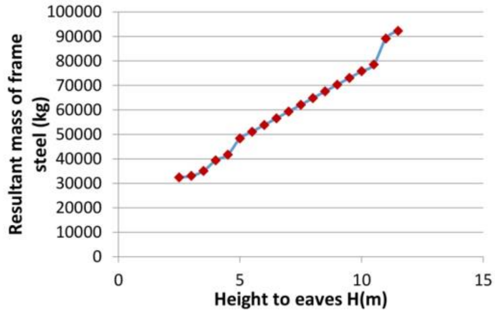
4.3. Results and discussion of Case study analysis

4.3.1. *Case A*

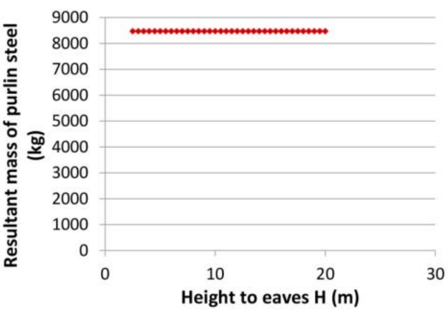
For a given length (20m), frame spacing (6.1m) and height from eave to apex (3.47m), the height to eave was varied from 2.5m to 22.5m at step size of 0.5m. Figures 5(a-f) present the



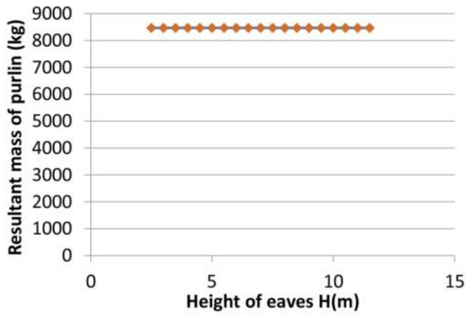
(a) Mass of frame steel versus the Height to eaves of fixed feet portal frame



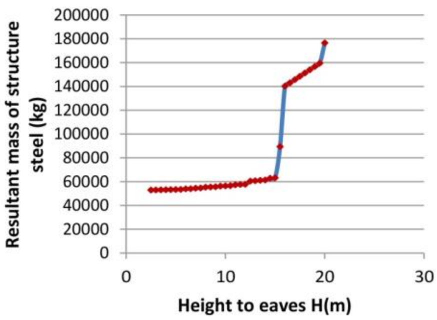
(d) Mass of frame steel versus the Height to eaves of pinned feet portal frame



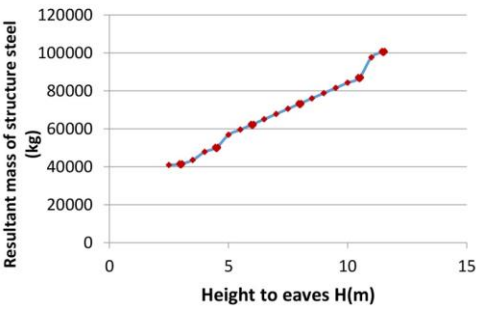
(b) Mass of purlin steel versus the Height to eaves of fixed feet portal frame



(e) Mass of purlin steel versus the Height to eaves of pinned feet portal frame



(c) Resultant mass of structured steel versus the Height of fixed feet portal frame



(f) Resultant mass of structure steel versus the Height to eaves of pinned feet portal frame.

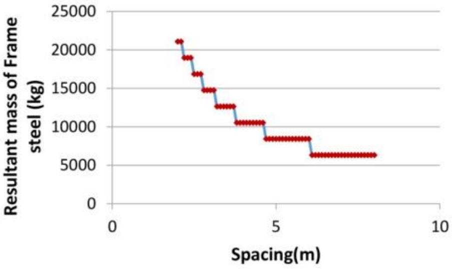
Fig. 5 Mass of steel for Case B design results of section optimization of stanchion in the structure for fix feet and pin feet. The figures graphically illustrate the relationship between change in respective masses of purlins, frames and structures for fixed or pin feet portal frames. The design with minimum resultant steel mass (cheapest design) that satisfied the constraints is considered the best. The best designs are highlighted. The minimum mass of 52,840.8kg and 40,881.7kg are obtained for fix feet and pin feet frames respectively when the stanchions were 2.5m high. Significant increase in masses of structures is noticed when height of stanchions was increased from14m to 14.5m and from 17.5m to 18m. The significant increase in mass of structure is due to stanchions slenderness requirement.

4.3.2. *Case B*

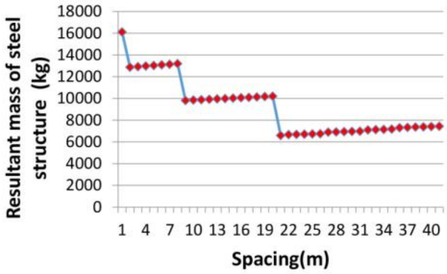
For a given span (20m), Height to eaves (10m), height from eaves to apex (3.5m), the spacing was varied from 2m to 8m at step size of 0.1m. Figures 6(a-f) present the optimization results of the fixed and pin feet frames. The figures portray the relationship between masses with respect to frame spacing. Mass of structure decrease as the frame spacing increase till the optimum mass was obtained at frame spacing 6.1m. Farther spacing resulted in increase in mass of the structure. All the three parts of the structure, the purlin, rafter and stanchion contributed to change in mass of the structure. Mass of purlin was highly nonlinear. Higher number of frames due to small frame spacing resulted in the initial very high mass of structure. As the spacing increased, the number of frames reduced hence mass of frame reduced. Huge reductions in mass of structural steel frame were noticed between frame spacing 3.7m and 3.8m; 4.6m and 4.7m; 6m and 6.1m. Also, significant increase in the masses of frame was observed when spacing was varied from 7.6m to 7.7m. Though 0.1m (100mm) can be considered to be insignificant in practice, but the effect in terms of mass reduction or increment is very significant. The effect of increasing mass of purlin became more significant as the frames get wider more due to the need for thicker steel section to compensate wider spacing. Initially, the increase in mass of purlin could not result to increase in mass of structure because of decrease in mass of frame. However, as the frames get wider, bigger sections are required for the purlin. The mass of purlin became more significant to the increase in mass of structure when the frames were 6.2m or more apart.

4.3.3. *Case C*

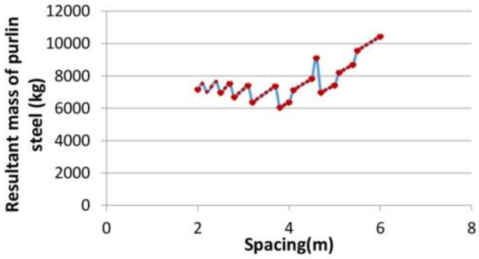
For a given Height to eaves (H=10m), height from eaves to apex (h=2m), frame spacing (s=6.1m), the span was varied from 4m to 29.5m at step size of 0.5m. Figures 7(a-f) show the result of change in span of fixed and pin feet portal frames. From the figures, the mass of structure steel of the fixed feet portal frame increased as the span increased. Expectedly, the increase in mass of the structure steel was due to increase in masses of purlin and rafter steel for the mass of stanchion steel remained constant as the span increased. Figures 7(d-f) however, showed initial reduction in mass of structure steel of pin feet portal frame when span was increased from 4.5m to 10.5m and afterward increased. The initial decrease in mass of structure steel was because of initial decrease in mass of stanchion steel. Contrary to the fixed feet portal frame, the mass of stanchion steel has a huge effect not only on the mass of structure steel but also on the graphical shape of pin feet portal frame.



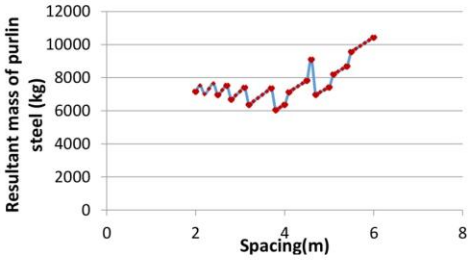
(a) Mass of frame steel versus the spacing for fixed feet portal frame



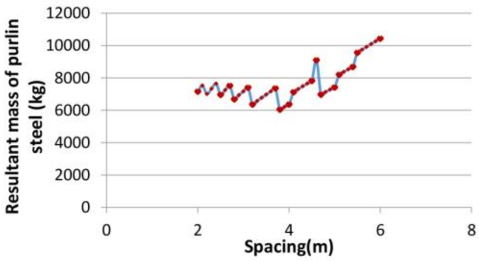
(d) Mass of frame steel versus the spacing for pinned feet portal frame



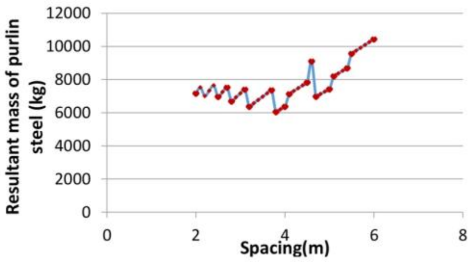
(b) Mass of purlin steel versus the spacing for fixed feet portal frame



(e) Mass of purlin steel versus the spacing for pinned feet portal frame

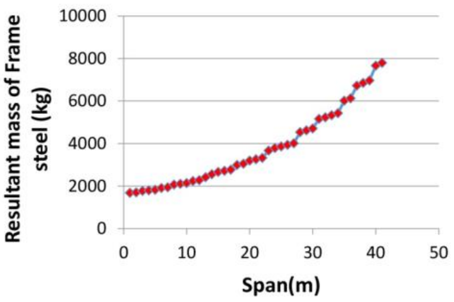


(c) Resultant mass of structured steel versus the spacing for fixed feet portal frame

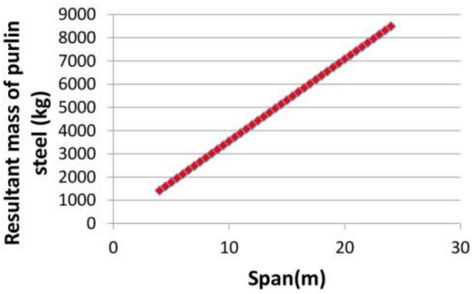


(f) Resultant mass of structure steel versus the spacing for pinned feet portal frame.

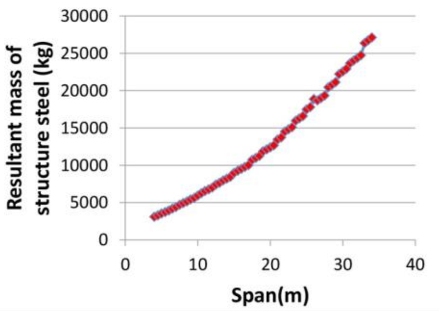
Fig. 6 Mass of steel for Case B design



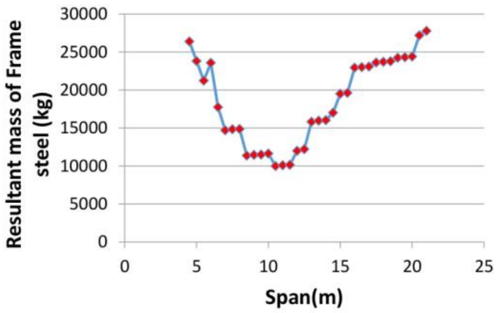
(a) Mass of frame steel versus the Span for fixed feet portal frame



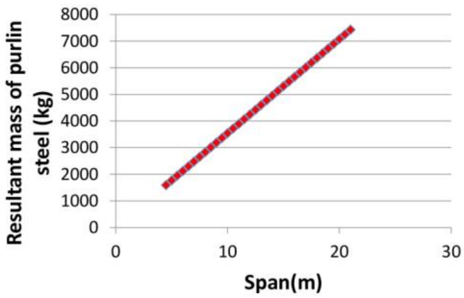
(b) Mass of purlin steel versus the Span for fixed feet portal frame



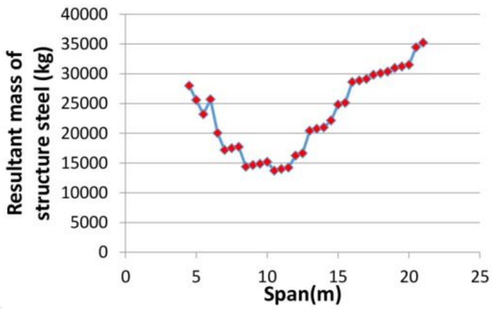
(c) Resultant mass of structure steel versus the Span for fixed feet portal frame



(d) Mass of frame steel versus the Span for pinned feet portal frame



(e) Mass of purlin steel versus the Span for pinned feet portal frame



(f) Resultant mass of structure steel versus the Span for pinned feet portal frame.

Fig. 7 Mass of steel for Case C design

4.3.4. *Boundary Conditions*

As shown in Figures 5 to 7, the mass of purlin remained the same despite similar increase in the height from ground to eaves and feet condition was changed from fixed to pin. This indicates that the change in the portal frame feet boundary conditions from fixed feet portal frame to pin feet has no effect on masses of purlin. However, significant change was experienced in mass of structure. For instance (Figure 5), mass of structure which was 59,000kg for fixed feet frame was increased to 80,000 kg for pinned feet frame at the same frame dimensions. The results suggest that fixed feet portal frames are more capable of achieving minimum weight at most variations of frame parameters.

5. CONCLUSIONS

The optimum and efficient structural design of a steel portal frame building involves considering various design alternatives. In this study, a mathematical model was developed (subjected to British Standard (BS 5950) code requirements for structural integrity as constraints) to achieve minimum mass optimization. Visual basic application (VBA) codes were written into a spreadsheet environment to implement the model.

The developed optimization model was validated using different sample shed structures of same volume (729m³) but of different height to span to length *(H: b: L)* ratios which were obtained using the Ratio method and the Step size method. The best parameter ratio of height to length to breadth obtained was 1:1:1 which is similar to what was obtained by other authors.

Parametric design case study analysis was also performed for three different design situations with a given span b, heights H and h and frame spacing S. The design cases include: 1) Given a span b, frame spacing S and height from eaves to apex h, the height from ground to eaves H was varied and corresponding masses of steel for purlin, rafter and stanchion were estimated. 2) Given a span *b*, heights *H* and *h*, the frame spacing *S* was varied, and corresponding masses of purlin, rafter and stanchion were determined and 3) Given height to eaves *H*, height from eaves to apex *h* and optimal spacing *S* of 6.1m, span *b* was varied, and corresponding masses of purlin, rafter and stanchion were determined. The minimum masses of steel for a fixed plan area of the buildings were obtained for each of the three scenarios. The minimum masses of steel for a fixed plan area of the buildings were obtained for each of the three scenarios.

From the results obtained, for a 20m span fixed feet frame at 6.1m frame spacing, 52,840.8 kg optimum mass was obtained at 2.5m height to eaves while maximum mass was 176,840.8kg at 22.5m heights. Also, optimum mass of 6206.5kg was obtained for horizontal rafter as against maximum mass of 71,664.3kg obtained at eaves to apex height 27.99m for a 15m span frame, with 9m height to eaves and 4m frame spacing. Similarly, optimum mass of 13,397.6kg was obtained at 6.1m frame spacing while the maximum mass of 28,242kg was obtained at 2m frame spacing for 20m span frame, 20m long structure, 10m height to eaves and 3.5m height from eaves to apex. Also, this research work as demonstrated how optimum parameters of steel formwork of fixed and pin feet single span single storey open frame building are obtained by minimum mass of structure steel.

The research work has established relationship between heights (H or h), steel frame spacing and mass of framework steel of fixed feet and pin feet single span single storey open frame buildings. Pinned feet frames were found to have larger masses of steel than fixed feet frames at most variations of frame parameters. It is recommended that design engineers should consider varying major frame parameters such as frame spacing and heights at pre-design stages in order to obtain optimal values of parameters which will ensure economical structures.

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OPTIMIZACIJA ZGRADA SA PORTALNIM RAMOVIMA SA JEDNIM POLJEM

Mnogi konstruktivni projekti se rade bez sveobuhvatne analize postizanja optimalnog dizajna. Da bi se postigla optimizacija minimalne mase, u ovoj studiji je razvijen matematički model podvrgnut zahtevima Britanskog standarda (BS 5950) gde konstruktivni integritet predstavlja ograničenje. Kodovi aplikacije Visual Basic (VBA) su pisani u okruženju proračunske tabele kako bi se model primenio. Razvijeni model optimizacije potvrđen je korišćenjem različitih primera konstrukcija hala iste zapremine (729m³), ali različitih odnosa visine prema rasponu (H: b: L), koji su dobijeni metodom Razmere i metodom veličine Koraka. Najbolji dobijeni odnos parametara visina - dužina i širina bio je 1: 1: 1, što je slično onome što su dobili drugi autori. Parametarska analiza slučaja projektovanja takođe je izvršena u slučaju tri različite konstrukcijske situacije sa datim rasponom b, visinama H i h i razmakom okvira S. Minimalne mase čelika za utvrđenu površinu zgrada su dobijene za svaki od tri scenarija. Preporučuje se da projektanti razmotre variranje parametara okvira kao što su razmak okvira i visina u fazi projektovanja kako bi dobili optimalne vrednosti parametara koji će osigurati ekonomičnu konstrukciju.

Ključne reči: *optimizacija, čelične konstrukcije, portalni ramovi, Visual basic, jedno polje*