Geometrically Optimum Design of Steel Portal Frames

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Abstract-Portal frames cover a high percentage of steel construction and demand flexible optimum cost solutions for design and construction purposes. This study determines the effects of change in geometry of portal frames on overall cost of the structure in terms of self-weight and will help practical designers to choose a quick economical bay spacing. The total width of portal frame was kept constant and change of bay width between portals and influence of shorter and larger span on portal design were the parameters under investigation. Initially, a 2D plastic analysis was performed on six different pinned base portal frames with varied span and bay spacing. The optimization was performed on the basis of member sizes and total weight of the frames. The most effective geometry was found to be the least selected bay width with shorter span. A 2D non-linear Finite Element (FE) model, reflecting actual lateral load field conditions, was then developed to validate the design of achieved optimal geometry of portal frames.

Keywords-Steel portal frames, geometrical optimization; bay spacing; strength-to-weight, finite element analysis

I. INTRODUCTION

In recent years, portal frames have become a must-to-adopt option to use as an industrial building. These structures offer sufficient open space and effective use of allocated land available in the building for industrial and storage purposes [i]. The versatility of these frames also lies in the facility of providing different eaves levels and openings in the same structure [i]. Moreover, internal columns can be easily replaced by valley beams in the case of multi-span portal frames. To support the future construction, built-in provisions for the building can be made at the design stage. Additionally, the excellent strength-to-weight ratio enables these frame in carrying

sufficient load and required spanning, satisfactorily. 'I' and 'H' sections are mainly used for columns and rafters in portal frames, however, for long span multi-bay portal frames, a few researchers focused to execute other types of cold-formed steel sections [i]. Portal frames carry high imposed loads and support the application of plastic analysis method in steel structures. If an elastic design is desired to be carried out, a torsional restraint must be provided under the haunch to maintain column stability. For the rafters, high bending moment in the plane of frame is the point of concentration for design process [ii]. A sagging moment near apex travels to the junction of rafter and column to create a high value hogging bending moment. In addition, rafters also sustain global compression due to the frame action [ii]. The behaviour of connections constituting the portal frame is significantly important [i]. These connections are the rafter-apex connection, column-base and the column-rafter connections and the connection between bracing members [i]. The connections either may be welded or bolted using gusset plates connected with the web of sections. Mainly, the column-rafter connections are designed to be moment-resisting in order to transfer bending moment from rafters to columns. This helps to reduce the size of rafter and to increase the span of frame with similar rafter size.

The use of cold-formed steel in several unique types of steel construction is widely recognized [ii-iv]. Further, the growing number of portal frame buildings with steel frames clearly shows the ability of structural steelwork to comfortably meet all of the requirements including minimum possible design and construction expenditures. For instance, the United Kingdom consumes 50% of the produced hot-rolled steel in single-storey buildings, mainly in portal frames [v]. A few studies have also brought to light more benefits of using cold-formed steel sections instead of traditional hot-rolled steel [vi, vii]. The major advantage of using cold-formed steel is that the weight and cost of a portal frame structure can be estimated precisely by the manufacturer which may pave the way for better structural optimization of portal frames.

The optimization of portal frames by analysing the effect of different geometries has not been discussed in the past. This research follows a simple approach and examines the influence of geometrical shapes on overall weight of structure by performing a plastic analysis using Quicksoft software. The model building was assumed to be located in Kuala Lumpur, Malaysia. BS5950 was referred to apply loading combinations and selection of member sizes. The total width of portal frame was kept constant and change of bay width between portals and influence of shorter and larger span on portal design was observed. Later, a non-linear FE model using Abaqus 6.13.4 [viii] was prepared based on the most optimal geometry. The model was prepared based on accurate field conditions and the results of linear analysis were validated. The effects of design decision, fabrication and erection on overall cost of whole project are also discussed.

II. LITERATURE REVIEW

The cost of material plays less than 50% role in optimizing a project [v]. The detailing, fabrication, erection and protection cover almost 60% cost of the project [ix]. The structural optimization in steel can be widely categorized into design and construction optimization. Furthermore, fabrication also makes a bridge in between design and construction. Recent researches in optimizing steel structures mainly focus on the concept of optimization during design process which is based on mathematical programming. Often used methods of design optimization are: Adaptive Random Search, Completive Evolution, Controlled Random Search, Simulated Annealing, Genetic Algorithms, Differential Evolution, and Particle Swarm Optimization [x]. Though, compared with construction optimization techniques, design optimization has more advantages because it does not require differential information other than the objective function, however, it is more difficult to be implemented as it depends on the gradient information about the objective function. Additionally, the involvement of Genetic Algorithms (GA) makes it more complex and lengthy process to apply [x].

The use of GA to optimize portal frames is well established. Reference [xi] considered the cross-section sizes of the columns and rafters, and both length and depth of the haunch as discrete variables using a binary-coded GA to achieve minimum weight of a portal frame under imposed load only. Position of lateral and torsional restraints was fixed under eaves haunch. He concluded with suitable universal beam and haunch sizes for his structure. The optimization of the same model, used by Saka, was further extended by Reference [xii]. They applied distributed GAs to minimize the weight of the structure and resulted with suitable column and rafter sizes. Reference [vii] used a Real-Coded GA to optimize the topography of portal frames and presented a précised optimum solution. Significantly, they replaced the hot-rolled steel sections with cold-formed steel.

A number of researches have performed serviceability design optimization. Reference [xiii] discussed the elastic design optimization technique of a single-storey steel building. Authors of [v] adopted two criteria to determine the serviceability deflection limit of portal frames; one suggested by Steel Construction Institute (SCI) and the other by industry. Their proposed GA was useful and demonstrated that the industry deflection limits are suitable to design deflection limits of their proposed portal frame model. The consideration about the working relationship between geometrical design of a structure and the optimization techniques during the manufacturing, fabrication and erection of the structure is rarely available. The literature reveals only a few studies applying design optimization methods to minimize the overall weight as well as cost of portal frames. Discussing the effects of geometry on portal frame optimization, reference [xiv] investigated the influence of using inclined columns in portal frames. His conclusion indicated that applying proper inclination to columns can increase the buckling load capacity of portal frames; hence, a more economical design can be achieved. Reference [xv] introduced the concept that using semi-rigid connections in portal frames considerably reduces the overall weight of structure. Authors of [xvi] also emphasized on using semi-rigid connections and performed design optimization operations focussing serviceability conditions in portal frames. Reference [xvii] applied design algorithms to achieve the minimum weight design of steel frames.

II. MODEL DETAILS

2.1. Layout

Two different types of layouts were selected for design purpose with different spacing. The span is 15 m for Structure 'A' and 30 m for Structure 'B'. The spacing of frames for both structures (bay width) varies as 5m, 6m and 7.5m, as shown in Figure 1, 2, 3, 4, 5 and 6 respectively, to achieve the optimum design of proposed steel portal frame. Eaves height is 7m and roof pitch is considered as 6°. The bases were assumed as pinned. The length of the haunch was measured from the centre of the column to the end of haunch and limited to 10% of the frame span in each case as illustrated in Figure 7. The depth of haunch was considered from underside of the rafter till its end. Light weight metal sheeting rails spanning between the columns of portal frame were used to counter adverse environmental impacts.

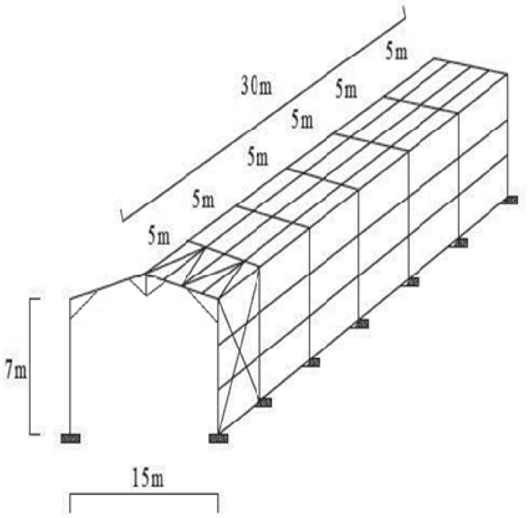


Fig.1. 5m Bay spacing in structure - A

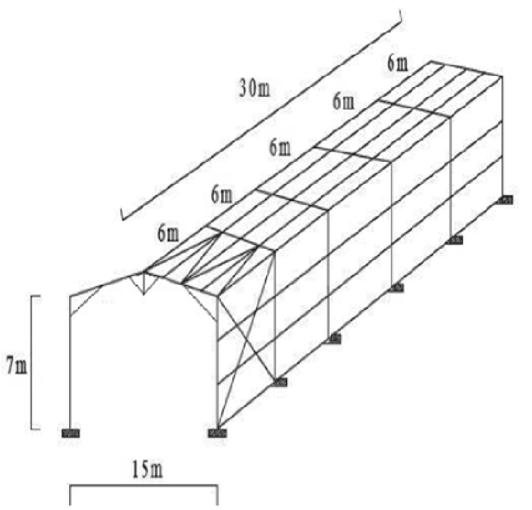


Fig.2. 6m Bay spacing in structure - A

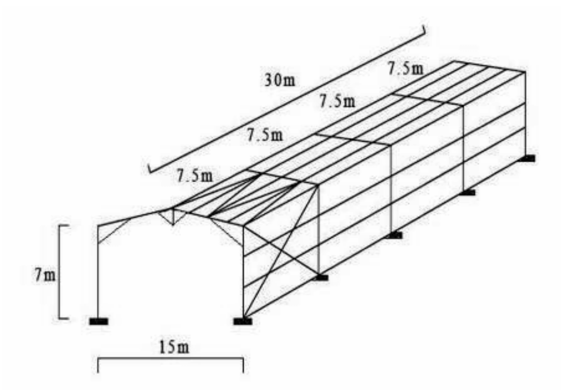


Fig.3. 7.5m Bay spacing in structure - A

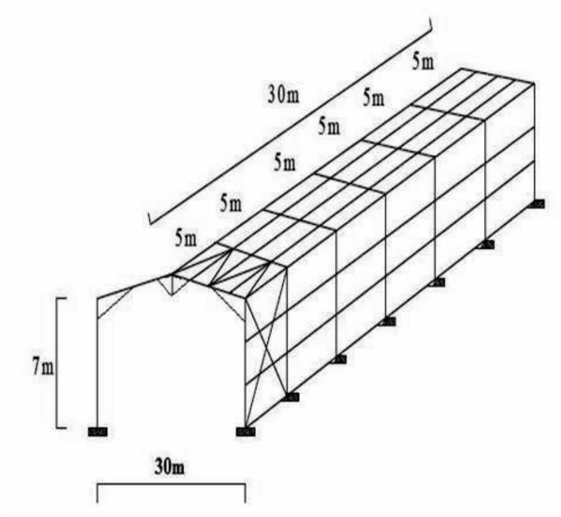


Fig.4. 5m Bay spacing in structure - B

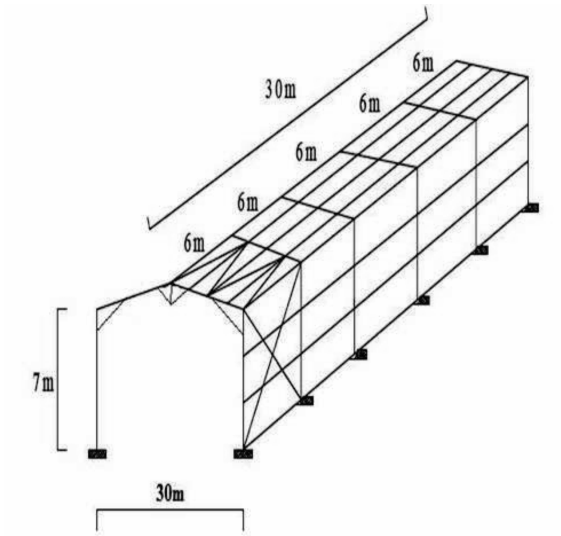


Fig.5. 6 m Bay spacing in structure – B

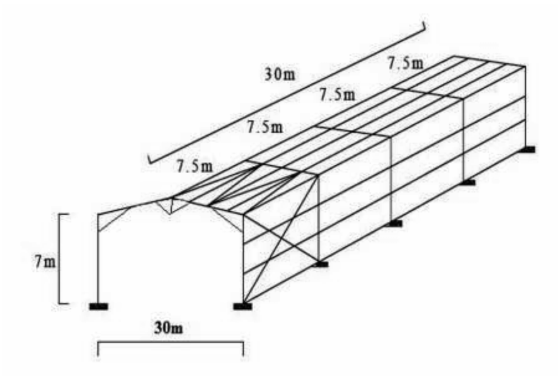


Fig.6. 7.5m Bay spacing in structure – B

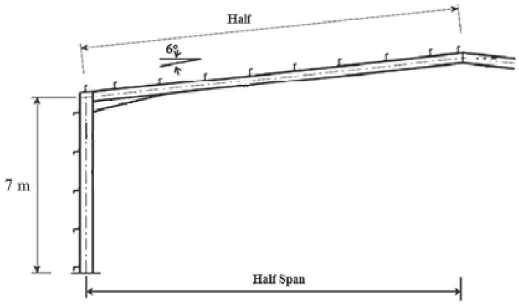


Fig.7. Eaves and haunches details

2.2. Section properties

Universal column (UC) and universal beam (UB) steel sections were proposed as columns and rafters respectively. The material properties were selected according to the most commonly used sections in the portal frames in the Malaysian construction industry and are given in Table I. Eaves haunch was designed following typical plastic design of portal frames. The haunches were supposed to be fabricated from the same section size of the rafter. Cold-formed C-section purlins were assumed at the roof. The weight of purlins is not considered in this study.

TABLE I

BASIC SECTION PROPERTIES

Connecting member	Steel grade (MPa)	Young's Modulus (GPa)	Poison's ratio	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)
Column	275	205	0.3	255	410
Rafter					
Purlin C-Section	-	210	0.3	305	550

2.3. Loading and design

The building is assumed to be located in Kuala Lumpur, Malaysia and data for wind loading and site distance from the sea was assumed according to the location [xviii]. The dead load and live load were considered as 0.66 kN/m2 and 0.60 kN/m2 respectively. BS 5950 [xix] was referred to assign section sizes and loading combinations and frame was checked for ultimate limit state and serviceability limit state. The frame is assumed to fulfil the criteria for in-plane stability of the sway check method and does not take into account the second order effects for analysis and design purpose. A plastic analysis was performed by using software named Quiksoft programme [xx]. The frames are analysed and designed through QuikPort analysis and design. The connections between columns and rafters were considered as moment resisting connections. All the connections were analysed and designed through QuikJoint program.

2.4. Optimization technique

A simple optimization technique based on trial of different geometries was adopted to optimize the structure. Keeping the total width of frames constant, the parameters considered for investigation are: (i) span of frames and (ii) variable bay widths.

II. RESULTS AND DISCUSSION

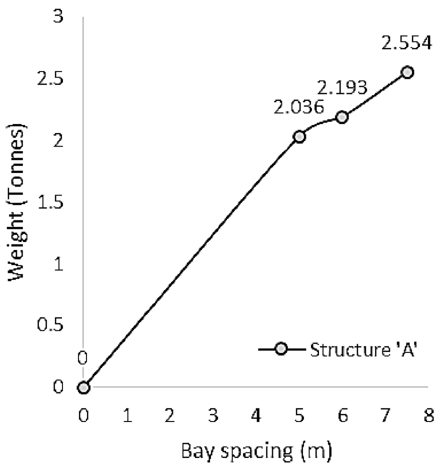
Table II summarizes the results obtained by the plastic analysis of single bay portal frame with different bay spacing and varied span. Spacing of 5m and 6m does not have much difference in the cases of both structure A. The weight of columns for 7.5m spacing is slightly greater than for 5m and 6m bay spacing. Consequently, the total weight also has small difference for all the types of spacing. Therefore, for overall cost of frame, it may be possible that there would be less cost require for fabrication and connection material and construction for higher bay spacing and overall cost may be equivalent to 5m bay spacing.

TABLE II
DIMENSIONS AND WEIGHT INFORMATION OF MEMBERS DESIGNED FOR ALL THREE FRAMES FOR STRUCTURES-A AND THREE FOR STRUCTURES-B

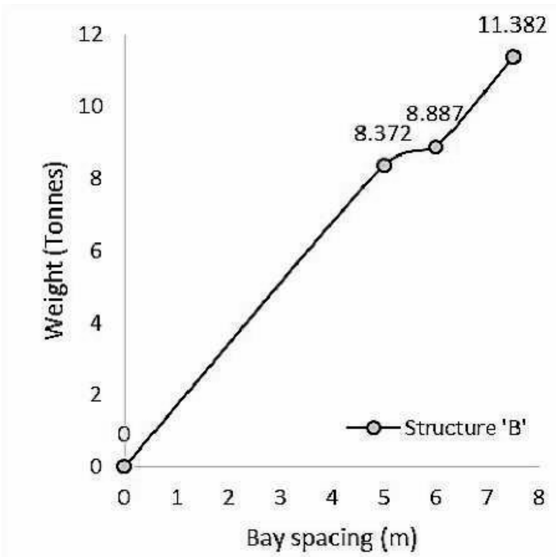
Structures	Total width (m)	Details		Spacing		
			-	5 m	6 m	7.5 m
"A"	15	Columns (2 bars per frame)	Dimensions	305*305*97UC	305*305*97UC	305*305*118UC
			Weight (tonnes)	1.163	1.163	1.415
		Rafters (2 bars per frame)	Dimensions	356*171*57UB	406*178*67UB	457*191*74UB
			Weight (tonnes)	0.873	1.030	1.139
		Total weight (tonnes)		2.036	2.193	2.554
"B"	30	Details		Spacing		
			-	5 m	6 m	7.5 m
		Columns (2 bars per frame)	Dimensions	305*305*240UC	305*305*283UC	356*406*340UC
			Weight (tonnes)	2.881	3.395	4.079
		Rafters (2 bars per frame)	Dimensions	610*305*179UB	610*305*179UB	610*305*238UB
			Weight (tonnes)	5.491	5.491	7.303
		Total weight (tonnes)		8.372	8.388	11.382

The effect of larger span greatly influenced on total weight of structure. The weight of columns with 7.5m bay spacing in structure B is almost twice of the weight of frame with 5m bay spacing. Comparison of 5m and 6m bay spacing exhibited that there is no change in rafter sizes for both frames, however, the column sizes slightly increased in 6m bay spacing. The overall weight of 7.5m bay spacing frame is highest again and it can be said that 5m bay spacing is the optimized spacing in terms of overall weight.

Figure 8 illustrates slight changes in overall weight of structure A with all types of spacing. However, increase in span influenced with higher weight members for all bay spacing choices. The weight of frame with 7.5m bay spacing in structure B is almost 4.5 times greater than the same frame in structure A. This shows that larger span has greatly affected the weight of the frame.



(a)



(b)

Fig.8. Variation in Total weight of Columns and Rafters according to change in spacing; (a) Structure 'A',
(b) Structure 'B'

IV. FINITE ELEMENT ANALYSIS

A FE model using Abaqus software was developed for all of the portal frames. A linear FE shell idealization of the cold-formed steel portal frame has been used to determine frame deflections. This employed shell elements for the I-sections. Both the columns and rafters were modelled using a feature

BEAM ELEMENT using a two-noded beam in plane. Beams are directly connected to the column, considering the connections as tie constraints instead of contact. Eaves and apex haunches were not modelled in order to estimate the bending stiffness of the members only. No initial imperfections are modelled in either the columns or the beams. The models were prepared for all six frames, however, only the results of the optimum structure (Structure 'A' with 5 m bay spacing) are presented in this study.

A lateral load of 15 kN was applied at the left column and that of 10 kN on the right column. A load of 2 kN acting on the left rafter in download direction and in upward direction on right rafter was applied. Pinned bases are simulated to apply practical field conditions.

Following assumptions were considered during the FE modelling of the frames:

1. Shear deformation is ignored;
2. Lateral-torsional and local buckling of the frame is not considered;
3. Only doubly symmetric sections are considered;
4. Local buckling and local failure of components in the base connections is neglected
5. Elastic-perfectly plastic steel behaviour is considered at member ends.

V. FE RESULTS

The frame deflection can be considered to be comprised of three components: (i). Deflection due to bending of the column and rafter members; (ii) Deflection due to bolt-hole elongation in the connections; and (iii). Deflection due to in-plane bracket deformation. This study considers the deflection due to the bending of the columns and rafters. Figure 9 shows the deflection of the members.

The suitability of the optimum structure was determined by applying the equal amount of lateral load on all frames and all six frames were tested. Only the deflection in the frame due to lateral load was considered as a result of FE analysis since the purpose of this study is to propose an optimum design of portal frames in terms of members' sizes, consequently the total weight of the frame. The model prepared for the based on the geometry of structure 'A' with 5 m bay spacing exhibited the same results which were predicted by other frames. Thus, it was validated that a bay spacing of 5 m for structure A is suitable for both design and construction purposes as it can sustain the same load and exhibit performance similar to the other tested frames with minimized weight and overall cost of fabrication and construction.

The major deflection occurred in the left column which is at its maximum at the point of intersection of column and rafter. The effect of absence of eaves haunch is clearly visible. This right rafter has also been bent due to the absence of apex haunch. Moreover, the insufficient bending stiffness of the section selected for rafter caused the bending in the member. For practical field conditions, either both the haunches should be fabricated from higher strength material as compared to the material used for rafters and columns.

The FE analysis could be further extended and the same model can be modified for various types of sections, locations and loading conditions and can be used for the design of portal frames in anywhere in the world. Moreover, the material properties can also be amended in the output. However, the investigation performed for geometrical optimization is general in nature and the philosophy can be applied in its present form.

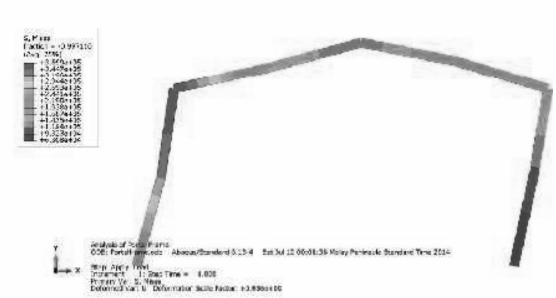


Fig.9. Finite Element Analysis of Structure 'A'

VI. CONCLUSIONS

This study emphasize on determining the effects of change in geometry of portal frames on overall cost of the structure in terms of self-weight. The total width of portal frame was kept constant and change of bay width between portals and influence of shorter and larger span on portal design was investigated by performing a plastic analysis using Quiksoft program. BS5950 was referred to apply loading combinations and selection of member sizes.

The results exhibited that keeping the total width constant, the change of spacing between the portal has varying effects upon the size of members and, consequently, on the total weight of frames. As more as the spacing of frames increases, the size of members increases. Minimizing the spacing of portals will minimize the overall cost of portal frames. Transportation and erection of low-weight member may decrease the cost of transportation and labour. However, the cost of assembly construction may be less in case of less number of members required for the structure.

It should be noted that the larger spans may greatly affect the weight of structure. The further study comparing the effect of a single bay larger and multi-bay span equal to the same as single bay span accompanied with different bay spacing may further elaborate the effects of change of span on overall cost of the structure. Furthermore, the research can be further expanded to study the cost reduction by comparing the welded and bolted connections, by including study about the variation in foundation of each of the six models or by having the market survey about labour costs for each of the proposed structure.

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