Portal Steel Trusses Vs Portal Steel Frames for Long Span Industrial Buildings

Hussein Haydar, Harry Far* and Ali Saleh

School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney (UTS), Australia

Portal frames and portal truss structures are two of the most cost effective and sustainable structural commodities for utilisation in the design and construction of long span industrial buildings. Although the application of both structure types as steel cladded structures is widely accepted, due to frame complexity and variation of frame types for use in single story buildings, that exceed spans greater than 30 meters, literature providing a comprehensive investigation on the concepts of portal trusses and portal frames is scarce. This study compares the behaviour of portal truss configuration with pitched portal frames for use in long span industrial buildings that exceed 30 meters with focus on weight, costs and time for construction. Furthermore, this study entails a numerical investigation that utilises SAP2000 computer program to model and structurally optimise the member properties for both portal frame and portal truss configurations. Based on the results obtained from the investigation, it has become apparent that the portal truss configurations are lighter and cheaper to fabricate and construct due to the smaller sections used in comparison to the pitched portal frame that require a shorter time for construction.

Keywords: *Portal Frames, Portal Trusses, Span Length, Construction Cost, Long Span Industrial Building*

1. Introduction

During past and present periods, light steel portal structures have been utilised as main structural elements in the erection of engineering applications and are extensively implemented around the globe as major modules in single level building applications. Several researchers (e.g. Salter et al. 2004; Woolcock et al. 2011; Dundu 2011; Milan and Patil 2015; and McKinstray et al. 2015) have studied the structural behaviour of portal structures spanning lengths amid 20 – 30 meters and have implemented the appropriate design procedures and analytical formulations to provide solutions. Although their studies identified the behaviour of portal frames and observed that weight saving is more pronounced when implementing a portal truss structure for spans greater than 30 meters, there is no sign of a detailed investigation that supports the behaviour of a portal truss which spans greater than 30 meters while considering the financial and practical aspects. Thus, this study has been conducted to provide a qualitative review by investigating and comparing the behaviour of portal trusses and portal frames for use in long span buildings, which exceed a span of 30 meters.

The investigation takes an engineering approach, by considering the weight, costs and time for construction for both structure types and uses 24 different design configurations where the internal column heights vary from 5 meters, 7.5 meters, 10 meters and the span lengths vary from 30 meters, 40 meters, 50 meters and 60 meters.

There are major design and construction implications that arise when recognising the qualitative characteristics between the implementation of a portal frame configuration or a portal truss configuration for a desired application. The behaviour of both structures are dependent on specific parameters including structural dimensions, weight, material properties, site conditions and load combinations (Dundu, 2011). Furthermore, it is suggested by Woolcock et al. (2011) that as the design span increases, a roof truss should be used in lieu of rafters. By doing so, the weight saving characteristics will be more pronounced. That is until the cost of fabricating the truss system is offset with the cost of fabricating a typical portal frame system as pointed out by Woolcock et al. (2011). However, as elucidated by Brohn et al. (1995), reducing the total weight of a portal structure will not always provide the most economical design and the relationship between cost and weight is not linear but rather parabolic. When designing a portal truss structure or any portal frame, Brohn et al. (1995) demonstrated that an engineer must assess if there is a possibility of a simpler configuration or if rationalisation of section sizes can lead to an improvement in the overall costs. In addition, as Brohn et al. (1995) and Woolcock et al. (2011) pointed out that considering the supporting foundations as fixed base costs more to construct due to possessing a more complex connection type, the portal frame and portal truss configurations in this study have been designed with simply supported foundations.

2. Studied Models

A common portal truss structure is comprised of a set of braced columns that support an overhead truss. A prominent attribute of a portal truss is the way its members are structurally designed to withstand uplift loadings due to wind. Figure 1 depicts the portal truss configurations examined in this study, where a pitch of 3 degrees has been adopted (European Design Manuals 2008; Woolcock et al. 2011; Brohn et al. 1995). As stated previously, the span lengths that have been considered are 30, 40, 50, 60 meters and the internal column heights are 5, 7.5 and 10 meters. The truss structure is comprised of a bracing system with top, bottom, vertical and diagonal chords that are connected by pin joints. The bracing system provides a higher stiffness and the utilisation of pin-ended members disallows the rotation within the joints, and keeps bending in the members negligibly small.

According to Woolcock et al. (2011), one of the pronounced difficulties in contrasting both structures is that building a truss above two lateral columns is distinctively higher than building with rafters assuming that the internal height clearance for both structures are equivalent. Henceforth, in order to provide a fair comparison between both structures, the overall height offsets between both must be kept minimal. Consequently, after a careful investigation, a pitch of 9-degrees has been adopted for all portal frame designs, while the portal truss espoused a top chord inclination of 3-degrees. Additionally, due to the haunch design, the clear internal height for the portal frames as depicted in Figure 2 does not apply to the entire frame span.

Figures 1 and 2 depict the frame configurations for all examinable cases. The portal frames examined in this numerical study have a generic pitched configuration, whereas the portal truss adopts a Pratt truss configuration. Both types of structures are easy to design and construct and in contrast to other types i.e. (scissors, vaults, gambrel, hip etc.) they are most commonly utilised (Duwadi & Ritter, 1997).

According to Woolcock et al. (2011) and Kirke (2004), any steel cladded structure must suit the intended application and must be designed in accordance to general principles of steel design and wind codes. This study applies the Australian Standards (AS 4100-1998), (AS 1170.0-2011) and (AS 1170.2-2011). Additionally, this study conducted a concise design optimisation procedure based on a 2nd order structural analysis in order to determine the most competitive structural design.

3. Steel Section Optimisation

When designing steel structures, engineers must consider how load combinations influence the behaviour of the frame members. Members that are not design optimised may fail due to the design loads imposing forces that are larger than the section and member capacities. The section and member capacity checks have been conducted in accordance to section 8 of AS 4100-1998 and the design actions have been developed by observing the requirements of AS 1170.

SAP2000 is a powerful computer program that considers the design approaches documented in AS 4100-1998. The steel design preferences for AS 4100 - 1998 have been implemented in this investigation and the program selects the appropriate material properties based on the combined action effects. This may be a tedious and long process if conducted by hand, fortunately enough, the development in computer programs has provided great assistance in the field of structural engineering.

4. Numerical Investigation

While conducting the investigation, there are limitations brought upon by various parameters, conditions and assumptions. It is therefore essential to illustrate the specific variables involved in the investigation which ultimately govern the boundaries and limitations of the projects scope. Although this investigation focuses primarily on the design of the portal frames and portal trusses, building dimensions need be established in order to carry out wind and pressure loadings applied to the frames. This numerical investigation is based on a number of cases which are divided into two types of structural models depicted in Figures 1 to 3. Both systems are governed by their column heights and span lengths and are limited to a two-dimensional single frame analysis, Table 1 provides emphasis on the building and frame dimensions.

4.1. Design Actions

This investigation considers the design actions of the columns, rafters, truss members and secondary elements (roof sheeting and purlins) for each separate configuration. Other elements such as roof insulations have also been accounted for in the design. The secondary elements significantly improve the structural stability for a full three-dimensional model i.e. long span building model. Mahendran (1997) depicted that the influence of gravity and longitudinal wind loads acting on a fully cladded frame is insignificant because the roof slope. However, under traverse wind loads, it is essential to consider the significance of full cladding as the deflection is much smaller in contrast to a bare frame, therefore the gravity loads due to secondary members are considered as they attribute to the structures economic costs (Steel Construction Institute, 2008)

Both models have been designed in accordance with AS/NZS 1170.2 (2002) for implementation in Sydney Australia, which is specified as a non-cyclonic region. The wind load combinations adopted from AS/NZS 1170.2 (2002) as well as the imposed actions specified in Table 2 have been examined in the design analysis. Although six load combinations have been presented, in accordance to AS/NZS 1170.0 (2002) imposed loadings and loads due to wind actions are not necessary to be considered simultaneously in an industrial portal frame building with non-trafficable roof. Therefore, the following most severe load combinations, from the presented load cases in Figure 4, have been identified and applied to both structures in SAP2000:

- Load Combination 1 (LC1): 0.9G + Load Case 1 + Load Case 2 (inside flange in tension)
- Load Combination 2 (LC2): 1.2G + Loa Case 3 + Load Case 4 (inside flange in compression)

Where both load combinations include the dead loads due to the frame and secondary members and the wind loads due to traverse wind maximum uplift, longitudinal wind with external roof pressure and wall suction internal pressure under transverse wind and internal suction under longitudinal wind illustrated in Figure 4.

5. Results and Discussion

5.1. Member Selection and Design Optimisation

From the second order analysis and design optimisation procedure conducted in SAP2000, the member sections and their corresponding capacities have been determined based on the most critical load combinations i.e. load combinations 1 and 2. Analysis results indicated a trend whereby the change in member cross section size increased linearly with the height and span as elucidated by Wu et al. (2012). Figures 5 and 6 show internal actions diagrams for the bending moments, shear and axial forces. Figure 5 depicts the second order analysis of a portal frame case where the span is 30 meters and the height is 5 meters while Figure 6 depicts the 40-meter span with a 5-meter height. Table 3 provides detail on all sections that have been optimised for the worst-case load combination (Load Combination 2). From tabulated values in Table 3, it can clearly be identified that the 40-meter span requires a steel member that must withstand higher design capacities. The 30-meter span was optimised with a 310UC137 rafter and 310UC118 columns while the 40-meter span re quires a larger 500WC267 rafter and 800WB146 column. This trend can be seen throughout all cases including the portal truss configurations, as the height and span increase, the load capacity of the members increase consequently requiring more sturdy and durable sections.

The models for the portal trusses are depicted in Figure 7. Tables 3, 4 and 5 provide a list of cross sections and corresponding design capacity ratios of all members adopted in all model configurations. For each portal truss configuration, the chord member subjected to the most severe design loadings had been selected. This was done to minimise fabrication and construction costs; the same section was adopted for all chord members even if capacity ratios were different. Similar considerations were applied to all verticals and all diagonals.

Since the portal truss configurations are more complex and contain more members, the sections that will be considered for diagonal, vertical and horizontal members will be designed according to the member with the largest capacity ratio.

One of the main objectives is to provide an effective cost analysis that elucidates which structure is more economical with respect to structural. From Table 3 the member capacities and sections are quite adequate for spans of 60m or less, the steel frame design analysis outputs a rafter member that has a capacity greater than 1 which demonstrates failure.

Although the columns provided in the design are able to withstand the effects of the loading, the rafters are inadequate as their capacity is above 1. However, if a high capacity steel was to be utilised in lieu of a 300PLUS-280 material such as a 600HCC386 or anything within this category then the rafters will yield a capacity lower than 1. In Figures 5 and 7, the moment in the truss system is greatly reduced compared to the portal frame, this is due to the larger lever arm of the truss chord members, while the axial compression remains almost unaffected. This provides a clear advantage when designing for combined actions and leads to smaller column sections.

From the design outputs presented in Table 3, 4 and 5, the utilisation of a truss provides a more sustainable structural configuration in contrast to using rafters as roofing elements. The utilisation of the chords as bracing elements reduces the sway of the structure as they provide the frame with larger stiffness. Therefore, since the portal truss configuration reduces the combined bending and axial action effects, the structure can be modelled to suit higher load capacities in contrast to the portal frame.

5.2. Cost and Weight Analysis

The following cost analysis provides a comprehensive review of the total fabrication costs for all portal frame and portal truss configurations. The focus turns from strength and performance to contrasting all 24 cases in reference to their total costs of fabrication. After consultation with One Steel manufacturers, the price for each member per meter has been determined. This has assisted in the computation of the steel frame costs. For a more detailed cost analysis, the price for construction including labour, delivery and time must be considered. According to several steel contractors, it generally takes longer to erect a portal truss in contrast to a portal frame due to the number of members and connections. In terms of costs, according to research conducted by quantity surveyor (Rider Levett Bucknall, 2011) the cost of fabrication, detailing and erection could range from $3000-$4200 per tonne. Based on the cases modelled in this study and their corresponding data from the steel optimisation examination, the costs to fabricate a portal frame is higher than the costs to fabricate a portal truss. This is due to the members selected having relatively larger and more expensive sections in contrast to the portal truss configuration.

5.2.1 Portal Frame Cost and Weight Analysis

The total lengths of the rafters have included the lengths of the haunches. In this study the haunch lengths have been determined as being 10% of the span length and are designed with the same cross-sectional properties as the rafters. The data presented in Table 6 provide emphasis on the total costs of fabricating the steel portal frame structure. It should be noted that the costs associated with labour have not been considered in Tables 6 and 7. However, as specified previously, a range between $3000-$4200 per tonne is assumed to cover the costs of construction and labour costs. From this relationship, it can be established that structures with the larger weight incur more cost.

The information in Table 6 is associated with Figure 8 which represents the total weight of each individual case against the total costs implicated with the specific configuration. A somewhat linear relationship can be exhibited in relation to costs and weight as the span and height increase, additionally the designed sections which are larger in size influence the cost per meter length. This is elucidated in Figure 8 where the 30-meter portal frame represents the lowest cost ultimately increasing in value as the span length and height increase.

From this indication, it can be determined that the most influencing factors are in fact the cross-sectional properties, height and span length with the first being the most critical. This relationship has been established with all portal frame cases examined in this study and has been emphasised graphically in Figure 8, where the structure with the largest weight will cost more to fabricate and construct.

5.2.2 Portal Truss Cost and Weight Analysis

Although the portal truss is a completely different configuration, an identical relationship can be established from the results of the portal frame where internal height and truss dimensions increase, a larger section is required to suit the specific loading conditions. Tables 6 and 7 provide tabulated outputs of the results from the design optimisation analysis including the total weight and costs for each configuration. Although the relationships may be identical, there is a great difference in the total weight and total costs for all portal truss configurations. The sections design optimised for the portal truss configurations are much smaller in size when compared to the portal frame section properties. The sections identified in Table 6 and 7 are also cheaper to fabricate and are much lower in weight, thus resulting in a much lower total cost.

Therefore, since the portal truss is design optimised with members that have much smaller sections, the price is relatively low across all cases. The price of fabricating a portal truss is approximately 40% cheaper than fabricating a portal frame, although a portal truss consists of more members, the larger sections used in the portal frame design are much higher in price. Once the costs for construction (manpower and time) are factored into the total costs, the portal truss configuration is still the much cheaper option according to Figure 9 and Tables 6 and 7. Since the cost for construction is based on a price per tonne, the savings for adopting the portal truss become more pronounced. The graph illustrates the relationship between the total cost and total weight for all portal truss configurations, where the total cost increases proportionally to the total weight of the structure.

As illustrated in Figure 10, the cost per tonne associated with both structures is almost constant with the truss configuration being slightly cheaper. Additionally, Figure 11 shows a comparison of the total average costs vs span length for the truss and frame configuration. The costs in Figure 11 are the costs presented in Tables 6 to 8 averaged at each span over the internal heights (5m, 7.5m and 10m).

From the trend lines in Figure 11, it can be seen that for spans over 30m, the average costs of portal frame construction increase y at a higher rate in comparison with the portal truss system.

5.3. Portal frame vs Portal Truss Cost Comparison

The information presented in Figure 10 illustrate the cost per tonne for all portal truss and portal frame configurations. The cost per tonne is influenced by the increase in span length, column height and particularly member cross sectional area. The costs per tonne for the portal truss exhibits a slightly cumulative linear trend whereas the cost per tonne for the portal frame is somewhat constant for all cases.

From an economic and feasible perspective, it is recommended that frames which are designed to span greater than 30 meters should implement the truss structure in lieu of the portal rafters. Financial implications arise due to the increase in tonnage required for frame construction consequently resulting in larger costs. As illustrated in Figure 10 and Table 6, it is more economical and sustainably feasible to implement a portal truss for use in large span building applications. When all cases are contrasted side by side, the total costs and amount of steel utilised for construction of portal truss configuration is far less than using the portal frame configuration

5.4. Time Associated with Construction

Time, cost and quality are three major aspects that must be maintained throughout a project's time-scale to ensure optimal construction is achievable. Thus far, the financial implications between both portal truss and portal frame structures have been examined in detail, consequently providing a clear emphasis on the financial variation across 24 different models. The financial aspect should not only be considered when using steel as the main structural commodity in construction but also consider, low weight, minimum construction dimensions and types of connections. According to Davison & Owens (2011), these three factors generally constitute to the speed of construction. Using members that are relatively low in weight will ensure the transportation time to site is reduced. The number of members and their corresponding connections also influence construction time, where a configuration with more connections and members will take longer to construct. The portal truss configurations examined in this study establish a lower weight in contrast to the portal frame configurations. However, since the portal frame models utilise less members and connections, the portal truss takes a longer time to construct as pointed out by Van Rensburg & De Vos (1996).

6. Conclusion and Recommendation

In this study, numerical investigation has been conducted to qualitatively examine the behaviour of portal truss structures compared to pitched portal frames for use in long span industrial buildings that exceed a span of 30 meters. The design optimisation and structural analysis was conducted for 24 variations of portal frame and portal truss configurations, where a finite element program (SAP2000) was used to model and assess all cases. All models have been designed to withstand the most severe load combination due to the design action effects. Accordingly, the members cross sectional properties have been quantified for all portal truss and portal frame configurations examined in this study. The portal frame models utilise larger sections to successfully sustain the loading effects influenced on the structure, whereas the portal truss models utilise much smaller sections. The portal truss configuration successfully manages and performs through all 12 configurations, with the capacity ratios all within adequate limits in comparison to the portal frame that requires high capacity sections to be used at spans greater than or equal to 40 metres.

According to the cost and weight analysis conducted in this study, the smaller steel sections have been identified as having a lower price point in comparison to the larger sections which are higher in financial value. Additionally, the total weight for both models is also based on the sections used, this is essential as it provides the basis for the construction costs as most steel building contractors provide prices per tonne. Ultimately, once the construction costs i.e. labour and transportation are factored into the total value, the portal truss provides the lighter weight and lower-cost alternative, whereas the portal frame results in a heavier and more expensive structure.

The time implications relating to both configurations has been detailed and although the portal truss configuration adopts the light weight and low-cost characteristics, it takes longer to construct compared to the portal frame. This is due to the larger number of members used within the truss structure, whereas the portal frame consists of two rafters and two columns only.

In conclusion, from the results obtained from the investigation, the portal truss configuration was found to be lighter, cheaper to fabricate and construct due to the smaller sections used in comparison to the pitched portal frame that established a shorter time for construction. As a result, it is recommended that a portal truss configuration be utilised in lieu of a pitched portal frame for applications that require a light weight and low-cost alternative for spans longer than 30 metres, where the project proposes adequate time for construction whereas the pitched portal frame is recommended for applications where there is a limitation on construction time. Additionally, unless high capacity sections are used, the span shall not exceed 50 meters, this however would result in a more expensive structure.

References

AS1170.0- 2011. Structural design actions – General principals. *Standards Australia, NSW, Australia.*

AS1170.2- 2011. Structural design actions – Wind actions. *Standards Australia, NSW, Australia.*

AS4100- 1998. Steel structures. *Standards Australia, NSW, Australia.*

Breust, T.D., 2006. The design and structural analysis of a steel portal framed shed for the Darling Downs Historical Rail Society.

Brohn, D., Brown, D., Henderson, R. and Rathbone, A., 1995. Modelling of steel structures for computer analysis. *SCI publication*, *148*.

Chen, W.F. and Duan, L., 2014. *Bridge Engineering Handbook: Superstructure Design*. CRC press.

Chen, W.F., 2008. Advanced analysis for structural steel building design. *Frontiers of Architecture and Civil Engineering in China*, *2*(3), pp.189-196.

Duggal, S.K., 2000. *Design of steel structures*. Tata McGraw-Hill Education.

Dundu, M., 2011. Design approach of cold-formed steel portal frames. *International Journal of Steel Structures*, *11*(3), p.259.

Duwadi, S.R. and Ritter, M.A., 1997. Timber Bridges In The United. *Public Roads*, p.33.

Far. H. 2016, Limit State Design, University of Technology Sydney.

Kirke, B., 2004. Steel structures design manual to AS 4100 (Doctoral dissertation, CSi Berkeley).

Mahendran, M. and Moor, C., 1997. *Three-dimensional Analysis of Steel Portal Frame Buildings* (Vol. 97, No. 5). Physical Infrastructure Centre, School of Civil Engineering, Queensland University of Technology.

McKinstray, R., Lim, J.B., Tanyimboh, T.T., Phan, D.T. and Sha, W., 2015. Optimal design of long-span steel portal frames using fabricated beams. Journal of Constructional Steel Research, *104*, pp.104-114.

Milan, M. and Patil Y. D., 2015, *Large Span Lattice Frame Industrial Roof Structure, Department of Applied Mechanics Sardar Vallabhbhai National Institute of Technology Surat-395007 India, pp. 01-07.*

Mosquera, J.C. and Gargoum, L.A., 2014. A sequential algorithm for minimum weight design of 2-D steel portal frames using Eurocode 3. *International Journal of Steel Structures*, *14*(1), pp.141-149.

Raven, G. (2009). Scheme development: Overview of structural systems for single-storey buildings. *Steel Construction Institute, 1(1)*.

Rider Levett Bucknall 2005, *Review of steel costs in medium rise steel framed buildings*, Australian Steel Institute, Sydney.

Rider Levett Bucknall 2015, *Riders digest 2015*, Rider Levett Bucknall, Sydney.

Salter, P.R., Malik, A.S. and King, C.M., 2004. *Design of single-span steel portal frames to BS 5950-1: 2000*. Steel Construction Institute.

Van Rensburg, B.W.J. and De Vos, G.P., 1996. Lower cost lightweight cold-formed portal frames.

Woolcock, S.T., Kitipornchai, S. and Bradford, M.A., 2011. *Design of portal frame buildings*. Australian Institute of Steel Construction.

Wu, J.R., Dong, C.C., Xu, A. and Fu, J.Y., 2012. Structural optimization of long span portal-rigid frames under wind action. In *the Seventh International Colloquium on Bluff Body Aerodynamics and Applications (BBAA7) Shanghai, China*.

Zhang, X., Rasmussen, K.J. and Zhang, H., 2016. Second-order effects in locally and/or distortionally buckled frames and design based on beam element analysis. *Journal of Constructional Steel Research*, *122*, pp.57-69.