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# Economical Aspect of Truss Design Through Geometry Configuration

Tan Hean Seong[1,*], Shek Poi Ngian[2], Rosli Mohamad Zin[1]

[1] Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[2] UTM Construction Research Centre, Institute for Smart Infrastructures and Innovative Construction, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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**ABSTRACT**

In engineering, truss structures are used extensively in bridge, tower, building, and numerous mechanical applications. Several studies have found that truss frames use the least steel weight when compared to other structural systems. The majority of truss frame design optimization research concentrated primarily on minimal weight design, and constructability, ease of fabrication, steel wastes, and the ideal geometric design parameter were not considered during the design optimization. Since the acceptable value range for factors like the span to depth ratio, truss frame typology, and diagonal angle is broad, there is no clear direction on how to determine the economical idea of truss frame geometry. To find the ideal geometry configuration for a truss frame, parametric studies were carried out, considering the truss frame span to depth ratio, truss frame typology, and diagonal angle. The study's conclusion offers a well-organized framework for choosing the best truss frame shape. According to the study's findings, there were no appreciable changes in the internal forces generated by the chords of the different truss typologies that may have resulted in substantial weight discrepancies. If constructability is a consideration, Warren trusses are a superior choice. When compared to proposals made by diverse sources, the projected truss span to depth ratio was significantly smaller. The study also showed that the member weight remains constant and does not significantly rise within a given range of the span to depth ratio.

## 1. Introduction

Truss structures are commonly used in civil engineering applications, including bridges, towers, and buildings [1]. The use of trusses as rafter in portal frame structure has proven to reduce the steel weight of the structure especially for a building span over 30 m [2-7]. The savings in steel weight for a truss frame not only able to reduce the overall construction cost but also able to reduce the energy consumption, which support sustainable development [8]. Reduction in steel weight for truss structure could be further enhanced through design optimization. Studies have been carried out on truss frame optimization focuses on constructability, ease of fabrication, and reduction on steel wastages [9, 10]. On the other hand, truss frame optimization could be carried out through geometry configuration. Guidance from the Steel Construction Institute (SCI) [11] has summarized the

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[*] *Corresponding author.*
*E-mail address: ths8didie@yahoo.com*

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optimization of truss design through geometrical configuration based on the span to depth ratio, truss typology, truss spacing and diagonal angle. For truss span of 15 to 30 m, the optimum span-to-depth ratio should be between 7 and 8. On the other hand, the economical spacing of truss frame should be between 4 to 10 m. Diagonal angle of the truss frame referring to the inclination of web member, which should be at approximately 50 degree or steeper to optimize the distance between truss members. Among all the truss typology, Pratt and Warren truss shows most economical configurations for all spans [10, 12]. However, the recommended value is in a wide range and the truss span is limited up to 30 m. Thus, the economical aspect on the truss configuration should be carried out for longer truss span to provide specific guidance on optimum truss design. Various research works [13-18] have been carried out on truss optimization that considered various aspects, such as constructability, natural frequency, cross-sectional minimization, sizing, shape, and topology for truss optimization. The proposed optimization method requires the industry to have deep understanding of programming language, artificial Intelligence, decision-making tools, and mathematical knowledge and may not be suitable for practicing engineer to implement the optimization method. Thus, this paper focuses on investigating the truss frame economical aspect by taking into consideration the optimal geometry configuration of truss frame. The outcome of the study is to the provide a structured framework to determine the most economical truss frame.

## 2. Parameters Deciding Truss Frame Geometry

Chang *et al.,* [10], Jarmai and Farkas [19], Bennett [20], Packer *et al.,* [21], Heinisuo and Bzdawka [22], Karoki *et al.,* [23], Descamps *et al.,* [24], Tyas *et al.,* [25] and Pyl *et al.,* [26] highlighted that the parameter to decide optimal truss frame geometry are truss span, truss depth, truss frame typology, and truss frame diagonal spacing. There are several truss systems with varied diagonal member configurations. Warren truss, Vierendeel truss, and Pratt truss are three examples of typical diagonal member layouts. The diagonal member configuration can influence both the structural weight and the cost of production. Regarding weight and manufacturing costs, Warren truss is significantly more economical. When compared to Pratt truss, it provides comparable structural rigidity. According to Parker *et al.,* [21], Warren truss typically offers the best cost-effective solution. In comparison to Pratt trusses, it has around half as many diagonal members and half as many connections, saving a significant amount of work and money. According to a study by Chang *et al.,* [10], the constructability of truss frames has an impact on how much it costs to fabricate a truss. They found that Vierendeel trusses are the most constructible, followed by Warren trusses, Warren trusses with verticals, Howe trusses, and Pratt trusses.

The rigidity and weight of the structure are strongly impacted by the truss depth. Less structural weight is needed, and the framing rigidity increases with truss depth. According to research by Haydar *et al.,* [6] and Farkas *et al.,* [27], there was a decrease in internal force in the top and bottom chord with increasing truss depth because of the expansion of the truss level arm. Steel Construction Industry (SCI) [11] advised "Building span/12-24" for truss ideal truss depth, but Gardner [28] literature suggests "Building span/10-15". According to Packer *et al.,* [21], the ideal number for the ratio will be closer to 15 if the building's entire costs are considered. For span ranges of 24 - 91 m, Ioannides and Ruddy [29] recommended an optimal span-to-depth ratio of 12:20.

The distance between the diagonal members that limit the truss's in-plane direction is known as the truss diagonal spacing. Diagonal spacing can be determine by using the ratio $\omega = H/a$, where H is the truss depth and a is the diagonal spacing [24]. A comparison of various ‘ω’ and how they affect cost- and mass-savings for truss frames has shown that the higher the ‘ω’ ratio, significant mass and cost saving can be achieved [21]. The fabrication and design of the top and bottom chord members of the truss frame will be impacted by the diagonal spacing. Welding presents significant challenges when the angle between a chord and a bracing element is less than 30°. The angle between a chord and a brace between two braces should, according to Packer *et al.,* [21], be between 30° and 90°.

## 3. Model Studies

The parametric study uses STAADPRO software to model and analyse truss frames with spans of 15, 20, 25, 30, 35, and 40 m. The following are the general truss frame analysis and design parameters:

i) The fixed roof pitch is 6 degrees (common practise in industry)
ii) Building eaves are 8 metres high (typical height for warehouses)
iii) The rafter has loads of 12 kN/m, 10 kN/m, and 8 kN/m.
iv) Only square hollow section (SHS) and rectangular hollow section (RHS) were taken into consideration.
v) The steel column size is in accordance with the preliminary sizing recommended by SCI [11], and the truss frame design is only limited to the rafter.
vi) In this study, frame stability factors like the huge delta and tiny delta effects were not considered.
vii) The restraint length is set at 1.5 m since this distance will result in the best member design.
viii) The SLS limit was considered in accordance with SCI's [11] suggestion, where the maximum vertical deflection allowed is span/200.

### *3.1 Truss Frame Typology Studies*

To accomplish the best weight design and most economical design, it was crucial to identify the efficient truss frame type. The most popular truss typology was compared in this parametric analysis to assess the impact of internal forces created in the top chord, bottom chord, and diagonal chord. The following criteria, including truss depth, diagonal member spacing, restraint length, and truss sectional member, were fixed to enable a fair comparison of each truss frame typology. The truss span varied in relation to the internal forces since the goal is to compare the internal forces created in different truss frame typologies. STAADPRO was used to analyse the truss frames, and building spans of 15, 20, 25, 30, 35, and 40 metres were modelled. The overall diagonal length for all truss frame typologies was the same because the truss diagonal angle was fixed at 40° to 61° and the diagonal members were organised in this way. There is only an axial force created in the truss frame due to the point load that was applied to the truss node. Table 1 displays the truss frame geometry and loading.

### *3.2 Truss Frame Span to Depth Ratio Studies*

In this investigation, the ratio of span to depth ranged from 12 to 21. Investigations were done into how the span to depth ratio affected the internal forces and sectional size of the truss frame. With loads of 12 kN/m, 10 kN/m, and 8 kN/m applied to the truss frame, truss frames with spans of 15 m, 20 m, 25 m, 30 m, 35 m, and 40 m were modelled and studied. The loadings were chosen because, according to observations, they are often employed in Malaysia's construction sector. Due to their cost-effectiveness, as is described in Section 2, Warren trusses were chosen for this inquiry. The span to depth ratio of 12 to 21 was used to calculate the truss depth, which is in conformity with the dimensions presented in Table 1. In accordance with Packer et al. [21], the truss diagonal angle was set at 60°. Using self-developed Excel tools, the maximum internal force in the top chord, bottom chord, and diagonal chord was extracted, and the best steel section was identified.

**Table 1**
Truss frame geometry and configuration

| Span (m) | Truss Depth (m) | Diagonal Spacing (m) | Warren Truss and Warren with Vertical Diagonal Angle | Pratt and Howe Truss Diagonal Angle |
|---|---|---|---|---|
| 15 | 1.2 | 1.25 | 62 | 44 |
| 20 | 1.5 | 1.67 | 61 | 42 |
| 25 | 1.6 | 1.79 | 61 | 42 |
| 30 | 1.9 | 2.15 | 61 | 42 |
| 35 | 2.0 | 2.00 | 64 | 46 |
| 40 | 2.2 | 2.01 | 65 | 48 |

## 4. Design Consideration

Individual members for truss frames are often selected from rolled or cold-formed section. Due to their effectiveness in compression and their tidy and appealing look in the case of exposed truss, structural hollow sections are growing in popularity. The top chord was in compression once the truss frame was loaded vertically, and vice versa if the load was reversed. Resistance to compression and tension was tested for the member design restriction. According to BS EN1993-1-1, the design processes for compression and tension members.

## 5. Results

To find the truss frame ideal geometry, the optimal value of each truss frame optimal design parameter was reported. To ascertain the maximum internal forces induced in the truss frames under varied span, truss typology, and span to depth ratio conditions, the truss frames were modelled and studied in line with Section 3. For data analysis, the top chord, bottom chord, and diagonal chord of a truss frame had their maximum tension and compression forces removed.

### *5.1 Optimal Truss Typology*

The highest internal forces of the chord members of the Warren, Pratt, Warren with Vertical, and Howe Trusses were extracted and tabulated. To ascertain the impact of the truss frame typology on the internal forces induced as the span expanded from 15 to 40 metres, the internal forces of each kind of truss frame were studied. The chart depicted in Figure 1 for the top chord maximum compression force summarises the internal force of various truss frame typologies. The Pratt truss had the largest internal pressures induced in the top chord of the truss, followed by the Warren truss, Warren with vertical, and the Howe truss, which had the lowest internal forces of all the truss typology studied. For building spans of less than 30 m, the disparities between the maximum internal force and the minimum internal force were in the range of 3.8% to 5.8%, while they were in the range of 11.8% to 14.5% for building spans of 30 to 40 m.

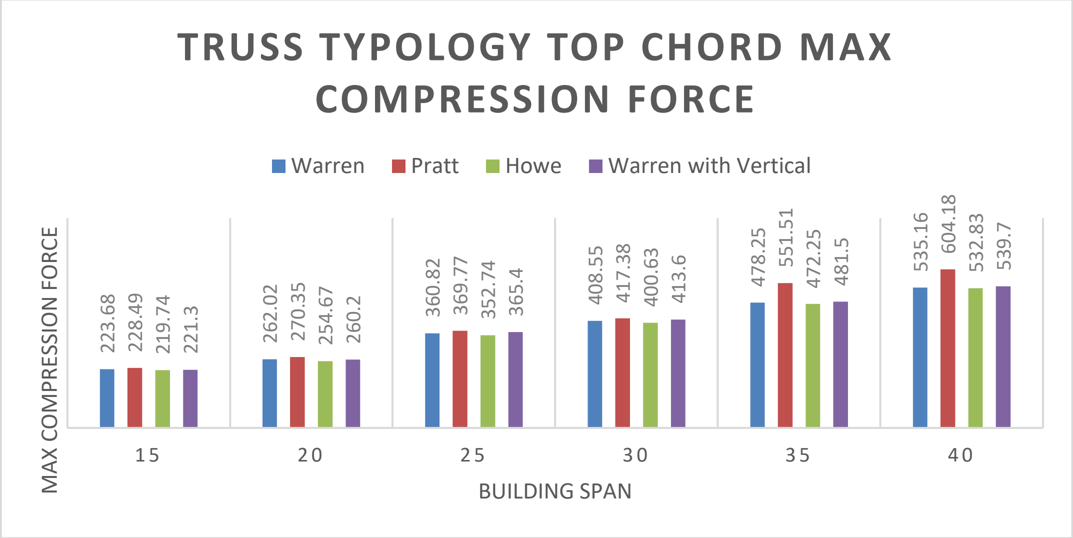

**Fig. 1.** Truss Typology Top Chord Maximum Compression Force

The maximum tension force on the bottom chord is shown in Figure 2. Pratt truss exhibits the greatest internal stresses, followed by Warren truss, Warren with vertical, and Howe truss, in that order. For building spans less than 30 m, the discrepancies between the maximum internal force and the minimum internal force were in the range of 2.24% to 2.85%, while they were in the range of 13.9% to 15.13% for building spans between 30 m and 40 m.

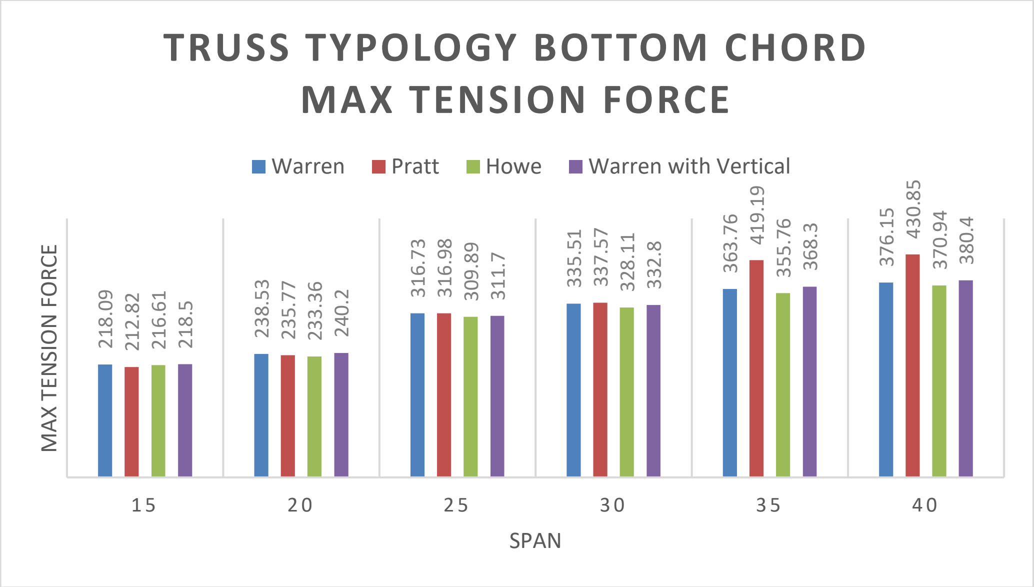

**Fig. 2.** Truss Typology Bottom Chord Maximum Tension Force

The tension force created in Pratt and Warren trusses with respect to vertical is nearly comparable, with Warren and Howe trusses seeing the largest tension force induced. There was a 38% to 44% discrepancy between the greatest internal force and the minimum internal force. Howe truss, Warren truss, Pratt truss, and Warren with vertical all produce the greatest compressive force. Between 87 and 92 percent separated the maximum internal force from the minimum internal force. The study also demonstrates that the Howe truss exhibits the greatest moment, followed by the Warren truss, Warren truss with vertical, and Pratt truss. Between 2% and 6% was the range in which the maximum and minimum moments differed.

### *5.2 Optimal Truss Frame Span to Depth Ratio*

STAADPRO was used to model and analyse the truss structure under different span and span to depth ratio conditions. For further data analysis, the highest internal forces for the top, bottom, diagonal, and column chords with truss span to depth ratios of 11 to 21 were extracted. As the span to depth ratio rose, the internal force of the truss frame increased linearly. Internal forces typically increased by 16% to 20% for every 2 kN/m increase for truss spans between 15 m and 40 m. With every increase in the span to depth ratio from 11 to 21, the internal force for truss spans between 15 and 40 m rose by 2% to 8%. For truss spans 20 to 40 metres, the discrepancies between the highest internal force observed in a span to depth ratio of 21 and the minimum internal force observed in a span to depth ratio of 11 were between 31% and 32%. However, the lowest internal force measured in the span to depth ratio of 11 for a 15 m span truss was 36%. The ideal steel section size was established using the greatest compression force on the top chord of the truss frame. The self-created excel spreadsheet was used to find the ideal steel section. Square hollow section, rectangular hollow section, and I-beam were the sections taken into consideration. Just the top chord of the truss was taken into consideration for the governing design of the steel member, which is primarily compression force, and the top chord of the truss frame contributed to most of the truss frame weight. The spreadsheet's best member weight designs for span to depth ratios of 11 to 21 are listed in Table 2 in kg/m. For truss spans of 20, 25, 30, 35, and 40 m, it is possible to determine from Table 2 the ideal span to depth ratio to attain the lowest weight.

**Table 2**
Summary of Span to Depth Ratio and Optimal Member Design

| Span | Range 1<br>Span to Depth Ratio | Average Weight (kg/m)<br>12kN/m | <br>10kN/m | <br>8kN/m | Range 2<br>Span to Depth Ratio | Average Weight (kg/m)<br>12kN/m | <br>10kN/m | <br>8kN/m |
|---|---|---|---|---|---|---|---|---|
| 20 | 12 - 14<br>(1.6m - 1.42m) | 9 | 7 to 9 | 6 to 7 | 15 - 19<br>(1.3m - 1.05m) | 10 to 11 | 8 to 9 | 7 to 8 |
| 25 | 11 - 13<br>(2.27m - 1.92m) | 10 to 11 | 9 | 7 to 8 | 16 - 19<br>(1.56m - 1.31m) | 12 to 13 | 10 to 11 | 9 |
| 30 | 13 - 15<br>(2.31m - 2m) | 12 to 13 | 10 to 11 | 8 to 10 | 16 - 18<br>(1.88m - 1.66m) | 13 to 14 | 11 to 13 | 10 to 11 |
| 35 | 11 - 13<br>(3.18m - 2.69m) | 13 to 14 | 10 to 11 | 9 to 10 | 14 - 18<br>(2.5m - 1.94m) | 14 to 16 | 12 to 13 | 10 to 11 |
| 40 | 14 - 16<br>(2.85m - 2.48m) | 16 to 17 | 13 to 14 | 10 to 11 | 18 - 20<br>(2.22m - 2m) | 16 to 18 | 15 to 16 | 12 to 13 |

The 20 m span truss frame, as illustrated in Table 2, has the least member weight for a span to depth ratio of 11 to 14. The ideal weight design ranged from 8 kg/m to 9 kg/m for a 12 kN/m load. The ideal weight design was 6.60 kg/m for loads under 8 kN/m and 7.78 kg/m for loads under 10 kN/m. With a ratio of 12 to 14, the sectional weight is the same. Weight variations of less than 2 kg/m are produced by truss frames with a span to depth ratio of 15 to 21. The ideal weight design ranged from 10 kg/m to 11 kg/m for a 12 kN/m load. The ideal weight design ranged from 9 kg/m to 10 kg/m for loads under 10 kN/m, and 7.78 kg/m for loads under 8 kN/m.

The span to depth ratio that results in the least member weight for a 25 m truss span is between 11 and 14. The ideal weight design ranged from 10 kg/m to 11 kg/m for a 12 kN/m load. The ideal weight design ranged from 9 kg/m to 10.5 kg/m for loads of up to 10 kN/m, and 6.60 kg/m for loads of up to 8 kN/m. Weight variations of less than 2 kg/m are produced by truss frames with a span to depth ratio of 15 to 21. The ideal weight design ranged from 10 kg/m to 11 kg/m for a 12 kN/m load.

The ideal weight design ranged from 9 kg/m to 10 kg/m for loads of up to 10 kN/m, and 7.78 kg/m for loads of up to 8 kN/m.

The span to depth ratio that results in the least member weight for a 30 m truss span is between 11 and 14. The ideal weight design ranged from 10 kg/m to 12.8 kg/m for a 12 kN/m load. The ideal weight design ranged from 8.9 kg/m to 10.2 kg/m for loads under 10 kN/m, and it was 7.78 kg/m for loads under 8 kN/m. With a ratio of 12 to 14, the sectional weight is the same. Weight variations of less than 2 kg/m can be achieved with a cross-sectional design using a truss frame with a span to depth ratio of 14 to 18. The ideal weight design ranged from 13.3 kg/m to 14.2 kg/m for a 12 kN/m load. The ideal weight design ranged from 10 kg/m to 13 kg/m for loads of up to 10 kN/m, and from 8.96 kg/m to 10.10 kg/m for loads of up to 8 kN/m. Weight variations of less than 2 kg/m are produced by truss frames with a span to depth ratio of 18 to 21. The ideal weight design ranged from 14 kg/m to 16 kg/m for a 12 kN/m load. The ideal weight design ranged from 10.10 kg/m to 10.84 kg/m for loads between 8 and 10 kN/m and 13.3 kg/m to 10.84 kg/m under those loads.

The span to depth ratio that results in the least member weight for a 35 m truss span falls between 11 and 13. The ideal weight design was 13.3 kg/m for a 12 kN/m load. The ideal weight was between 10.10 kg/m and 10.84 kg/m for loads of up to 10 kN/m, and 8.96 kg/m for loads of up to 8 kN/m. Weight differences less than 2 kg/m can be achieved in a cross-sectional design using a truss frame with a span to depth ratio of 14 to 21. The ideal weight range for a 12 kN/m load was 14.2 kg/m to 16 kg/m. Under 10 kN/m load, the ideal weight design ranged from 12.84 kg/m to 14.2 kg/m, and under 8 kN/m load, it ranged from 10.10 kg/m to 11.70 kg/m.

The span to depth ratio that results in the least member weight for a 40 m truss span is between 11 and 15. The ideal weight range for a 12 kN/m load was 13.3 kg/m to 16 kg/m. The ideal weight design ranged from 11.7 kg/m to 13.3 kg/m for loads of up to 10 kN/m, and from 10.10 kg/m to 10.84 kg/m for loads of up to 8 kN/m. The cross-sectional design of a truss frame with a span to depth ratio of 15 to 21 has weight differences smaller than 3 kg/m. The ideal weight range for a 12 kN/m load was 16 kg/m to 19 kg/m. The ideal weight design ranged from 10.84 kg/m to 13.30 kg/m for loads between 8 and 10 kN/m and from 13.3 kg/m to 16 kg/m.

The internal forces generated by the chord members that differed significantly among the different truss typologies did not result in a noticeable weight variation. The Pratt truss, however, is stiffer than the other truss typologies, which might result in less moment being transmitted to the column. According to Figure 3, the reduction in Pratt truss column moment over Warren truss, Howe truss, and Warren with vertical was in the range of 1% to 3.3%, 1.4% to 6.1%, and 0.1% to 2.2%. Steel columns made with Pratt trusses can be the best option. Nonetheless, if the constructability issue were considered and the recommended diagonal angle of 60° by Packer *et al.,* [21] were considered, Warren truss might prove to be favourable because to the lesser diagonal members. In comparison to a Pratt truss, a smaller diagonal member could result in a lighter structure. Contrary to Warren truss, Pratt truss involves the manufacture of two distinct types of diagonal members. According to Farkas' equation [27], Pratt truss requires more manhours to cut and build. The result is in line with the conclusions of Chang *et al.,* [10], according to which Pratt was placed fourth and Warren truss was ranked second in terms of constructability.

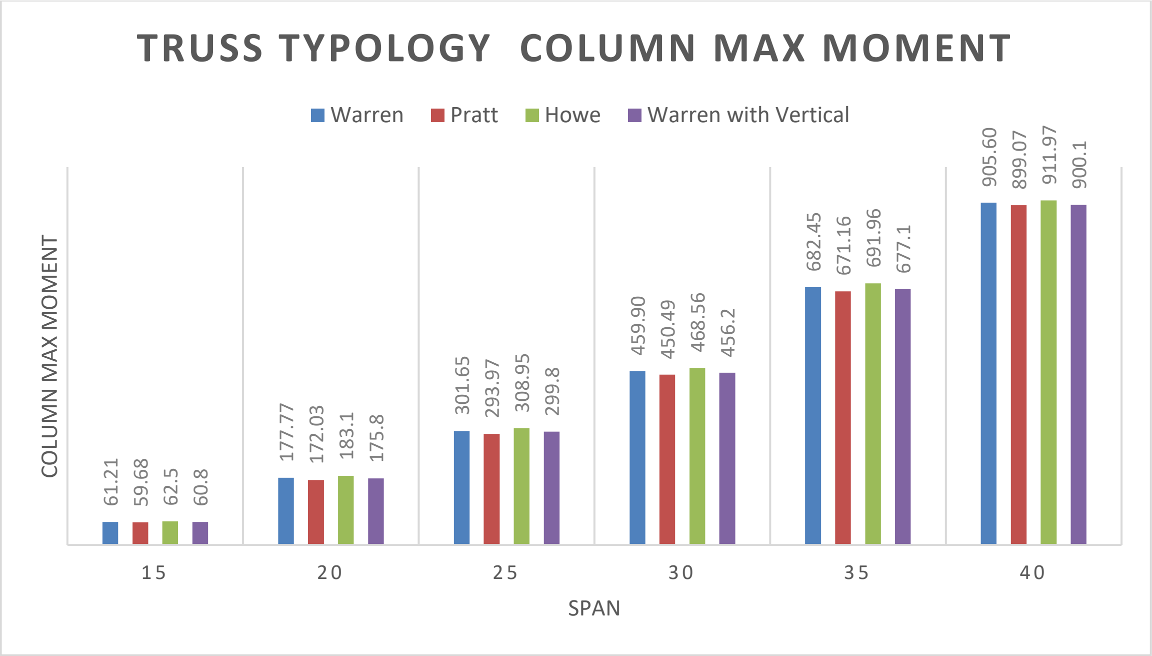

**Fig. 3.** Truss Typology Column Maximum Tension and Compression Force

Increased truss depth may reduce internal forces acting on the top and bottom chords and increase truss frame stiffness. However, the overall weight of truss diagonal member will be increased. The diagonal member length increased by 3.2% to 7.8% for every increase in the span to depth ratio, which could lead to an increase in the total length and weight of the diagonal members. While compression buckling controls the longer diagonal member design, deeper trusses with longer diagonal members may necessitate larger sections. For a specific span to depth ratio range, the member design weight was the same. In both ranges, the weight disparities for the span to depth ratio were often less than 2 kg/m. While determining the ideal truss frame span to depth ratio, it is important to take into account a variety of factors, including the building's height, the length of the diagonal members as a whole, and the increasing use of secondary components like wall girts and wall cladding. The range of 14 to 20 was the ideal truss frame span to depth ratio for heights between 15 and 40 m. The ideal span to depth ratio for truss spans less than 20 metres was in the range of 15 to 19, for truss spans between 20 and 30 metres, it was in the range of 16 to 19, for truss spans between 30 and 35 metres, it was in the range of 14 to 18, and for truss spans between 35 and 40 metres, it was in the range of 18 to 20. The recommended span to depth ratio was put forth, and the range is much smaller than what is suggested in the literature in order to achieve the best truss structure.

## 6. Conclusions

This study has outlined several conclusions as follows:

i) Pratt trusses might create the best steel column design. Warren trusses, however, might be preferable because to the fewer diagonal members if the required diagonal angle of 60° were considered if the constructability aspect were considered.
ii) In determining the ideal truss frame span to depth ratio, it is important to take into account a variety of factors, including the building's height, the length of the diagonal members as a whole, and the increasing use of secondary components like wall girts and wall cladding.

iii) The recommended span to depth ratio was offered, and the range is considerably smaller than what is suggested in the literature in order to create the best truss frame.

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