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Critical Design Criteria for Standard, Truncated, and Parallel Chords Cold-Formed Steel Trusses

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Abstract

The design of cold-formed steel trusses can be a very complicated and long repetitive process involving up to 28 load combinations added to serviceability checks depending on the design standards being used. This process is particularly tedious if a near optimal solution is required. Additionally, the risk of introducing human errors is usually quite high as it is a process often done by hand. FRAMECAD Structure is a niche software solution born from the desire to provide a complete solution for constructing with cold-formed steel by a company selling roll-forming machines. FRAMECAD Structure specialises on automating the calculations and design of cold-formed steel framed panels, trusses and joists with minimal user input. However, computational-oriented software applications are often not optimised for performance, hence the inefficiency in obtaining a design solution, i.e. the proposed solution is either not optimal or takes a considerable time to compute. To provide guidelines on the design of cold-formed trusses, this research uses FRAMECAD Structure to study which design parameters are critical and what impact they have on optimising the design outcome.

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1. Introduction

Research on the optimisation of cold-formed steel structures has primarily focused on portal frames and the use of genetic algorithms (Phan et al., 2011; Phan, Lim, Tanyimboh, & Sha, 2013; Phan et al., 2013, 2015, Phan, Lim, Tanyimboh, & Sha, 2012, 2017; Wrzesien et al., 2016) adapting research developed on traditional hot-rolled steel portal frame buildings (Mckinstray et al., 2015; Mckinstray, Lim, Tanyimboh, Phan, & Sha, 2014, 2016). Optimisation through genetic algorithms has been researched for both 2D (Belén, Gero, Bello García, & Del Coz Díaz, 2005; Deb & Gulati, 2001; Flager et al., 2014) and 3D hot-rolled steel trusses (Belén, Gero, Bello García, & Del Coz Díaz, 2006). There have been only a few research projects reported in the literature on the optimisation of cold-formed steel roof trusses (Dawe & Wood, 2006; Tashakori & Adeli, 2002; Xu, Min, & Schuster, 2000). This research has set out to fill the gap by investing which design parameters are critical and formulating the findings into a set of design guidelines.

Figure 1 Typical Cold-Formed Steel Roof Trusses (courtesy of FRAMECAD)

Cold-formed steel trusses such as those shown in Figure 1 above are widely used for roof systems. However, the design of these trusses is notably complicated (Mysore, Watson, & Gad, 2008) due to the number of members and their geometry making use of tedious trigonometry in the calculations. The present study proposes to identify critical parameters for the design of standard (Figure 4), truncated (Figure 5), and parallel chords (Figure 6) trusses in order to improve the design efficiency of these elements using a software application. Production of the channel sections (Figure 2) can be done by press-braking or using a roll-former such as the one shown in Figure 3 below.

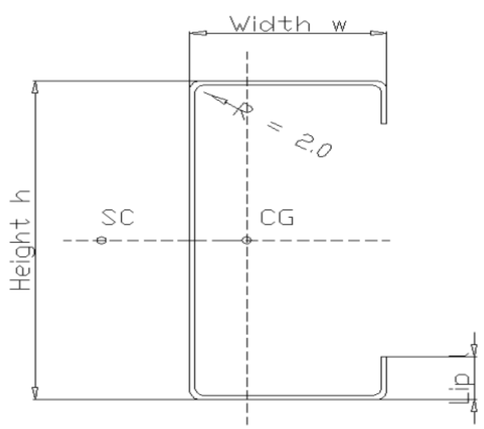


Figure 2 A Typical Geometry of a Channel Section

Figure 3 FRAMECAD F325iT Production System

FRAMECAD Structure is a dedicated computer-assisted cold-formed steel design and engineering software system developed by FRAMECAD in New Zealand. The design and calculation of trusses within FRAMECAD Structure is based on finite element methods. The system embeds international structural design standards to extend its compliant cold-formed steel design application worldwide. The software also fully supports ISO 16739 Industry Foundation Classes for interoperability and data exchange with the open standard BIM (Building Information Modelling) that is gaining popularity in the industry.

The main purpose of using a software application for the design and calculations of cold-formed steel framed structures is to improve on the efficiency and minimise the risk of errors. However, there is a large number of parameters to be taken into account for the calculation process, such as load combinations, roof pitch, section shape, section thickness, steel grade, etc. hence, being able to automate the calculations while taking in account all of these parameters in order to define the critical parameter, i.e. the parameter with the greatest influence on the calculation of any type of truss, would help make the calculations quicker and more accurate for this type. This improved efficiency and reduced risk of errors can both be achieved by automating the order in which the parameters are changed in the process of reaching an optimum design. The parameters analysed in the present study are detailed in Table 1 below.

Table 1 Design Parameters

Parameter	**Lower value**	**Upper value**	**Step**	**Default value**
Roof type	Steel	Tiles		Steel
Roof Pitch	5°	45°	5°	20°
Truss Height	200 mm	1000 mm	100 mm	600 mm
Truss Span	2000 mm	7000 mm	500 mm	5000 mm
Web Pattern	1	6		6
Members Section	S89	S150	S89; S100; S150	S100
Material Thickness	0.75 mm	1.55 mm	0.75 mm; 0.95 mm; 1.15 mm; 1.55 mm	0.95 mm

In the present study, we considered trusses composed of channel sections (Figure 2) members and we considered a truss spacing of 600 mm. We analysed sections made out of 550MPa steel (grade G550). Dimensions of the channel sections analysed are detailed in Table 2 below. These sections have been selected as the most commonly used cold-formed Cee-sections for trusses within the FRAMECAD building system.

Table 2 Dimensions of the Analysed Channel Sections

Section	Height (h)	Width (w)	Lip (l)
S89	89 mm	41 mm	12 mm
S100	100 mm	41 mm	12 mm
S150	150 mm	41 mm	12 mm

2. Parametric Analysis

Standard trusses, such as the one shown in Figure 4 below, are the only type of structural trusses used for gable roofs and are the most popular truss shape in use. The height of these trusses is dictated by the truss span and roof pitch, hence the influence of height has not been studied in the case of standard trusses.

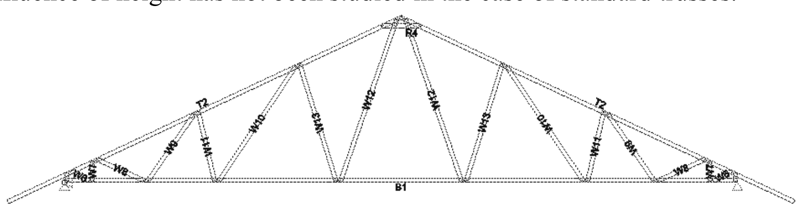


Figure 4 Uplift View of a Standard Truss

Truncated trusses, as shown in Figure 5, are composed of four types of elements:

- One horizontal bottom chord
- Two oblique top chords
- One horizontal top chord
- Several webs

Each of these elements has to be dimensioned in order to create the most optimised truss.

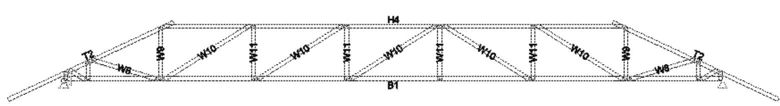


Figure 5 Uplift View of a Truncated Truss

Parallel chords trusses present a single slope where both the top chord and bottom chord have the same pitch, as shown in Figure 6 below. They represent the third type of geometry analysed in the present study.

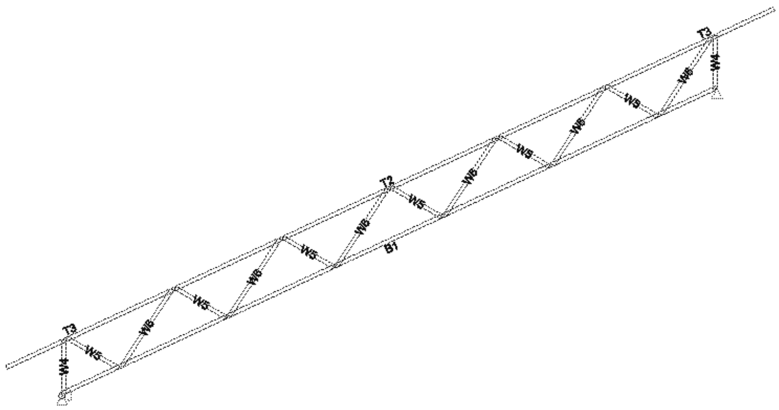
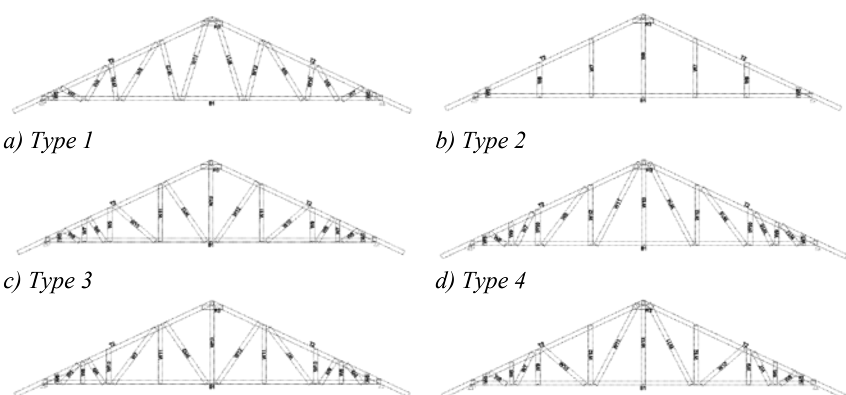


Figure 6 Uplift View of a Parallel Chords Truss

The disposition of the webs according to specific patterns has a significant impact on the load path and stability of the complete truss. For the purpose of this study, we considered six types of web patterns presented in Figure 7 below.



a) Type 1 *b) Type 2*

c) Type 3 *d) Type 4*

e) Type 5 *f) Type 6*

Figure 7 Web Pattern Types

2.1. Calculation Method

The calculations are performed using the FRAMECAD Structure software, which employs a finite element method as well as an automated checking process for design compliance with normative requirements from various standards embedded into the system. For the purposes of this study, all 8 load cases required for the design in accordance with the NASH NZ 2010 Building Standard (NASH NZ, 2010) are listed in Table 3 below and tested for each truss design. Design parameters corresponding to a hypothetical low-rise building located in Auckland, New Zealand have been used. A wind speed of 32 m/s was assumed for the design of each truss.

2.2. Testing Protocol

Each of the truss parameters identified as potentially having an impact on the design is analysed individually. Base values are set for each of these parameters so as to isolate the influence of each parameter on the results. They are listed in Table 1.

The roof type determines if the loads accounted for in the calculation come from a sheeted or tiled roof. The pitch of the roof is also tested along with the span, members section and members section thickness. Web Pattern refers to the way the webs are arranged in between the top and bottom chords along the truss. The different web patterns tested are presented in Figure 7 above.

Table 3 Load Combinations for Roof Trusses (NASH NZ, 2010)

	Load combination	**Check type**	**Serviceability limits**
LC1	$0.44\ W_u$	Serviceability	$\Delta \leq$ min (L/240; 15mm)
LC2	1.0 G + 0.7 S	Serviceability	$\Delta \leq$ min (L/300; 15mm)
LC3	1.0 Q	Serviceability	$\Delta \leq$ min (L/300; 15mm)
LC4	1.2 G + 1.5 Q	Strength test	-
LC5	$0.9\ G + 1.0\ W_u$	Strength test	-
LC6	$1.2\ G + 1.0\ W_d$	Strength test	-
LC7	1.2 G + 1.0 S	Strength test	-
LC8	$1.2\ G + 1.5\ P_e$	Strength test	-

where,
G = dead load (kN)
Q = live load (kN)
W_u = upwards wind load (kPa)
W_d = downwards wind load (kPa)
S = snow load (kN)
P_t = design point load (kN) (set to 1 kN for this study)
P_e = minimum of $5/8*P_t$ and 0.5 kN
L = member length (mm)

Results that will be analysed include the ratio between the resisting capacities of the truss versus the optimum resisting capacity for the truss under the considered loads and a corrected total assembled weight.

The influence of various design parameters will be analysed following the correction of the assembled weight. The correcting factor will be determined in regard to the truss usage. In the case where the truss is not used to its maximum capacity according to the load cases analysed, the assembly weight will be increased by 1% for each percent under full capacity. In the case where the truss is to fail according to the load cases tested, the assembly weight will be increased by 2% for each percent above the full capacity.

However, given that this method can introduce a bias due to the manipulation of the total assembly weight based on the distance to optimum, a further testing should be undertaken based solely on the optimum design of trusses so that to eliminate the truss usage parameter and the bias due to this factor.

2.3. Results Analysis Protocol

Results will be analysed using XY scatter plots as to identify trends and which parameters have the most impact on the design outcome, measured with respect to the weight of the truss.

This analysis will be cross-checked with a centrality analysis. Centrality analysis comes from the network analysis in Social Sciences and allows one to identify the most central element of a network (Epskamp, Cramer, Waldorp, Schmittmann, & Borsboom, 2012). Considering our parameters and results as a network, this centrality analysis allows us to identify which parameters are the most central and hence the most critical in the design process. This second analysis will allow one to identify parameters that are the most central to the variations on the corrected assembly weight. The same data was used to plot graphs using Microsoft Excel and RStudio software packages. The difference resides in the correlation estimate made in RStudio in order to produce the network graph representation. Such estimate is not calculated in Microsoft Excel. The correlation graphs have been produced taking into account a threshold of 0.1 in order to improve the accuracy of the representation and enhance the readability of the generated graphs.

3. Analysis Results

This section presents the results of the analysis for each parameter. Both the scatter plots and centrality analysis graphs are commented accordingly to highlight the influence of each design parameter on the total assembly weight of a truss and therefore identify parameters that are critical in the design.

The corrected assembly weight is expressed in kg/m^2 in each of the plots (Figures 8 to 13) below. The weight taken into account is the weight of the entire truss corrected as described in the testing protocol (Section 2.2).

3.1. Analysis Results for Individual Design Parameters

Roof Type (Figure 8)

As expected a higher load on the roof lead to a heavier truss in the case of both truncated and standard trusses though lead to a lighter parallel truss.

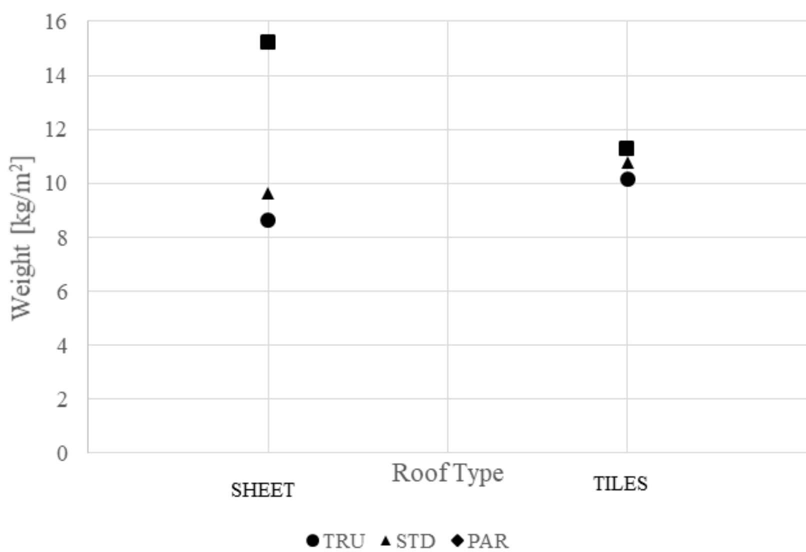


Figure 8 Corrected Assembly Weight vs Roof Type

Roof Pitch (Figure 9)

This plot shows how the pitch has little to no influence on the weight for truncated and standard trusses within the 10 to 30 degrees range, which corresponds to commonly used roof pitches. Parallel trusses are showing more sensitivity to that parameter for the data that has been gathered with the truss weight increasing linearly in the same range.

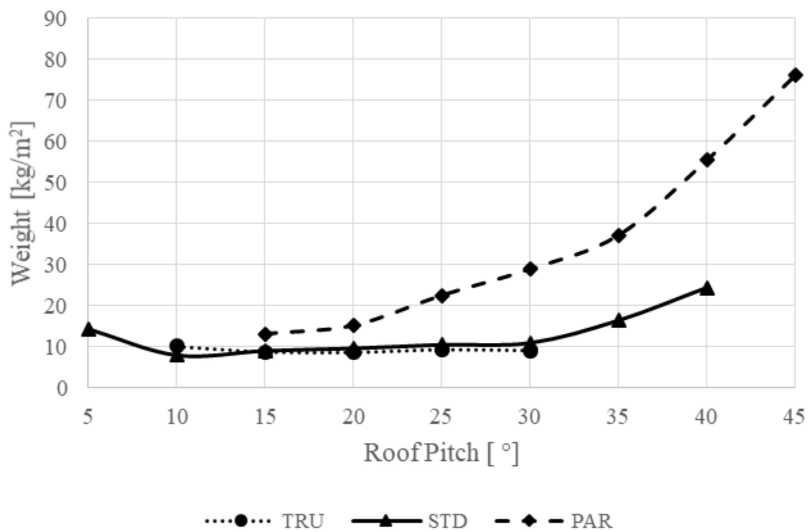


Figure 9 Corrected Assembly Weight vs Roof Pitch

Height (Figure 10)

The weight of parallel trusses seems to evolve linearly with the truss height whereas the weight of truncated trusses seems to stabilise when the height reaches 600 mm. In this graph, standard trusses aren't represented as height isn't a design parameters for these in the model used to run this analysis. When testing for the influence of height, we already know that given a pitch and a span the height of a standard truss does not change, therefore the results for standard trusses are not presented in this case.

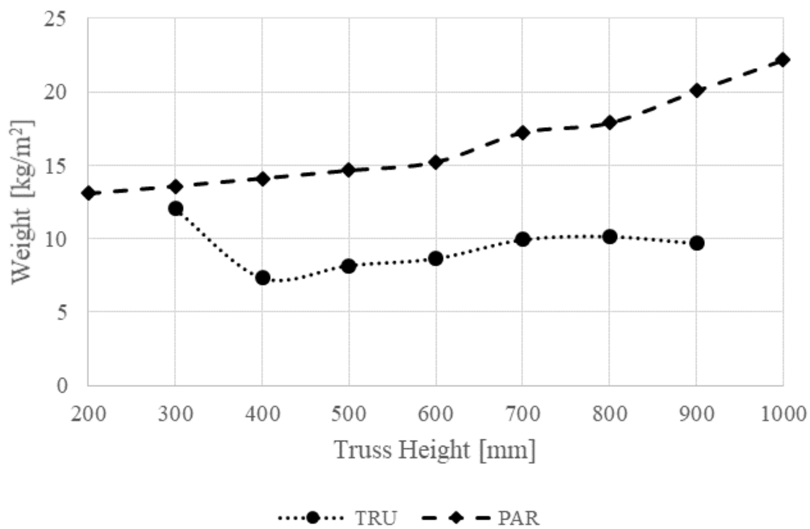


Figure 10 Corrected Assembly Weight vs Height

Truss Span (Figure 11)

This plot shows that the span does not have a strong influence on the truss weight for both truncated and standard trusses. However, the influence of the span becomes notable when it reaches 4 meters in the case of parallel trusses.

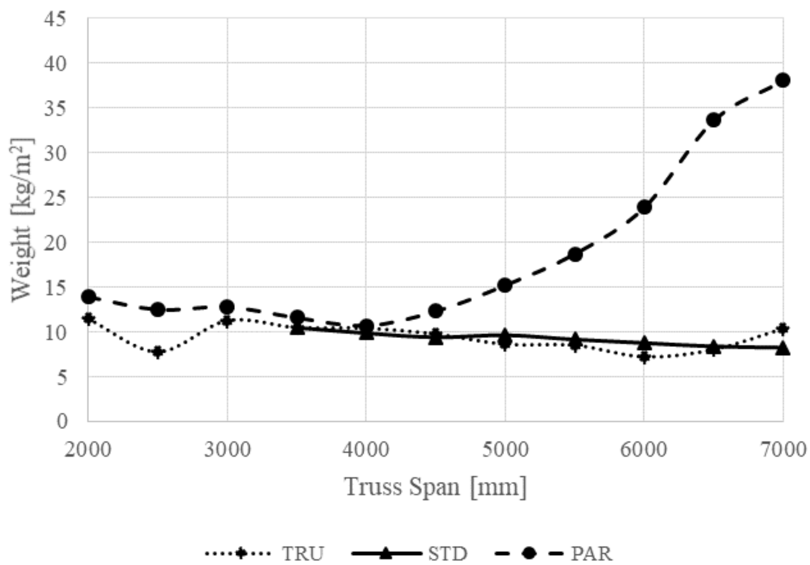


Figure 11 Corrected Assembly Weight vs Truss Span

Web Pattern (Figure 12)

This plot demonstrates how adding more webs in order to stiffen the trusses doesn't necessarily leads to a heavier truss. For truncated and standard trusses, the web pattern has little influence (to the exception of the second web pattern that leads to a minimum weight for both truncated and standard trusses. Parallel trusses seem more sensitive to the web pattern used with their weight varying more importantly depending on the web pattern used.

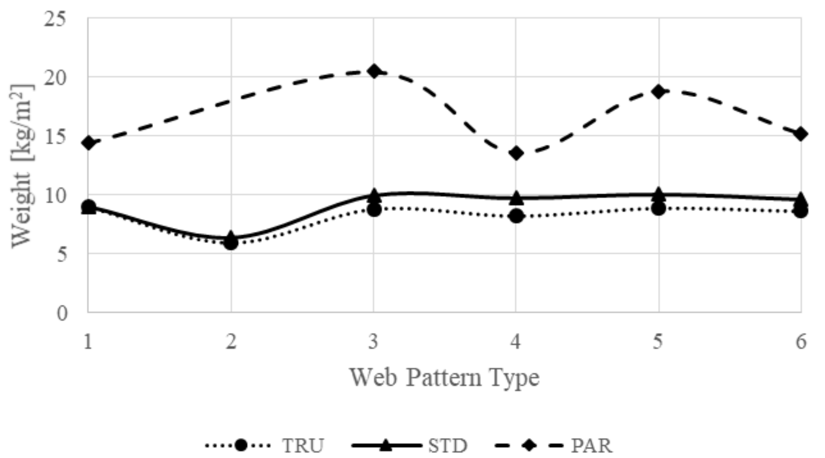


Figure 12 Corrected Assembly Weight vs Web Pattern

Members section and thickness (Figure 13)

The thickness of the material seems to have a linear influence in most cases though a thickness of 0.95mm demonstrate a minimum in several cases (i.e. for the S89 truncated and standard trusses and for the S150 parallel truss).

When looking at the sections, we can notice that a bigger section doesn't give a heavier truss notably in the case of the truncated trusses where the S100 section leads to a lighter truss for all the thicknesses analysed. In all other cases, to the exception of what happened with a thickness of 0.95mm, larger sections lead to heavier trusses for both standard and parallel chords trusses.

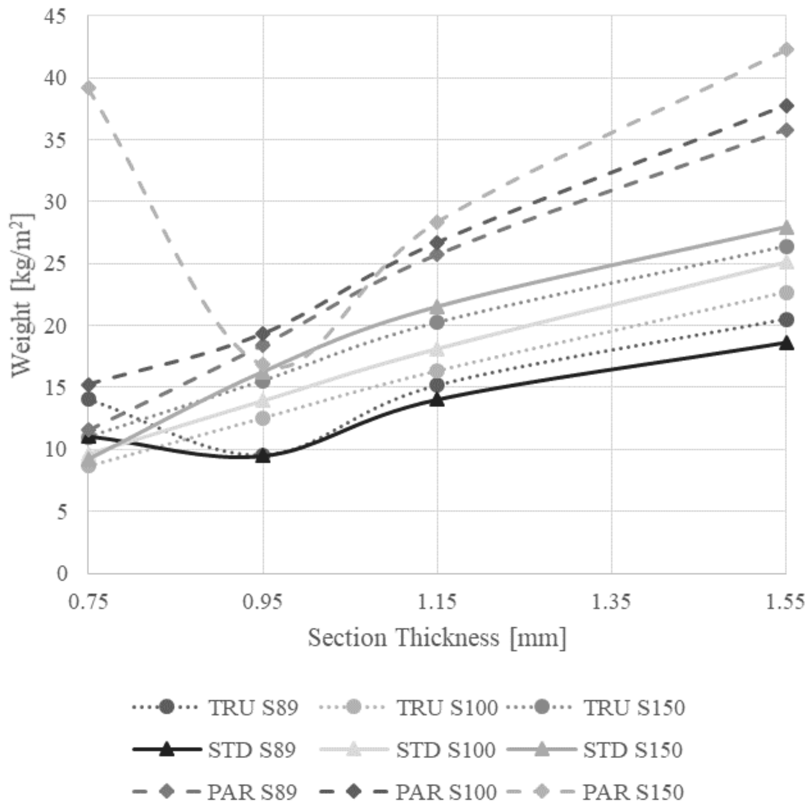


Figure 13 Corrected Assembly Weight vs Section Thickness

Analysis summary

The analysis results above indicate that the parameters having the most impact on the design of trusses, in general, are the roof type (i.e. applied load) and the member section (both geometry and thickness). In addition, the height parameter has a strong influence on the design of parallel chords trusses. Overall, parallel chords trusses are the ones showing the most influence to each of the tested parameters.

3.2. Centrality Analysis Graphs Extracted from RStudio

In this section we are using centrality analysis graphs to identify the most influential parameters aside of the roof type and members geometry (section and thickness). In the figures below, each of the parameter analysed is represented as a node of the graph. Centrality analysis then weight the strength of the correlation in between the parameters and represent such correlation with a link. The thicker the line to represent a link, the stronger the correlation in between two parameters.

Standard truss

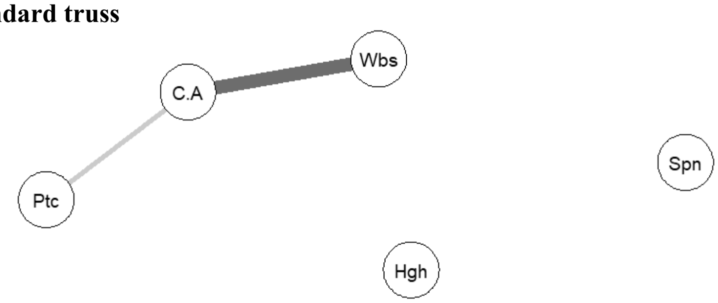


Figure 14 Standard truss design parameters network

This figure shows how the corrected assembly weight (C.A) is more strongly correlated to the web patterns (Webs) and the roof pitch (Ptc). These findings are consistent with what was interpreted from the XY scatters plots generated by Microsoft Excel once the roof type and members geometry are removed from the data. It is reasonable to conclude that the web patterns and pitch are the two other important parameters in the design of standard trusses. This graph also shows no correlation between the corrected assembly weight and the truss height (Hgh) which makes sense considering that the height does not enter into account in the design of standard trusses with the model being used.

Truncated truss

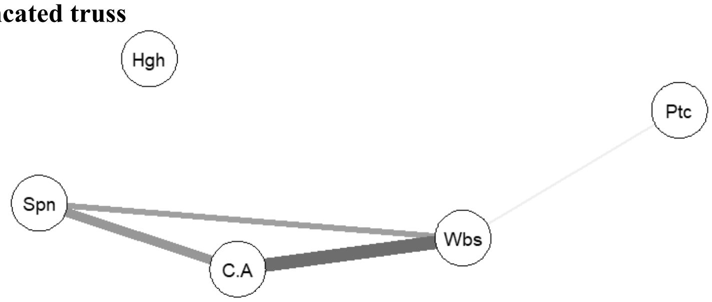


Figure 15 Truncated truss design parameters network

The figure above shows a good correlation between the C.A and Wbs as well as the truss span (Spn). This is consistent with the findings from the scatter plots from Microsoft Excel. The poor correlation between C.A and Hgh demonstrates that Hgh does not have as much of an influence on C.A as Spn or Wbs.

Parallel chords truss

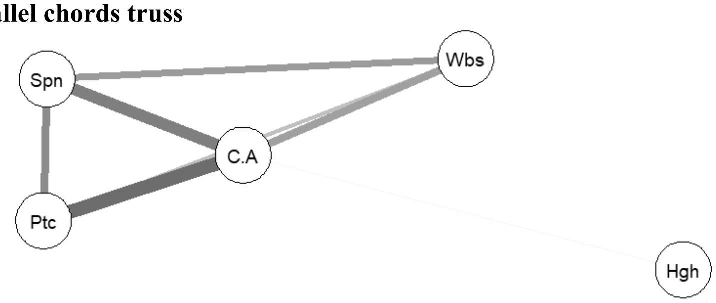


Figure 8 Parallel truss design parameters network

This graph shows a strong correlation between the C.A and Ptc and Spn and a weaker correlation with Wbs. This is consistent with findings from the scatter plots from MS Excel. The lack of correlation between the C.A and Hgh demonstrates that Hgh does not have as much of an influence on C.A as Spn or Wbs.

4. Conclusions and Future Work

In conclusion, we can say that the most critical parameters in the design of cold-formed steel trusses are the applied load (i.e. roof type) and the geometry of the members (i.e. section type and material thickness). Furthermore, the chosen web pattern is critical for all truss shapes considered here. Additionally, in the case of standard trusses, the roof pitch is also influential; in the case of truncated trusses, the span shows some significant influence; and in the case of parallel chords trusses, both the pitch and span show similar levels of correlations with the total assembly weight.

Further research should be carried out to investigate other truss geometries and the influence of these parameters on the design of trusses designed to work in the 90 to 100% range of their maximum capacity without failure. In addition, an experimental meta-analysis or physical experiments should be undertaken in order to validate the results obtained in this study.

Further work regarding the analysis of this dataset will compare and contrast the graphs obtained from RStudio with similar datasets versus experimental datasets in order to test for significant overall differences between these graphs using the NetworkComparisonTest package (van Borkulo et al., n.d.; Van Borkulo, Epskamp, & Maintainer, 2016) in R. Further work will be undertaken in collaboration with researchers from Social Sciences in order to study the interest of network analysis to test the validity of an engineering model.

Acknowledgment

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