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Research paper

Feasibility Study on Replicating Tree Design Structure in Trusses Subjected to Lateral Loading

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Abstract

This paper explores the question as to whether designs found in nature can assist in improving current design of structures. The objective of replication of nature is to increase strength and durability with further emphasis on reducing material usage. The basis of this investigation starts with frame structure in the shape of the slope of a tree stump. The study focusses on the effectiveness of various truss design and how it compares to the design found in nature. Although the tree design was found to be no better than the existing frame structures (in terms of rigidity), it still may be potential in other application. In comparison to conventional truss design, the design following tree stump demonstrates a higher flexibility that may prove to be potentially beneficial in resisting lateral load resulting from wind or earthquake.

Keywords: *Deflection; Lateral load; Tree design; Truss analysis,*

1. Introduction

In nature, animate and inanimate objects thrives to find ways or methods to survive the harshest environment. This survival depends on the ability to adapt seamlessly with the environment. To understand the fundamental concept behind nature's design, this study aims to test the shape of the tree buttress through a common structure known by many engineers as "Trusses". Trusses have been around in the engineering world for quite a while. They are known to be efficient, light and strong. Due to these characteristics, trusses are applied on many structures no matter the size. They can be both aesthetically pleasing and functional. They can also be integrated easily within a broad range structures. This research seeks to show a path towards the unity of technology and nature with the possibility of energy and resource saving through lightweight construction, analogous to that found in animals and plants.

2. Background and methodology

2.1 The tree design structure

Claus Mattheck demonstrated a design rule (Figure 1) that can be implemented into many types of designs to achieve maximum stability with minimal material wastage. The method to develop this shape profile is known as the "Method of Tensile Triangles". The design and concept have been extended into designing mechanical parts that can withstand high fatigue and strength, allowing them to be more durable than before. This research intents to maintain the shape of the standard tree design rule of triangle presented by Mattheck [2] and to compare it with current/conventional truss design.

Fig. 1: The shape profile of Method of Tensile Triangles follows closely to the shape of buttresses.

2.2 Research methodology

In most cases, trusses are usually designed as either rectangular or triangular as believed by engineers to be the best structural shape. This is usually accompanied with equal dimension spacing for a better overall cost to performance ratio (in terms of fabrication, installation and cost). These conventional truss designs will be evaluated with the other truss designs. A simplified truss analysis process is shown in Figure 2.

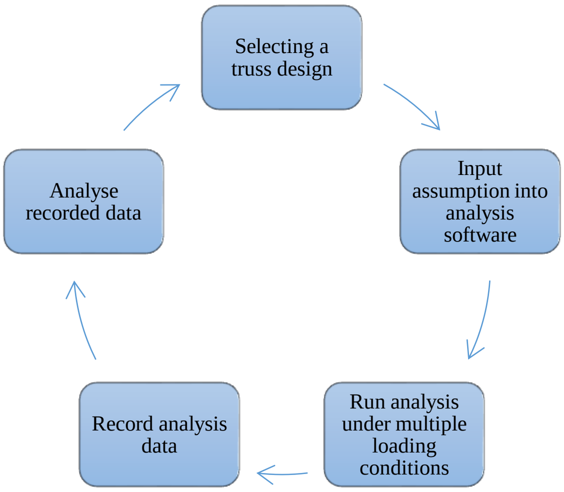


Fig. 2: General truss analysis process.

19 different truss models were evaluated with a total of 266 truss combinations. This paper will only highlight the relevant truss models. To determine its behaviour, effectiveness, efficiency, overall performance and response, it will discuss the following in five sections. The aspects covered in each section are the displacements, beam stresses (values only) and total material usage.

1. Comparison of conventional truss design with tree design truss.
2. Comparison of different shaped trusses with tree design ratios.
3. Comparison of conventional trusses with different ratios.
4. Effects of manipulating the base width of tree design ratio trusses.
5. Overall results of all the analysed trusses.

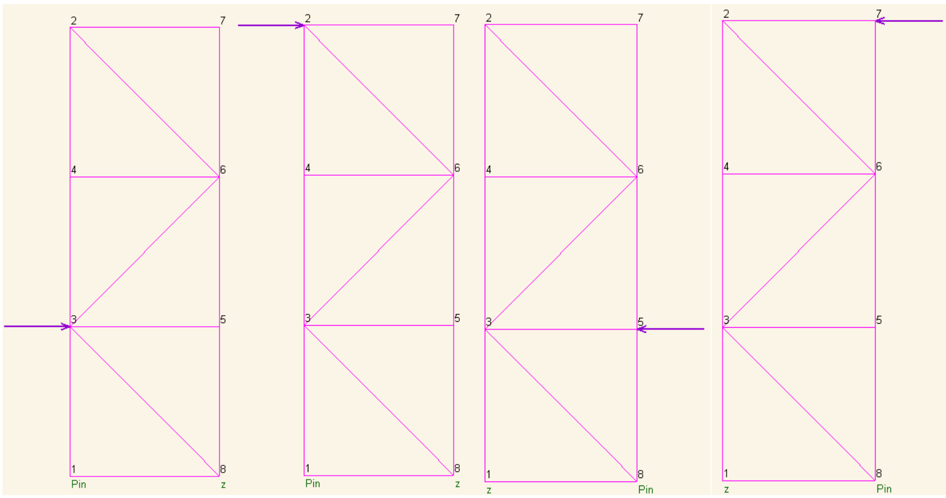
2.3 Description of truss analysis

Presented in this paper are 7 different truss models with 2 different load combinations. They were analysed using Oasys GSA Suite 8.6. It should be highlighted that the terminologies presented are not general terms. The loading conditions and terminologies used in this paper are shown in Figure 3 and Table 1.

a) Bottom left
b) Top left
c) Bottom right
d) Top right

The trusses evaluated in this paper as shown in Figure 4 are

a) Tree Design Truss;
b) 3 Pieces Equal Dimension Standard Truss;
c) 3 Pieces Equal Dimension Triangular Truss;
d) 3 Pieces Tree Design Ratio Standard Truss;
e) 3 Pieces Tree Design Ratio Triangular Truss;
f) 5 Pieces Equal Dimension Standard Truss
g) Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width.



a) b) c) d)

Fig. 3: Definition of loading condition (example)

Table 1: Definition of truss models

Type	Term	Definition
Ratio Spacing	Equal dimension	The spacing ratio between joints is 1. The total height of truss is divided into equal parts. (E.g. 3 pieces trusses will be divided into 3 equal parts; Similarly, 5 pieces trusses will be divided into 5 equal parts.)
	Tree design ratio	The spacing ratio follows the tree design rule of thumb. Therefore, the spacing between each joint is deferent. The spacing ratio of a tree design structure is approximated to (1: 1.1: 1.5).
Trusses	# piece	The total height of truss is divided by #, which is the number section.

To determine this experiment's validity and accuracy, all trusses are evaluated under the following conditions

1. statically determinate, stable and in equilibrium;
2. all loads are applied to joints;
3. fixed load;
4. pin and roller support (adjusted according to the loading direction);
5. members joined together by smooth pins (no transfer of moment);
6. circular steel hollow section (STD CHS 100 10);
7. bar elements.

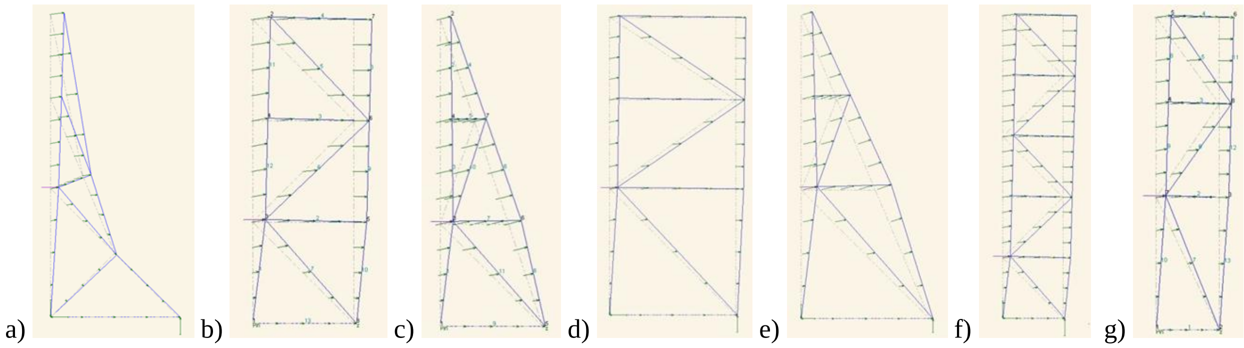


Fig. 4: Analysed truss designs models

The equations for the static equilibrium, structural determinacy and structural stability [1] can be defined as shown in (1), (2) and (3), respectively.

$$\Sigma F_x = \Sigma F_y = 0 \quad (1)$$

$$2J = M + R \quad (2)$$

$$2J - 3 = M \quad (3)$$

Where, Fx=Forces in the x direction, Fy=Forces in the y direction, J=Number of Joints, M=Number of Members, R=Number of Reaction.

3. Results and discussion

The structures shown in Figure 4 are the truss designs analysed in this paper. The descriptions to the respective illustrations shown in Figure 4 are mentioned in section 2.3.

3.1. Comparison of conventional truss design with tree design truss

To determine the effectiveness and practicality of the tree design structure against conventional truss design. The results are shown in Table 2. From the results obtained as shown in Table 2, the 3 Pieces Equal Dimension Standard Truss design has the lower overall displacement and it excel exceptionally in reducing deflection on the top loading condition. The outcome is expected as the 3 Pieces Equal Dimension Standard Truss design has a much less slender top that provides better stiffness than the other two trusses. The performance of the 3 Pieces Equal Dimension Triangular Truss design was average in comparison to the other trusses. It performs exceptionally well when the loading condition is at its bottom left. This is most likely due to diagonal bar and its angle of approach providing lateral support at the node of the loading point. The Tree Design Truss performed the worst among the three trusses but showed significant displacement resistance when it is loaded at the bottom righthand side. This should also be expected as there are more diagonal bars supporting the load at its node, thus, having higher stiffness. However, when considering the total material used, the 3 Pieces Equal Dimension Triangular Truss design is the best design truss among the three trusses as it only requires an additional 0.28% length of steel than the tree design truss and it can reduce significant amount of displacement. Thus, the conventional truss is better than the tree design truss.

Table 2: Results of Tree Design Truss & Traditional Design Trusses

Type	Loading	Tree Design Truss (Tree)	3 Pieces Equal Dimension Standard Truss (Standard)	Difference	3 Pieces Equal Dimension Triangular Truss (Triangular)	Difference	Best Truss Design
Displacement (mm)	Bottom Left	2.538	1.686	33.6% less	1.22	51.9% less	Triangular
	Bottom Right	0.3072	1.445	370.4% more	1.158	277% more	Tree
	Top Left	36.16	7.066	80.5% less	14.73	59.26% less	Standard
	Top Right	35.01	7.027	79.9% less	14.49	58.61% less	Standard
Von Mises Stress (MPa)	Bottom Left	15.01	15.01	0	15.01		All designs
	Bottom Right	7.503	15.01	100.1% more	15.01	100.1% more	Tree
	Top Left	54.39	31.83	41.48% less	33.55	38.32% less	Standard
	Top Right	54.39	31.83	41.48% less	33.55	38.32% less	Standard
Total Length of Steel (m)		50.04	67.24	34.4% more	50.18	0.28% more	Tree

Table 3: Results of the Tree Design Structure & Tree Design Ratio Conventional Trusses

Type	Loading	Tree Design Truss (Tree)	3 Pieces Tree Design Ratio Standard Truss (Standard)	Difference	3 Pieces Tree Design Ratio Triangular Truss (Triangular)	Difference	Best Truss Design
Displacement (mm)	Bottom Left	2.538	1.947	23.3% less	1.582	37.67% less	Triangular
	Bottom Right	0.3072	1.641	434.18% more	1.486	383.72% more	Tree
	Top Left	36.16	5.276	85.41% less	9.78	72.95% less	Standard
	Top Right	35.01	5.228	85.07% less	9.475	72.94% less	Standard
Von Mises Stress (MPa)	Bottom Left	15.01	15.01	0	15.01	0	All designs
	Bottom Right	7.503	15.01	100.1% more	15.01	100.1% more	Tree
	Top Left	54.39	25.04	53.96% less	27.2	49.99% less	Standard
	Top Right	54.39	25.04	53.96% less	27.2	49.99% less	Standard
Total Length of Steel (m)		50.04	75.32	50.52% more	53.7	7.31% more	Tree

3.2. Comparison of different shaped trusses with tree design ratios

To identify the effects of applying the tree design spacing ratio (between the horizontal joints) on conventional truss, it is compared with the Tree Design Truss. The results are shown in Table 3. From the results obtained in Table 3, a similar overall performance of the different shaped design was obtained as in section 3.1. The Triangular Shaped Truss design still has a better overall performance than the other two trusses. The Tree Design Ratio or the ratio in the “Method of Tensile Triangles” does indeed improve the overall performance of the trusses. For an additional 7.31% length of steel in the 3 Pieces Tree Design Ratio Triangular Truss, excluding the bottom right loading results, it can reduce up to 70% or more deflection and experiences a stress reduction about 50% when compared to the tree design truss. The angle of approach of the diagonal bars and the overall width of the truss does help in increasing stability as well as stiffness This however comes with a cost to the span to depth ratio as the tree design ratio requires a longer width than the width of the equal spacing truss.

3.3. Comparison of conventional trusses with different ratios

To determine efficiency and practicality of applying the different spacing ratio into the two-conventional truss design mentioned in section 3.2, they are subsequently compared with its non-modified conventional truss designs. The results are shown in Table 4 and Table 5.

Table 4: Comparison Results of Different Spacing Ratio for the Standard Design Truss

Ratio Spacing		Tree	Equal	Efficiency
Displacement (mm)	Bottom Left	1.947	1.686	Equal: 13.41% less
	Bottom Right	1.641	1.445	Equal: 11.94% less
	Top Left	5.276	7.066	Tree: 25.33% less
	Top Right	5.228	7.027	Tree: 25.6% less
Von Mises Stress (MPa)	Bottom Left	15.01	15.01	All designs
	Bottom Right	15.01	15.01	All designs
	Top Left	25.04	31.83	Tree: 21.33% less
	Top Right	25.04	31.83	Tree: 21.33% less
Total Length of Steel (m)		75.32	67.24	Equal: 10.72% less

Table 5: Comparison Results of Different Spacing Ratio for the Triangular Design Truss

Ratio Spacing		Tree	Equal	Efficiency
Displacement (mm)	Bottom Left	1.582	1.22	Equal: 22.88% less
	Bottom Right	1.486	1.158	Equal: 22.07% less
	Top Left	9.78	14.73	Tree: 33.61% less
	Top Right	9.475	14.49	Tree: 34.61% less
Von Mises Stress (MPa)	Bottom Left	15.01	15.01	All designs
	Bottom Right	15.01	15.01	All designs
	Top Left	27.2	33.55	Tree: 18.93% less
	Top Right	27.2	33.55	Tree: 18.93% less
Total Length of Steel (m)		53.7	50.18	Equal: 6.6% less

Table 4 and Table 5 compares the difference between the two-similar overall shaped designs with different spacing ratios. For both conventional shaped trusses, it performs better under the bottom loading conditions compared to the tree design ratio infused design. From the results obtained, for an increase 10.72% of steel length in the tree design ratio rectangular shaped truss, there is a reduction of about 25% of deflection and a stress reduction of about 21% for only the top loading condition when compared to the equal dimension truss design. The triangular shaped truss also shows the similar pattern when the tree design ratio is used in its design. For an increase of 6.6% of steel length, its deflection can be reduced up to 35% and its stress can be reduced up to 19% for only the top loading condition. Therefore, the tree design ratio does provide a significant improvement into the overall performance of the truss design but with a higher base width as concluded in Section 3.2.

3.4. Effects of manipulating the base width of tree design ratio trusses

To study the effects of using the tree design ratio spacing on conventional truss design with smaller base width. This truss structure will be compared with the same base width as in the 5 Pieces Equal Dimension Standard Truss. The results are shown in Table 6. The results obtained as shown in Table 6 is as expected, as reducing the base width and its lateral stiffness will significantly reduce its overall deflection resistance as well as overall stability. The 5 Pieces Equal Dimension Standard Truss performed better than the Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width. Although the 5 Pieces Equal Dimension Standard Truss performed better than the Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width, the deflection resistance between the two designs are almost similar for the top loading condition. This is because in comparison to the 5 Pieces Equal Dimension Standard Truss, for a decrease of about 13% in total length on the Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width, there was only a decrease deflection resistance of about 12.5%. Hence, the load transfer of the Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width from the loading point to its base is significantly better at the top than bottom loading condition. This is most likely due to its orientation of the diagonal bar of the top loading conditions that follows better with its force flow than the bottom loading condition. Therefore, further study could be conducted regarding tree design ratio with smaller bases.

Table 6: Results on the effects of a smaller base width for both the Equal Dimension Standard Truss Design & the Tree Design Ratio Standard Truss Design

Type	Loading	5 Pieces Equal Dimension Standard Truss (Standard)	Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width (Tree)	Efficiency
Displacement (mm)	Bottom Left	1.288	5.362	Equal (76% less)
	Bottom Right	1.144	5.217	Equal (78.07% less)
	Top Left	14.63	16.73	Equal (12.55% less)
	Top Right	14.62	16.67	Equal (12.3% less)
Von Mises Stress (MPa)	Bottom Left	15.01	24.86	Equal (39.62% less)
	Bottom Right	15.01	24.86	Equal (39.62% less)
	Top Left	53.05	53.06	All designs
	Top Right	53.05	53.06	All designs
Total Length of Steel (m)		64.6	56.22	Tree (12.97% less)

3.5. Overall results of all the analysed trusses

The overall results for all the analysed trusses are shown in Table 7.

Table 7: Overall Results of the Truss Design

Type	Loading	Tree Design Structure	3 Pieces Equal Dimension Standard Truss	3 Pieces Equal Dimension Triangular Truss	3 Pieces Tree Design Ratio Standard Truss	3 Pieces Tree Design Ratio Triangular Truss	5 Pieces Equal Dimension Standard Truss	Tree Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width	Best Truss Design
Displacement(mm)	Bottom Left	2.538	1.686	1.22	1.947	1.582	1.288	5.362	3 Pieces Equal Dimension Triangular Truss
	Bottom Right	0.3072	1.445	1.158	1.641	1.486	1.144	5.217	Tree Design Structure
	Top Left	36.16	7.066	14.73	5.276	9.78	14.63	16.73	3 Pieces Tree Design Ratio Standard Truss
	Top Right	35.01	7.027	14.49	5.228	9.475	14.62	16.67	3 Pieces Tree Design Ratio Standard Truss
Von Mises Stress (MPa)	Bottom Left	15.01	15.01	15.01	15.01	15.01	15.01	24.86	All designs except for one design
	Bottom Right	7.503	15.01	15.01	15.01	15.01	15.01	24.86	Tree Design Structure
	Top Left	54.39	31.83	33.55	25.04	27.2	53.05	53.06	3 Pieces Tree Design Ratio Standard Truss
	Top Right	54.39	31.83	33.55	25.04	27.2	53.05	53.06	3 Pieces Tree Design Ratio Standard Truss
Total Length of Steel (m)		50.04	67.24	50.18	75.32	53.7	64.6	56.22	Tree Design Structure

The results in Table 7 clearly show that displacement resistance, stiffness, rigidity and stability are affected by the angle of approach of diagonal bars (arrangement of internal members), the number of diagonal bars, the width of the truss (span to depth ratio) and the spacing at each truss section. The effects on the internal arrangement of internal members are critical as it helps to determine its overall strength, but it also depends on the type and direction of loading conditions. The Tree Design Ratio mainly affects the inclination of each member in the truss design due to a larger base width as well as a different proportion of internal spacing. The internal arrangement of members also affects the amount of lateral support in each loading face.

The tree design truss has both the lowest total steel length and the lowest amount of displacement resistance. This is expected as the tip of the truss is very slender. The high flexible tip may be suitable for other civil engineering application (e.g. earthquake design structures to absorb and dissipate excess energy from seismic waves) and a higher stiffness at the lower end (base) that may be suitable for retaining structures that requires a solid and stable foundation. The large base footing in the tree design structure may provide improved stability to a structure. Hence, it may be possible for this feature to work towards a better passive seismic dampening system in structures without the need of an active mechanical dampeners. Therefore, there may be a possibility of saving cost, material, time as well as workmanship that adds up to a more sustainable design.

All the Equal Dimension Truss designs demonstrated a better overall performance against the Tree Design Truss. Generally, the higher the length of steel or material usage, the higher the stiffness but its effectiveness to resistance deflection depends on its load path (e.g. the 3 Pieces Tree Design Ratio Triangular Truss). The Tree Design Ratio in the 3 pieces triangular truss design has gain a significant benefit and it is very comparable with the 3 Pieces Equal Dimension Standard Truss design under the bottom loading condition. The displacement resistance under the bottom loading condition has a difference of about 2.84% - 6.6% and for under the top loading condition has a difference of about 35% -38%. It uses about 20% less steel length than the 3 Pieces Equal Dimension Standard Truss design. Therefore, the 3 Pieces Tree Design Ratio Triangular Truss is probably the best overall design in comparison to the other trusses. Nevertheless, the best truss design in lowering displacement is the Rectangular Shaped Truss design. The Tree Design Ratio spacing provides a realistic base width length for a structure.

The tree design ratio spacing is in its most stable or suitable condition when it is used accompanied with its designed rule of thumb. The minimum base width of the tree design ratio spacing is needed to overcome the need of higher stiffness, thus, reducing material required. Reducing its base accompanied with its tree design ratio spacing will severely affect its stability as well as it deflection resistance performance. This is mainly due to its span to depth ratio. Although the results for the top loading conditions shows a comparable deflection resistance performance in the Tree

Design Ratio with 5 Pieces Equal Dimension Standard Truss Base Width as compared to the 5 Pieces Equal Dimension Standard Truss due to its better force flow, it is generally not a good overall truss structure as it suffers under the bottom loading condition.

Results and conclusions made may not be conclusive due to insufficient testing and modelling. One possibility is to analyse the tree design structure in horizontal position (rotated 90° degrees) instead of a vertical position. This is solely a preliminary study for civil engineering application and therefore, there may be other boundaries and modelling combination that is not covered in this research. Further research is still required.

4. Conclusion

The triangular shaped truss design performed the best in terms of cost to performance ratio but the rectangular shaped truss design remains the best lateral resisting truss structure. The introduction of the tree design ratio spacing into the conventional truss structure does improve its overall displacement resistance performance with a relatively low amount of addition length of steel. The tree design shows the possibly of creating a more sustainable design with its reduced usage of the limited resources available (through its total area and volume), thus, allowing more workable space without detrimental effects on its strength or performance. There may be other possibilities that are yet to be discovered but are only limited by our creativity.

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References

[1] Hibbeler, R. (2009). Structural analysis. 7th ed. Singapore: Pearson Prentice Hall, pp.89.

[2] Mattheck, C., Kappel, R. & Sauer, A., (2007), Shape optimization the easy way: The "method of tensile triangles." International Journal of Design and Nature, 2(4), pp.301–309.