DESIGN OF STEEL TRUSS CANTILEVERED FORMWORK

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Abstract:

The architectural design of buildings with non-typical floors creates risky situations at which cantilevered slabs and beams are extended while the floor beneath has no cantilevered slabs on which the false-work could rest. The design proposed in this paper is based on using steel cantilevered trusses to support the formwork system with no need for extending the false-work along the height of the building. A closed form solution for the truss was formulated and validated using a commercial software. A parametric study was performed using the closed form solution to study the variations of the straining actions within the truss member with the truss dimensions. The study was extended in order to pick the most economic dimensions of the truss for each cantilevered truss span.

Keywords: Structural Engineering; Construction Engineering; Structural Steel; Formwork Design.

1 INTRODUCTION.

Vertical shores, or posts, and scaffolding are used with formwork to support concrete girders, beams and slabs until these members gain sufficient strength to carry their own weight. The types of shoring and scaffolding systems may vary in material and size of each. They may be made from wood or steel, aluminum or from a combination of two of these materials. In large projects, steel shores are more commonly used than job-fabricated wood shores for supporting formwork for concrete beams and slabs. Most of these steel shores are patented. Patented shores are available and adjustable over a wide range of lengths, for most of them; adjustments in length can be made in small increments and more durable. However, the initial cost of these steel shores is higher than that of wooden shores, sometimes it is more difficult to attach intermediate braces than it is for wood shores and sometimes more susceptible to buckling than wood shores due to their slenderness (Peurifoy & Oberlender, 2011) (Bennett & D'Alessio, 1996).

The architectural design of buildings with non-typical floors creates risky situations at which cantilevered slabs and beams are extended while the floor beneath has no cantilevered slabs on which the false-work could rest. The use of typical vertical shoring to support an irregular cantilever five or six floors high (or even more) could be typically seen in several countries. The stability of such shores (whether steel or wood) is under a major question mark in addition to the fact that assembling such shores and bracing them for such big heights is for sure a time consuming task (Chandrangsu & Rasmussen, 2011). Hence, it is more suitable to utilize the existing structure to extend formwork from it to support the formwork used in such cases without having shoring activities for the full height of the building beneath the cantilever under construction. One of the advancements reached in such field is the so-called “Flying Deck Forms” that are composed of a set of components assembled into units, called decks, for forming concrete slabs in multistory buildings. The same set of flying deck forms could be used repeatedly to form multiple floor slabs in a building that could have different dimensions. After the concrete that has been placed in a slab is sufficiently cured, the flying deck form for the slab is removed (without disassembly of the parts), moved

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(flown) horizontally outward, away from the building, and then moved up and back inward to the building to a new location, and used again to form another concrete slab if needed (D'Alessio & Bennett, 1996). However, and as it is obvious in Figure 1, this assembly involves a significantly large amount of steel that could be not necessarily needed if the cantilever is not exceeding few meters. This would increase the direct cost of the assembly itself in terms of the material cost of its steel truss and the indirect cost of transporting such a large truss to the site and within the site itself. This capital intensiveness of such types of forms makes the conventional shoring and formwork systems preferred by several engineers and contractors over flying forms (Shapira, 1995).

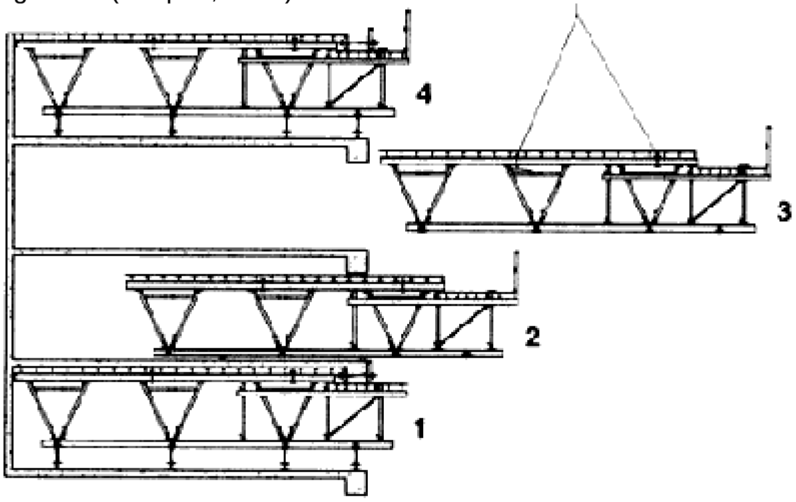

Figure 1: Moving a flying form from one position to another position (Guam Forming and Scaffold LLC).

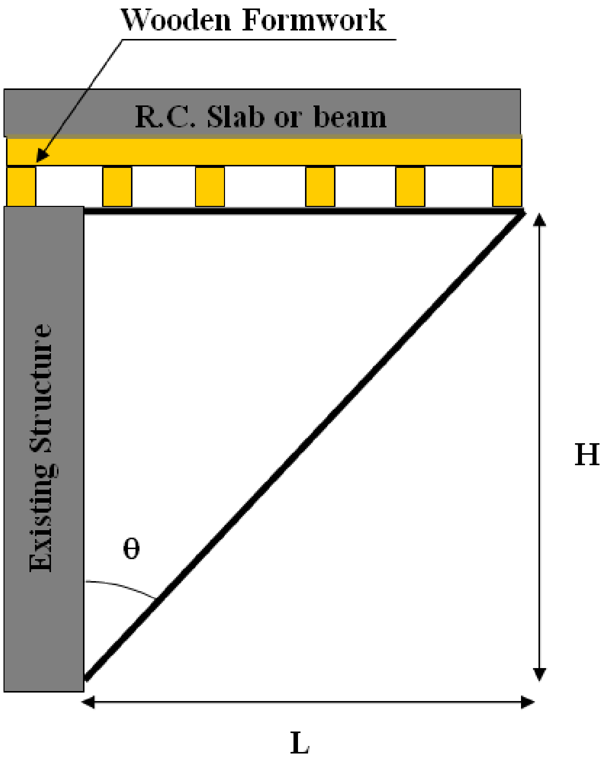

Figure 2: The proposed steel truss supported cantilevered formwork.

Also telescopic beams that have a trapezoidal shape in its side view are commonly used as its upper side could be extended up to 2-3 m out of its lower side however its use is limited as it depends on pouring the full slab (the inner and cantilevered portion) together and it also has a limitation in its cantilevered portion that couldn't extend to more than 3 m away from the existing structure (Elbeltagi, Hosny, Elhakeem, Abd-Elrazek, & Abdullah, 2011). However, such a system will also involve using a large amount of steel members.

This paper proposes a simplified design based on using steel cantilevered trusses to support the formwork system with no need for extending the false-work along the height of the building. As shown in Figure 2, the cantilevered steel truss is attached to the existing structure. This temporary structure could be easily disassembled and transported when compared to the flying deck forms. In addition to that the direct cost of such a two-member cantilever truss will be significantly less than that of the flying deck forms due to the reduction in material weight reflecting material cost and the unit cost of the assembly.

2 METHODOLOGY.

2.1 Closed Form Solution

As shown in Figure 2, the cantilevered form work having a length of (L) shall be supported by a steel truss having depth of (H). The truss is composed of an upper chord T-section member and a lower chord equal angle member making an angle (θ) with the vertical existing structure. The truss is hinged to the existing structure at its top and bottom. The trusses are spaced at an equal spacing of S in the transverse direction. Hence the distributed load (W) on the upper chord member is calculated by the relation:

[1] $W = W_{st} + W_w + S\gamma t$

Where W_{st} is the own weight of the upper chord, W_w is the own weight of the wooden formwork system, γ is the unit weight of reinforced concrete (approximately 25000 N/m^3) and t is the average thickness of the concrete slab and/or beam.

Consequently the distributed load will cause a reaction (P) on each joint at the ends of the upper chord:

[2] $P = WL/2$

Studying the static equilibrium of the joint at the free tip of the truss:

$\Sigma F_y = 0$

$P + F_{lc}\cos\theta = 0$

[3] $F_{lc} = -P\sec\theta$

Where F_{lc} is the compression force in the lower chord member and F_{uc} is the tension force in the upper chord member. Similarly:

$\Sigma F_x = 0$

$F_{uc} + F_{lc}\sin\theta = 0$

[4] $F_{uc} = -F_{lc}\sin\theta = P\tan\theta$

Knowing also that the bending moment within the simply supported upper chord member is calculated according to the relation:

[5] $M_{uc} = WL^2/8$

2.2 Validation

The developed closed form solution was validated by solving four different cases of trusses with four different dimensions using the proposed solution and re-analyzing these trusses using the commercial software SAP2000. This validation process was done for a range of distributed loads starting from 10000 N/m to 22500 N/m. The four cases are presented in Table 1 and represent the variation in the most practical cases when it comes to the real realistic dimensions of cantilevered formwork. As shown in Figure 3, the results of each of the four cases analyzed on SAP2000 coincided with the results produced using the closed form equations. Hence, the closed form solution is valid in terms of accuracy.

Table 1: The four different validation cases.

Case #	1	2	3	4
H (m)	3	3.4	3.8	4.2
L (m)	3	4	5	5

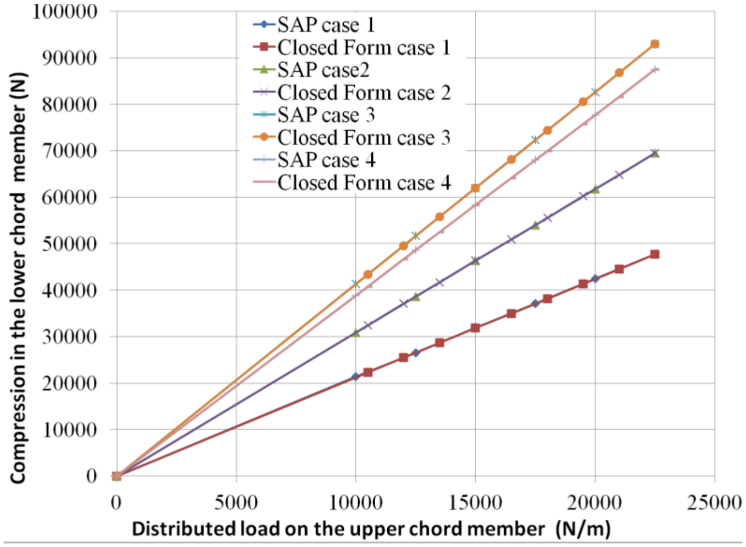

Figure 3: Results of the four validation cases.

3 PARAMETRIC STUDY

3.1 Straining Actions

The closed form solution was used in order to evaluate the axial forces in the lower and upper chords of the truss and the bending moment in the upper chord members. The parametric study was performed for eight different values of the truss height (H) ranging from 2.2 m to 5 m. The five values of the cantilever span (L) ranged from 1 m to 5 m. Hence, forty different cantilevered trusses with different dimensions were analyzed using the closed form solution. The distributed loads on the upper chords ranged from 10500 N/m to 22500 N/m.

From comparing the results reported in Figure 4, Figure 5 and Figure 6 it could be noticed that the axial compressive force in the lower chord member increases with the increase in length however it decreases with the increase in truss height. This is expected to create a challenge when it comes to selecting the most optimum design as the larger is the length of the member, the more is the cost of construction while according to these results, the larger is the truss depth, and the smaller is the lower chord member cross-section needed. In addition to all of that the increase in height and/or span will consequently increase the length of the lower chord member which will raise an issue when it comes to design as the increase in the member length will force the designer to use a member with a larger cross-section in order to resist buckling.

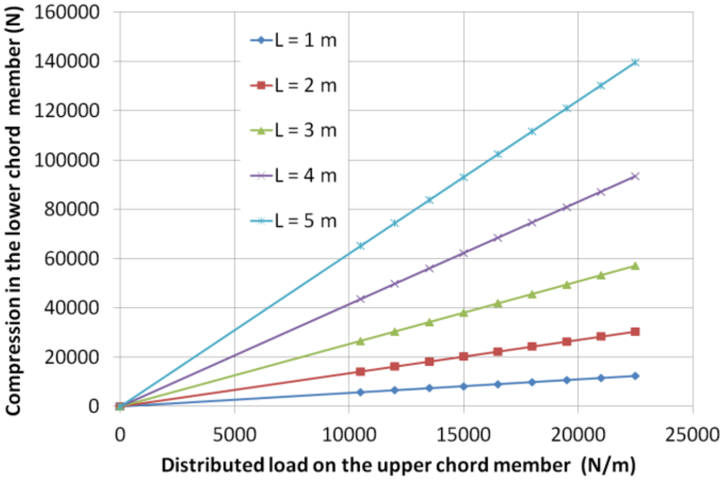

Figure 4: F_{lc} for H = 2.2 m.

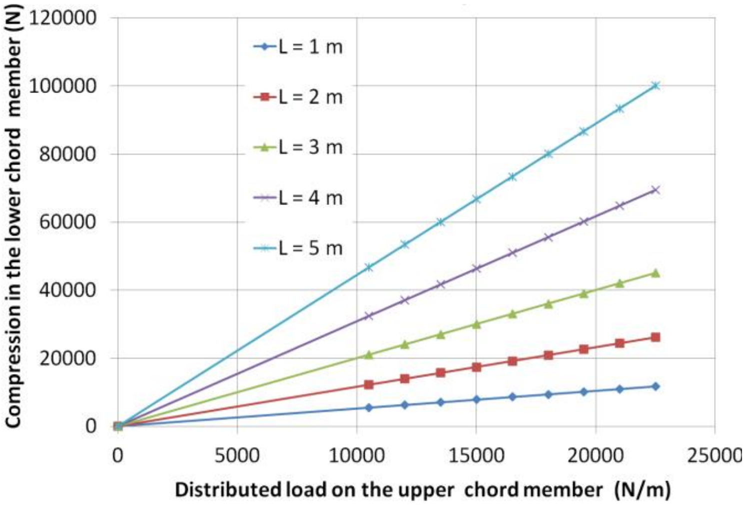

Figure 5: F_{lc} for H = 3.4 m.

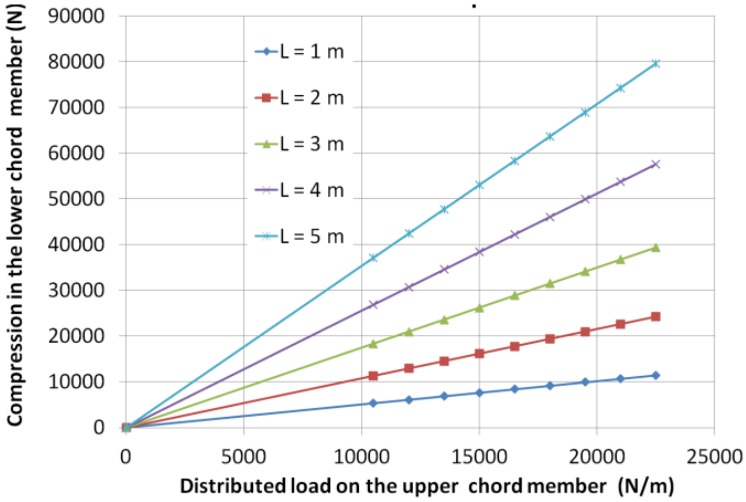

Figure 6: F_{lc} for H = 5 m.

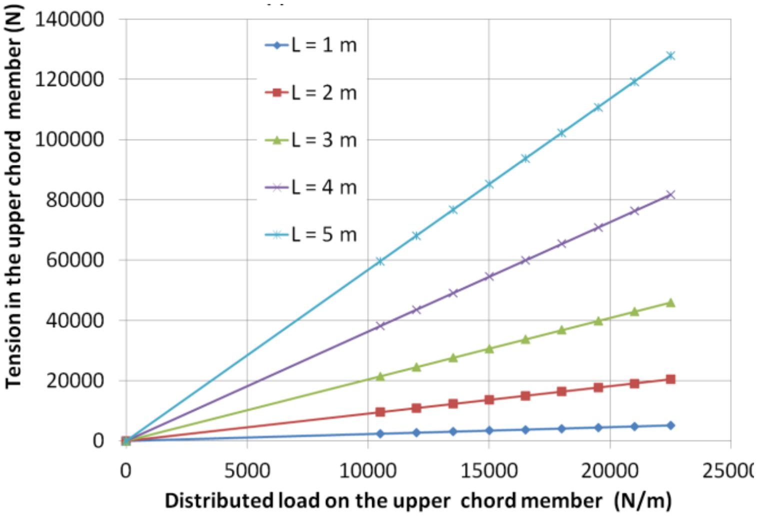

Figure 7: F_{uc} for H = 2.2 m.

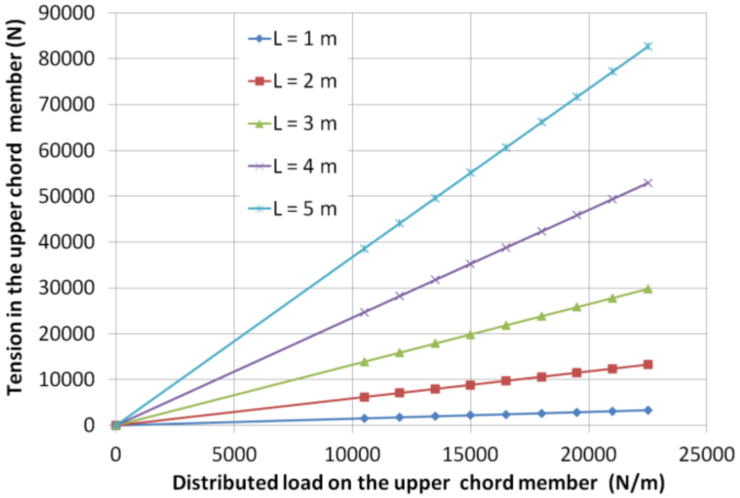

Figure 8: F_{uc} for H = 3.4 m.

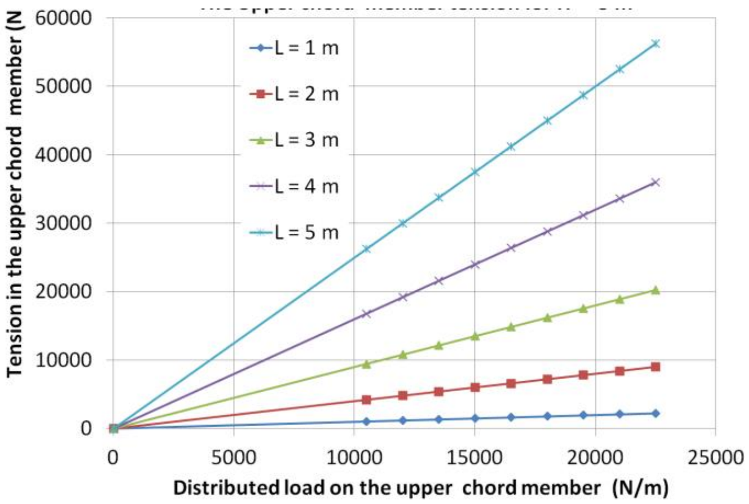

Figure 9: F_{uc} for H = 5 m.

From comparing the results reported in Figures 7, 8 and 9, it could be noticed that the axial tensile force in the lower chord member increases with the increase in length however it decreases with the increase in truss height. This is expected to create a challenge when it comes to selecting the most optimum design as the larger is the length of the member, the more is the cost of construction while according to these results, the larger is the truss depth, and the smaller is the lower chord member cross-section needed. However, another factor comes into the picture when it comes to design which is the bending moment that increases with the square of the upper chord length (the span) which could force any designer to significantly increase the upper chord cross-section in cases with large cantilever spans. Hence, and according to what was experienced in the parametric study so far, finding the most economic and safe configuration is not a straight forward task and one needs to perform a set of designs in order to answer the design question.

3.2 Structural Design

The structural design was performed for the members in each of the forty different trusses analyzed in the parametric study under the highest uniform load (22500 N/m). The designs were performed according to the Canadian Institute of Steel Construction provisions (CISC, 2008). All of the designs were performed in order to meet the safety requirements with the lightest weight members. The target of this process is to pick the most economic truss by determining the truss height that will correspond to the lightest weight truss for each cantilever span.

The upper chord member that is subjected to a combination of bending moment and axial tensile force was designed to be a T-section cut from an I-beam while the lower chord member was designed as an equal angle L-section in order to have the same moment of inertia, and consequently the same effective buckling length, on each of its minor axes. The truss was assumed to be sufficiently braced in the transverse direction (the horizontal plane perpendicular to the plane of the truss members). Based on this assumption, the end conditions used to calculate the effective buckling length are considered to be pinned–pinned conditions.

After designing each of the two chords for each of the forty truss configurations, the unit mass of each truss member was multiplied by its length in order to acquire the member mass. Then for each truss configuration the masses of the two members were added in order to produce the total mass of the truss chords. The results are presented in Table 2, Figure 10, Figure 11 and Figure 12.

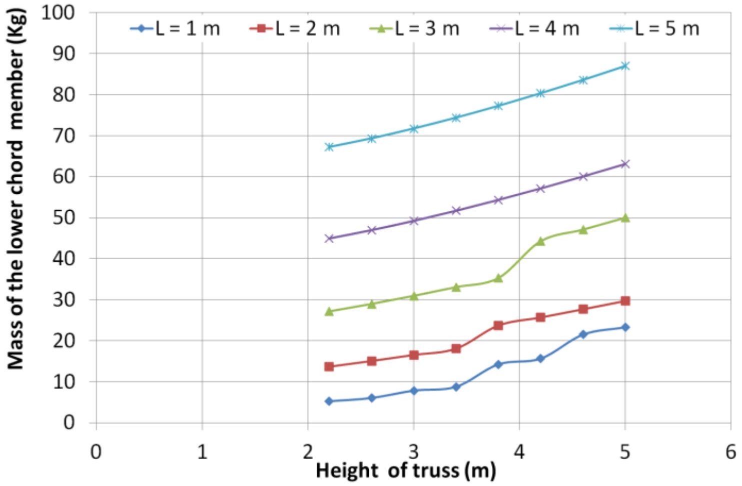

Figure 10: Variation in the lower chord mass for different truss dimensions.

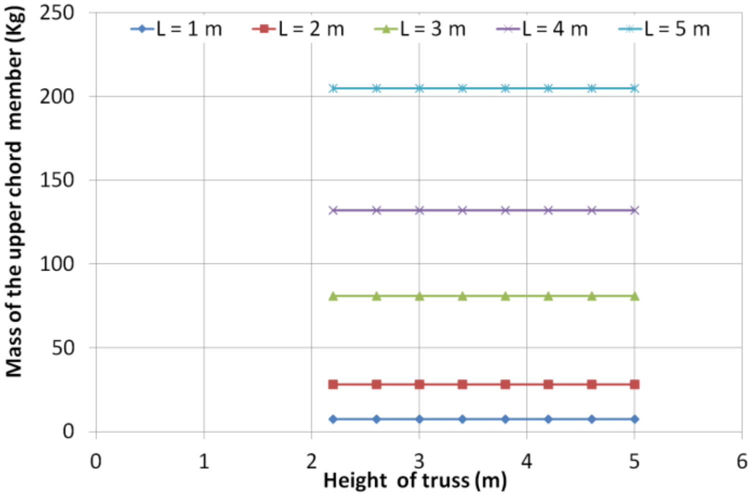

Figure 11: Variation in the upper chord mass for different truss dimensions.

From the variation in the lower chord mass presented in Figure 10 one could obviously see the significant effect of the change in the cantilevered truss span (L) and the truss height (H) on the mass of the lower chord truss member. The variation in L changes the concentrated load (P) acting at the free end of the truss hence directly affecting the value of the axial force in the lower chord. In addition to that, any change in the truss span or its height will change the length of the lower chord and consequently the critical buckling load for this member under compression will be significantly affected as it is inversely related to the square of the member effective length (CISC, 2008). Hence, changing the height (H) or the span (L) or changing both of them affected the effective member length of the lower chord and increasing any of these two dimensions caused a need for a stiffer member in order to be capable of having a higher critical buckling load and avoid failure due to buckling.

On the other hand, the situation for the upper chord member subjected to a tensile force was different. From the variation in the upper chord mass presented in Figure 11, one could obviously see the significant effect of the change in the cantilevered truss span (L) on the mass of the upper chord truss member. The variation in L changes the concentrated load (P) acting at the free end of the truss hence directly affects the value of the axial force in the upper chord. In addition to that, the variation in L significantly affects the bending moment in the mid-span of the member as the bending moment is directly proportional to L^2. However, as the bending moment is the governing factor in the design of the upper chord member and as the truss height doesn't affect this bending moment, the change in the truss height does not affect the intensity of the stresses in the upper chord that are primarily affected by the bending moment. In addition to that, the upper chord member is not subjected to compression hence the issue of the critical buckling load being affected by the member length that was faced in the case of the lower chord member under compression is not applicable when it comes to the upper chord member.

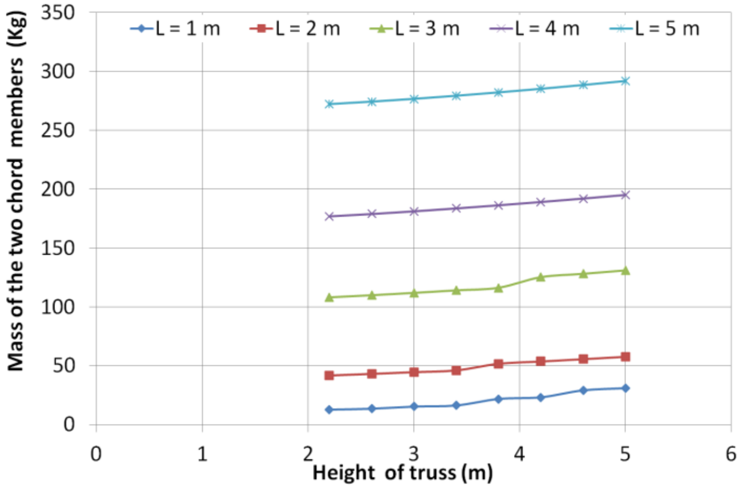

Figure 12: Variation in the total chords mass for different truss dimensions.

Figure 12 shows the variation in the total chords mass with the truss height and the truss span. According to what could be seen in Figure 12 and Table 2, the total mass of the truss members significantly increases with the increase in the span. However, it could also be seen that the increase in height will not cause an increase in the truss mass as large as the increase in mass caused by the increase in span. As mentioned before, this is mainly attributed to the difference in type of loading and straining actions that the upper and lower chords are subjected to. The increase in the cantilever span (L) caused multiple effects as it increased the bending moment in the upper chord hence creating a necessity for a stiffer upper chord member and it also increased the axial compressive force in the lower chord member and increased the member unsupported length hence creating a necessity for a stiffer lower chord member to increase its ability to resist buckling. Hence, and as it is also apparent from the values reported in Table 2 and the shape of the curves in Figure 12, for each cantilever span the least massive truss is the one with the minimum height reflecting the most cost saving situation as most of steel fabricators base their prices on a unit price per unit weight of steel.

It could be also noticed from comparing the results presented in Table 2, Figure 10, Figure 11 and Figure 12, that changing the height had a minor effect on the total mass when compared to changing the span that had a more significant effect on the total mass. This is attributed to the fact that changing the height doesn't affect the upper chord mass while changing the span significantly affects the upper chord mass. It is also attributed to the multiple effects of changing the span on both the axial force and the effective member length resisting buckling in the lower chord under compression while changing the height doesn't affect the force intensity with the same extent as it affects the effective member length, that caused the effect of changing the span to be more apparent than the effect of changing the truss height even in the lower chord member itself.

Table 2: The design of truss chords for different truss dimensions.

L (m)	H (m)	Lower Chord Section	Upper Chord Section	Total Mass (kg)
1	2.2	L44x44x3.2	WT100x7.5	12.7
	2.6	L44x44x3.2	WT100x7.5	13.5
	3	L51x51x3.2	WT100x7.5	15.3
	3.4	L51x51x3.2	WT100x7.5	16.2
	3.8	L51x51x4.8	WT100x7.5	21.7
	4.2	L51x51x4.8	WT100x7.5	23.1
	4.6	L64x64x4.8	WT100x7.5	29.0
	5	L64x64x4.8	WT100x7.5	30.8
2	2.2	L64x64x4.8	WT155x14	41.6
	2.6	L64x64x4.8	WT155x14	43.0
	3	L64x64x4.8	WT155x14	44.5
	3.4	L64x64x4.8	WT155x14	46.0
	3.8	L76x76x4.8	WT155x14	51.7
	4.2	L76x76x4.8	WT155x14	53.7
	4.6	L76x76x4.8	WT155x14	55.7
	5	L76x76x4.8	WT155x14	57.7
3	2.2	L76x76x6.4	WT205x27	108.1
	2.6	L76x76x6.4	WT205x27	109.9
	3	L76x76x6.4	WT205x27	111.9
	3.4	L76x76x6.4	WT205x27	114.0
	3.8	L76x76x6.4	WT205x27	116.3
	4.2	L89x89x6.4	WT205x27	125.2
	4.6	L89x89x6.4	WT205x27	128.1
	5	L89x89x6.4	WT205x27	131.0
4	2.2	L102x102x6.4	WT265x33	177.0
	2.6	L102x102x6.4	WT265x33	179.0
	3	L102x102x6.4	WT265x33	181.3
	3.4	L102x102x6.4	WT265x33	183.7
	3.8	L102x102x6.4	WT265x33	186.3
	4.2	L102x102x6.4	WT265x33	189.1
	4.6	L102x102x6.4	WT265x33	192.0
	5	L102x102x6.4	WT265x33	195.1
5	2.2	L127x127x6.4	WT305x41	272.2
	2.6	L127x127x6.4	WT305x41	274.3
	3	L127x127x6.4	WT305x41	276.7
	3.4	L127x127x6.4	WT305x41	279.4
	3.8	L127x127x6.4	WT305x41	282.3
	4.2	L127x127x6.4	WT305x41	285.3
	4.6	L127x127x6.4	WT305x41	288.6
	5	L127x127x6.4	WT305x41	292.0

4 CONCLUSIONS AND RECOMMENDATIONS.

The closed form solution was valid and considered as a firm basis to perform the parametric study. The following conclusions could be drawn from the performed parametric study:

- The axial forces in the upper and lower chord members were proportional to the cantilevered truss span and the truss height.
- The magnitude of the compression force in the lower chord was higher than the magnitude of the tensile force in the upper chord.
- The cantilever truss span is the main factor governing the weight of the designed steel members whether they are upper or lower chords.
- The longer is the cantilever span the heavier is the cantilever truss.
- The truss height has a negligible effect on the weight of the designed upper chords due to the fact that the main contributor to stresses is the bending moment in the simply supported chord and the axial tension force has a very minor contribution when it comes to tensile stresses within the member.
- Both, the truss height and the cantilevered span affect the weight of the designed lower chords due to the fact that the sole contributor to stresses is the axial compressive force in the chord and the member is sensitive to buckling which is affected by the member length that is function of both the height and the span of the truss.
- For each cantilever span the total mass of the cantilevered truss is minimized when the truss height is minimal and consequently the cost is minimized when the truss height is minimal.

Based on these drawn conclusions, it is recommended to:

- Perform further research to study the variation in the different factors affecting the constructability of the different truss configurations with different dimensions.
- Study the different bracing alternatives and whether changing such alternatives may change the critical buckling loads through changing the effective buckling lengths and the economical soundness of such alternatives.
- Study the behavior of the cantilevered truss form under wind loads and whether the presence and intensity of such load cases will create a necessity to significantly change the design of one or more of the truss members.

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