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DESIGN OF FUNICULAR ARCHED TRUSS STEEL FALSE-WORK

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Abstract: The patented steel formwork systems used in construction cost a lot, take time to be erected and reduce the space in the construction site as they prevent motion underneath the system. The proposed new system depends on developing a formwork system using the concept of the funicular arch. The proposed system costs less than the existing patented system because it incorporates fewer amounts of steel, environmental friendly because it uses less material and provides more space in the site for workers and materials to flow in the construction site. The new system also reduces the time needed for erecting the system and consequently saves time and cost.

Keywords: - Construction Engineering; Formwork Design; Funicular Arches; Structural Engineering; Sustainability; Steel;

1. Introduction

Building construction has been environmentally problematic as it is considered to be one of the major sources of greenhouse gas emissions in addition to the buildings being one of the largest energy consumers globally as buildings produce approximately 33% of greenhouse gases and consume 40% of the energy worldwide (Allouhi, et al. 2015). On the other hand the construction activities directly produce 12.6% of the building carbon dioxide emissions all over the world (Peng 2016). However, the choice of building materials and the various aspects within a building design highly affect the carbon dioxide emissions along the building life cycle (Jiang, et al. 2013). Hence, it is essential to study the effect of the various aspects related to building design and materials that affect the amounts of the greenhouse gas emissions and the overall energy consumption within a building in order to produce a design that is ecofriendly in addition to being safe, efficient and economically sound.

Most concrete structural members, especially concrete slabs, are cast in place which creates the need for temporary structure that supports these members until they are strong enough to support their own weight. Formwork supported by false work can act as this temporary structural members allowing concrete to harden to take its final desired shape until it gains the required compressive strength. Any formwork system consists of some main components such as plyform or plywood, which is the first interaction between the formworks system and the freshly poured concrete, joists, stringers and shores.

As stated above, plyform or plywood are the sheets that supports the freshly poured concrete for the slab and transfer the loads to the joists which acts as secondary beams that transfer the loads to the main beams called stringers. The stringers are supported by shores and can be simply supported or composed of multi span depending on the design of the formwork system (Peurifoy and Oberlender 2011).

The most common type of shores used in the construction industry is the steel patented shore systems although there are other types of shore systems that are made from wood or aluminum. These patented systems are available in a wide range of heights and can be adjusted in small increments to suit the job. However, these systems require high initial cost than any other shore systems (Bennett and D'Alessio 1996).

To overcome the problem of high initial cost, wooden trusses are used instead of stringers and are supported with steel pops or trusses depending on the job conditions they are expected to be exposed to in order to increase the supported span by the system (PERI 2015). However, these wooden trusses have constant depths which affects the financial saving expected from these trusses. Moreover, the fact that they are patented creates additional cost and consequently increases the initial cost expected from these wooden truss systems.

Throughout history arches made of stones or bricks have been used by ancient civilizations such as the Romans, Greeks and the concept was transferred to Islamic and Gothic civilizations (Wikimedia Foundation, Inc. 2016). These arches were semi-circular, horse-shoe and parabolic arches. However, despite the concept of arches have been known since the first civilizations in history, it had been constructed in the modern civilization only two hundred years ago. This was when the funicular arched trusses appeared because they give a major advantage through their parabolic shape to decrease the axial forces in the diagonal and upper chord members (Leet, Uang and Gilbert 2006). Consequently, the funicular arched trusses will have less deflection and less axial forces which mean that they can support larger spans. These characteristics of the funicular arched trusses allowed it to be used in the construction of long-span bridges (Darwish, et al. 2015). However, the funicular arched trusses has never been used as the basis of a formwork/false work system.

This research paper focuses on proposing a design of formwork system that follows the funicular steel truss concept. This will decrease the axial forces on the members and decrease the mid-span deflection and consequently the cross section of each member in the steel truss. This system will replace ten of the currently used patented shores by only two steel trusses. Within this study, the variation of forces in each type of the members are studied when changing the span together with its impact on construction ease, time, its effect on the space availability within the construction site and its positive impact on the environment in terms of saving a large amount of steel used in shoring activities.

2. Model

2.1 Theoretical concept

According to (Leet, Uang and Gilbert 2006), an arch is considered funicular if it has an intermediate hinge in the midpoint, hinged at the two supports and obeys the parabolic equation as follows:

[1] $y = -4hx2/L2$,

where x and y are the horizontal and vertical coordinates measured from the midpoint of the arch, h is the height of the truss and L represents the arch span.

When an arch that follows the previously mentioned equation is subjected to a uniformly distributed vertical load, it is found that the shear forces and the bending moments within the arch have a zero value (Leet, Uang and Gilbert 2006). Applying this fact to a truss that follows the concept of the funicular arch, the upper chord and the diagonal members will be zero members and the loads will transferred to the bottom chord members through the vertical members of the truss. Consequently, the bottom chords of the funicular arched truss carry high compressive axial forces.

In the funicular arched truss, the upper chord will act as a beam that carries the uniform load and transfer it to the vertical members. To reduce the bending moment on these upper chord members, the member covering right equidistant bays are treated to be two main members, each of them covering 4 equidistant bays, which are connected at the intermediate hinge at the midpoint of the arch. Therefore, the maximum bending moment that acts on each horizontal member can be calculated using the following equation:

[2] $Mu = wa2/9$,

where Mu is the maximum bending moment, w is the distributed load and “a” is the length of each bay (which is equal to L/8).

Using the method of joints to solve the funicular arched truss, it was concluded that the upper chord members and the diagonal members are all zero members. Further, it was concluded that the axial force in each of the exterior vertical members of the truss satisfies the following equation:

[3] $P_{vext} = -wa/2$. Moreover, the forces in the interior verticals were found to satisfy the following equation:

[4] $P_{vint} = -wa$.

Furthermore, the bottom chord member was found that they satisfy one general equation which is

[5] $Pij = -wL_{ij}L/h$

Where P_{ij} is the axial force within the member connecting nodes i and j, L_{ij} is the length of the member, L is the truss span and h is the truss height.

2.2 Model Description:

The truss proposed in this research paper consists of thirty steel tube members. As shown in Figure 1, there are eight vertical members; the two outer vertical members are steel tubes of 25.4 mm diameter, the four inner verticals are steel tubes with a diameter of 25.4 mm inch, the most two inner vertical members are steel tubes of 16 mm. the case is different for the bottom chords because the forces decreases in the inner bottom chords. The two outer bottom chords are steel tubes of 31.75 mm diameter, the diameter decreases in the following two members to be 25.4 mm, and the diameter is decreasing in the following two members to be 19 mm and the two most inner bottom chord members are 16 mm diameter as they carry the least compressive force. Further, figure 1 shows that the height of each vertical member is a function in the total height of the truss. The outer vertical member will be equal to the total height of the truss, the height of the following member will be 9h/16, the height of the following member will be h/4 and the most inner vertical member will have a height of h/16. The length of the diagonal members and the bottom chord members can then be calculated after determining the heights of the vertical members and the distance "a" which is the length of the horizontal members.

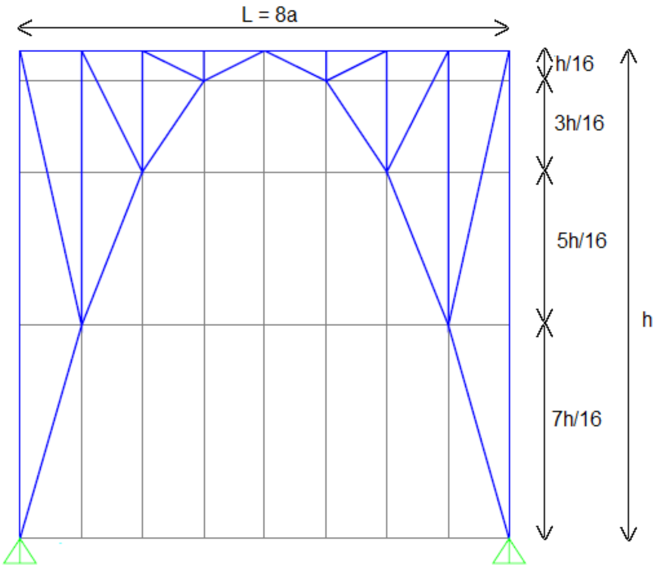

Figure 1: Proposed Funicular Arched Steel Truss

Furthermore, the upper horizontal chord members, the diagonal members and the bracing members have a diameter of 16 mm. All of these steel tubes have 1 mm thickness. Table 1 summarizes the diameters of all the members in the proposed funicular arched truss. The data in the table is for half of the truss. Its numbering system is as follows: the connection between the upper chord members are given the odd number from (1, 3, 5, 7 and 9) and the connections of the bottom chord members are given the even numbers (2, 4, 6, and 8), however, they meet with the upper chord members in the intermediate hinged which has the number 9.

Table 1: Diameters of the member of the proposed funicular arched steel truss

Member Name	Member Number	Diameter	Thickness (mm)
Exterior Vertical (EV)	EV (1-2)	1 inch	1
Stringer	S	16 mm	1
Interior Vertical (IV)	IV (3-4)	1 inch	1
	IV (5-6)	1 inch	1
	IV (7-8)	16 mm	1
Bottom Chord (BC)	BC (2-4)	1.25 inch	1
	BC (4-6)	1 inch	1
	BC (6-8)	19 mm	1
	BC (8-9)	16 mm	1
Diagonals (D)	D (1-4)	16 mm	1
	D (3-6)	16 mm	1
	D (5-8)	16 mm	1
Scissors (SC)	SC (34-34)	16 mm	1
	SC (56-56)	16 mm	1

The proposed system consists of units that consist of two trusses that are arranged back to back on the site where the concrete is to be poured. Each two trusses forming a unit will be connected together with bracing members that are connected to the inner vertical members. The bracing is very important in these four members to avoid failure due to buckling. This allows for more space between the units of the trusses. Wooden members will be put on top of the trusses to act as joists and will be fixed on the U-heads fixed on the steel tubes acting as the vertical members. The plywood or plyform will be fixated on the top of the wooden joists using nails and therefore the complete formwork system is formed.

2.3 Validating the Closed Form Model:

A finite element model was built on SAP2000 (Computers and Sturctures Inc. 2016) to validate the results of the closed form solution, stated above. The validation was performed on a truss that has a height of 3 m and a span of 2.4 meters. The applied distributed load was 3.97kN/m and the output of the model is shown in figure 2.

The results after running the model on SAP2000 were as expected and in consistence with the concept of the funicular arch. Table 2 summarizes these results. The upper chord and the diagonal members were proved to be zero members. The vertical members were found to be following the previously mentioned equations. The values of the forces in the exterior members were expected to be carrying 0.562 kN while the SAP2000 model gave a value of 0.62 kN. The values of the forces in the interior verticals were expected to be 1.192 kN while the SAP2000 model gave 1.2 kN.

On the other hand, the bottom chord members were found to be carrying the highest axial forces among all the members in both the closed form model and the SAP2000 model. The first bottom chord with the largest diameter was expected to have a compressive force of 4.28 kN while the SAP2000 model gave a result of 4.34 kN. The following bottom chord with the second largest diameter was expected to have a compressive force of 3.13 kN while the SAP2000 model gave a result of 3.16 kN. The following bottom chord was expected to carry a force of 2.03 kN while the results from the SAP2000 gave 2.04 kN. The last bottom chord with the smallest diameter among the bottom chord members was expected to carry 1.12 kN while the SAP2000 results gave 1.13 kN.

From analyzing the results of the finite element model and comparing them to the closed form model, it was found that the axial forces in the bottom chord members are nearly the same with a difference that ranges from 0.46% to 1.39%. Further, the vertical members had the same case but with wider range of difference that was between 0.64% and 3.85%.

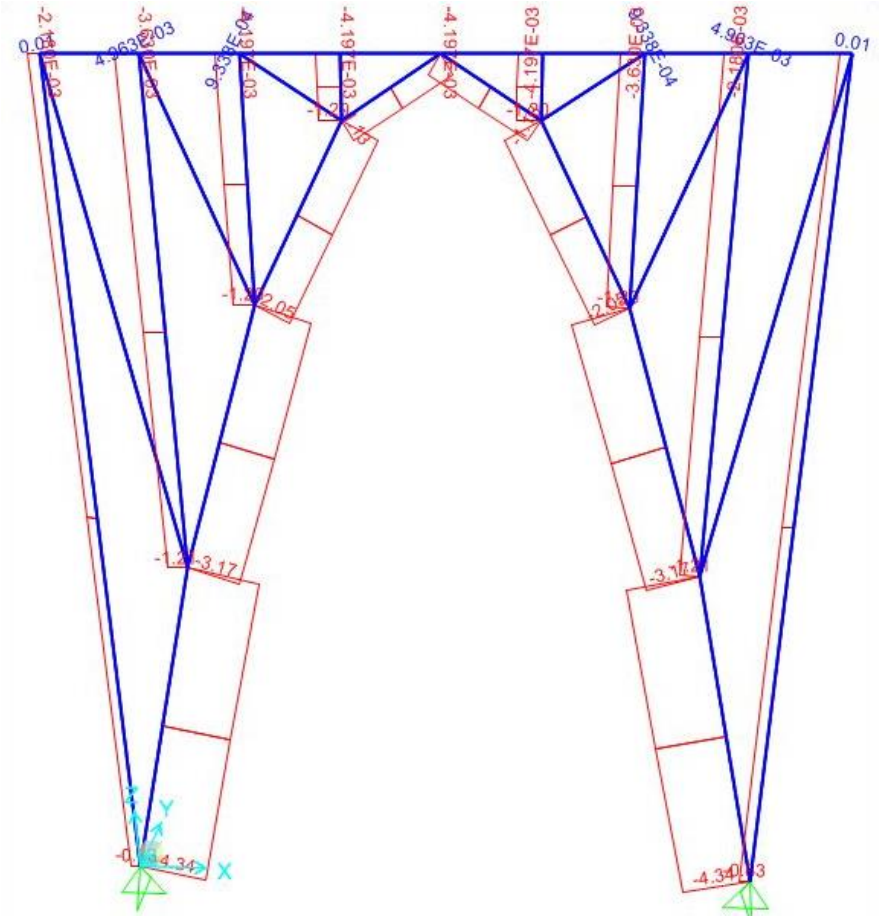

Figure 2: Forces in the Members of the Truss (3D aerial view from the top)

On the other hand, the upper chord members and the diagonal members are zero members. However, there was a difference within the order of a few Newtons because of the approximate method used by the finite element model in addition to the fact that these few Newtons can be ignored comparing to the forces in other members that are in the order of kN. It is worth to mention that all the members designed in this system have high safety factor for all members and can withstand any additional load without failing. Therefore, it is safe to say that the closed form model is valid since there are small differences between the closed form model and the finite element model that was processed by SAP2000.

Table 2: Forces in the members of the truss

Member Type	Member #	Member Length (m)	Expected Load (kN)	SAP Load (kN)	Difference %
Exterior Verticals (EV)	M(1-2) Right	3	0.596	0.62	3.85%
	M(1-2) Left	3	0.596	0.62	3.85%
Inner Verticals (IN)	M(3-4) Right	1.6875	1.192	1.2	0.64%
	M(3-4) Left	1.6875	1.192	1.2	0.64%
	M(5-6) Right	0.75	1.192	1.2	0.64%
	M(5-6) Left	0.75	1.192	1.2	0.64%
	M(7-8) Right	0.1875	1.192	1.2	0.64%
	M(7-8) Left	0.1875	1.192	1.2	0.64%
Bottom Chord (BC)	M(2-4) Right	1.346	4.28	4.34	1.39%
	M(2-4) Left	1.346	4.28	4.34	1.39%
	M(4-6) Right	0.984	3.13	3.16	0.99%
	M(4-6) Left	0.984	3.13	3.16	0.99%
	M(6-8) Right	0.6375	2.03	2.04	0.64%
	M(6-8) Left	0.6375	2.03	2.04	0.64%
	M(8-9) Right	0.35377	1.12	1.13	0.46%
	M(8-9) Left	0.35377	1.12	1.13	0.46%

Stringer	M(1-9) Right	1.2	0	0	0.00%
	M(1-9) Left	1.2	0	0	0.00%
Diagonals (D)	M(1-4) Right	1.71396	0	0	0.00%
	M(1-4) Left	1.71396	0	0	0.00%
	M(3-6) Right	0.80777	0	0	0.00%
	M(3-6) Left	0.80777	0	0	0.00%
	M(5-8) Right	0.35377	0	0	0.00%
	M(5-8) Left	0.35377	0	0	0.00%

3 Soundness of the New System

3.1 The Lightweight of the System

The proposed system is characterized by its light weight. As mentioned earlier, two trusses of the new system can replace ten units of the patented steel shore system. By calculating the weight of the members of the patented shores system it was found the weight of ten units can reach almost 27.5 kg. However, the equivalent number of units from the new system can reach a weight of 15.5 kg by a difference of 56%.

This is a very important aspect for the new system because it decreases the total weight of the system needed to construct one slab. For example, as stated earlier, the SAP2000 Model was for a distributed load of 3.97 kN and the span of the truss is 2.4 meters. By fixing the uniform distributed load to which the both systems are subjected and increasing the spans in the increments of 0.6 meters (from 2.4 meters up to 6.6 meters), it was found that the diameters of the new proposed system did not change by changing the span. The capacity of the members in the new system was found that it can withstand the expected loads on the system even after the span reach 4.8 meters. However, an increase in the thickness of the exterior vertical is necessary in order to withstand the spans from 5.4 meters up to 6.6 meters. Meanwhile, the other members where found that they can withstand the load up to 6.6 meters. The effect of increasing the thickness of the exterior vertical resulted in a total difference in the total weight of the new system of 1.71 kg.

Figure 3 shows the weights of the patented steel formwork systems and compares them to the weight of the new proposed system. It is clear that the weight of the patented system increases significantly in wide spans, however, the weight of the new proposed system is almost fix for the spans from 2.4 meters up to 4.8 meters and increases slightly in spans from 5.4 meters up to 6.6 meters.

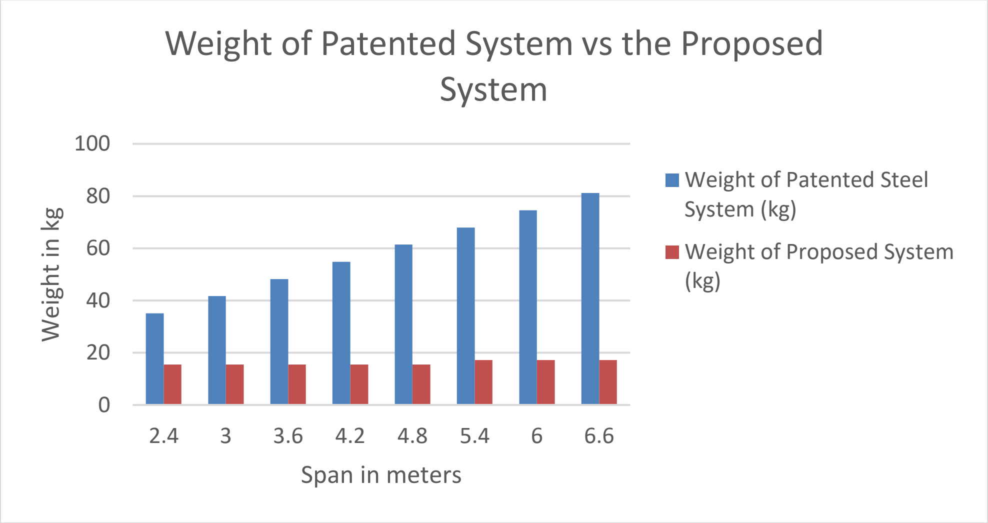

Figure 3: Weights Differences in both systems

Further, table 3 illustrates the efficiency of the new systems after increasing the span. It was found that, originally, the new system has a 56% saving in the weight when the span is 2.4 meters. This effectiveness increases and can be clearly noticed in the very wide span such as the span of 6.6 meters where the reduction in weight is 79%.

Table 2: Percentages of reduction in weight

Span (m)	Weight of Patented Steel System (kg)	Weight of Proposed System (kg)	Percentage of reduction in weight
2.4	35.09	15.5	56%
3	41.67	15.5	63%
3.6	48.25	15.5	68%
4.2	54.83	15.5	72%
4.8	61.41	15.5	75%
5.4	67.99	17.21	75%
6	74.58	17.21	77%
6.6	81.16	17.21	79%

Moreover, the light weight of the new system will make it easier to transport on site. The whole system can be lifted using a crane on one or two batches maximum and can help the crane to reach higher elevations since the load is small compared to the other system.

Further, the system can be moved easily on site using manual means. Any workers should be able to carry it since the total weight of the two halves of the system is 15.5 kg. However, if the system had to be carried manually, it should be moved half by half to avoid any accidents on site.

3.2 Constructability Time

Constructability time is very important in comparing formwork systems since it gives a sense of the complexity of the system and how the workers will deal with it in the assembling and the disassembling process. The new proposed system follows the same concept of the already existing system but only rearranges the members of the formwork system to be more efficient and carry more loads.

It consists of the regular steel tubes and the main part assembling these tubes is the bolt and the nut. This means that the workers will not need time to get familiar with the system once they understand how to assemble it. The new system is very easy to assemble because it is transported on site in two halves and the workers will only have to connect the two halves by bolts and nuts connected to the middle plate that will act as an intermediate hinge when the system is loaded. Therefore, there will be no need of skilled workers because any semi-skilled or unskilled labor can tie the bolts and the nuts in the intermediate hinge.

3.3 Construction Space

One of the common problems in construction sites is the limited space available for material storage. This problem causes difficulties in creating safe paths for the workers to move around the site and for the material storage. The patented steel shore system contributes heavily in this problem since it closes all the area below it and prevents movement. Despite this fact, workers usually move between the shores which creates unsafe work conditions because the workers can hit their head or lose their balance and can be seriously injured.

The new proposed system creates a very wide space under the trusses. This allows creating safer paths for the workers to move around the site without jeopardizing their health and consequently reduces the accidents on site. Moreover, the wide space under the truss will allow the flow of materials and will make storing them easily. This will allow in increasing the amount of material to be stored on site and in the same time decreases the amount of material wasted because of wrong storage conditions.

4 Conclusion and Recommendation

By analysing the results from the previous sub-sections, the following can be concluded about the new proposed system:

- It proved to be lighter in weight than the old patented systems in a wide range of spans.
- It has proven that by using less material in the fabrication of the system it can withstand high loads in very wide spans compared to the old patented systems.
- It is economically friendly since it uses less material which means less energy consumption and less pollution
- It is practical in allowing more area under the system for the labor to move and for storage of materials.
- It needs less number of labors since it is very light and easy to assemble.
- Consequently, the research team recommends the following:
- More experimental testing should be conducted (part of it has already started by the same research team)
- There should be verification under different load cases such as wind loads
- Full scale prototypes should be fabricated and tested on site in order for the users to its feasibility in real jobs on

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