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The American University in Cairo

School of Science and Engineering

Design and Constructability of Funicular Arched Steel Truss (FAST) False-work

A Thesis Submitted to

Department of Construction Engineering

In partial fulfillment of the requirements for

The degree of Master of Science

by Ahmed Y. El Sayed

Under the supervision of Dr. Khaled Nassar

and Dr. Mohamed Darwish

May/2017

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I would like to express my sincere appreciation to the support of my mother, father and close friends throughout my studies. Their continuous efforts and supports provided me with the energy and persistence to pursue my academic goals.

I would like also to thank my advisors for their encouragement, support and unlimited support throughout my work in this research. They always provided me with valuable and strong feedback on my work which gave me the opportunity to enhance my research and get better results. My advisors believed in me and my abilities to reach results in this research and ensure its potential application in the construction field.

Once again, my deepest and sincere appreciation goes to everyone who supported me throughout my journey.

ABSTRACT

- University: American University in Cairo
- Thesis Title: Design and Constructability of the Funicular Arched Steel Truss False-work
- Student Full Name: Ahmed Yehia Abd El Aziz El Sayed
- Name of Thesis Supervisors: Dr. Khaled Nassar and Dr. Mohamed Darwish
- Summary:

The commercially available systems currently used in construction require high initial cost, take time to be erected and reduce the space in the construction site for the movement of material, equipment and labor as they prevent movement underneath them. The FAST system depends on developing a new false-work system depending on the concept of the funicular arch. It decreases the cost of the false-work as it uses less material and therefore needs lower initial cost than the commercially available systems. Further, the new system is environmentally friendly as it achieves a range between 45% and 50% saving in the amount of CO_2 emitted to air due to the use of less material. The savings in the material used in the FAST system ranges between 45% to 51% depending on the covered area and it also provides more space in the construction site for the materials, equipment and workers to move underneath the system. The system also decreases the time needed for erection by range between 67% and 80% depending on the area and consequently helps in saving time and cost. To prove all of these advantages, experimental work is conducted on full scale models to study the mechanical and structural properties of the system.

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1. CHAPTER ONE: INTRODUCTION

1.1 Background

The terms formwork and false-work are used interchangeably. However, both of them have different definitions. Formwork is defined as “the total system of support for freshly placed concrete and includes the sheathing that is in contact with the concrete as well as all supporting members, hardware, and necessary bracing”. Formwork can be assembled from different materials such as wood with steel or aluminum with wood. On the other hand, False-work is “a temporary structure erected to support work in the process of construction”. This means that false-work only includes the shoring that supports the other parts of any system supporting the freshly poured concrete (Nawy, 2008).

Although both terms can be used in combination or interchangeably as mentioned earlier, they can be differentiated as follows: the formwork is considered to be the horizontal system that supports heavier concrete members while false-work is considered to be the temporary girders and shores and the lateral bracing that is supporting the system until concrete sets. Formworks have two different types: Job built forms or prefabricated forms. The prefabricated forms are those forms that are commercially used and have standard sizes and they are usually made of steel or aluminum. The prefabricated forms are usually used for more than once and they have higher life cycle. On the other hand, the job built forms are those who are built to suit only one job and often made of wood. They are used when the requirements of a job cannot be met by the commercially available systems. The lifespan of these forms are often very small since it is fabricated to suit a specified job (Nawy, 2008).

1.2 Guidelines for False-work Design

Planning the cost of concrete structures starts in the design development stage. The designers should think of the whole process from the permanent material to the erection, installation and the stripping of the false-work. During this stage, a designer with sufficient knowledge about the design of false-work systems will develop one or two alternatives of the structural design of the building. This is important because it helps the designer choose the design that can be constructed with the least cost.

Therefore, the constructability of the structure plays a vital role in the decision of choosing false-work and consequently affects the cost (Peurifoy and Oberlender, 2011).

According to Peurifoy and Oberlender, there are some guidelines that should be followed to ensure an economic design that will not increase formwork cost:

1- Prepare the structural and architectural drawings of the building simultaneously to ensure that considering false-work cost will not compromise the structural or architectural needs of the building.
2- During the designing stage of the structure, the methods and the materials used in fabrication, erecting and stripping the false-work should be studied.
3- The structural members should comply with the standard dimensions available for the commercially available false-work systems.
4- The columns should be placed uniformly.
5- The sizes of the members such as columns and beams should not change drastically to avoid any more cots in the fabrication, erection and stripping of the false-work. For instance, the designer can retain the same columns size for several floors, if this is practicable (Peurifoy and Oberlender, 2011).

Therefore, it is obvious that the designer can achieve economic design for the false-work by repeating the design, follow the dimension standard of the different structural members and the dimensional consistency throughout the building (Peurifoy and Oberlender, 2011).

1.2.1 Design Repetition

Following the concept of mass production and assembly lines that are utilized in the manufacturing of automobiles, it is a fact that any work that is done on a repetitive basis causes reduction in time and costs. This can be achieved in false-work system by having the same layout from bay to bay or from floor to floor (Peurifoy and Oberlender, 2011).

1.2.2 Dimensional Standards

The concept of this point is that the designer should choose dimensions for the structural members that match the standard sizes of the false-work used. By doing this, the designer will allow for cost saving since the system will be erected as it is without any adjustments that might cost more direct cost due to the increased number of labor hours. If this concept required any adjustment in the design, this can be achieved by modifying the reinforcement percentage or the depth of the member (Peurifoy and Oberlender, 2011).

1.2.3 Dimensional Consistency

The dimensional consistency throughout any structure can be achieved by maintaining constant depth of horizontal structural member, constant spacing between beams and columns, maintaining columns dimensions from one floor to the other and maintaining storey heights. The dimensional consistency means that the false-work used in one floor can be used for the following floor and consequently this means reduction in the cost of false-work since one set of the system can be used multiple times. Further, this will help in future expansion of the building in case additional floors needs to be added to the building (Peurifoy and Oberlender, 2011).

1.3 Economy of False-work and the Sizes of Concrete Members

Generally, the dimension of the columns in the lower floors can be used for the upper floors accompanied by a reduction in the reinforcement percentage. However, this should be achieved while maintaining the code requirements. If there is a change to be done in the dimensions of the column, it would be more practicable if the change is done in only one dimension while maintaining the other dimension as it is. This might help in achieving cost savings in the false-work of the columns (Peurifoy and Oberlender, 2011).

The false-work of columns needs special attention because the dimensions of the columns can be subjected to significant changes and also some column designs might need additional labor or material. For instance, the orientation of the columns from one floor to the other may cause additional costs due to additional labor cost which are needed to accommodate these changes. Further, if the columns have capitals, this might cause disruptions to the false-work erection. Furthermore, the beam-column intersection needs special attention when erecting its false-work. This is because if the column has different width from the beam, the connection must be constructed to behave structurally as it was supposed to. In case the width of the beam is larger than the width of the column, this means that the supporting system used for the beam bottoms must be notched to fit around the upper part of the columns. Also, if the column width is larger than the width of the beam, the supporting system must be widened to the column width at each intersection. The same concept is followed with beams. The width of the beams should be chosen in accordance with the available formwork dimensions in the market (Peurifoy and Oberlender, 2011).

1.4 Problem statement:

The commercially available false-work systems have been used in every single construction project that requires concrete pouring and represents a considerable amount of the budget of the construction of the structural members in any building. These systems are characterized by their heavy weight, the long time needed for erection, the high initial cost and the short life cycle of the systems. In addition, these systems also require big trucks to be transported to site and large cranes to transport them from one place to the other on-site. Further, their manufacturing process is associated with intensive energy consumption for the systems made from steel or Aluminum and the design of these systems prevent the flow of workers, materials and equipment underneath the system.

The frequent use of the aforementioned systems forces the manufacturers to develop the techniques used in the installation of these systems. The development of these techniques includes adding more accessories to increase the control over the quality of the poured concrete members. However, the characteristics of these systems can be changed by developing the design of the false-work systems. The design should be changed in order to target some of these characteristics without affecting the structural integrity of the false-work system used to support the work on top of it. The developing of a new design shouldn't target adding more accessories to the commercially available system, however, it should target the structural concept followed to develop the physical form of the system that will change the characteristics and their effect on the cost, time and the environmental impact of the system.

1.5 Scope

The scope of this thesis is to develop the conceptual and functioning design of a new false-work system that depends on the innovative concept of the funicular arch. The design will utilize the used concepts in the market inside Egypt starting from the manufacturing process, the assembly process and ending with the connections used to connect the different members of the truss. Further, the properties of the design will be studied. This includes the physical properties of the design such as the weight and the structural behavior of the members when it is subjected to loads. This will be achieved by testing a full scale model of the design in the structural lab. The experimental work will include testing the design under real life conditions in order to have a visual and detailed mode of behavior that this design will show on site.

Further, the design will be assessed and compared to the commercially available systems in the market. This comparison will include: weight of the system, constructability, its effect on the construction space available, the time needed for transportation the system on-site and off-site, on-site storage of the system and the amount of CO_2 emission reduced due to using the system in different ranges of construction areas. All of these values will be calculated for the commercially available and the new system and then a conclusion will be made to determine the effect of the FAST system on the aforementioned factors. All of these factors will be transformed into numbers and the cost savings due to this FAST system shall be determined.

1.6 Objectives

The main objective of this thesis is to develop a new sustainable false-work system using the innovative concept of funicular arch. The system aims to target the disadvantages of the commercially available systems. That's why there are some sub objectives that need to be fulfilled that include:

1.7.1 Develop the conceptual and functioning design of the FAST system

The design includes creating the form of the truss and determines the connections used to connect the different members of the truss. The design shall utilize the same basic ideas of the available systems in the market such as the types of connections (welded or bolted) and maintaining the same ideas of assembly that the workers are used to. This will be achieved by developing the shop drawings of the FAST system that will be used to manufacture three full scale trusses that represents the main component of the system.

1.7.2 Ease of construction

This includes two points. The first point is that the system can be easily fabricated in the workshop/factory. This can be achieved as stated earlier by maintaining the easy concepts that all the workers are used to. The second point is that it is easy to be erected on-site. This will be achieved by assembling the two halves of the truss individually off-site and connecting them on-site will depend on adding the intermediate hinge connecting both halves and a tie rod. This will be proved by calculating the time needed for assembling one half of the truss in the workshop/factory and the time needed for the erection of the system. A demo will be conducted before the experimental work and the time needed for the erection shall be determined.

1.7.3 Lightweight of the FAST system:

This can be achieved by choosing tubes with small diameters and thicknesses. This achieves two main goals. The first one is that it helps in reducing the weight of the system since the concept of the system itself allows for the loads to be supported in a more efficient way. The second goal is that these hollow tubes with small thicknesses will decrease the dead load of the system while maintaining the structural integrity of the system. The weight of the commercially available systems needed to cover different ranges of construction areas will be calculated and then compared to the weight of the FAST system needed to cover the same area.

1.7.4 Savings in transportation

This will be determined through two main points. The first point is off-site transportation and the second point is on-site transportation. As for the first point, the capacity of the trucks needed to transport the system from the workshop/factory will be determined and compared to the equivalent number of frames of the commercially available system. The number of trips needed to transport the system will also be considered. The second point includes determining the weight of the system and the capacity of the cranes needed to transport the system from one place to the other.

Further, the number of turns/packages needed to transport the system from one floor to the other shall be studied.

1.7.5 Decreasing storage space

The storage space needed for storing the system will be compared to the commercially available system. This objective will be achieved by taking real life pictures of the commercially available systems while being stored on site and comparing it to photos of the FAST system being stored and the proposed storage technique in terms of the volume needed for each system to be stored. The storage situation will be studied in terms of space needed and the safety of the workers using the current storage situation and the proposed system.

1.7.6 Increasing construction space

The space created by the design of the FAST system will be assessed. The impacts of the space will be studied and compared to the problems that the commercially available systems created on-site. The comparison will include additional space to store materials and equipment and the creation of safer paths for the workers and the equipment to use on-site.

1.7.7 Studying the contribution of the FAST system to sustainable development

This will be studied by determining the amount of CO_2 produced by the factories during the manufacturing process of steel and how the use of the FAST system will decrease this amount, the equivalent amount of CO_2 due to the consumption of this energy and the amount of hazardous waste produced due to the manufacturing of steel. All of these parameters shall be studied and compared with the effect of the commercially available systems on the environment to process the FAST system's environmental soundness.

1.8 Research Methodology

This section illustrates the methodology followed in conducting this research. Figure 1 shows a flow chart that describes every step in the research methodology starting with the literature review that discusses the different false-work system and their disadvantages and their effect on the environment. Then it is followed by the design and constructability of the system which is related to the model description used and the soundness of the system; then the experimental work conducted on this research and then conclusion and future recommendation

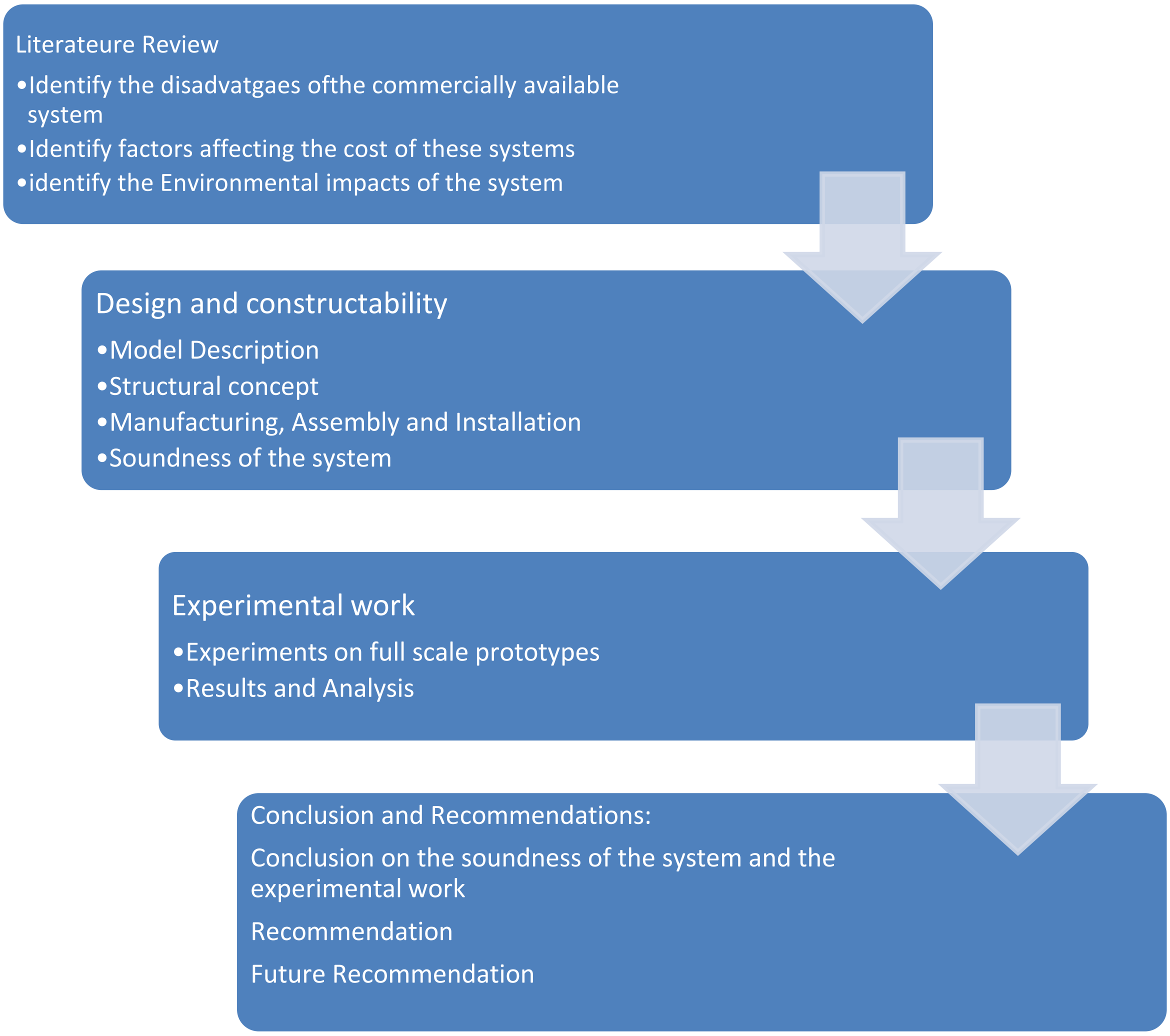

Figure 1: Research Methodolgy Flow Chart

1.9 Thesis Organization

This thesis is organized into five chapters as illustrated below:

1.9.1 Chapter 1: Introduction

It provides a background for the definition of the formwork and false-work followed by the guidelines of the false-work design. Also, it gives a quick overview over the relation between the cost effectiveness of the false-work systems and the sizes of the concrete members and the sequence of fabricating, installing and stripping the false-work system. The chapter also states the problem statement, scope and objectives, research methodology and thesis organization.

1.9.2 Chapter 2: Literature Review

It presents the literature review for this research that includes the different false0work systems, their disadvantages and advantages and the history and the development of the false-work systems throughout history. It also discusses the false-work economics, the effect of steel production and construction on the environment.

1.9.3 Chapter 3: Design and Constructability

It includes the description of the model, the manufacturing process, the assembly and the parametric study used to study the soundness of the system.

1.9.4 Chapter 4: Experimental Work

It includes a description of the experimental work followed by stating its results and the analysis of these results.

1.9.5 Chapter 5: Conclusion and Recommendations

It includes the conclusion from the parametric study for the new system and the conclusion of the experimental work. It also presents the recommendations and the proposed future research related to this thesis.

2. CHAPTER TWO: LITERATURE REVIEW

2.1 Types of Formworks and Shoring Systems

2.1.1 Conventional (Traditional) False-work

The conventional (traditional) false-work system consists of a number of main components that includes: joists, stringers and shores. As shown in figure 2, this is the skeleton of the formwork system after being erected. The description of the skeleton components from the top to bottom is as follows:

- The load supported by the sheathing is transferred to the joists. The joists are the horizontal structural members that support the decking system and transfer the load to the stringers.
- The stringers are the members that are supporting the joists and transfer the load to the shores. The spacing between the different stringers and the different joists is determined based on the size of the wooden member of the stringers, the joists and the applied load.
- The last structural member in the system is the shoring. Shores are the vertical or inclined members that support the stringers, joists and the decking. The most common stringer sizes are 4x4inch (100mm x 100mm) and 6x6 inch (152.4mm x 152.4mm) and the available heights range from 6 to 16 ft (1.8 meters to 4.8 meters) and can carry loads with a range from 2500 to 9000 lb (11000 N to 40000N) depending on the type and length of the member. The shores are rested on the ground above the mudsills. The function of the mudsill is to distribute the load coming from the shores to ground and avoid having any concentric loads on a specified point under any of the shores to avoid failure in the ground and consequently to the system.
- The shores of the system are then braced using the cross bracing members. These members are designed to withstand compression or tension in some special cases. The main function of the diagonal cross bracing in the formworks system is to withstand the lateral loads that will affect the system (Nawy, 2008).

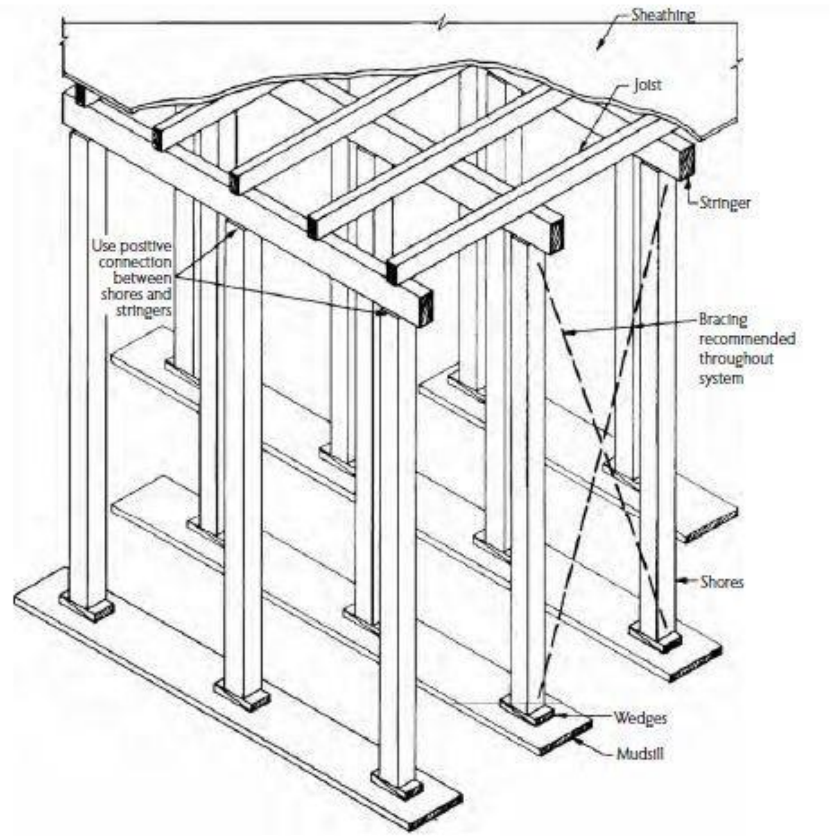

Figure 2: Typical System of the Conventional Formwork (Nawy, 2008)

2.1.2 Single Post Shores

The Single Post Shores consist of a lower tube attached to it the base plate on which the shore rests with an adjusting nut to allow for fine height adjustments. Inside this lower tube, there is a telescopic device that has a pin to allow for larger adjustments. The telescopic device has a U head attached to it on which the joists and stringer will rest (Forming America, 2012)

The design of the single post shore system should be done with caution. This is because this system needs to be braced on intervals that will allow the shores to withstand the expected vertical loads and avoid failure. If the working heights exceed the height of a single shore, then another shoring system should be used to avoid failure in the shoring system as the system will not be stable in this case. However, the system is available in a wide range of heights to allow more flexibility. The heights of the system range between 1.85 to 4.65 meters. The load path in this shoring system is the same as the previously mentioned load path in the conventional system. The load is transmitted from the joists to the stringers then to the shoring system. This means that the stringers should be considered in the bracing system to make sure that the whole system is stable (Forming America, 2012)

2.1.3 Heavy Duty Shoring Frames

This type of shoring was the logical development after the first generation of steel shoring. In this system, the frames were standardized to have an outer diameter of 60.3mm or 63.5mm (2 and 3/8 or 2.5 inch) with a wall thickness of 3.2 mm. This new system increased the capacity of the shores to reach up to 177.93 kN. Further, the new shoring system came with more changes. The main feature of this system was changing the standard width of the old system (1.524 meters) to be more convenient and has a width of 1.22 meters width by 5 or 6 ft (1.524 to 1.83 meters) high. This also was accompanied by the development in the shoring accessories. The accessories are made out of stronger and thicker materials to withstand the high vertical loads supported by the heavy duty frames. Larger U-heads, screws legs and standardized bracing sizes were introduced which made the heavy duty system more adaptable and easy to use for the contractors (Forming America, 2012)

2.1.3.1 Telescopic Tube (Screw Leg Extension)

Further, there is another important part to add. This part is the telescopic tube. The telescopic tube is an adjustment device that is used to set the height of the frame to the desired height to increase the flexibility of the system. These telescopic tubes were called extension legs. As shown in figure 3, the screw-leg extensions can be put in top of the tower below the U heads or at the end of the tower above the base plate. This means that this addition accessory gave a wide range of flexibility by allowing the adjustment of the tower height from the top and the bottom of the frame leg (Forming America, 2012).

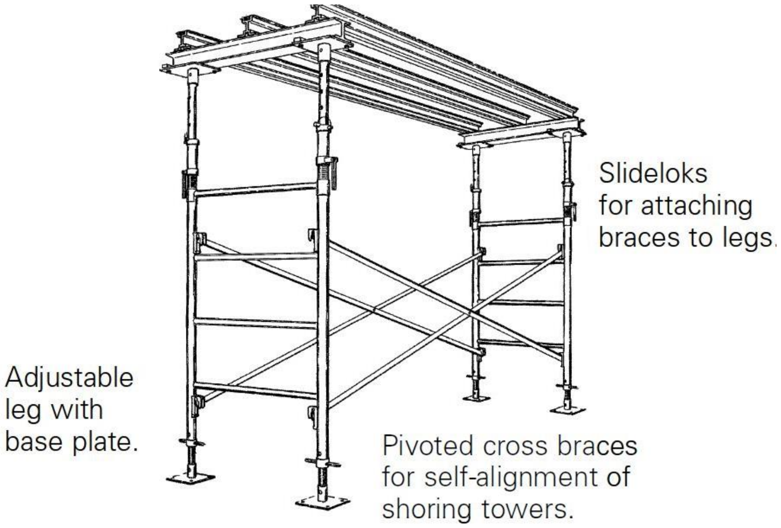

Figure 3: The Position of the Telescopic Tubes in the Heavy Duty System (Forming America, 2012)

2.1.3.2 Types and characteristics of the screw leg extensions

Generally, the capacity of the frame leg is lowered by adding the screw-leg extensions. It is very important when using these extensions to check the manuals supplied by the manufacturers of this extension to understand the extent of their effect on the load capacity of the different types of frames. When a screw-leg extension is added to a frame leg, the result is a specific nondeductible extension to the leg. This is known as the “dead-leg” as shown in figure 4. This dimension should be added to the total height of the frame before adding the required adjustment through the screw-leg extension.

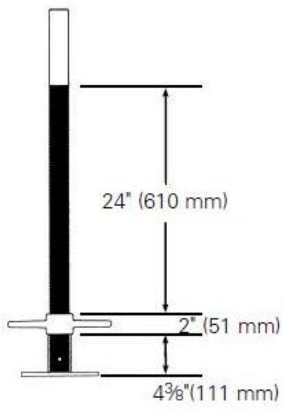

Figure 4: Extension Leg (Forming America, 2012)

However, extensions up to 300 mm will not affect the load capacity significantly while extensions more than 300 mm will affect the load capacity of the frame leg. Notwithstanding the above, it is still very important to check the manuals supplied by the manufacturers to determine the exact effect of using a screw-leg extension. It is worth to mention that there are more types of the screw-leg extensions. The extra-long screw legs are legs that can have a total length of 600 mm or more when they are fully open. They are generally used with the heavy duty frames; however, it is important to check the allowable loads of the frame legs when using this type of extension (Forming America, 2012).

Further, there are other extension devices that give additional flexibility more than the screw legs. These extensions are called shore staffs or adjusting collars. These collars are 50mm in diameter and have a length between 0.3 meters to 1.5 meters. They are placed inside the frame legs which gives larger range of adjustment. They have equidistant pinholes that can be on a distance of 7.5, 10 or 15 mm. These pinholes have a diameter of 12.7 or 15.9 mm to allow for hardened steel pins to fix the piccolos on the desired length. As shown in figure 5, the piccolos consist of an extension tube with the opening for the pins and there is also an additional adjusting collar that is used for fine adjustment. The dead leg of the piccolos can be 203.2mm and the total length when it is fully open can reach from 300mm to 1500mm depending on the total length and the size of the frame used with this piccolo (Forming America, 2012).

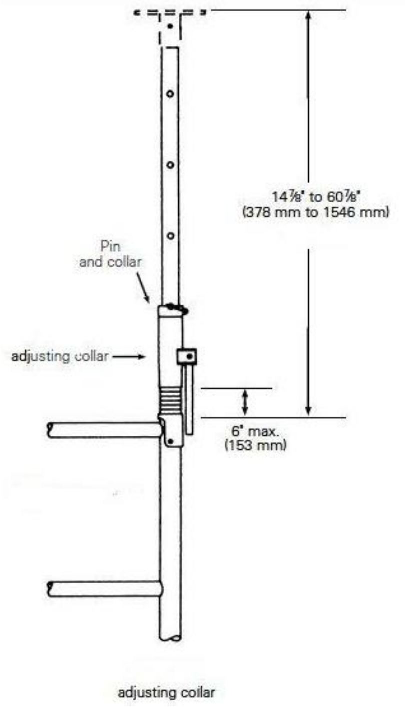

Figure 5: Adjusting collars (Forming America, 2012)

2.1.3.4 Bracing Systems

Figure 6 shows the bracing of the scaffold types. It can span a distance between frames that ranges between 0.6 and 3 meters. This distance can be expanded to range between 3.6 to 4.5 meters when using the long-span horizontal shoring beams. Further, there is another means of bracing. This method depends on horizontal tubes and coupler ties connecting the four legs of the shoring system in the two perpendicular planes. However, caution must be taken in order to avoid sagging of the braces or pull the frames away from their position (Forming America, 2012)

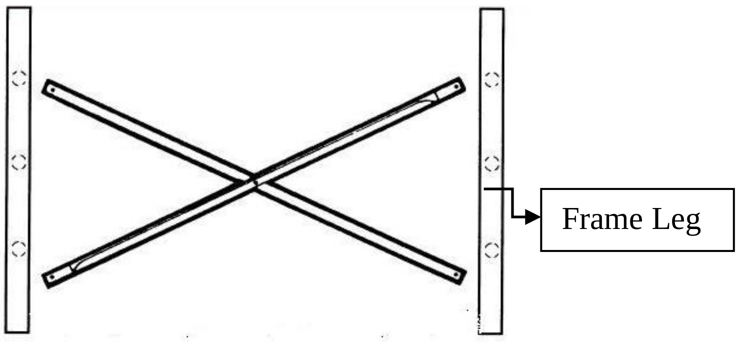

Figure 6: Bracing Members conceptual form (Forming America, 2012)

2.1.3.5 Advantages and Disadvantages of the Heavy Duty Shoring System

This development had a number of advantages that highlighted the credibility of the steel shoring systems. Firstly, increasing the capacity of the legs means less number of frames used. The frames are now capable of covering more span since the leg can withstand more vertical loads. Secondly, the design procedures become simpler because the bracing system was standardized on the new dimension of the heavy duty system and the less number of units needed made it easier to design the formwork system compared to the older systems. Finally, the introduction of standardized cross bracing was a breakthrough in the industry because it decreased the problems that can happen due to wrong bracing and also decreased the time needed for erecting the system. However, the development of the heavy duty frames has some disadvantages. The first disadvantage is that it increased the weight of the system because of the increased diameter and thicknesses of the used tubes. Further, it takes more time and labor to construct the new system because of its own weight and the fact that it needs more time to ensure the correct installation of this system to avoid any failure (Ratay, 2007).

2.1.4 Table False-work System

The term table shoring system describes all the systems used in forming and shoring the concrete structures using modular panels that are moved from floor to floor as shown in figure 7 (Elbeltagi et al, 2011)

One of the most used systems in case of the presence of enough crane capacity is the table false-work system. The main components of this system are the table making the forming surface and supported by wooden or steel. The depth of the trusses and the distance between them, under the forming table, vary depending on the job that the system will be used for (the distance in open facades). It consists of two frames which satisfy the job conditions regarding height and depth, four adjustable jacks and four caster wheels (Elbeltagi et al, 2011).

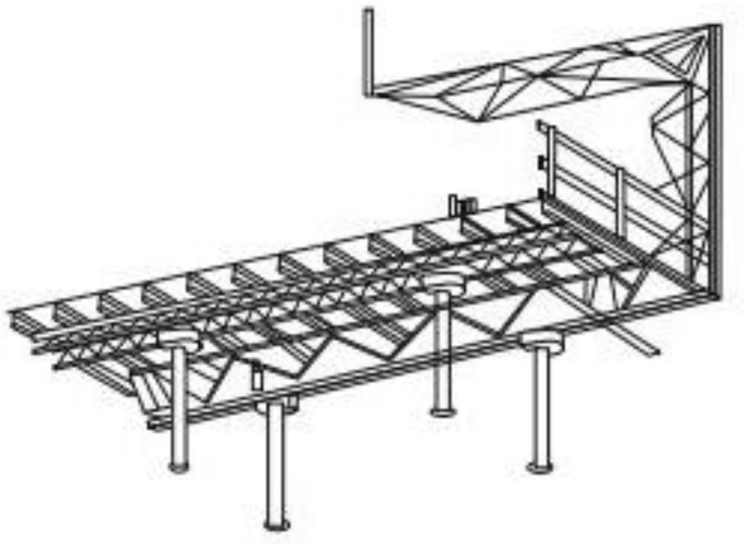

Figure 7: Table False-work System

2.2 History and Development of Steel-Frame Shoring

In the late 1930s and the beginning of the 1940s, a new type of scaffolding appeared to replace the tube-and-coupler metal scaffolds. This system was the new welded-steel-frame scaffolding which was simpler and more efficient in terms of usage and transportation than the older system. The new welded-steel-frame system consisted of a number of frames which are equidistantly arranged and connected together with cross-bracing in order to replace the units of the older system which are connected together by loose scaffold couplers. In the 1950s, the new system began to be used as vertical false-work/shoring support for the formwork of the horizontal structural elements such as slabs and beams. As a result, its manufacturing was standardized to produce frames with a standard width of 0.6, 0.9 and 1.5 m (2, 3 and 5 ft.) (Ratay, 2007).

Figure 8 shows the difference between the old and the new system. It can be observed that the tube-and-coupler system consists of a number of vertical posts and two horizontal members called Runners to connect the posts together. The system is braced by an inclined member to control sway in the system. All the members in this system are tubes that are connected together by couplers. On the other hand, the new system consists of welded-steel-frames that are put on top of each other in order to reach the desired height of the concrete structure. The frames are put beside each other and are connected with cross-bracing members that are connected to the legs of the frames to provide lateral support for the new system. The welded-steel-frame system is more stable than the older system since most of the members are welded together and the cross bracing is connected to the frames through a small piece of steel welded to the legs of the frames which provides more stability (Ratay, 2007).

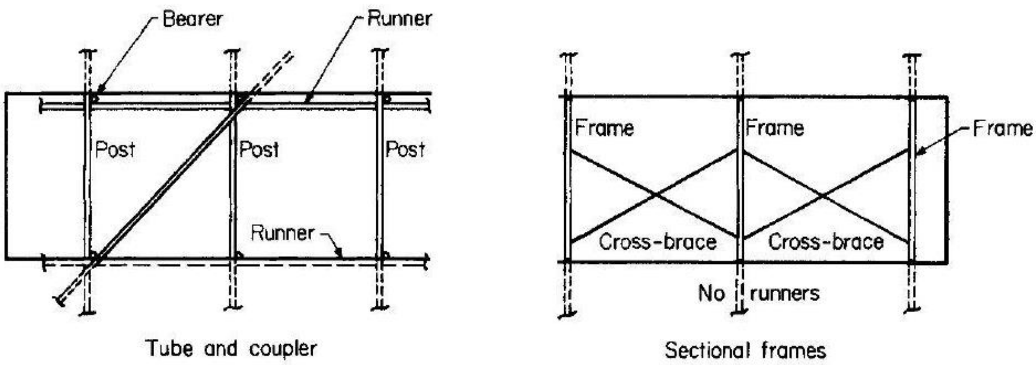

Figure 8: Comparison between the Tube and Coupler System and the Welded-Steel-Frame (Ratay, 2007)

However, the welded-steel-frame system had some drawbacks that appeared due to the increase of the applications that it is used in. The first drawback was related to stringer, wooden ledgers, used to support the sheets on the concrete that will be poured. Figure 9 shows that the earliest users of this system used to put the wooden ledgers directly on the top of the header bars of the frame. This method caused problems because releasing the shoring after concrete setting required the lowering of the frames to break the bond between the system and the concrete. As shown in figure 10, this was a complicated and dangerous process. The figure shows that if one leg is lowered without lowering the other leg with the same amount creates a gap between the lowered leg and the plywood supporting the concrete. This caused dangerous titling of the frames and the bond between the concrete and the plywood might not be broken as required (Ratay, 2007).

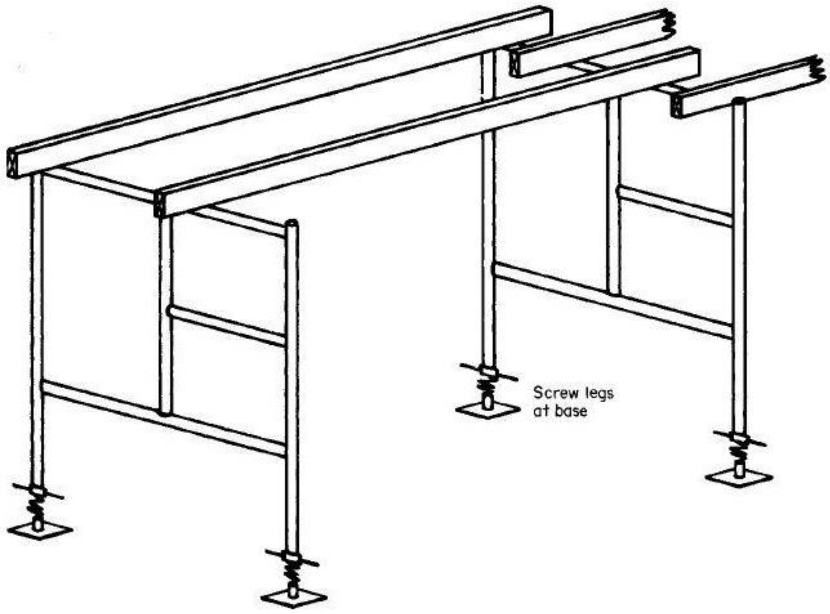

Figure 9: Stringers were put directly on the top of the Header (Ratay, 2007)

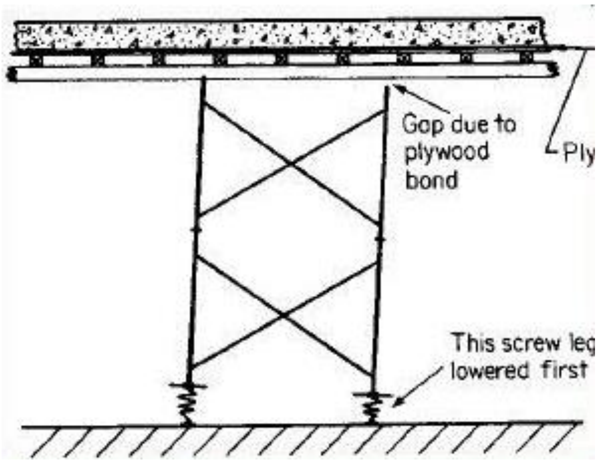

Figure 10: Lowering one leg of the Shore causes serious tilting (Ratay, 2007)

However, in case of lowering both legs in the same time as shown in figure 11, this will allow the bond between the concrete and the plywood to be broken without causing any risks to the labor or the structure. This can be easily done if the height of the structure equals to two or three frames of the new system but it will be risky and dangerous to lower the stem if it consists of four or more frames due to the complications that may be caused due to the load of the structure and the height of the frames (Ratay, 2007).

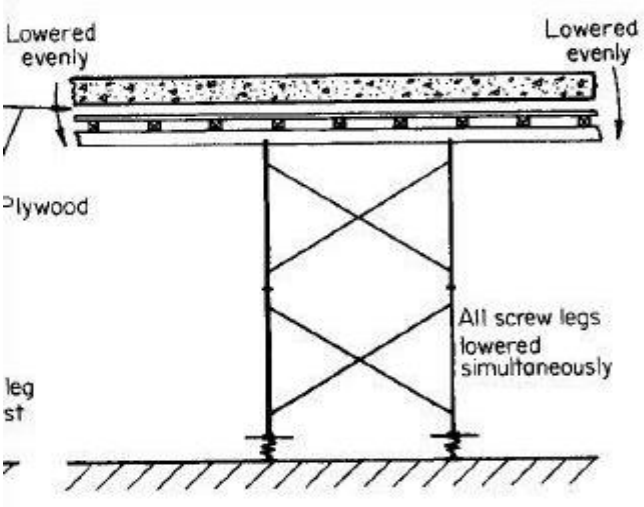

Figure 11: Lowering both legs evenly (Ratay, 2007)

The second drawback of this system was also related to the wooden ledgers. The wooden ledgers had to be 100mm (4 inch) wood in order to be laterally braced and could be loaded to their full strength. Moreover, the headers of the frames were insufficiently strong in order to reach the capacity of the frame legs. Due to practical limitations and the local crushing of the wood ledgers, the header was only able to support 50% of the capacity of the whole frame (i.e. one leg of the frame). This meant that twice the theoretical number of the frames will be used in order to support the same expected concrete loads. The result was doubling the needed cost of the system and a critical problem with the efficiency of the new system. The previous drawbacks triggered a solution in order to take advantage of the full potential of the new welded-steel-frame system. The solution was to apply the load of the concrete structure concentrically on the frames legs. This led to the addition of a new accessory that will help in achieving the main goal of applying the loads directly to the frame legs, bracing the ledgers and avoid additional weight to the system. The new addition was the U-heads. As shown in figure 12, the U-heads were customized according to the size of the wooden ledgers which gave flexibility to the system. Moreover, the U-heads were fixated on top of an adjustable threaded screw leg of open adjustment up to 600mm which gave the system more flexibility in the construction. The results of adding this accessory to the system were remarkable. The production of different standardized widths of the system led to increase the capacity of the frames to range from 13,344 and 22,240 N per leg (Ratay, 2007).

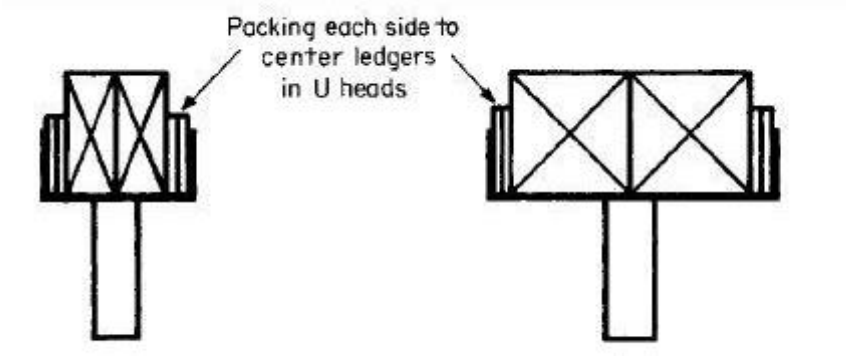

Figure 12: U-head added to the system (Ratay, 2007)

2.3 Self-Weight of the system

The weight of the systems can vary greatly according to the manufacturer of that system. However, table 1 shows the weights of the components of a random heavy duty system. On the other hand, a standard normal frame tower will weigh 10 to 20% percent less than the heavy duty system. Therefore, the standard normal frame tower will have a weight that ranges between 128 kg to 145 kg. However, it is worth to mention that there is a rule of thumb which is to deduct 5% from the allowable capacity of the leg due to self-weight. This is very important in the design of the system in order to avoid any early failure in it (Ratay, 2007).

Table 1: Components of the Heavy Duty System and their weight (Ratay, 2007)

Component	Heavy Duty System
2 Frames	29 kg each= 58 kg
4 Coupling pins	0.9 kg each= 3.6 kg
2 cross braces	9 kg each= 18 kg
Total	80.6 kg per tower= 80.6 kg
Total weight	160.2 kg

2.4 Formwork Economics

Formwork is one of the largest cost components in building structural frames. The cost of the formwork system can exceed the cost of concrete or steel and in some extreme situations it can cost more than both concrete and steel. The design of formwork is very important because it can help in reducing the cost of constructing a structural frame by 25% (Taher et al, 2014).

The efficiency of the design of the formwork can also reduce the cost by reducing the amount of time needed to construct the structural elements in addition to the cost of the formwork material itself. This means less direct and indirect cost by decreasing the number of working hours of labor and by saving material by reducing waste. The benefits of an efficient design of the formwork also includes: increased productivity for labor, reduced potential for errors and enhance the safety procedures and conditions. In addition, there is a direct relationship between the design of the structural members and the formwork costs. Usually, structural engineers think about how each single member will be able to withstand the expected loads that these members will be subjected to. This is because the main perception for this task according to Peurifoy and Oberlender is that "*the least amount of permanent materials in the structure will result in the least cost*". However, this perception neglects the effect of having different dimensions for the structural members of the building. For instance, having numerous models of columns in the same floor for a building means more time will be needed to fabricate and erect the formwork needed to support these columns. Therefore, focusing only on decreasing the amount of permanent material might result in increasing formwork cost. This is not an economic approach since the formwork cost represents one third to two thirds of the cost of the concrete structures (Peurifoy and Oberlender, 2011).

2.5 Models for choosing False-work Systems:

The cost minimization in the construction industry includes: formwork, labor, concrete, reinforcing steel and transportation. Since formwork appears in the beginning and the end of the construction process, it is appropriate to say that it has direct impact on the construction cost (Fathy, 2015).

According to Hanna, 1999, selecting a formwork system is a critical decision.

This is because of the effect of the cost of formwork on the overall construction cost of the building especially for the large structural members such as slabs. Therefore, choosing the wrong formwork system will have drastic effect on the construction. The formwork system should be chosen while considering some factors such as system's productivity, safety, durability and many other factors that are determined according to the site conditions (Hanna, 1999).

Hanna and Senouci, 1995, conducted a research on the formwork system to determine the components of the formwork system that affects directly the cost of the formwork system. The factors considered in their study included sheathing, joists, stringer and wood shores. They also included different combinations available for different slab formwork components. All of these data were the input for an optimization program that its results will be compared against the cost of the traditional formwork system. It was found that by optimizing different formwork components, a percentage of 9.9% of the formwork cost can be saved (Hanna and Senouci, 1995).

Further, the increase of the number of buildings that have irregular shapes changed the way contractors think about the cost of formwork. This is because this irregular shape requires special layout planning of formwork. The way of preparing the layout of formwork depended on the mere experience of engineers; however, it yielded high costs. A new approach was proposed by Kim et al, 2012 that helped in decreasing the cost of the formwork system by combining a new table formwork system with a normal and systematic layout planning method. The new system showed an increase of 15.5 % in covering the area of irregular shapes and this corresponded to 23.9 % of the material cost (Kim et al, 2012).

Some researchers developed a new model that helps in selecting the suitable type of formwork in constructing the buildings. During the research, the formwork selection system was divided into two modules: Wallform and Slabform. These two modules represent the vertical and horizontal system respectively. The two systems were separated because the information required for each system is different and they both have different functions in the site. This gives the user of the model more flexibility in entering the data to the model and consequently gives better decision. The model used is a system that depends on collecting data from different experts in choosing the formwork system. The information is loaded in two databases in the form of rules (if-then rules). The input of the user is through multiple choice questions and the model processes these inputs to reach a conclusion. The conclusion of this model is a probability that ranges from between zero to `0 which indicates the relevance of the choice to the inputs. The model also gives recommendation regarding the sheathing, shoring and can recommend some manufacturers.

Another model was developed by Kamarthi and other researchers developed a model that depends on the concept of the Neuroform model. The model focused on five false-work systems: Conventional wall-form systems, Ganged form system, slip form system, Jump form systems and self-raising form systems. The network has 15 input nodes and 15 decision factors with 5 output nodes that correspond to the five chosen vertical false-work. The model was tested using two cases. The first case was tested on a case that had diversity in terms of the building design, location and characteristics of site provided by a contractor in Washington, D.C and the second case was tested on a case described in article that discussed the selection of vertical false-work systems. The Neuroform model was validated using the results of the Wallform model, previously discussed, and it gave the same results. This proved the soundness of the Neuroform model since the Wallform model was validated by more than one expert in the field (Kamarthi et al, 1992)

Another model for false-work/formwork selection for tall buildings was developed by Yoonseok Shin and other researchers in Korea. The model depended on boosted decision tress (BTDs) and was compared to other model such as decision trees (DTs) and artificial neural networks (ANN). The models were tested using actual data from a case study of a tall building construction in Korea. The results showed that this system has better results than the DT and ANN models. This is because the BTD system incorporates more information about the systems and therefore more flexible and can accommodate different cases and consequently yields better results (Shin, et al, 2012).

A model used for the estimation of the acceptability of a new false-work system was developed using Neural Networks. The model included five main systems: conventional formwork wood system, telescopic beam and props system, shore brace system, table form system and early-striking system. The data acquisition was done using a questionnaire in which 40 experienced experts from 10 different contractors took part in. the results should that a neural network model gives reliable results and is suitable for the estimation of the acceptability of new false-work systems in Egypt (Elazouni et al, 2005).

Another fuzzy logic model was developed to evaluate alternative construction technology. The model was tested on the choice of false-work system to a hypothetical project that consists of 20 stories with identical floor plane of 800 m^2. The two alternatives were: the conventional false-work system and a lightweight aluminum system. For the conventional system, requires a crew of 45 workers that will finish one floor in a range of seven to eight days. The contractor estimates the probability of finishing the floor in seven days at 20%, eight days at 60%, nine days at 80%, and 10 days at 100%. The aluminum system alternative is new to the company and the assembly process of the FAST system was explained to the workers. Despite the expected higher quality and speed that will result from using this system, the company was not sure its effect on the duration of the project because it is a FAST system for the workers. The company expected that the same number of the workers would take a period of six to twelve days per floor. The inputs to the system were the cost of each alternative and the output is expected to be the one with the highest profit with the probability of achieving this profit. The model gave that the chosen alternative shall be the conventional system with a profit of $ 35,690 and a probability of 90% (Chaoe and Skibniewski, 1998).

Tong and some researchers developed a probabilistic neural network (PNN) model. Five factors were included in the model: Building height and structural system, Concrete finish, Site conditions, Availability of equipment and Building shape. The input for the model was these factors and each factor was given a specified number after being divided into sub categories and a number of 97 data sets for the selection of formwork were entered. The model showed that some systems such as the conventional wall form and the slip form gave accurate results however, systems such as panel form will need further advice from experts (Tong et al, 2005).

2.6 Environmental Impact of Steel False-work Production

Improving resource utilization in the industrial processes and reducing waste generation during the life cycle of the product have been major means to achieve the sustainable development since its inception. This means that the energy consumption and resource processing will be examined closely in order to have deeper understanding of the expected release of the gaseous, liquid and solid waste (Fischedick et al, 2014).

Dematerialization is one of the ways used in achieving greater efficiency in the resource utilization. It is defined as "*the reduction of the amount and materials required to service economic functions (e.g. production of consumer goods or provisions of services)*". The recycling and the reuse of materials can close the loop for the process of dematerialization. The reuse and the recycle of materials reduce the waste generation during the life cycle of the product in addition to decrease the need of fresh inputs during the processing of material. It is worth to mention that among the products used in the industries, metal have unlimited opportunities of recycling and reusing (Fischedick et al, 2014).

2.6.1. Steel Industry

Nowadays, steel is being produced through processes that are powered by coal or gas. The process that depends on coal as fuel for the production process uses a blast furnace (BF) to reduce the iron ore into molten iron which is refined to steel in a basic oxygen furnace (BOF). On the other hand, the process that depends on natural gas as fuel changes the natural gas into reduction gases, mainly carbon monoxide and hydrogen. These gases turn the iron ore into direct reduced iron (DRI) or hot briquette iron (HBI) and then the steel is refined into an electric arc furnace (EAF) (Fischedick et al, 2014).

The previously mentioned processes needs intensive amount of coal or natural gas in order to change the iron ore into the metallic state. This is because the processes need very high heat to complete the reduction of the iron ore. Energy efficiency has been improved in the processes that depends on natural gas as the main fuel, however, the amount of carbon dioxide and greenhouses gases emitted to the air cannot be eliminated (Fischedick et al, 2014).

There are two main processes used in the production of steel. The first method is called Blast Furnace/ Basic Oxygen Furnace which uses coal as stated earlier. The amount of CO_2 produced from this method is a total of 1050 kg for every ton of liquid steel. While the second method is called the Mirdex process which uses natural gas as illustrated above. The amount of CO_2 produced from this method is a total of 470 kg for every ton of liquid steel.

Figure 13 shows the amount of carbon dioxide emission per every ton of liquid steel for most of the steel production processes. As it can be observed from the graph, the BF/BOF process has the higher production of the carbon dioxide emissions since it depends purely on the combustion of coal followed by the Hi-Carbon DRI. the other alternative methods which does not depend on coal as the main fuel for the reduction of iron ore, for instance Mirdex process, has low carbon dioxide emissions compared to the conventional method of BF/BOF (Fischedick et al, 2014)..

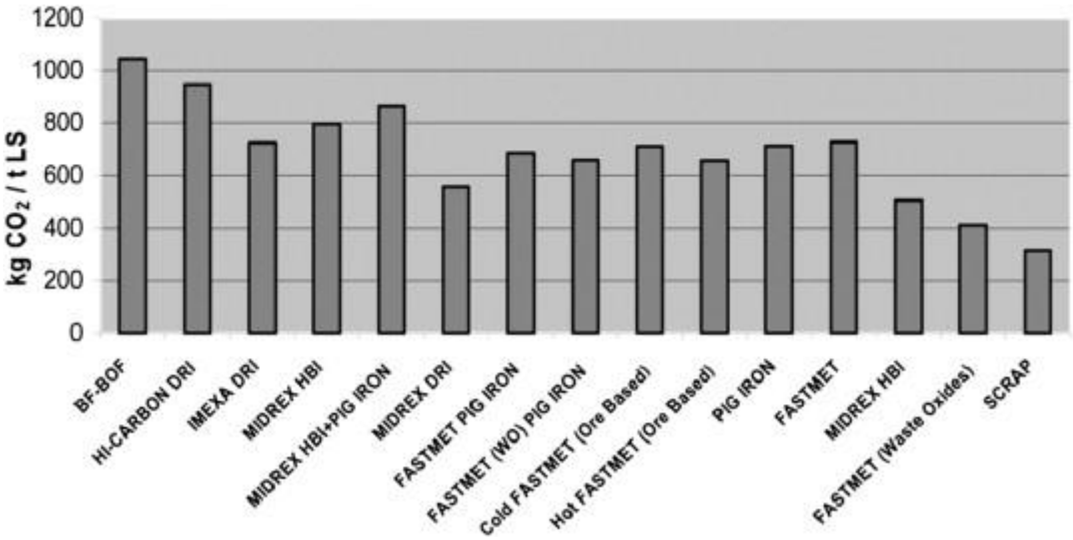

Figure 13 : Environmental Impact of Steel Production (Fischedick et al, 2014)

2.6.1.1 Reduction of the impacts of energy consumption

The only way of reducing the impacts of energy consumption is by reducing the amount of energy consumption because steel production is an intensive energy consuming industry. This can be done through several approaches. For instance, improvement of the furnace efficiency and energy recovery from the by-products of the process such as slag or from the furnace itself can reduce the amount of energy consumption (Tongpool et al, 2010).

2.6.1.2 Steel Recycling:

There are two sources of steel when it comes to production. The first source is the pig iron which is extracted from the iron ore and has not been used in any production process before. The second source is iron scrap which is the iron that has been used before in the life cycle of the steel product and now is considered waste material. A comparison between the use of pig iron and scrap iron shows that the use of iron scrap in the production of steel can lower the environmental impacts drastically

Further, using the iron scrap will help in reducing the amount of energy needed in the manufacturing of steel. For instance, in Thailand, there is an amount of 38280 tons of municipal solid waste that is produced every day; 1.15 ton of this waste is ferrous waste. It was reported that the use of iron scrap saved 5.34 MJ/kg of steel. This means that if all the ferrous waste produced in Thailand per day was recycled, there would be energy saving of 6141 MJ/day (Tongpool et al, 2010).

2.6.1.3 Efficient Use of Steel

Although the use of iron scrap in the production of steel consumes less energy, it was found that the waste from this process contains hazardous waste material such as lead, cadmium and chromium which need special treatment. On the other hand, the use of pig iron produces more negative environmental impacts than the iron scrap. This raised the question of whether steel should be recycled or should be produced for long-life use. It was found that due to the long-life of all steel products, the negative environmental impacts can be controlled since the iron ore extracted will be limited. Consequently, until a clear and deep study is done on this hypothesis, it would be better if we used the steel produced efficiently. To decrease the waste of ferrous materials nowadays, there should be better material handling to lengthen the life of steel products and to develop the production process to decrease the internal flaws (Tongpool et al, 2010).

2.7 Steel Construction Role in Sustainable Development

The idea behind this concept is to have a healthy future for the steel construction section. It helps the business sector to work and in the same time maintain the health and the welfare of the community and the environment. This can be achieved through the different phases of the construction as follows:

2.7.1 The Construction phase

During the construction phase, the on-site dealing with material can cause negative effect on the surrounding environment. These impacts include: noise, pollution, traffic congestion and dust. In order to decrease the effect of these negative impacts, more off-site fabrication should be utilized in the industry. This helps in decreasing the on-site effects and increases the quality of the fabricated parts and increase the construction speed (Burgan and Sansom, 2006).

Despite most of the steel parts used in construction are fabricated off-site, the amount of processing from one part to the other differs. For example, dealing with the I-beams or C-section differs from the steel formwork. However, both of them have the same benefit which is high quality and decreasing the amount of processing on-site (Burgan and Sansom, 2006).

Furthermore, the off-site fabrication process can decrease the amount of waste by controlling the design and manufacturing process. This can be done by optimizing the design using computer software and in manufacturing the products by using automated or semi-automated production lines (Burgan and Sansom, 2006).

2.7.2 The in-use phase

It is well-known that the amount of energy needed in operating the building is considerably higher than the energy needed to manufacture the products within it (embodied energy). The ratio between the operational energy of a building designed to last for 60 years and the embodied energy is 10:1. Therefore, it became necessary for the designers to take into consideration some measures to help in reducing the operational energy of the building. These measures include: the shape and the orientation of the building, reducing the heat loss from the building form, reducing cooling loads and innovate some energy saving and energy producing measures. The concept of "Fabric Energy Storage" (FES) is utilized to reduce the cooling loads of the buildings. This is one of the most effective methods that depend on the ability of the building to absorb heat during the night and losing it at night. This is done by enabling the fabric of the building to transfer the heat easily. This is done by exposing the underside of the floor slabs and is measured using a parameter called "Admittance". The higher this parameter is, the greater the ability of the building to store and release heat energy (Burgan and Sansom, 2006).

2.7.3 Life Extension

Extending the life of the steel products achieves a number of sustainable development goals. It helps in using more resources and reducing the waste significantly. This can mainly be done by restoring and reusing the steel products used in the building or in manufacturing the products in addition to recycling.

Reusing has its advantages over recycling. It decreases the amount of energy needed to recycle and reprocess the steel. To maximize the life extension of a steel product, the product should be designed to fit different uses in its different life stages and to control its premature replacement (Burgan and Sansom, 2006).

2.7.4 End of Life phase

This is a very important corner in the sustainable development of the efficient use of steel. This can be achieved by reducing the waste produced from the steel products at the end of its life and to ensure that the steel is reused or recycled at this stage. The standardization of the steel members and products helped in boosting the use of recycled steel and reusing it at the end of its life. Further, this will help in decreasing the problem of the high demand on steel and the shortage of supply from iron ore. As shown in figure 14, the use of crude steel overrides the use of scrap steel by 200% and therefore, achieving the sustainable development will take a great role in satisfying the market needs and decreasing the negative impacts of the steel production on the environment and increase the efficient use of steel in the world as a whole (Burgan and Sansom, 2006).

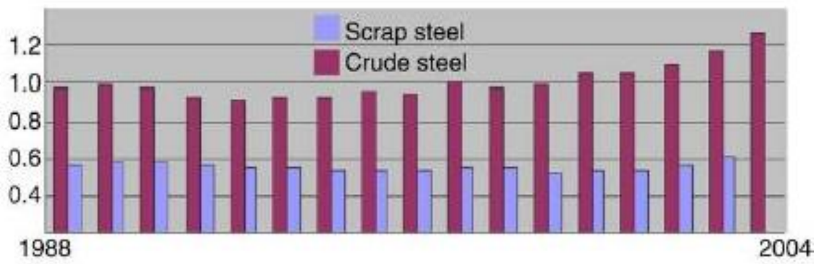

Figure 14 : Demand on Crude and Scrap Steel (Burgan and Sansom, 2006)

2.8. The Research Gap

The idea of this research is triggered by the desire to develop a sustainable substitute of the current formwork systems.

The current formwork systems have passed by a number of developments and breakthroughs; however, there are no researches that aim to change the design of the formwork system. All the researches focus on changing the material from wood to steel or aluminum. These systems are still suffering from a number of unavoidable disadvantages. Such disadvantages cause problems during the frequent and continuous use of these systems in every construction project. The frequent use of these systems made the people mitigate the disadvantages. However, there were no real attempts to solve these disadvantages.

The list of major disadvantages that are faced during the usage of these systems includes the lack of construction space, the heavy weight, large space needed for storage, environmental impact, the transportation of the system, constructability time and the economics of the system.

As for the economics of the old systems, it is well-known that the commercially available systems need high capital because they use a lot of steel. Further, they need more trucks and cranes with higher capacity to transport the system off-site and on-site. Moreover, the commercially available systems reduce the space beneath them because a high number of frames used to support the loads expected on the system. This big number means more weight is needed to cover the desired area. Consequently more cost is needed.

In addition, the construction time of these systems are long because of their weight and the numerous components of the system. Also, the need of big number of frames to cover any area means more time consumed in the erection of the system.

Furthermore, the commercially available systems need more space in the construction site to be stored. The large dimensions of the components of the system and the big number needed to do the job makes the presence of a big storage space a must. Moreover, the absence of storage space for the system can cause unsafe conditions for the workers in the site.

The commercially available systems have a huge negative impact on the environment. This is because they use a lot of steel which means more CO_2 emissions in the atmosphere and also more hazardous materials that will be used in the manufacturing and processing of the steel. Also, the trips needed for the transportation and the type of transportation have indirect effect on the environment.

Therefore, this thesis aims to develop a system that target all of these disadvantages and is environmentally friendly and to study its properties.

3. CHAPTER THREE: DESIGN AND CONSTRUCTION

3.1 Theoretical Concept

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 (Darwish et al. 2015). 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 have never been used as the basis of a formwork/false-work system.

This chapter focuses on proposing a design of false-work 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 several frames of the currently used commercially available 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.

The proposed system consists of a truss where the upper chord and the diagonal members are zero members. These members although they increase the weight of the truss, their presence is very important for three main reasons. The first reason is that it acts as a second line of defense in case of failure of one of the other members. The second reason is that it is important to withstand the working loads such as loads due to transportation or due to installation. The third reason is the stability of the system. These members are very important to the structural integrity of the system and the system would lose its stability in their absence.

According to Leet, Uang, & Gilbert, an arch is considered funicular if it has an intermediate hinge in the midpoint, hinged at the two supports and obeys the parabolic equation 1 as follows:

$$y = -4hx^2/L^2 \quad [1] \qquad \text{(Drawish, 2015)}$$

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, & Gilbert, 2006). Applying this fact to a truss that follows the concept of the funicular arch, the upper chords and the diagonal members will be zero members and the loads will be 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 members covering eight 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 equation 2:

$$M_u = wa^2/9 \quad [2] \qquad \text{(Drawish, 2015)}$$

Where M_u 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 equation 3:

$$P_{vext} = -wa/2 \quad [3] \qquad \text{(Drawish, 2015)}$$

Moreover, the forces in the interior verticals were found to satisfy equation 4:

$$P_{vint} = -wa \quad [4] \qquad \text{(Drawish, 2015)}$$

Furthermore, the bottom chord member was found that they satisfy one general equation which is equation 5:

$$P_{ij} = -wL_{ij}L/h \qquad [5] \qquad \text{(Drawish, 2015)}$$

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.

3.2 Model Description

The model under study in this thesis is a truss that covers a span of 2.4 meters and has a height of 3 meters. This span was chosen specifically because it is the smallest dimension that a room could have in the Egyptian code of Practice. The span between the two trusses is chosen to 1.8 meters and the design capacity of the truss is determined to be 1.75 ton based on an assumption that this system is used to pour slabs up to 0.24 meter thickness.

The truss proposed in this thesis consists of thirty steel tube members. As shown in figure 15, 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, the most two inner vertical members are steel tubes of 16 mm diameter. The case is different for the bottom chords because the forces decrease 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.

Furthermore, the upper horizontal chord members, the diagonal members and the bracing members have an outer diameter of 16 mm. All of these steel tubes have 1.25 mm thickness. Table 2 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 2: Diameters of the member of the proposed funicular arched steel truss

Member Name	Member Number	Diameter (mm)	Thickness (mm)
Exterior Vertical (EV)	EV (1-2)	25.4	1.25
Stringer	S	16	1.25
Interior Vertical (IV)	IV (3-4)	25.4	1.25
	IV (5-6)	25.4	1.25
	IV (7-8)	16	1.25
Bottom Chord (BC)	BC (2-4)	31.75	1.25
	BC (4-6)	25.4	1.25
	BC (6-8)	19	1.25
	BC (8-9)	16	1.25
Diagonals (D)	D (1-4)	16	1.25
	D (3-6)	16	1.25
	D (5-8)	16	1.25
Scissors (SC)	SC (34-34)	16	1.25
	SC (56-56)	16	1.25

Figure 15 shows 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.

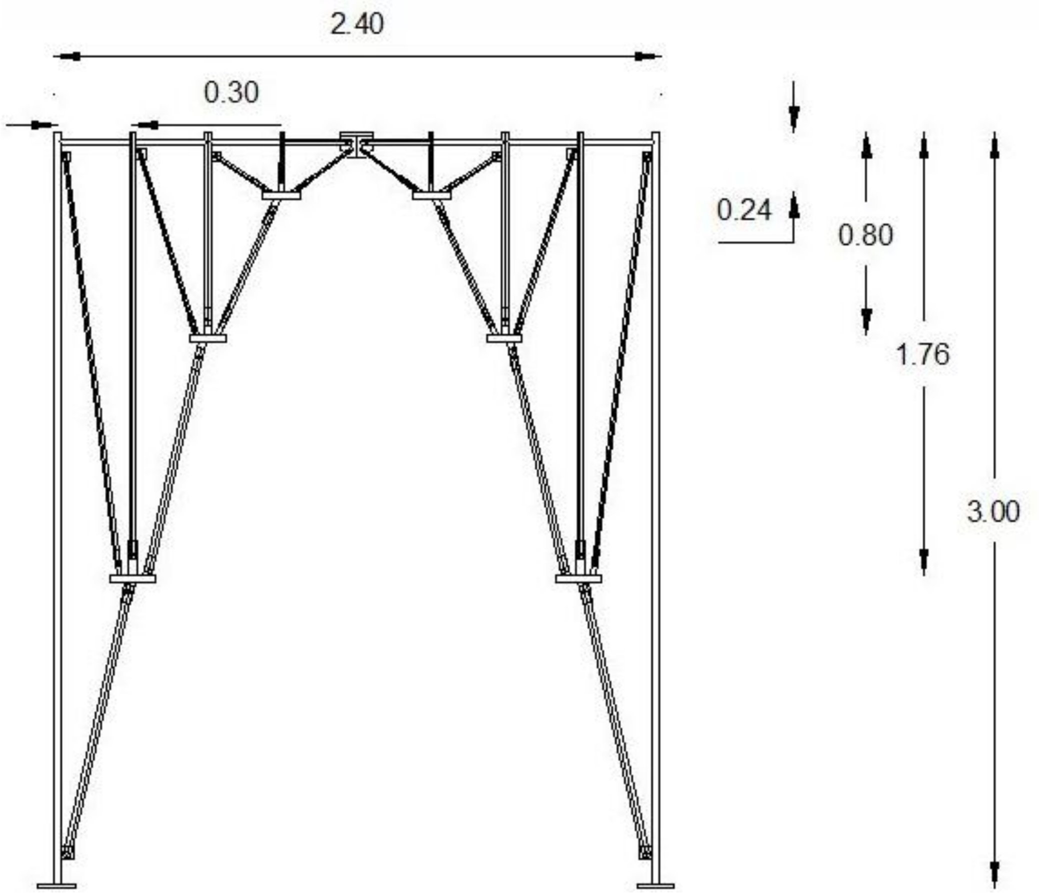

Figure 15 : The Lengths of the Members in the Proposed Truss

3.3 Manufacturing the Model

The chosen span means that the all the horizontal members will have a length of 0.3 meter. Further, the chosen height means that the exterior vertical has a length of 3 meters minus the base plate which was decided to have a height of 15mm and consists of 3 plates with a dimension of 100 x 100 mm and a thickness of 5 mm. Therefore, the height of the tube representing the exterior vertical is 2.985 m.

After determining the main dimensions of the truss, the shop drawing for each member in the truss was prepared in order to have a detailed design about each member before starting the manufacturing. Based on the shop drawings, the procurement of the materials needed in the manufacturing included: hollow tubes with dimensions ranges between 16 mm and 1.5 inch (38.1 mm) with only two thicknesses: 1.25mm and 2mm. The thickness of the tubes was chosen to ensure that the members are not over designed and to control the weight of the system without affecting the capacity of the members.

The manufacturing process started by cutting all the members that will be needed to manufacture 3 samples of the truss. All the exterior verticals, interior verticals, diagonals, horizontal members, bracing members, the U heads, the plates used in making the intermediate hinge connection and the small plates used to connect the diagonal members and the first bottom chord member were cut to the dimensions needed. The strategy in the manufacturing process was to prepare all the parts needed to assemble one half and then start in the assembly process to determine how much time it takes to assemble one half. The first step was cutting the U heads to the required dimensions. The U heads have a width of 160mm and a length of 16mm and were welded to the top of the verticals using a 40 x 40 mm plate. Further, three plates with a dimension of 100 x 100 mm and thickness of 5 mm were welded together and then welded to the bottom of the exterior verticals to act as the base plate of the system.

The next step was to weld the plates that are connecting the diagonals to the verticals and the bottom chord members to the exterior vertical. A total of 6 plates with a dimension of 40 x 40 mm and have 8 mm holes are welded in each truss hole to connect the diagonal members. Further a total of 2 plates with a dimension of 50 x 50 mm and a hole of 12 mm diameter are welded to the exterior verticals to connect the first bottom chord to the system.

After that, the members are cut to the required dimensions. As shown in table 3, the members are cut to these dimensions, however, each set of members have been treated differently depending on where they are incorporated in the system. For instance, the horizontal members are cut to their dimensions and then welded to the vertical members; therefore, they don't need their end to be flattened as they are welded directly on the body of the vertical tubes. On the other hand, the first bottom chords and the diagonal members are cut to their dimensions and then flattened from one of its end because have a 12 and 8mm respectively to be connected to the exterior vertical using the small welded plates. Further, the vertical members and the rest of the bottom chord members, except the last one which is flattened at one of its ends, are only cut to their dimensions without any further processing since they will be only fitted inside the connections.

Table 3 : Lengths of each member in the truss

Member Name	Member Number	Length (mm)
Exterior Vertical (EV)	EV (1-2)	3000
Stringer (Upper chord)	S	272.5
Interior Vertical (IV)	IV (3-4)	1700
	IV (5-6)	700
	IV (7-8)	200
Bottom Chord (BC)	BC (2-4)	1225
	BC (4-6)	975
	BC (6-8)	575
	BC (8-9)	325
Diagonals (D)	D (1-4)	1650
	D (3-6)	750
	D (5-8)	275
Scissors (SC)	SC (34-34)	1220
	SC (56-56)	900

3.4 The Assembly Process

The assembly process started with preparing a squared frame with dimensions of 3 meters high and 1.2 meters length in order to fit the dimensions of one half of the truss. This frame consisted of hollow square tube welded together to form the required shape. As shown in figure 16, the exterior vertical was put on the end of the frame and was fixed to the frame using welding to make sure that it will not move during the assembly process. Then, the other verticals are fixed by the same way after putting the horizontal members between them and fixing them using welding to ensure that they are equidistant as intended. The next step was to manufacture the connections. The first tube in the first connection was the one that the interior vertical member (3-4) is fitted into. This is because it is considered a trustworthy baseline to start from, since the verticality of the member is checked. After that, the tube is fixed using welding to the horizontal tube in the connection. The other tubes were fixed using the same procedure after determining their place on the horizontal tube using the shop drawings.

After finishing all the connections, all the tubes fixed by welding are completely welded in their final position. The same applies for the rest of the connections. It is worth to mention that the assembly process took around 25 minutes this excluding the time of preparing the frame and figuring out the procedures to follow in the assembly.

Figure 16 : Fixing the members to the Square Frame

3.5 Connections in the Proposed System

The connections between the horizontal members and the vertical members are welded connections. Further, the diagonal members are connected to the vertical members using a bolt that is bolted in a 40 x 40 mm plate with a thickness of 50 mm. Furthermore, only the first bottom chord member is bolted to a 50 x 50 mm plate with a thickness of 50 mm while all the other bottom chord members are fitted from both sides in the tubes of the connections.

The connections between the different members of the truss have a number of models to suit the different angles of the members and their positions in the truss (interior vertical, diagonal member or bottom chord member).

The concept followed in developing the connection between the members is as follows: each connection consists of a horizontal hollow tube with a diameter of 31.75mm and wall thickness of 2mm and welded to it a number of 4 tubes that suits the angle of the member that is fitted into it. The welded 4 tubes have a diameter larger than the diameter of the member to be fitted in. For example, if the member has an outer diameter of 19mm then the diameter of the tube should be 19mm plus its thickness, which is 1.25 mm multiplied by 2, therefore, the diameter of the tube should be 22mm. However, due to the imperfections of the tubes and constructability reasons, the diameter chosen should be 25.4 mm to allow for the member to fit in smoothly inside the tubes.

Therefore, each member with an outer diameter of 16mm is fitted into a tube with an outer diameter of 22mm, each member with an outer diameter of 19mm is fitted into a tube with an outer diameter of 25.4 mm, each member with an outer diameter of 25.4 mm is fitted into tube of an outer diameter of 31.75mm and each member with an outer diameter of 31.75mm is fitted into a tube with an outer diameter of 38.1 mm.

For constructability reasons, all the tubes in all the connection have a fixed length of 105 mm. The lengths of the members were designed in order to insure that the members are resting on the horizontal tube and that the overlap distance inside the tube is equal to the full length of the tube. However, the tubes have a hole that is on a distance of 50mm from the top of the tube. A pin with a diameter of 8mm is used to fix the members inside the tube in order to make sure that the member will not slip when it is subjected to loads.

Figure 17 shows the connection at point 2 in the truss. This connection has 4 tubes welded to the horizontal tube. The diagonal member that has an outer diameter of 16 mm is fitted inside the left tube that has an outer diameter of 22mm. The middle tube has an outer diameter of 31.75mm to allow the 25.4 mm diameter interior vertical to fit in. and for the tube on the right a member of an outer diameter of 25.4

mm is fitted inside a 31.75mm. The bottom chord member has an outer diameter of 31.75 mm and is fitted into a tube of an outer diameter of 38.1mm. Due to the significant difference in between the bottom chord member and the hollow tube it is fitted in, the tube is flattened in order to give it an oval shape that allows it to be welded to the horizontal tube.

Figure 17: Connection at point 2 in the truss

3.5.1 Bracing Connections

The bracing connections between the two trusses follow the same concept as the connections between the members in the bottom chord. These connections are used between the inner vertical members in order to decrease the effect of buckling. As shown in figure 18, the bracing connection between the first interior vertical (member 3-4) has the shape of the letter X and the tubes also have the hole where the pin is used to fix the bracing in their place.

Figure 18: Connection at Bracing members

3.5.2 Intermediate hinge connection

As shown, in figure 19, the connection that acts as the intermediate hinge consists of a tapered plate that has 4 holes with a diameter of 10 mm to allow for the last two horizontal members and the last two bottom chord members to be connected to. Another plate is welded perpendicularly to the tapered plate to allow for the U head to be welded to.

Figure 19 : Intermediate Hinge Connection

3.6 Tie Rod

A tie rod with an outer diameter of 19mm is added to the system in order to withstand the thrusting force that will try to open the arch once it is subjected to high loads. The presence of the tie beam added stiffness to the system and more stability during movement and before setting up the complete unit (Two trusses with the bracing). Further, it allows the setup of the truss to be easy since it holds the two halves together, fixes the span at the desired length since it reduces the risk of the arch to open; and reduces the sway of the truss.

3.7 Erecting the FAST System

The proposed system consists of units consisting 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 placed on top of the trusses to act as joists and will rest 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.

3.8. Setting-Up Procedures

1- As shown in figure 20, the first step is to bring two opposite halves in front of each other and connect them together using the intermediate hinge connection.

Figure 20: Putting the two halves of the truss in front of each other

2- As shown in figure 21, the second step is to connect the tie rod to the bolts of the first member in the bottom chord.

Figure 21: the Tie Rod is connected to the bolts of the bottom chord

3- The two trusses are erected as shown in figure 22.

Figure 22: Erecting the Trusses

4- The connections of the bracing are prepared by fitting in the bracing members inside each connection before connecting them to the trusses as shown in figure 23.

Figure 23: Connecting the bracing system to the truss using a ladder

5- The last step will be to add the joists on top of the U heads as shown in figure 24.

Figure 24 : The joists are put on top of the U heads

3.9. Soundness of the FAST System

3.9.1. The Lightweight of the System

The proposed system is characterized by its light weight. Assuming that the commercially available systems leaves a distance of 0.6 meter between every frame and the other; one unit of the proposed system will be able to replace eight units of the commercially available systems. This number was achieved based on comparing the area covered by one unit of the proposed system (2.4 m x 1.8 m) by the same number of frames from the commercially available systems. To cover a span of 1.8 meters, four units of the commercially available frames are used to be perpendicular to the direction of the 2.4 meters distance. And then another 4 units are used to cover the rest of the 2.4 meters. Therefore, there are 8 units needed to cover the area covered by one unit of the proposed system.

The chosen commercially available system is one of the lightest systems that could be used in the market in Egypt. By calculating the weight of the members of the commercially available shores system it was found the weight of eight units can reach almost 63.65 kg. However, the equivalent number of units from the FAST system can reach a weight of 42.5 kg by a difference of 33%.

This is a very important aspect for the FAST system because it decreases the total weight of the system needed to construct one slab. By fixing the uniform distributed load to which the both systems are subjected and increasing the spans in the increments of 1.2 meters (from 2.4 meters up to 7.2 meters), it was found that the diameters of the FAST system did not change by changing the span until a span of 6 meters. The capacity of the members in the FAST system was found that it can withstand the expected loads on the system even after the span reach 4.8 meters with a minimum factor of safety of 1.7 in the exterior vertical member because it is the most critical member in the system because of its buckling length. However, an increase in the thickness of the exterior vertical is necessary in order to withstand the spans from 6 meters up to 7.2 meters. Meanwhile, the other members were found that they can withstand the load up to 4.8 meters. The effect of increasing the thickness of the exterior vertical resulted in a total difference in the total weight of the FAST system of 1.25 kg.

Figure 25 shows the weights of the commercially available steel formwork systems and compares them to the weight of the FAST system. It is clear that the weight of the commercially available system increases significantly in wide spans, however, the weight of the FAST system is increases slightly for the spans from 2.4 meters up to 7.2 meters. This is because the lengths of the bottom chord members and the length of the diagonals increase with the increase in the span. Further, the increase in the diameter of the exterior vertical and bottom chord member (4-6) causes increase in the weight in spans of 6 and 7.2 meters.

However, it is worth to mention that after a review has been done to the types used in the Egyptian market, it was found that there are a number of systems used in Egypt that have different uses and different weights. This is because every formwork system can be economically used for a specified task. For instance, the coupler system is used for the heavy duty tasks. Further, it was also found that the system that its weight is used in this comparison is the most commonly used system. Further, the system used in this comparison is one of the lightest systems as mentioned earlier. According to the brochures of Pioneers Company, one of the most famous companies in the field of formwork, the chosen commercially available system is the most sold system in the common types of buildings in Egypt such as the residential buildings, villas and office buildings.

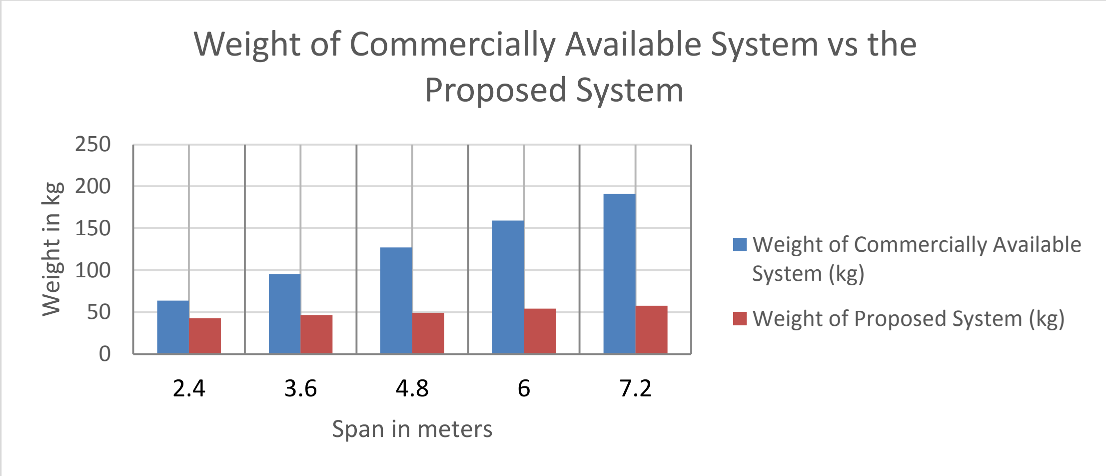

Figure 25 : Weights Differences in both systems

Further, table 4 illustrates the efficiency of the FAST systems after increasing the span. It was found that, originally, the FAST system has a 33% saving in the weight when the span is 2.4 meters. This means that, according to the previous assumption of the number of frames is used to compare the weight and the number of units in the two systems, that there is a saving of 4.89 kg/m^2. This is calculated by dividing the weight of the eight units of the commercially available systems (63.65 kg) used to cover the area of 2.4 x 1.8 m (4.32 m^2) to get the value of the weight of this system needed for each m^2 from the floor area which yields a value of 14.73 kg/m^2. While the weight needed from the proposed system to cover the same area is calculated by dividing the weight of one unit of the system (42.5 kg) by the area (4.32 m^2) which yields a value of 9.84 kg/m^2. The difference between these numbers gives the savings in the weight of the systems per unit area.

This effectiveness increases and can be clearly noticed in the very wide span such as the span of 7.2 meters where the reduction in weight is 70%.

Table 4: Percentages of Reduction in Weight

Span	Weight of Commercially available Steel System (kg)	Weight of Proposed System (kg)	Percentage of reduction in weight
2.4	63.65	42.5	33%
3.6	95.46	46.6	51%
4.8	127.28	49.1	61%
6	159.1	54.25	66%
7.2	190.92	57.5	70%

3.9.2. Transportation

The light weight of the FAST system will make it easier to transport to the site and on-site. As for the transportation to site, the most common types of trucks used to transport are cars with maximum capacity between 2.7 tons and 4.7 tons. The reason behind this is that the lightweight of the proposed system makes it possible to transport more trusses and therefore, more area can be covered on-site by the system. On the contrary, the commercially available systems weigh more than the proposed system. This means that fewer frames can be transported and therefore, fewer frames can be carried and more trips are needed to transport all the required frames.

As for the transportation on site, the system can be transported by the smaller cranes available with no need to rent or buy a crane with high capacity to transport the system. This helps in two major points in construction. The first point is time because the proposed system can be transported easily in lesser number of packages/turns in the crane. The second point is the cost savings due to the need of cranes with smaller capacity to transport the system from place to place. For example, a company called Leibherr has a variety of mobile crane models that have a capacity that ranges from 35 tons to 1200 tons (Leibherr, 2016). The smallest mobile crane with model name "LTM 1030-2.1" has a capacity of 35 tons (Leibherr, 2016). By comparing the weights mentioned earlier for the commercially available systems and the proposed system, it was found that this crane can carry weight of the commercially available systems that is equivalent to cover an area of 2376 m^2. On the other hand, the crane can carry weight of the proposed system that can cover an area of 3969 m^2. Further, the system can be moved easily on site using manual means. One worker can lift one half of the truss with its accessories without any help. However, if the system had to be carried manually, it should be moved half by half to avoid any accidents on site.

3.9.3. Construction Time

Construction 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 FAST 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 FAST 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 and to fix the tie rod. 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.

Furthermore, in a demo done for this system before the experimental work, it was found that two workers needed less than 7 minutes to erect the system and 2 minutes to put the joists on top of the U heads. This means that the whole system can be erected in less than 10 minutes. Therefore, the FAST system decreases the time needed for the erection and the stripping of the system and this advantage could be noticed when there are a big number of units to be erected. Further, it is worth to mention that the workers, who erected the system in the demo, were doing this job for the first time. If this job is done repeatedly, the time needed for erecting the system will decrease significantly because the learning curve of the workers increases with experience. The commercially available systems take time to be erected because it consists of more than two components in addition to the accessories of the system. Further, the commercially available system needs time to be adjusted and needs more units to cover the same area covered by the FAST system.

3.9.4. Construction Space

One of the common problems in construction sites is the limited space available for material storage and safe movement of construction and equipment. This problem causes difficulties in creating safe paths for the workers to move around the site and for the material storage. The commercially available 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 FAST 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 small equipment and will make storing them easier. This will allow 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.

3.9.5. Environmental Impact

The FAST system has direct and indirect environmental impacts. The direct impacts include the decreasing of the amount of CO_2 emitted to the atmosphere due to the energy consumed in the production process and the amount of hazardous waste materials from the processing of steel. The indirect impacts include the decrease of the amount of CO_2 emitted during the transportation of the system.

For the direct impacts, according to Fischedick et al, 2014 and as shown in figure 13 in the previous chapter, the amount of carbon dioxide produced per every ton of produced liquid steel can reach up to 1050 kg CO_2/ ton of LS. Based on the previous calculations of the weight reduction percentage, according to Tongpool et al, 2010, the amount of carbon dioxide saved due to the proposed system is 462 kg CO_2/ton of LS. This is a huge breakthrough in the field of environmental impacts of steel production. The reduction will not include only the amount of carbon dioxide produced during the production of steel but it will also extend to the amount of electricity saved during the production/processing of the steel. Therefore, it can be concluded that if the formwork system will be used to cover an area of 100 m^2, this means that a total weight of the commercially available systems equals to 1473 kg will be needed to cover this area while a weight of 882 kg of the FAST system will be needed to cover the same area, based on the average weight per m^2 mentioned earlier. Consequently, the amount of CO_2 produced from the commercially available systems will be 681 kg of CO_2 while the FAST system produces 407.48 of CO_2. Therefore, the total amount of CO_2 savings in an area of 100 m^2 is equal to 273.57 kg which means 2.7 kg/m^2.

In addition, the amount of energy consumed in the steel production is decreased. For example, the largest factory in Egypt that uses electricity in the production of steel produces a total amount of 3 million tons of steel every year. The amount of electricity consumed in the production of this amount equals to 3 billion kilowatt of electricity per year. By calculating the amount of electricity needed in the production of one kg of steel, it was found that one kg of steel consumes 1 kilowatt of electricity. This is equivalent to 1000 joules/second/power for every kilogram of steel. Consequently, the savings in electricity can reach an amount of 5910 joule/second/power for the amount of steel saved when using the FAST system.

Furthermore, the environmental impacts will also include decreasing the amount of hazardous waste produced from the use of steel such as zinc and cadmium. And finally, the idea that the proposed FAST system can have long-life span will help in decreasing the frequency of manufacturing steel and will consequently decrease the amount of CO_2emitted to the atmosphere during the life cycle of the system.

For the indirect impact, the amount of fuel saved due to the decreased number of trips needed for the transportation of the system to site is studied. As mentioned earlier, less number of trips is needed to transport the proposed system since it has less weight. According to the Central Agency of Public Mobilization and Statistics (CAPMAS), a truck that can carry up to 5 tons consumes 12.5 liters per kilometer with an average speed of 100 km/h. This means that by decreasing the number of trips, savings in the amount of fuel consumed and the amount of CO_2 can be achieved.

3.9.6. Storage of the System

Due to the large dimensions and the numerous components of the commercially available systems, it needs a lot of space to be stored on site. As shown in figure 26, the system is lying on a large area and the quantity on this storage is only a part of the total amount of frames that are needed to finish the job. The volume of the space needed for this system to be stored equals (1m x 3m x 0.1 m) which equals 0.3 m^3. Further, the storage of the formwork by this way decreases the lifetime of the frames since it is subjected to high heat, corrosion and continuous deformation due to the inappropriate way of dealing with formwork.

On the Contrary, the FAST system can be easily stored on site. This is because its components are less than the commercially available system. For example, the volume needed for the storage of this system is (1/3 x 1.2m x 3m x 0.1) which equals 0.12 m^3. Therefore, savings in the volume of space needed to store the FAST system is 40%

As shown in figure 27, the system is stored safely inside the workshop where it was manufactured. Four trusses are stored in a narrow area due to the fact that the dimensions of the half truss are small and the halves can be accumulated above each other to decrease the occupied space. As shown in the figure, the way of storing the trusses does not show that it causes any danger because the components are assembled together and their edges are not sharp.

Furthermore, the system can be stored in congested areas in the site with minimal effect on the safety of the place. Figure 28 shows the trusses stored inside the lab where the experimental work took place. The lab was congested and there were a lot of structures and items that can cause safety issues, however, the system is stored neatly.


Figure 26: Storing the Commercially available systems on Site


Figure 27: the System is stored in the Workshop

Figure 28: The system is stored inside the lab

3.10. Parametric Study

3.10.1. Description

The chosen area ranges to work on will be for three different slabs. The first slab has an area of 10 m x 11.5 m (115 m^2), the second slab has an area of 20 m x20 m (400 m^2) and the third slab has an area of 25 m x 25 m (625 m^2). The reason behind choosing these different area ranges is to determine the difference of using the FAST system instead of the heavy duty system. The comparison of the two systems will be in terms of the number of units used to cover the same space and the environmental impacts.

As mentioned earlier, the commercially available systems will be used to cover the area of the slab in the three areas. As shown in figure 29, the heavy duty system is represented by two nodes and a line between them. The length of the line is 1 meter measured from the center lines of the two nodes. The number of frames used to cover the slab is 119 frames. The distance between the frames is assumed to be 0.6 meter in the vertical direction and 0.6 in the horizontal direction.

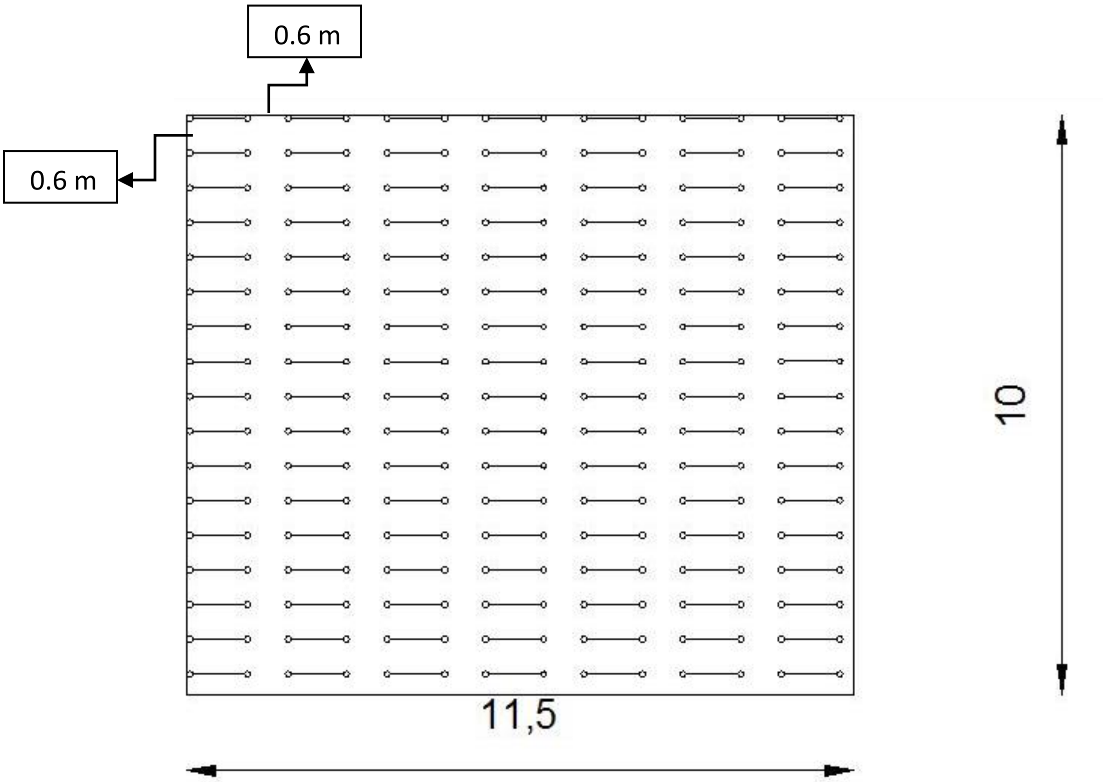

Figure 29: The Plan with the Commercially available System

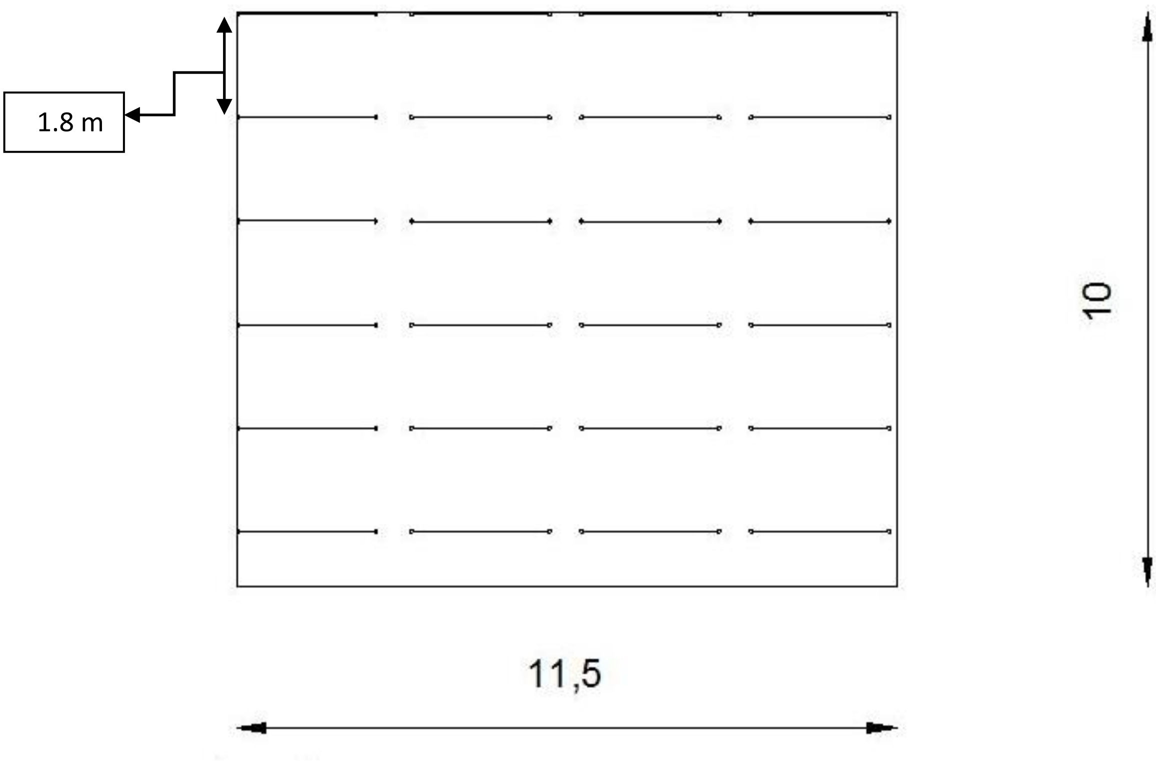

Figure 30: The Plan with the FAST System

On the Contrary, the FAST system needed only 24 trusses (i.e. 12 units). The FAST system is represented also by two nodes and one line that is 2.4 meters which is the span of the truss as shown in figure 30.The number of units is based on the assumptions that every unit is 1.8 meters apart from the other unit in the vertical direction and the units are 0.6 meter apart in the horizontal direction.

For the area of 400 m^2 and the 625 m^2, the same assumptions were followed in order to determine the number of frames needed to covert theses areas.

3.10.2. Comparison between the Heavy Duty system and the FAST system

3.10.2.1. Total weight

As mentioned earlier, for the area of 115 m^2, the heavy duty system needed 119 frames to cover the area while the FAST system needed 24 trusses (i.e. 12 units) to cover the area. This means that the weight of the heavy duty system is 946.66 kg which is corresponding to 8.23 kg/m^2 while the weight of the FAST system is 486 kg which is corresponding to 4.22 kg/m^2. This means that the saving in the weight of the system is 460.66 kg with a percentage of 51.33%.

While for the 400 m^2 area, the number of frames needed from the heavy duty system is 408 frames which correspond to a weight of 3246 kg (8.1 kg/m^2). On the contrary, the FAST system needed 78 trusses (i.e. 39 units) with a total weight of 1657.5 kg (4.14 kg/m^2). This means that in this area range the savings is equal to 51.11%

For the 625 m^2 area, the number of frames needed from the heavy duty system is 645 frames which correspond to a weight of 5131.8 kg (8.2 kg/m^2). On the contrary, the FAST system needed 110 trusses (i.e. 55 units) with a total weight of 2337.5 kg (5.85 kg/m^2). This means that in this area range the savings is equal to 45.55%

3.10.2.2. Total Time consumed

According to an educational video published on Doka YouTube Channel, 2 workers can erect 24 units from the heavy duty system in 69 minutes. By taking this number as the basis of calculation, one unit needs almost 3 minutes to be erected. Consequently a time of 357 minutes (i.e. 6 hours) is needed to erect all the 119 units needed to cover the area of 115 m^2, 1224 minutes for the 400 m^2 area (i.e. 20.4 hours) and 1935 minutes for the 625 m^2 area (i.e. 32.25 hours)

On the other hand, one unit of the FAST system (i.e. two trusses) needs 7 minutes to be erected. Consequently, to erect 12 units of the proposed system, a total of 114 minutes is needed (i.e. almost 2 hours). This gives a total savings of 4 hours (67%

reduction in time) between the heavy duty and the FAST system for the 115 m^2. While for the 400 m^2 area, it takes 273 minutes (i.e. 4.55 hours) with a saving of 75% in time. For the 625 m^2 area, it takes 385 minutes (i.e. 6.42 hours) with a saving of 80%.

3.10.2.3. Total Time needed for Transportation

In this point of comparison, two sub-points are considered. The first point is the capacity of the truck used in transportation while the second point is the travel time to the site. As for the first point, both of the weights of the two systems are less than 1 ton for the 115 m^2 area, however, due to volume considerations the FAST system can be transported on a smaller truck than the heavy duty system. Therefore, this yields savings in the cost of transportation. For the 400 m^2 area, the heavy duty system can be transported on two packages if a 2.7 ton truck is used while the FAST system can be transported in only one package. For the 625 m^2 area, the heavy duty system will be transported in three packages while the FAST system will be transported in one package.

As for the second point, the travel time for the FAST system will be faster since it is carried on a smaller truck and the weight it carries is less than the weight of the heavy duty system by range between 45% and 51%.

3.10.2.4. Total Weight of CO_2

As mentioned earlier, the amount of CO_2 produced due to the production of one ton of liquid steel is 1050 kg of CO_2. This means that the savings in the carbon dioxide due to the use of the FAST system is 539.7 kg of CO_2 which yields a saving of 51.4%. For the 400 m^2 area, the amount of CO_2 emitted is 3408.3 kg of CO_2 for the heavy duty system while the FAST system causes the emission of 1740.4 kg of CO_2 with a saving of 51%.

For the 625 m^2 area, the amount of CO_2 is 5388.4 kg for the heavy duty system while it is 2454.4 kg in case of the FAST system. This yields a saving of 45.55%.

Table 5 shows the summary of the comparison between using the heavy duty system and the FAST system in the previous area ranges.

Table 5: Comparison Summary

Area Range (m^2)	Point of comparison	Heavy Duty System	FAST System	Saving %
115	Total Weight (kg)	946.66	486	51.33%
	Total Time Consumed (hours)	6	2	67%
	Transportation	Needs more time and larger trucks	Needs less time and can be transported using smaller trucks.	
	Total Weight of CO_2 (kg)	1050	539.7	51.40%
400	Total Weight (kg)	3246	1657.5	51.11%
	Total Time Consumed (hours)	20.4	4.55	75%
	Transportation	2 packages	1 package	50%
	Total Weight of CO_2 (kg)	3408.3	1740.4	51%
625	Total Weight (kg)	5131.8	2337.5	45.55%
	Total Time Consumed (hours)	32.25	6.42	80%
	Transportation	3 packages	1 package	76%
	Total Weight of CO_2 (kg)	5388.4	2454.4	45.55%

4. CHAPTER FOUR: EXPERIMENTAL WORK

4.1. Description

The experimental part of this thesis includes the testing of three trusses. During the design of the experiment, the expected real life situation is taken into consideration. It is expected that during the pouring of concrete on site, the pump will pour the concrete on top of one unit which causes one of the trusses to be loaded while the second one is not subjected to the same load until the freshly poured concrete is poured on top of it. Therefore, during the experiment, the unit is subjected to load only on top of one of the trusses. The specimens are experimented until they reach failure in order to determine the maximum load and maximum deflection that can be expected from the system.

During testing the specimens, the three trusses will take turn to form one unit of the proposed formwork system. This means that the test will always have one unit subjected to the load while being connected to another unit using the bracing members. For example, when testing the first unit, only one truss will be loaded while the other truss is not subjected to any loads. This goes on until the turn of the third specimen comes. The test of this specimen faces a major problem. The problem is that the other two specimens are loaded to failure and the behavior of both of them cannot be expected because they are expected to have a considerable amount of plastic deformation. However, it is expected that the failure in the truss will only occur in one half of the truss due to the presence of the intermediate hinge. The presence of the intermediate hinge prevents the failure to propagate to the other half of the truss and therefore, there is always one half of the truss that will not go through plastic deformation. Consequently, the flexibility of the system will be utilized by taking the two halves of the other two trusses that did not fail and form one new truss to use it as a bracing system for the third truss.

4.2. Loading Case

It is expected that the trusses are exposed to a number of loading cases such as loading during transportation, loading during installation, loading during construction before pouring concrete and the loading during the pouring of concrete. The chosen loading case in this experiment is the loads due to the pouring of concrete only. The specimens will be tested to failure under this type of load without including the effect of the other types of loads.

During the preparation for the test, it was very important to determine an efficient loading method in order to load the truss symmetrically during the test. The expected failure load of the truss was expected to be between 1.75 and 2 tons. This is calculated through the critical load of the exterior vertical which was expected to fail earlier than the other members due to its large unsupported length. The critical load for the exterior vertical is determined using Euler's equation and is calculated to be 125 kg. Since we have 2 exterior verticals that can withstand a load of 125 kg and another 6 inner verticals that can withstand twice as the exterior vertical, it is found that the load that can be carried by the truss is 125 kg multiplied by 14 which is 1.75 ton. However, when the intermediate hinge point is taken into consideration and is treated as a load bearing point, the load can reach 2 tons. However, whether one could depend on the point of intermediate hinge to transfer the load or not is a debatable issue as will be further discussed in this chapter.

The loading scenario is very important to set in order to determine how the proposed system will behave when the concrete is completely poured and the system is subjected to the whole load of the structural member. There are two options in determining the loading method. The first option is use a wooden beam to load the system. This option was precluded because the behavior of the wooden beam was not easily expected since its failure load could not be accurately calculated due to the uncertainty in the wood properties. Therefore, there are expectations that the wooden beam itself will fail during the test before the specimen and therefore, the load will not be transferred to the truss. The second option was to use steel beam to load the truss. This method was chosen because steel will have the enough capacity to withstand the load that is applied to the truss. However, the chosen steel beam was chosen to be as lightweight as it can be. This is because the weight of the beam will be added to the load read from the load cell. The steel beam was attached to two wooden beams tied together in order to make sure that the wooden beams will be touching the system to transfer the load symmetrically to the truss since the steel beam length was less than the span of the truss.

The details of the experimental work in this thesis are illustrated in details in this chapter. The illustration includes the equipment used in the experiment, setting up the experiment platform, setting up the models and the experiment itself.

4.3. Equipment Used

4.3.1. The Crane

As shown in figure 31, the crane was used to move the steel beam attached to the wooden beams with a weight of 145 kg from place to place. For example, it was used to move the beam from the floor to the top of the truss. Further, it was also used to move the beam from the top of the truss to the ground when the specimens are changed.

Figure 31 : the Crane used in the moving of the Beam

4.3.2. Linear Variable Differential Transformer (LVDT)

It is a device used to record the displacement of a point. It consists of two parts. The first part is shown in figure 32. It is a device that has a magnetic base that allow for the device to be fixed on a metallic base. Further there is a place where the needle that moves when the displacement happens is fixed.

The second part of the LVDT is the needle which is shown in figure 33. As shown in the figure, it has a wire that is connected to the reading device that transforms the electrical signal into numbers on the software of the computer. The needle is the most important part in the LVDT because it is the part that gives the reading of the deflection. It has a spring that moves when there is displacement and transmits the signals to the reading device.

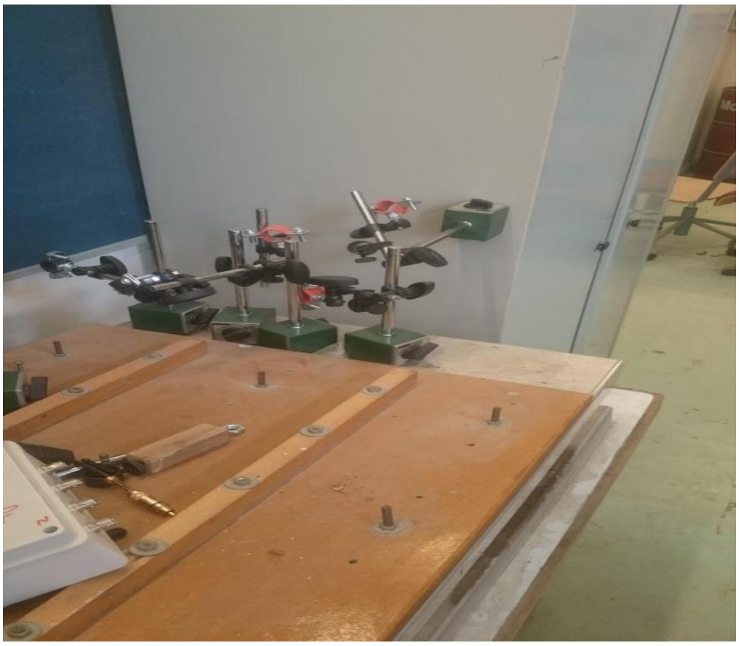

Figure 32 : the first part of the LVDT

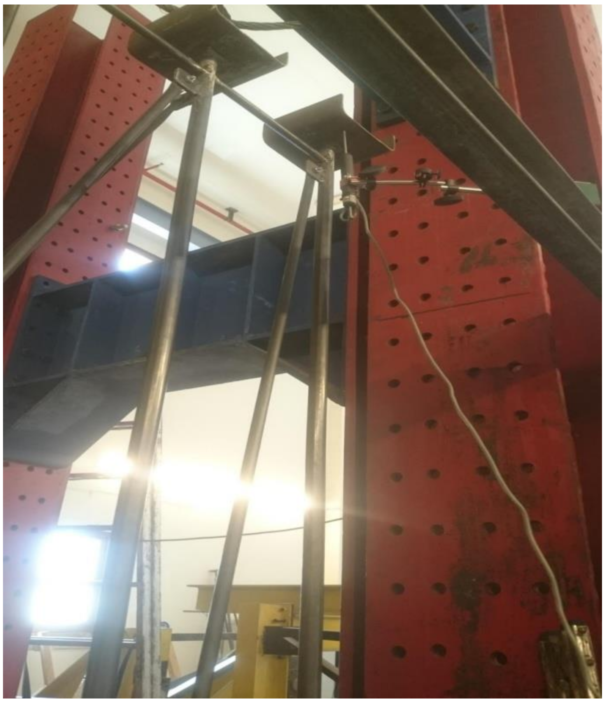

Figure 33 : the needle connected to the place where the displacement is to be measured

4.3.3. Reading Device

The reading device is used to transmit the electric signals read by the needle of the LVDT to the computer which transmits it to numbers. Figure 34 shows the reading device. The LVDT is connected to the back of the reading device through a wire.

Figure 34 : the Reading Device

4.3.4. The Laptop

Figure 35 shows the laptop is connected to the LVDTs readings and to the load cell. It reads the displacement from the LVDTs through special software to translate the electric signal of the displacement to numbers and read the load from the Load cell.

Figure 35 : the Laptop

4.3.5. Hydraulic Pump

The hydraulic pump is used to transmit the load to the load cell that applies the load to the truss. It works manually. The technician has to push the jack shown in figure 36 in order to apply the load. The reason behind using this manual pump is that it increases the load in small increments. Further, since the load expected for the specimens to fail is between 1.75 and 2 tons, it would be more suitable if a more sensitive load applying device such as the hydraulic pump is used because the increments of increasing the load are not large.

The hydraulic pump is attached to the load cell through the shown hose in figure 36. This hose transmits the load applied manually to the load cell. The load cell moves down to apply the load with every pressure through the jack. However, this method has a very clear drawback. The drawback is that the load may be fluctuated for every movement of the jack of the hydraulic pump which might cause fluctuation in the readings.

Figure 36 : the Hydraulic Pump

4.3.6. Load Cell

The load cell is the device that applies the load directly to the specimen. In this test, the load cell was powered manually through the hydraulic pump due to the sensitivity of the range of the loads that the experiment has. Figure 37 shows the load cell. It is fixed in the beam of the platform and is centered in the space between the two columns of the platform to avoid any eccentricity of the loads. Further, the specimens have to be fixed under the load cell directly to avoid any eccentricity of the loads or any tipping or accidents due to problems in the position of the specimen with respect to the load cell.

Figure 37: The Load Cell

4.3.7. The Balance

As shown in figure 38, it is an electronic balance used to measure the weights of the joists, the wooden and steel beams used in loading the specimens.

Figure 38 : the Balance

4.4. Setting up the Experiment

The first step in setting up the experiment is to prepare the platform on which the test will take place.

As shown in figure 39, the platform consists of four columns and four beams connected to these columns. The columns have places for pins in order to give flexibility to the height of the specimen used in the test. The beams have these holes in order to connect the beam to the columns. Due to the height of the specimens in this test, the beam has to be raised in order to give space for the specimen, the joists and wooden and steel beams to be placed correctly in addition to allowing space for the load cell to be lowered when applying the load.

The beam was connected to the pulley to be raised safely after calculating the needed height for the specimens. This was a complicated and time consuming process since all the bolts connecting the beam to the two columns had to be untied and then wait for the beam to be raised to the targeted level and then tie the bolts again. The bolts have to be checked after they are fixed to make sure that they are not loose.

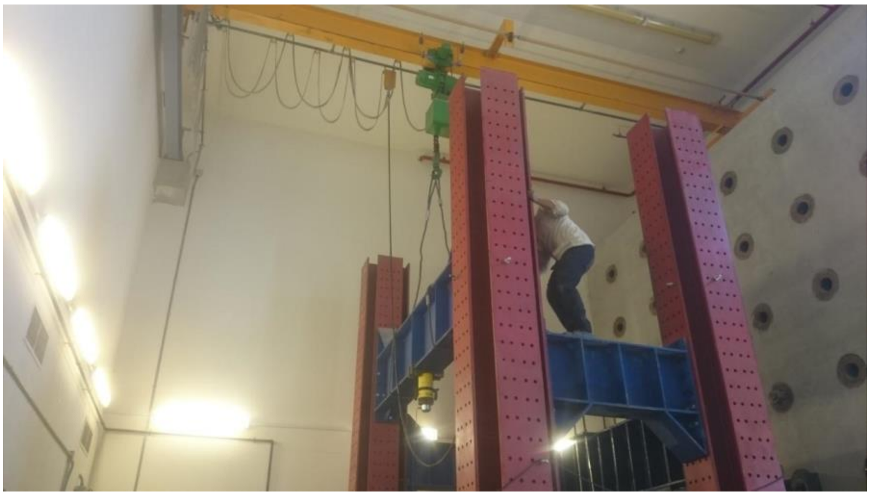

Figure 39: The beam is connected to the pulley to raise its Level

The second step was to prepare the specimens to the experiment.

As previously mentioned, the test includes one unit of the proposed system. This means that there should be two trusses erected and connected together using the bracing system. The specimens are assembled exactly as was followed in the demo. As shown in figure 40, two halves are placed in front of each other, and then the intermediate hinge connection is used to connect both halves together. After that, the tie rod is used to connect the two halves from the lower connection of the exterior vertical with the outermost lower chord. Then, the second truss is assembled in the same way and the bracing system connecting the two trusses is installed as shown in figure 41.

Figure 40: Assembling the trusses

Figure 41: Connecting the Bracing System

After that, a steel beam is connected to the columns of the platform in order to act as a base for the LVDTs used in the test. As shown in figure 42, the beam is installed on a level that is near the level of the U heads since the LVDTs will measure the deflection of the points directly under the U heads.

Figure 42: Installation of the Steel Beam

The next step is to install the wooden joists on top of the U heads to simulate the actual conditions on site. The length of the wooden joists is 2.4 meters in order to cover the spacing between trusses (1.8 meters) and give extra length to the wooden joist to rest steadily on the two opposite U heads as shown in figure 43. But before the installation, the joists are weighed using the balance.

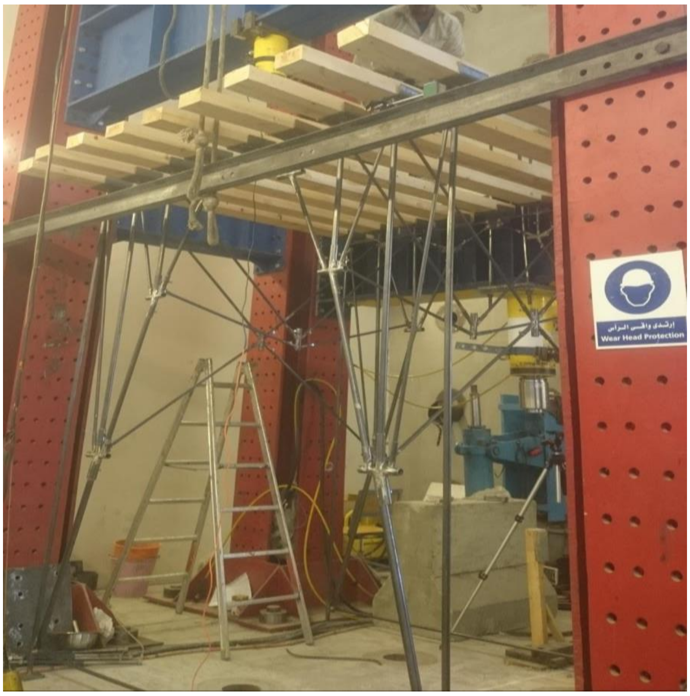

Figure 43: The installation of the joists

The following step is to prepare the beam that will used to apply the load symmetrically on the truss. The beam consists of two wooden beams and on top of them a steel beam. The wooden beams are connected together using a steel wire to make sure that the wooden beams will not slip and that they will act as one unit to avoid any asymmetry in the application of the load during the experiment. Figure 44 shows the method of connecting the two wooden beams together.

Figure 44: Connecting the two Wooden Beams

The steel beam is then moved on top of these two wooden beams using the crane and then fixed to them. The whole unit is weighed and then transported using the crane to be placed it on top of the truss as shown in figure 45.

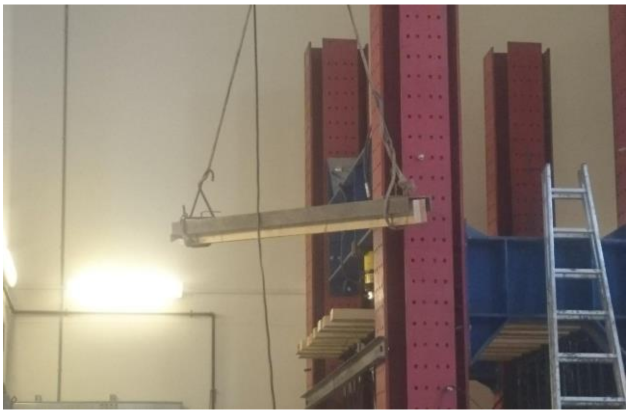

Figure 45: Moving the Beam using the Crane to the Platform

The last two steps in setting up the experiment are to connect the LVDTs to the points where the deflection is to be measured and to connect the hose of the hydraulic pump to the load cell. The chosen points where 5 points: the two external verticals, the inner verticals number (5-6) and the intermediate hinge connection as shown in figure 46. The LVDTs were put directly under the U heads in order to measure the deformation in these points. The reason behind choosing these points is as follows: measuring the deformation at the exterior vertical members is very crucial because they are the most critical members in the truss. They are expected to fail due to buckling before any of the other members because they have a length of 3 meters. For the LVDTs connected to the interior vertical, the deformation is measured in these embers is important to check the soundness of the bracing system and its effect in resisting the buckling in the interior vertical members. For the intermediate hinge, the deformation should be measured in this point to study the effect of the loading on the intermediate hinge and to understand its behavior after reaching the max deflection and its consequences on the system. Figure 46 shows the LVDTs positions in the trusses during the test.

Then the hose of the pump is connected firmly to the load cell.

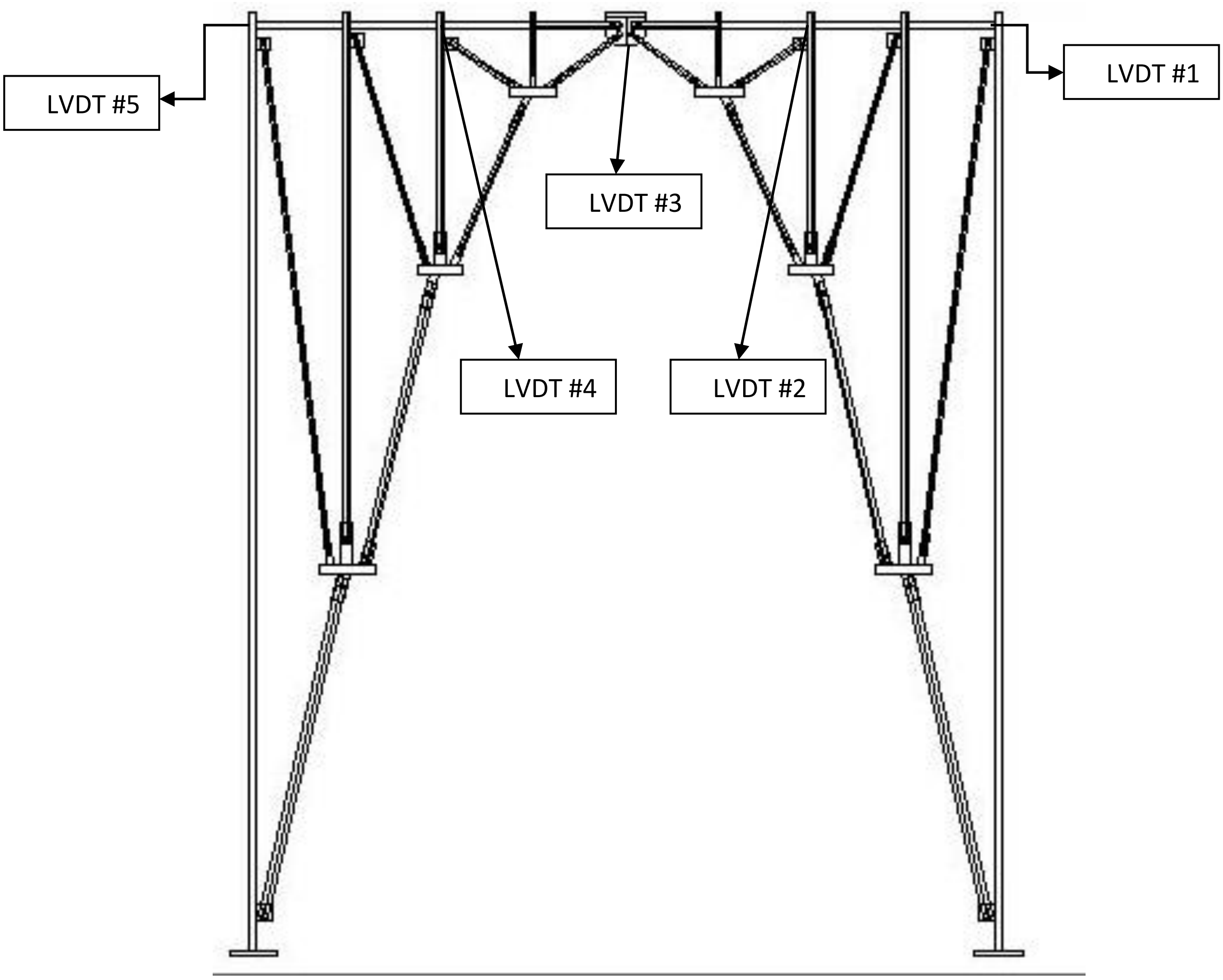

Figure 46: The LVDTs connected to the points where deflection is to be measured

4.5. The Experimental Procedures

1- After finishing the setup of the experiment, the deflection readings from the LVDTs is checked to make sure that they are calibrated.
2- The technician starts to apply the load using the jack of the hydraulic pump.
3- The LVDTs and the load cell reading are recorded by the software in the Laptop.
4- The loading of the truss is continued until failure.
5- Pictures for the failed members are taken
6- After the failure of the truss, the load is released from the hydraulic pump .

4.6. Results

As mentioned earlier, there are three specimens to be tested. The three specimens are tested to failure and the load vs. the deflection is recorded via the LVDTs and the software in the laptop.

After finishing the three tests, three excel sheets with the load readings vs. the deflection occurred for every load reading are produced. The excel sheets also have the maximum, minimum and average values for both the loads and the deflection in the five LVDTs used in each test for each truss. The following is detailed description of the results in each specimen.

4.6.1. Specimen #1

In the first specimen, the maximum load recorded is 1325.78 kg. This load is only the vertical load that is applied using the load cell and another load of a total of around 200 kg is added. The added load is the load of the nine wooden joists which weight 13.46 kg each and 144 kg of the wooden beams and the steel beam used to apply the load uniformly. This makes the total load applied to the first specimen equals to 1525.78 kg.

Further, the maximum deflection recorded is recorded for LVDT #1 which is attached to the right exterior vertical. The max deflection in LVDT 1 is 21.92 mm. The deflection of LVDT #1 is followed by the deflection of LVDT #2 which recorded a value 14.84, followed by LVDT #3 attached to the intermediate hinge which has a value of 5.43mm, followed by LVDT #4 which has a value of 2.94 mm and then

LVDT No.5 which represents the exterior vertical on the left which has a value of 1.84 mm.

As shown in figure 47, the exterior vertical at the right experienced out of plane buckling which caused the value of the deflection at the LVDT attached to this point to reach 21.92 mm and therefore, reaches failure. However, the truss which is connected to this specimen did not witness any plastic deformation. It was visually observed that this truss experienced small deflection and then returned back to its normal case after releasing the load. Figure 48 shows the aforementioned truss after releasing the load at its normal state.

Figure 47: the Deflection at specimen #1

Figure 48: the Truss members did not have any Plastic Deformation

Table 6 shows the summary of the recorded value of the load and deflection for specimen #1.

Table 6: Deflection Summary for Specimen #1

Name	Vertical Load Cell kg	LVDT #1	LVDT #2	LVDT #3	LVDT #4	LVDT #5
Unit	kgf	mm	mm	mm	mm	mm
Maximum	1325.78	21.9235	14.8425	5.43094	2.9376	1.84192
Minimum	0	-0.311708	-0.291847	-0.374547	-10.5963	-2.60766
Average	735.859	4.78588	4.1989	1.08541	0.797039	0.604848

4.6.1.1. Load Deflection Curve for LVDT #1

As shown in figure 49, the load deflection curve shows typical behavior of steel. The behavior started linear; however, the linearity was lost due to the effect of the buckling on the member's behavior. The last part of the graph shows that the deflection in the point where the LVDT is attached witnessed permanent deformation even after releasing the loads.

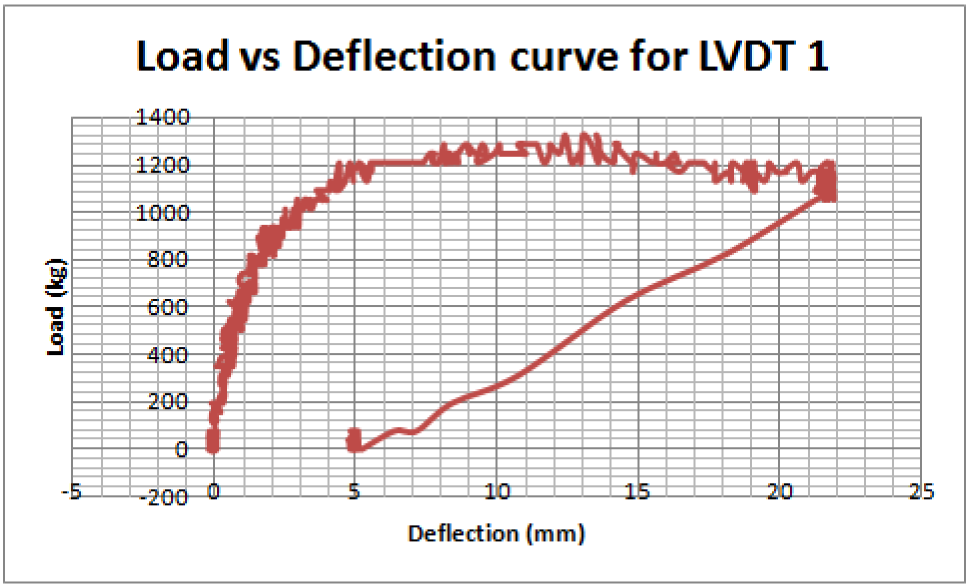

Figure 49: load vs. deflection curve for LVDT #1

4.6.1.2. Load Deflection curve for LVDT #2

As shown in figure 50, the readings for the second LVDT showed the same behavior as LVDT #1. However, the max deflection was different. The yielding happened at values that are near the values of LVDT #1.

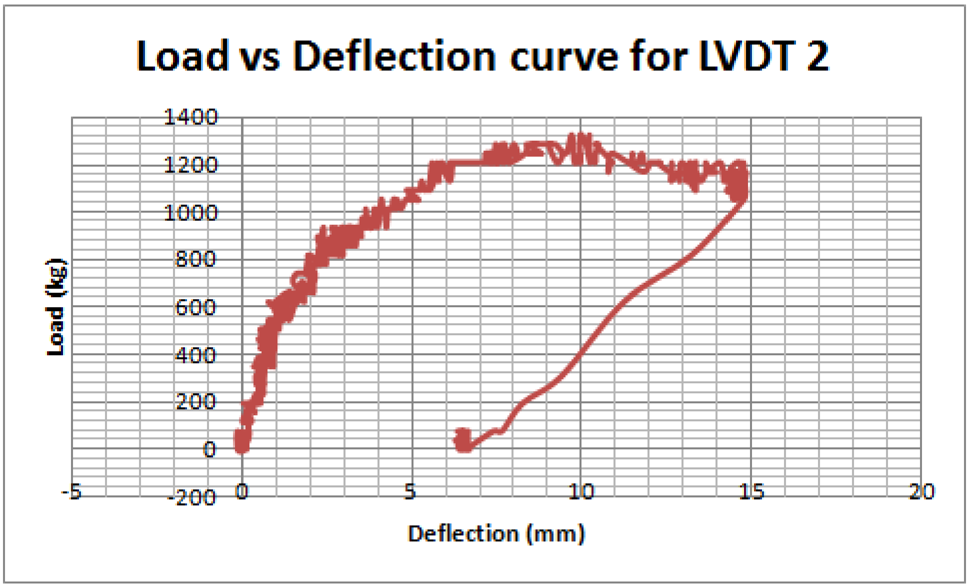

Figure 50: Load vs. Deflection Curve for LVDT #2

4.6.1.3. Load Deflection curve for LVDT #3

As shown in figure 51, the readings of this LVDT witnessed a lot of fluctuation. This is caused because of the way of applying the load. The load is applied using hydraulic pump which needs the technician to press the jack and forth and since this LVDT is attached to the intermediate hinge connecting the two halves and the first point to take the load because it is directly under the load cell, these fluctuations appeared.

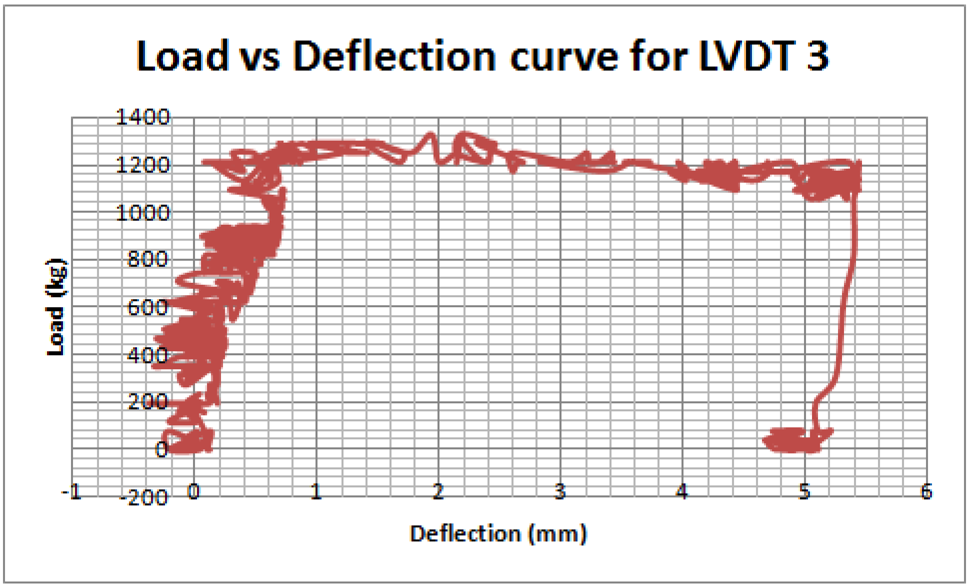

Figure 51: Load vs. Deflection Curve for LVDT #3

4.6.1.4. Load Deflection curve for LVDT #4

As shown in figure 52, the readings in LVDT #4 show negative values. This shows that the other half of the truss was carrying the load while the half where this LVDT is located was trying to pull out. Further, the fluctuation is caused by the pulling out of this half of the truss since it moves back and forth with every pressure applied to the jack of the hydraulic pump.

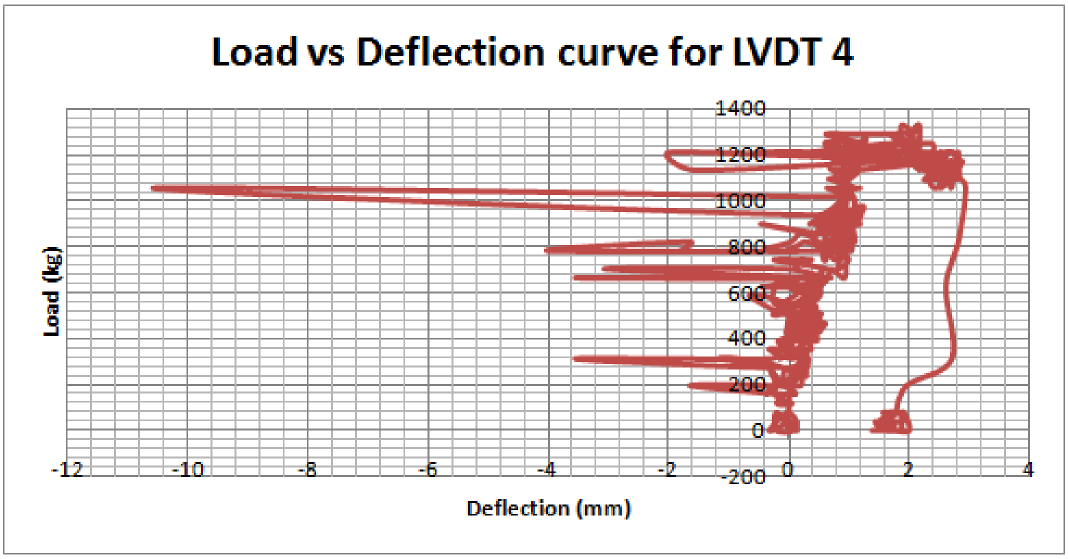

Figure 52: Load vs. Deflection Curve for LVDT #4

4.6.1.5. Load Deflection curve for LVDT #5

As shown in figure 53, this LVDT shows the same behavior as LVDT #4 because it was in the same half of the truss that was trying to pull out.

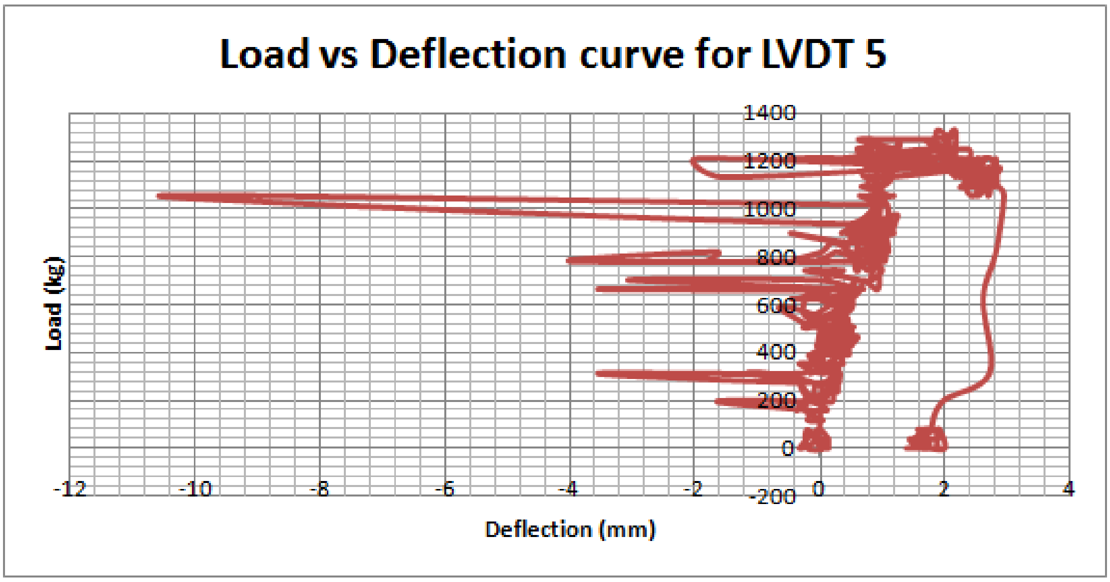

Figure 53: Load vs. Deflection Curve for LVDT #5

4.6.2. Specimen #2

In the second specimen, the maximum load recorded is 1403.77 kg. By adding the weight of the wooden joists and the wooden beams and the steel beam, the total load applied to the first specimen becomes to 1603.77 kg.

Unlike the first specimen, the maximum deflection recorded is recorded for LVDT #5 which is attached to the left exterior vertical. The max deflection in LVDT #5 is 14.81

mm. The deflection of LVDT #5 is followed by the deflection of LVDT #4 which recorded a value of 13.09 mm, followed by LVDT #3 attached to the intermediate hinge which has a value of 8.36mm, followed by LVDT #1 which has a value of 6.48 mm and then LVDT #1 which represents the exterior vertical on the right which has a value of 2.53 mm.

As shown in figure 54, the exterior vertical at the left experienced out of plane buckling which caused the value of the deflection at the LVDT attached to this point to reach 14.81 mm and therefore, reaches failure. However, the truss which is connected to this specimen did not witness any plastic deformation. It was visually observed that this truss experienced small deflection and then returned back to its normal case after releasing the load as the case was in specimen #1.

Figure 54: the Left Exterior Vertical experiences out of Plane Buckling

Table 7 shows the summary of the recorded value of the load and deflection for specimen #2.

Table 7: Deflection Summary for Specimen #2

Name	Vertical Load Cell kg	LVDT #1	LVDT #2	LVDT #3	LVDT #4	LVDT #5
Unit	kgf	mm	mm	mm	mm	mm
Maximum	1403.77	2.53523	6.48317	8.36489	13.0933	14.8182
Minimum	0	-0.457172	-0.291847	-0.436972	-2.68581	-2.60766
Average	996.484	1.21821	3.86859	3.98175	5.08693	5.45354

4.6.2.1. Load Deflection curve for LVDT #1

As shown in figure 55, the load deflection curve shows the presence of negative deflection values which means that this point was trying to pull out because the other half of the truss was carrying the load.

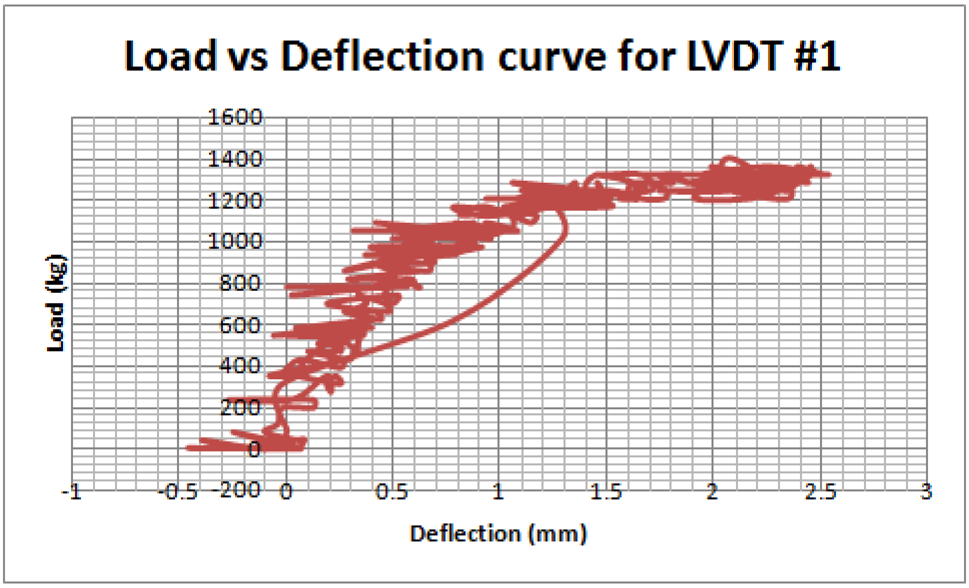

Figure 55: Load vs. Deflection Curve for LVDT #1

4.6.2.2. Load Deflection curve for LVDT #2

As shown in figure 56, the readings of LVDT #2 show the same behavior of LVDT #1. However, it is not as clear as LVDT #1. The behavior here shows very small deflection since this point does not carry much load because the other half of the truss carries the entire load.

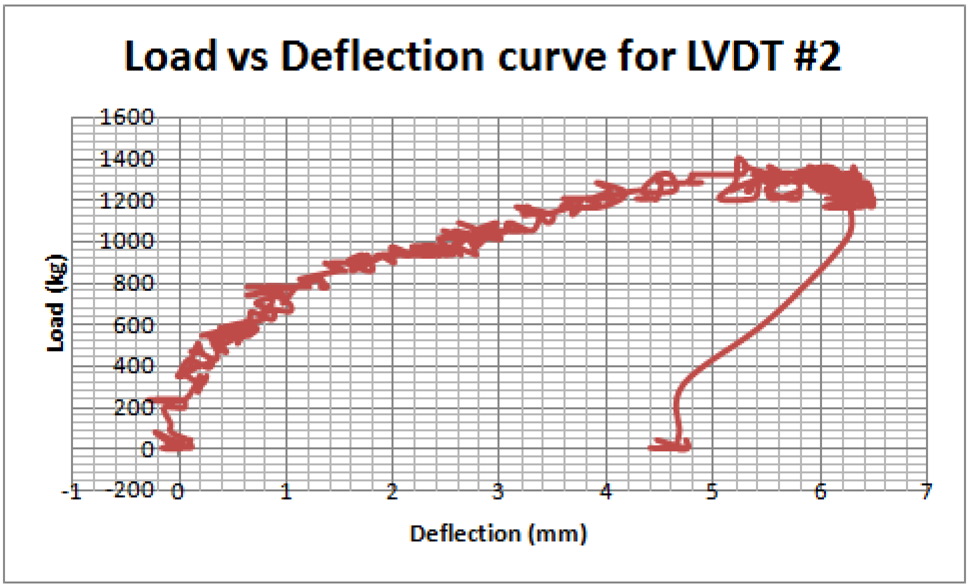

Figure 56: Load vs. Deflection Curve for LVDT #2

4.6.2.3. Load Deflection curve for LVDT #3:

As shown in figure 57, LVDT #3 attached to the intermediate hinge connecting the two halves of the truss shows normal behavior with less fluctuation unlike the corresponding LVDT in specimen #1. This means that the intermediate hinge was not affected by the way of applying the load to the same extent as the corresponding specimen #1. Further, the intermediate hinge spent more time supporting the applied load and took longer time to fail than specimen #1. Such behavior might indicate problems with the assembly of this specimen. The intermediate hinge in this specimen did not have full contact with the load cell applying the load which minimized the fluctuation in the load.

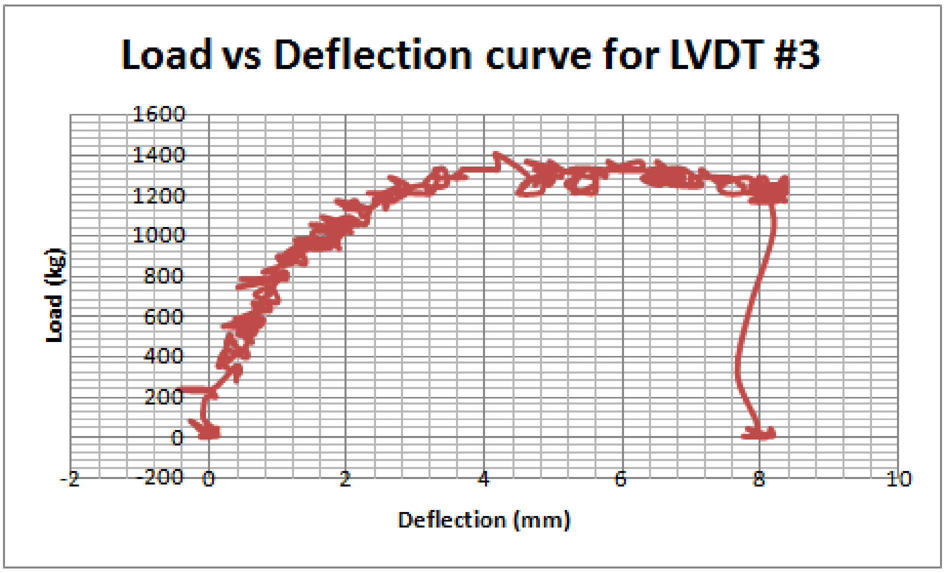

Figure 57: Load vs. Deflection Curve for LVDT #3

4.6.2.4. Load Deflection curve for LVDT #4:

As shown in figure 58, LVDT #4 was affected by the way of applying the load. This shows problems with the assembly of this specimen as this indicate that this point was in direct contact with the load applied. Further, this explains the fact that this half of the truss carried the load and therefore has higher values of deflection than the points in the other half.

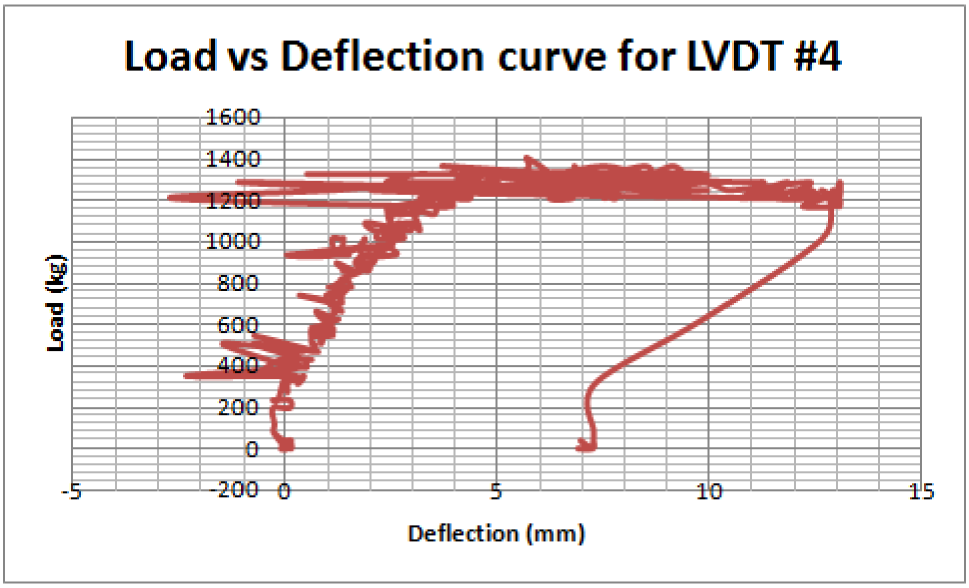

Figure 58: Load vs. Deflection Curve for LVDT #4

4.6.2.5. Load Deflection curve for LVDT #5:

As shown in figure 59, the load deflection curve for LVDT #5 shows the highest deflection with the highest load fluctuation. This means that due to the properties of this exterior vertical (length and small diameter) it witnessed the most deflection and was carrying the maximum load and that's why it failed.

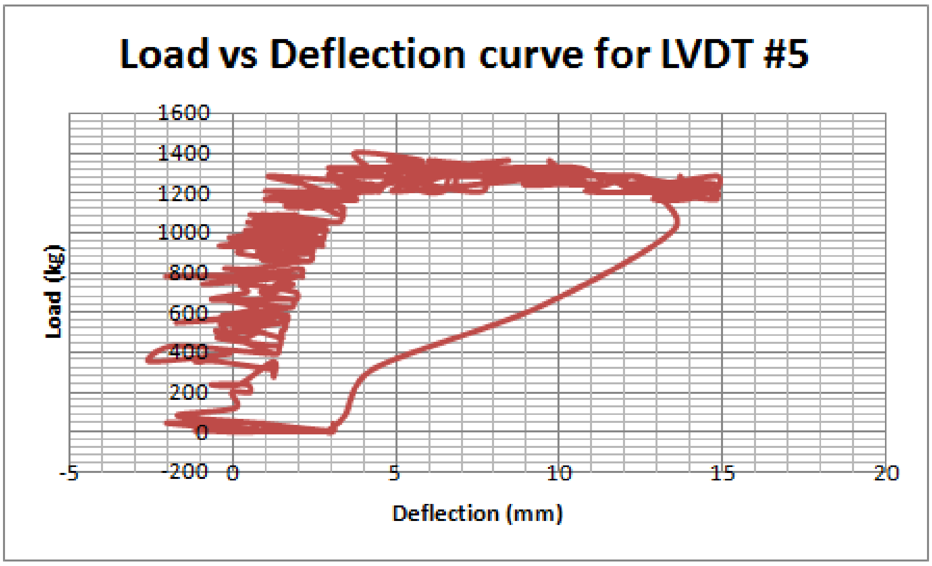

Figure 59: Load vs. Deflection Curve for LVDT #5

4.6.3. Specimen #3

In the third specimen, the maximum load recorded is 1637.33 kg. By adding the weight of the wooden joists and the wooden beams and the steel beam, the total load applied to the first specimen becomes to 1837.33 kg.

Further, the maximum deflection recorded is recorded for LVDT #1 which is attached to the right exterior vertical. The max deflection in LVDT 1 is 17.81 mm. The deflection of LVDT #1 is followed by the deflection of LVDT #2 which recorded a value 9.25 mm, followed by LVDT #3 attached to the intermediate hinge which has a value of 5.99mm, followed by LVDT #4 which has a value of 2.39 mm and then LVDT #5 which represents the exterior vertical on the left which has a value of 1.65mm.

As shown in figure 60, the exterior vertical at the right experienced out of plane buckling which caused the value of the deflection at the LVDT attached to this point to reach 17.81mm and therefore, reaches failure. However, the truss which is connected to this specimen did not witness any plastic deformation. It was visually observed that this truss experienced small deflection and then returned back to its normal case after releasing the load as the case was in specimen #1 and specimen #2.

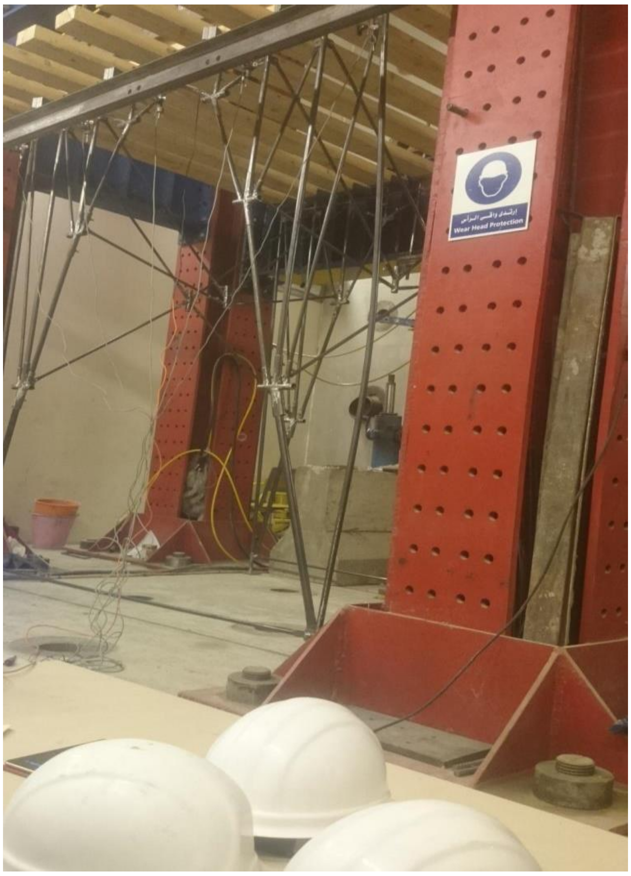

Figure 60: the Deformation in the Right Exterior Vertical

Table 8 shows the summary of the recorded value of the load and deflection for specimen #3.

Table 8: Deflection Summary for Specimen #3

Name	Measurement time	Vertical Load Cell kg	LVDT #1	LVDT #2	LVDT #3	LVDT #4	LVDT #5
Unit	msec	kgf	mm	mm	mm	mm	mm
Maximum	74500	1637.73	17.8089	9.25571	5.99276	2.39205	1.65566
Minimum	0	0	-0.415611	-0.396078	-0.45778	-3.88183	-3.29062
Average		936.105	7.91877	4.24026	2.96031	0.842252	0.392253

4.6.3.1. *Load Deflection curve for LVDT #1*

As shown in figure 61, the load vs. deflection curve of LVDT #1 shows that the right exterior vertical experienced the maximum deflection since it was carrying the entire load after its re-distribution.

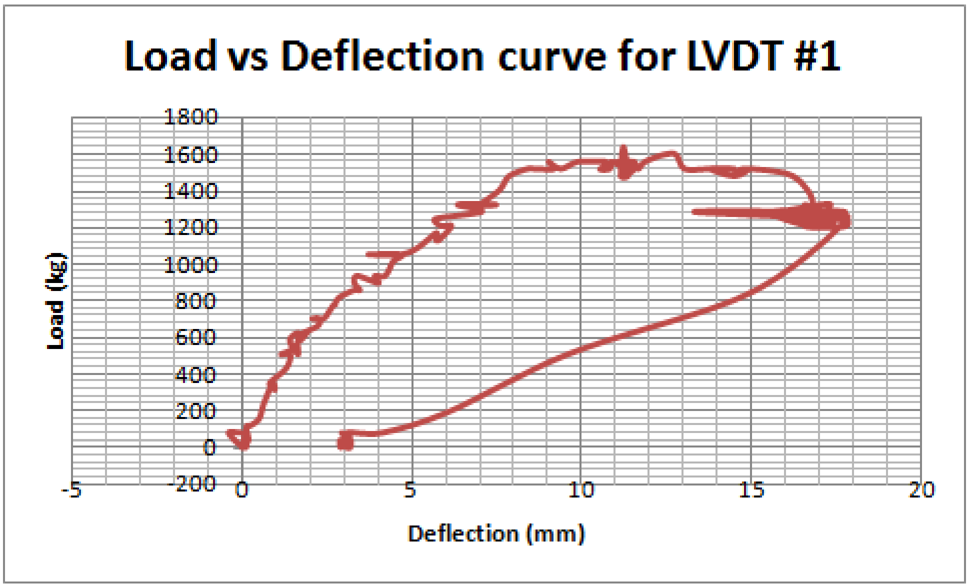

Figure 61: Load vs. Deflection Curve for LVDT #1

4.6.3.2. *Load Deflection curve for LVDT #2*

As shown in figure 62, the load deflection curve shows the same behavior of LVDT #1 because it is in the half of the truss that carries the load.

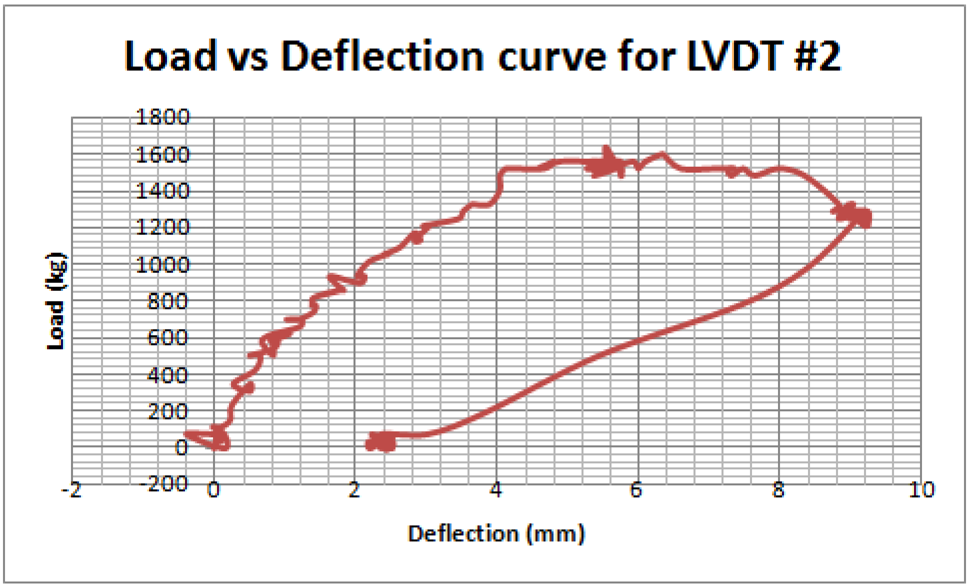

Figure 62: Load vs. Deflection Curve for LVDT #2

4.6.3.3. Load Deflection curve for LVDT #3

As shown in figure 63, LVDT #3 attached to the intermediate hinge shows the same behavior as specimen #1 except for the high load fluctuation.

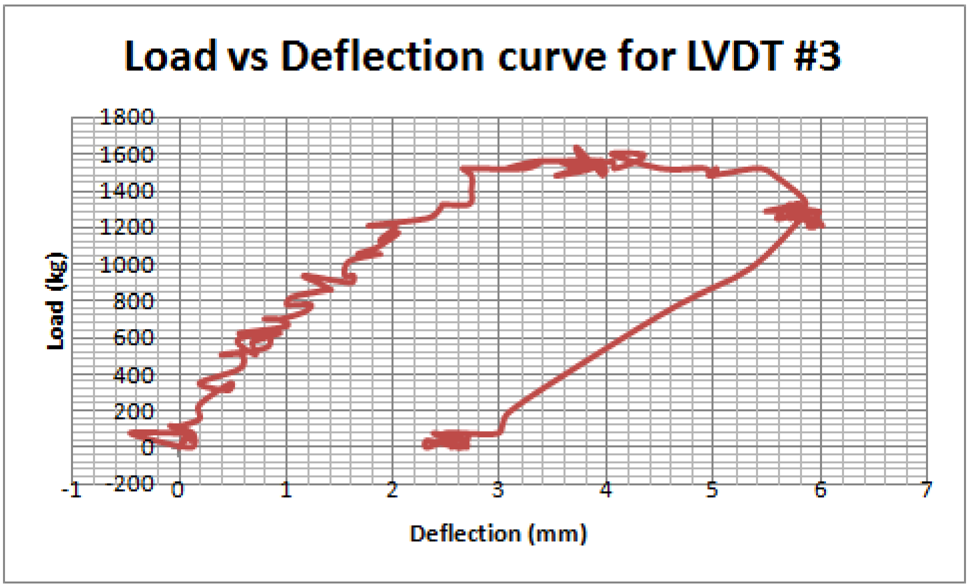

Figure 63: Load vs. Deflection Curve for LVDT #3

4.6.3.4. Load Deflection curve for LVDT #4

As shown in figure 64, the load deflection curve shows negative deflection values which means that this point was trying to pull out because the other half of the truss was carrying the load.

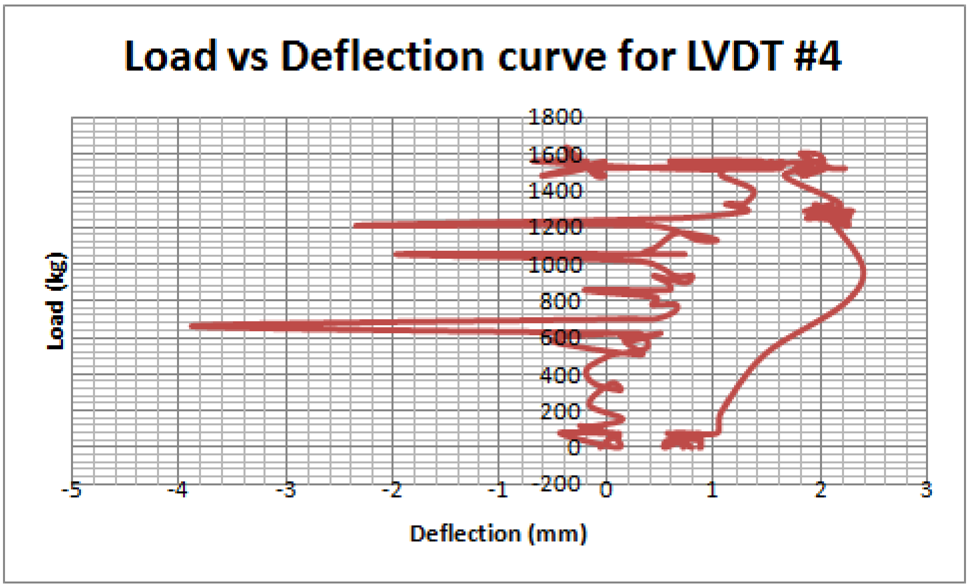

Figure 64: Load vs. Deflection Curve for LVDT #4

4.6.3.5. *Load Deflection curve for LVDT #5*

As shown in figure 65, the load deflection curve of LVDT #5 shows the same behavior as LVDT #4 because both points are in the other half of the truss that are not carrying the load.

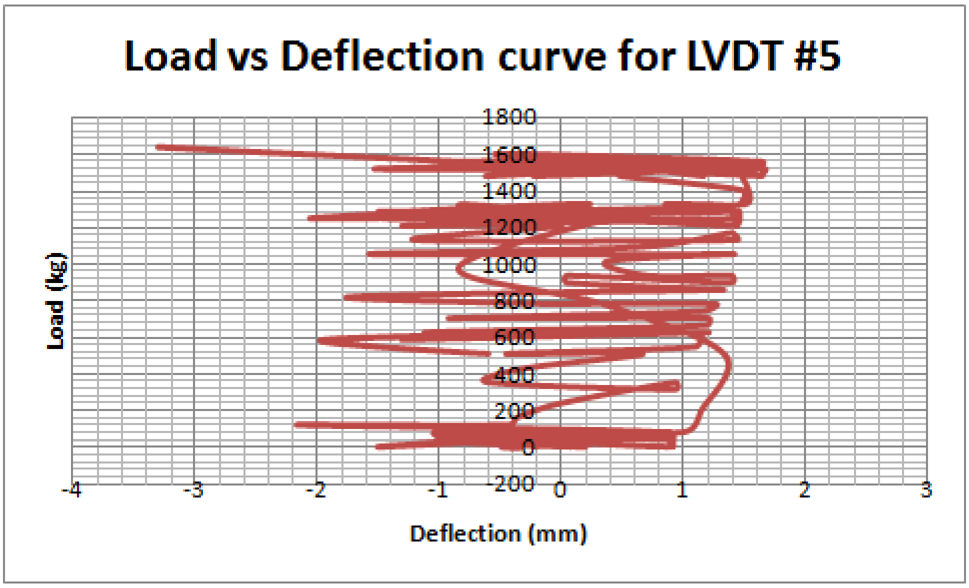

Figure 65: Load vs. Deflection Curve for LVDT #5

4.7. Analysis and Discussion

From the preliminary analysis of the data of the tests, it was found that the failure happens in only one half of the truss. This is because the presence of the intermediate hinge at the middle of the arched truss prevents the propagation of the failure to the other half. Further, it gives an indication that the redistribution of loads happens in only one half of the truss. Table 9 summarizes the results of the experimental work with the reasons of failure for each specimen.

Table 9 : Experimental Work Summary

Specimen #	Design Load (kg)	Failure Load (kg)	Reasons
1	1750	1525.78	Early buckling and imperfections during transportation
2	1750	1603.77	Early buckling and imperfections during transportation
3	1750	1837.33	Buckling

The following detailed analysis of the results and the load deflection curves of all the LVDTs illustrate the behavior of the truss during the loading before the failure and after the failure.

4.7.1. Specimen #1

4.7.1.1. Intermediate hinge

As shown in figure 66, the maximum value of deflection in LVDT #3 which represents the intermediate hinge is reached before LVDT #1 which represents the exterior vertical member where the failure happened; reaches its maximum deflection value. Further, it shows that the other LVDTs show minimum deflection which proves that the beam used to apply the load lost its contact with the intermediate hinge due to its deflection and redistributed the load to one of the halves of the truss.

It is worth to mention that the maximum value of deflection for the intermediate hinge is reached multiple times; however, the chosen point of loading is where the maximum value is reached for the first time. Further, the figure shows the progressive failure that happened in the truss. It shows that the intermediate hinge failed at an earlier value than the exterior vertical because of the early buckling that happened in this member.

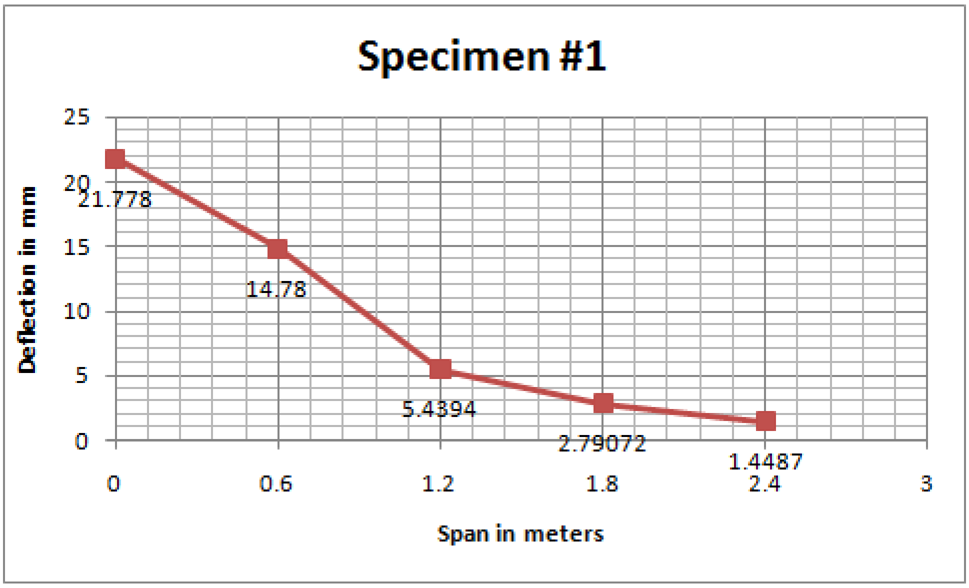

Figure 66: Deflection of all points at the Max Point of Deflection in the Intermediate Hinge for Specimen #1

4.7.1.2. Point of failure

As shown in figure 67, at the point of failure of the exterior vertical member, which is the most critical member, the other point on the half of the failed member showed higher values than the corresponding points in the other half of the truss. Further, the maximum deflection of the intermediate hinge is maintained. This proves again that the redistribution process happened.

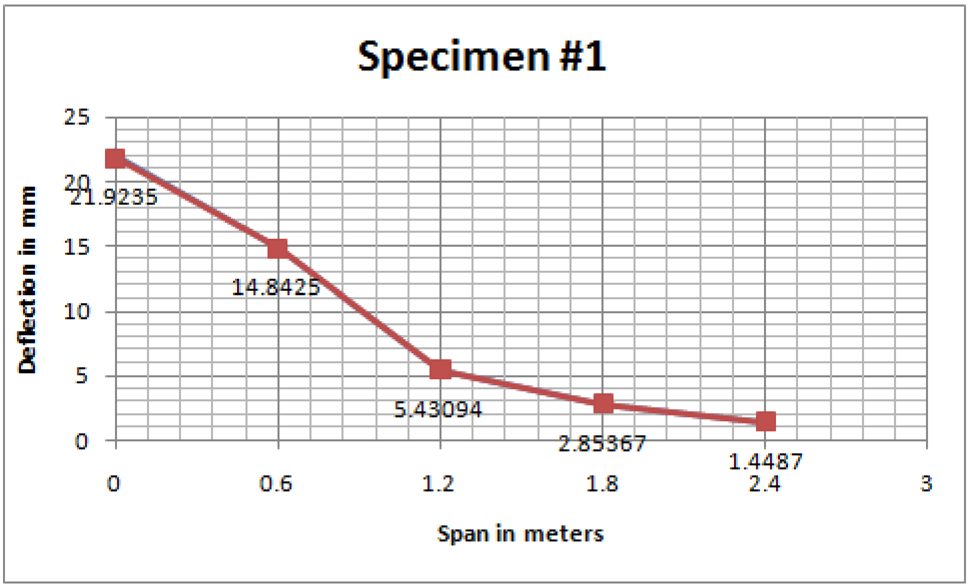

Figure 67: the Deflection value at the point of Failure for Specimen #1

The results of the test show that throughout the whole test the LVDT at the exterior vertical member has values more than the LVDT at the intermediate hinge. This proves that the exterior member experienced early buckling due to its long length and the lack of bracing in the out of plane direction. Further, this figure shows that when the intermediate hinge loses contact with the beam used to apply the load uniformly, the load is redistributed to the two halves of the truss. The half that carries more loads after the redistribution experiences higher deflection in its members and fails first.

Moreover, due to the loss of contact between the beam and the intermediate hinge, the expected symmetry in the values of deflection is also lost and this further accelerated the buckling in the failed exterior member which failed due to reaching the critical buckling load.

4.7.2. Specimen #2

4.7.2.1. Intermediate Hinge

As shown in figure 68, the maximum value of deflection in LVDT #3 which represents the intermediate hinge is reached before LVDT #5 which represents the exterior vertical member where the failure happened; reaches its maximum deflection value. As it was the case in specimen #1, it shows that the other LVDTs show minimum deflection which proves that the beam used to apply the load lost its contact with the intermediate hinge due to its deflection and redistributed the load to one of the halves of the truss.

Further, the figure shows that specimen #2 has the same behavior of specimen #1 in terms of the progressive failure that happened in the truss. It shows that the intermediate hinge failed at an earlier value than the exterior vertical because of the early buckling that happened in this member.

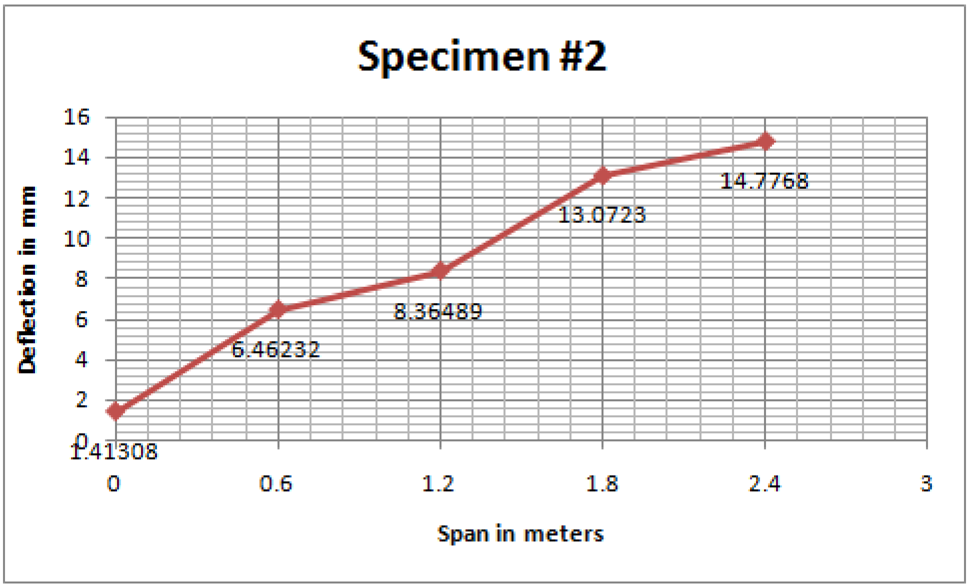

Figure 68: Deflection of all points at the Max Point of Deflection in the Intermediate Hinge for Specimen #2

4.7.2.2. Point of failure:

As shown in figure 69, at the point of failure of the exterior vertical member, which is the most critical member, the other point on the half of the failed member showed higher values than the corresponding points in the other half of the truss. Further, the maximum deflection of the intermediate hinge is maintained. This proves again that the redistribution process happened. This is the same behavior as specimen #1.

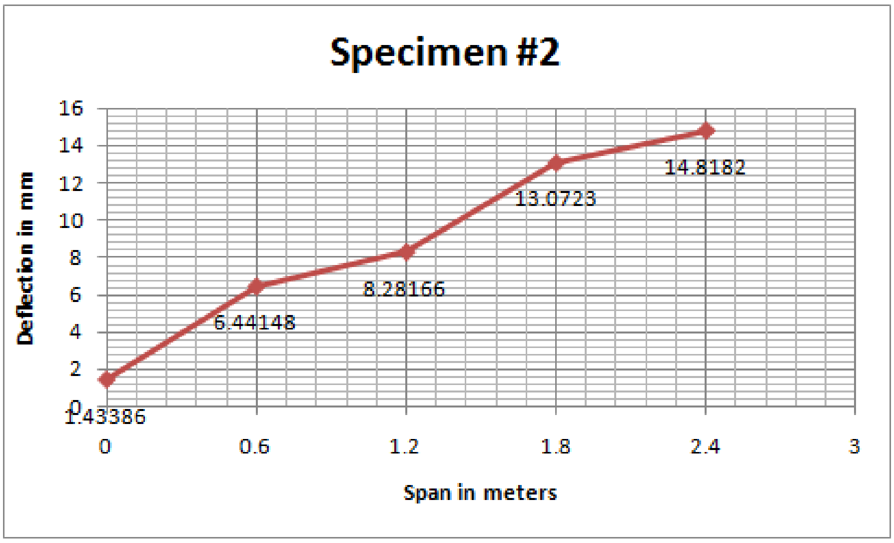

Figure 69: the Deflection Value at the Point of Failure for Specimen #2

The results of the test shows that throughout the whole test the LVDT at the exterior vertical member has values more than the LVDT at the intermediate hinge. This proves that the exterior member experienced early buckling due to its long length and the lack of bracing in the out of plane direction. Further, this figure shows that when the intermediate hinge loses contact with the beam used to apply the load uniformly, the load is redistributed to the two halves of the truss. The half that carries more loads after the redistribution experiences higher deflection in its members and fails first.

Moreover, due to the loss of contact between the beam and the intermediate hinge, the expected symmetry in the values of deflection is also lost and this initiated the early buckling in the failed exterior member which failed due to reaching the critical buckling load.

4.7.3. Specimen #3

4.7.3.1. Intermediate Hinge:

As shown in figure 70, the maximum value of deflection in LVDT #3 which represents the intermediate hinge is reached before LVDT #5 which represents the exterior vertical member where the failure happened; reaches its maximum deflection value. As it was the case in specimen #1 and specimen #2, it shows that the other LVDTs show minimum deflection which proves that the beam used to apply the load lost its contact with the intermediate hinge due to its deflection and redistributed the load to one of the halves of the truss.

Further, the figure shows that specimen #3 has the same behavior of specimen #1 and specimen #2 in terms of the progressive failure that happened in the truss. It shows that the intermediate hinge failed at an earlier value than the exterior vertical because of the early buckling that happened in this member.

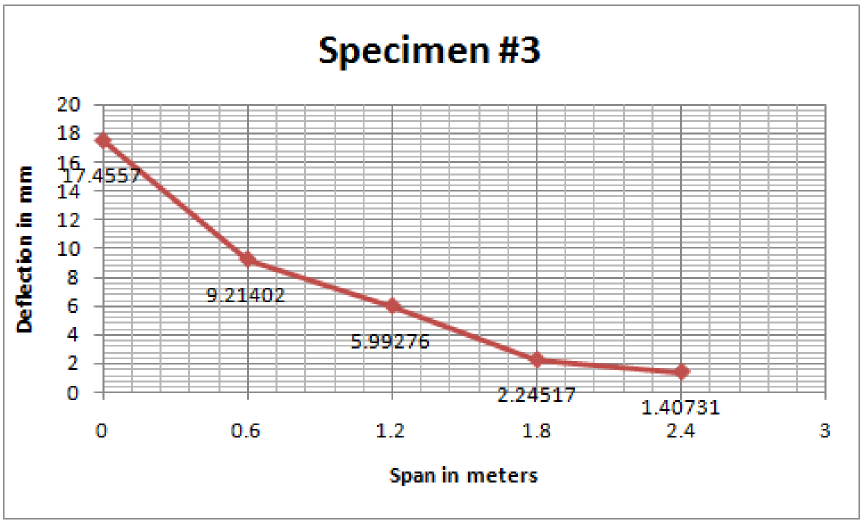

Figure 70: Deflection of all points at the Max Point of Deflection in the Intermediate Hinge for Specimen #3

4.7.3.2. Point of failure:

As shown in figure 71, at the point of failure of the exterior vertical member, which is the most critical member, the other point on the half of the failed member showed higher values than the corresponding points in the other half of the truss. Further, the maximum deflection of the intermediate hinge is maintained. This proves again that the redistribution process happened. This is the same behavior as specimen #1 and specimen #2.

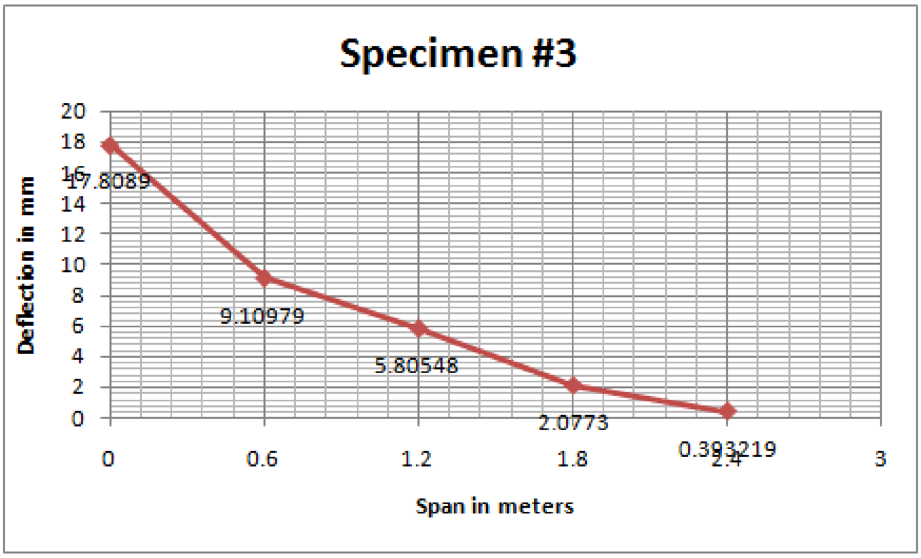

Figure 71: the Deflection Value at the Point of failure for Specimen #3

The results of the test shows that throughout the whole test the LVDT at the exterior vertical member has values more than the LVDT at the intermediate hinge. This proves that the exterior member experienced early buckling due to its long length and the lack of bracing in the out of plane direction. Further, this figure shows that when the intermediate hinge loses contact with the beam used to apply the load uniformly, the load is redistributed to the two halves of the truss. The half that carries more loads after the redistribution experiences higher deflection in its members and fails first.

Moreover, due to the loss of contact between the beam and the intermediate hinge, the expected symmetry in the values of deflection is also lost and this initiated the early buckling in the failed exterior member which failed due to reaching the critical buckling load.

The previous analysis shows that the behavior of the three trusses is consistent. Generally, the intermediate hinge reaches its maximum deflection and then a redistribution process of load happens to one of the halves of the truss. This redistribution process causes one of the halves to be carrying the loads while the other half does not experience the same behavior. The redistribution of the loads is accompanied by loss of symmetry in the values of the deflection. This is caused due to the loss of contact between the intermediate hinge and the beam used to apply the load. It causes the load to be carried on one of the two halves and this causes difference in the values of the deflection from one half to the other, although both should be the same

Further, the analysis shows that progressive failure happens in the truss from the beginning of the process of load application. This is proven through the observation of the deflection values in the LVDTs which shows that the exterior members starts to fail from the first moment of load application. Finally, the half that does not experience the load re-distribution shows that these members are trying to pull out as a reaction to the loading of the other half of the truss.

5. CHAPTER FIVE: CONCLUSION

From the previous chapters, it is concluded that the research pertinent to this thesis passed through a number of steps. The first step was to develop the conceptual design that will be the basis of the research. The developed concept depended on the funicular arch concept that yielded the final shape of the truss used in the system. The second step was to develop the shop drawings of the model and start the manufacturing of the full scale modeled used in the experimental work. The manufacturing process started and depended on all the ideas and techniques available in the market in order to ensure the constructability of the system. After finishing the manufacturing and before starting the experimental work, a demo was conducted to determine the construction time needed for the erection of this system. After that, the experimental work is conducted and the results showed the imperfections of the design and showed the effect of the distribution of load on the values of deflection for the different points of the system. At the end, the soundness of the system was proved in terms of economy, constructability, storage and environmental sustainability.

Based on the previous tests and analysis, a number of points have been reached and the details are illustrated in the following points.

5.1. Efficiency of the system

The system proved its efficiency in a number of fields such as the constructability, erection, assembly, weight of the system and construction space.

- For the constructability, it was proved that the constructability of the system is not complicated as it may seem to be. All the components of the system including the horizontal, vertical, diagonal member, the bracing system and the connection are easy to construct. This is because the system has standardized components that can be cut in huge amounts before the assembly.
- Further, the system is easy to assemble. The idea of assembling this system depends on assembling it in the workshop like a simple puzzle. The components of each half-truss can be assembled in a very short time as long as the labor working on the assembly process knows the place and position of each component. However, the only part of the assembly process that might take long time is the welding process. The welding between the different

members is very important since it is the main connecting element between the members. The welding process takes part in connecting the horizontal members with the verticals, the small plates that connects the bracing and the diagonals to the system, the weld between the U heads and the plates on top of the verticals and the most important part which is the welding of the tubes in the connections where the member is fitted into.

- Furthermore, the erection of the system is its most important advantage over the existing commercially available systems. The erection of the system is very fast and easy compared to the other systems. It only took three workers less than 7 minutes to erect the system and 2.5 more minutes to place the beam joists on top of the U heads. This is a breakthrough since it decreases the time of erecting the system because of its simplicity and the small number of components that is used to erect the system.
- Moreover, the lightweight of the system is very advantageous from the following perspectives:
    - The lighter weight is reflected in lower material costs of the steel used in the fabrication.
    - As most workmanship in the steel manufacturing industry is paid per unit weight of the steel structure, the labor cost will also be reduced due to the reduction in the total weight of the fabricated false-work.
    - The lightweight allows the workers to hold one half of the truss and move it from one place to another without waiting for cranes to lift it from one place to another.
    - The system can be lifted faster and easier within the site than the other system since cranes can lift the needed number of units in a number of times that are less than the other systems.
    - The lightweight makes it easier to transport the system from its manufacturing place to the site because more units can be transported by the same cars used to transport the older systems. Further, this means that the cost of transportation is also decreased. Using different transportation cars that have less capacity or the same capacity as used

in the commercially available systems to transport more units from the FAST system means less cost and less impact on the environment.

- In addition to that, the FAST system proved that it saves more space for the materials to be stored and for the movement to flow underneath it. This means that, in contrary to the commercially available systems that have multiple units to cover the same span, the system saves money for allowing materials to be stored and decreasing the amount of waste materials that results from unsafe storing conditions.
- Further, the system creates safer paths for the workers who will have enough space to pass under the system without having to move between the steel shores as they used to. This helps in decreasing the amount of accidents on site.
- In addition, the system itself can be stored in very limited space. The commercially available systems had very wide dimensions that needs more space to be stored. This created problems on site because it affects the area allowed for material storage and the area allowed for safe paths. The FAST system allows for the storage of a considerable number of its unit in space that is less than space needed for the commercially available systems. The components of the systems increase the flexibility of storing its units because the components can be put after assembly or before assembly and the difference in the occupied space will not differ considerably.
- Finally, the system proved its environmental soundness. The use of the FAST system causes reduction in the amount of steel used by significant amount. This means that less electricity will be used in the factories to produce the required amount of steel. Consequently, fewer amounts of CO_2 emissions will be emitted to air. Furthermore, the waste hazardous material that is needed during the manufacturing of steel products such as zinc and chromium. Moreover, the amount of CO_2 that is emitted during the transportation of the system from the workshop/factory is reduced because of the need to smaller trucks and lesser trips to transport the required amount of units to the site.

5.2. Conclusions from Experimentation

- From the results of the experimental tests, it was observed that the exterior member is the first member that experiences early buckling in the system which agrees with the initial design.
- By analyzing the results, it was found that the aforementioned member has a deflection value that exceeds the intermediate hinge although it is not directly subjected to the load cell that applied the load in the test. These large deformations are resulting from the p-delta effect due to the long length of the member (3 meters) and the absence of any bracing system that might stiffen the member and increase its buckling capacity and ability to resist loads.
- Furthermore, the behavior of the truss after the deflection of the intermediate hinge was analyzed. In the three specimens, it was found by analyzing the deflection values that the intermediate hinge and the exterior member, the most critical member, experience the maximum deflection nearly within the same time frame. However, it is found that the intermediate hinge experiences maximum deflections just prior to the exterior member. This gives the indication of the presence of a process of redistributing the loads that the truss is subjected to. After the failure of the intermediate hinge, the load is redistributed throughout the system and one of the two halves carries the loads that the intermediate hinge cannot withstand. This leads to the presence of huge deflection in one of the two halves especially in the exterior member of this half while the second half has minimal deflection. However, the second half is exposed to pulling out effect due to the fact that the other half is carrying most of the loads and this is a normal reaction since the failure of the intermediate hinge prevents the propagation of the failure to the second half.
- Moreover, the second truss in the unit in all the three tests does not show any sign of plastic deformation. During the three tests, it was observed that the one of the exterior vertical members deflects slightly and then goes back to its normal state after the release of the load. This is a very important observation since it gives an indication about how the formwork system will work in case the concrete is only poured on top of one of the trusses in the unit.

5.3. Recommendations

There are a number of issues that need improvements in the design. These issues include: the redistribution of load process, strengthening the exterior vertical member and increasing the stiffness of the system.

5.3.1. Increasing the Stiffness of the System

During the erection of the system as mentioned earlier, the intermediate hinge was moving out of plane as it was not braced. This issue can be faced by adding a tube that connects the inner connections in the system to be put horizontally. This will add stiffness to the system and prevents the intermediate hinge from moving out of plane. Therefore, the maximum deflection of the intermediate hinge can be decreased and therefore can withstand higher loads.

5.3.2. Distribution of the Loads

This issue can be addressed by adding the screw leg extensions. These extensions will allow more flexibility in determining the desired height. Further, they will give the user of the system the ability to make sure that all the U-heads above the vertical members are on the same level. This means that in case of the failure of the intermediate hinge, the system will redistribute the loads more efficiently. Consequently, the failure load can be increased since both halves will take roles in supporting the redistribute weight. This takes advantage of the fact that the failure will not propagate to the other half of the truss in case one of the halves starts facing higher deformations than the other half.

5.3.3. Strengthening the Exterior Vertical

The exterior vertical member experiences early buckling because of it has 3 meters un-braced free length. Because of this, the member became the most critical member in the system. Therefore, it should be braced in the plane and out of plane directions. For the in plane direction, the member can be connected to the horizontal tube in the nearest connection by welding another tube that connects both. Further, a small plate might be welded to its back in order to add a bracing system with the opposite truss in the unit.

5.4. Recommendations for Future Research

5.4.1. Testing the system when subjected to Lateral Loads, Wind Load and Earthquake Loads

The system should be tested when subjected to these loads because the scope of this thesis included only testing the system when subjected to vertical uniform loads. This is important to determine the needed stiffness of the system and study its behavior under these loads and how to strengthen the system against the lateral loads.

5.4.2. Full Scale Prototypes should be tested on Actual Conditions on Site

This is very important because this will help in testing the soundness of the system when subjected to the real work conditions that include tough handling from the workers, weather conditions and erroneous storage methods and the most important condition which is pouring the concrete on top of the system using a pump and using the equipment that are usually used on-site to level the surface of concrete. Further, this will give indication on the behavior of the system when subjected to high live loads such as the workers that are walking on top of the reinforcement steel during the pouring of concrete and also when the curing process starts.

5.4.3. Feasibility study of the System

The feasibility study shall include the number of workers needed to fabricate and assemble the system off-site. This is important because labor has direct impact on the cost of the manufacturing and consequently will affect the price of selling the system to the end user. Further, the number of workers needed on-site to erect the system shall be included in the labor cost. Moreover, the life cycle of the system should be studied. This shall include the number of uses by the contractor and the effect of the weather conditions and the tough handling of the workers on the system. This is important because it is a part of the system’s advantages. The system will not be credible if it loses its integrity due to the different site conditions and the contractors will refrain from using it, even if it costs less than the commercially available system.

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