AN INVESTIGATION ON CONSTRUCTION SEQUENCE OF AN ARCH-SHAPED TENSEGRITY STRUCTURE

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AN INVESTIGATION ON CONSTRUCTION SEQUENCE OF AN ARCH-SHAPED TENSEGRITY STRUCTURE

By

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ABSTRAK

Tumpuan kajian ini adalah *tensegriti* prisma berbentuk lengkung pelbagai lapisan yang tidak teratur. Struktur *tensegriti* berbentuk lengkung terdiri daripada empat lapisan praktikal dengan panjang 4m dan ketinggian 2m dibina untuk mengkaji urutan pembinaan dan kesan berat badan pada konfigurasi akhir. Tali dawai keluli 1.5mm dan tiub aluminium 38.1 mm digunakan untuk anggota ketegangan dan pemampatan. Kajian ini bermula dengan proses penentuan bentuk dimana kaedah pengiraan komputer yang menggunakan pendekatan linear dengan menggabungkan keadaan hubungan panjang dan persamaan kesimbangan daya digunakan. Daripada hasil carian bentuk, nisbah daya yang diperlukan untuk digunakan ditentukan. Berdasarkan data kekuatan kabel, tahap tekanan pra-tekanan untuk digunakan pada setiap kabel ditentukan. Daya pra-tekanan di dalam kabel ddiperkenalkan melalui pemanjangan kabel. Melalui pendirian model tensegriti berbentuk lengkung 4 lapisan, urutan pembinaan bermula dari lapisan pertama dan meneruskan sehingga lapisan keempat akhir dirumuskan, diuji dan akhirnya berjaya ditubuhkan. Adalah didapati bahawa sokongan sementara yang tepat dari hujung anggota mampatan dan tahap tekanan pra-tekanan yang mencukupi dalam anggota kabel adalah penting untuk mengekalkan keteguhan struktur ketegangan. Berat badan anggota mampatan didapati menjejaskan ketinggian akhir serta panjang struktur ketegangan berbentuk lengkung.

ABSTRACT

The focus of this study is irregular multi-layer arch-shaped prism tensegrity. A 4-layer practical scale arch-shaped tensegrity structure with span of 4m and height of 2m was constructed in order to study the sequence of construction and effect of self-weight on the final configuration. 1.5mm steel wire rope and 38.1 mm aluminum tube were used for tension and compression members, respectively. The study started with form-finding process where a computing tool that uses a linear approach by combining length relationship condition and force balance equation was used. From the form-finding results, force ratios needed to be applied were determined. Based on cable strength data, the level of pre-stressing force to be applied to each cable were then decided. The pre-stressing forces in the cables were applied during construction through forced elongation achieved by means of turn-buckles. Through the erection of the 4-layer arch-shaped tensegrity model, the construction sequence starting from first layer and proceeding until the final fourth layer was formulated, tested and finally successfully established. It was found that proper temporary support of ends of compression member and sufficient level of pre-stressing force in cable members are crucial to maintain rigidity of the tensegrity structure. Self-weight of the compression members was found to affect the final height as well as the span of the arch-shaped tensegrity structure.

TABLE OF CONTENTS

ACKNOWLEDGEMENT .... **II**

ABSTRAK .... **III**

ABSTRACT .... **IV**

TABLE OF CONTENTS .... **V**

LIST OF FIGURES .... **VII**

LIST OF TABLES .... **X**

CHAPTER 1 .... **1**

1.1 Background 1
1.2 Problem Statement 3
1.3 Objectives 4
1.4 Scope of Work 4

CHAPTER 2 .... **5**

2.1 Type of tensegrity structure 5
2.2 Form finding tensegrity structures 8
2.3 Development and construction of lightweight prestressed skeletons 11
2.4 Summary 26

CHAPTER 3 .... **27**

3.1 Overview 27
3.2 Form-finding of multi-layer tensegrity 30
3.3 Procedures of Form-Findings 35
3.4 Selection of material 43
3.5 Connection 44
3.6 Tensile test 45
3.7 Physical modelling 47

CHAPTER 4 .... **48**

4.1 Introduction 48
4.2 Form-finding 48
4.3 Connection detail 55

.... 55
4.4 Tensile Test 56
4.5 Construction of the model 62
4.6 Discussion.. 67
4.7 Summary 70
CHAPTER 5 71
5.1 Conclusion.. 71
5.2 Limitation and recommendation 72
REFERENCES 73

LIST OF FIGURES

Figure 1-1: A Simple Tensegrity Structures (www.tensegrityit.nl)................................ 1

Figure 1-2: The first tensegrity structures by Kenneth Snelson in 1948-the “X-piece”.. 2

Figure 2-1 An eample of prism tensegrity (Bansod et al..,2014).................................... 5

Figure 2-2 An example of diamond tensegrity (Bansod et al.., 2014)............................ 6

Figure 2-3 An example of zig-zag tensegrity 6

Figure 2-4 Example of multi-layer tensegrity structures 7

Figure 2-5 Tension truss system 12

Figure 2-6 Tension truss dome completed in 1991.. 14

Figure 2-7 Simple and additional tension members 14

Figure 2-8 Mock-up for manual prestress introduction 15

Figure 2-9 Two truncated triangular prism skeletons during construction................... 16

Figure 2-10 Manual tension introduction 17

Figure 2-11 White Rhino 1 (exterior view)(completed in 2001).................................. 17

Figure 2-12 White Rhino 1 17

Figure 2-13 Structural components of membrane structure 19

Figure 2-14 Details of tensegrity skeletons 19

Figure 2-15 Exterior view of White Rhino (II) (completed in 2017) 20

Figure 2-16 Interior view of the La Plata Stadium 21

Figure 2-17 Schematic roof frame of the La Plata Stadium 21

Figure 2-18 Images during the construction phase of the La Plata Stadium 22

Figure 2-19 The Kurilpa Bridge in Australia comleted in October 2009...................... 23

Figure 2-20 The modelling and design of the bridge at difeerent construction stages .. 24

Figure 2-21 Laboratory scale models in triangular prism with height of 1.2m 25

Figure 2-22 Actual practical scale model with a height of 3.0m (Low,2018)............... 26

Figure 3-1: The flow chart of research methodology 29

Figure 3-2: Six joints of the first and second polygon with their connected members . 31

Figure 3-3: The four subsequent joints of the connection polygon 33

Figure 3-4 Interface at the input data of the first layer 36

Figure 3-5 Interface at the output data of the first layer 36

Figure 3-6 Formation of the first layer of tensegrity structure 37

Figure 3-7 Interface at the input data of the second layer.. 38

Figure 3-8 Interface at the output data of the second layer.. 38

Figure 3-9 Formation of second layer of tensegrity structure....................................... 39

Figure 3-10 Interface at the input data of the third layer 40

Figure 3-11 Interface at the output data of the third layer 40

Figure 3-12 Formation of third layer of tensegrity structure 41

Figure 3-13 Interface at the input data of the fourth layer.. 42

Figure 3-14 Interface at the output data of the fourth layer.. 42

Figure 3-15 Formation of fourth layer of tensegrity structure...................................... 43

Figure 3-16 Elongation of the cable... 46

Figure 4-1: 3D visualisation of model using AUTOCAD 53

Figure 4-2: Connection details at joint... 55

Figure 4-3: Connection details of model 56

Figure 4-4: Graph of force against elongation of cable sample 2................................. 57

Figure 4-5: Tension member sample 60

Figure 4-6: Tensile member test of the connection tension member............................ 61

Figure 4-7: The failure of the connection tension member at aluminium tube 61

Figure 4-8: Connecting cable to their position 63

Figure 4-9: Temporary support of the structure... 63

Figure 4-10: Support of bottom end of compression member at the base 64

Figure 4-11: The tensegrity structure after tightening of the turnbuckle in the cable ... 64

Figure 4-12: Measuring the length of the structure 65

Figure 4-13: Measuring the height of the member’s midpoint of the conjunction ring 66

Figure 4-14: Front view of the model 69

Figure 4-15: Up-lifting of the bottom end of compression member at the support 69

LIST OF TABLES

Table 4-1 Coordinates of joints of the first ring of the first layer 48

Table 4-2 Coordinates of centroid of the second ring of the first layer 48

Table 4.3: Coordinates of the second ring of the first layer... 49

Table 4.4: Coordinates of the second conjuction polygon of the first layer 49

Table 4.5: Coordinates of centroid of the second ring of second layer 50

Table 4.6: Coordinates of the second ring of the second layer...................................... 50

Table 4.7: Coordinates of the second conjunction polygon of the second layer 50

Table 4.8: Coordinates of centroid of the second ring of third layer 51

Table 4.9: Coordinates of the second ring of the third layer 51

Table 4.10: Coordinates of the second conjunction polygon of the third layer 52

Table 4.11: Coordinates of centroid of the second ring of fourth layer......................... 52

Table 4-12 Coordinates of the second ring of the fourth layer 53

Table 4.13: Force ratio and final length of each member of model............................... 54

Table 4-14 Result of tensile test of the cable of model from Low(2018)...................... 56

Table 4.15: Result of force and elongation based on cable sample 2 58

Table 4.16: Elongation and shortened length (in mm) of the cables of model 59

Table 4.17: The average's height midpoint each member... 66

CHAPTER 1

INTRODUCTION

1.1 Background

Structures of tensegrity are the combination of discontinuous compression member (strut) and continuous tension member (cable). By applying the pre - stress force over the cable, the tensegrity structure shows its rigidity. Figure 1.1 shows the structure of tensegrity containing compression (strut) and tension (cable)

Figure 1-1: A Simple Tensegrity Structures (www.tensegrityit.nl)

The term of tensegrity was described by Buckminster (1962) as the island of compression members (strut) are living in the ocean of continuous member (cables). Pugh (1976) provides a further definition of tensegrity, which is a tensegrity system when a set of discontinuous compression members interact with a set of continuous tension members in order to define a stable volume in space. Motro (2003) gives another definition of tensegrity structures, a system in a stable self - balanced state consisting of discontinuous set of compressed components within the continuum of tensioned components. The first person to build the first tensegrity structures was Kenneth Snelson (2012). Figure 1.2 shows the first tensegrity structure "X - piece"

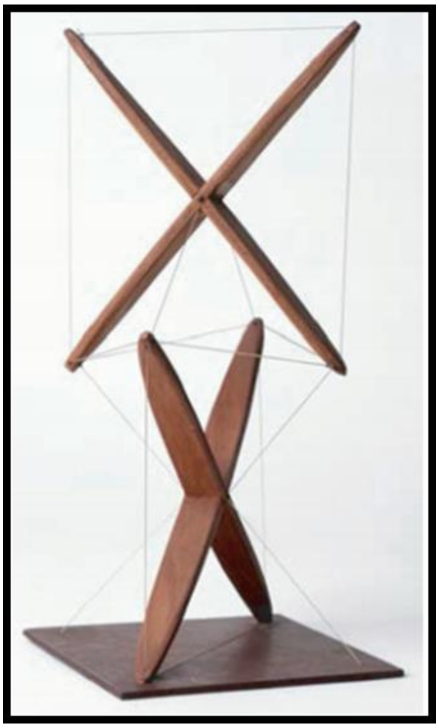


Figure 1-2: The first tensegrity structures by Kenneth Snelson in 1948-the “X-piece” (Snelson 2012)

1.2 Problem Statement

Due to its high sensitivity where its shape is unstable during construction, the construction of tensegrity structures is difficult. The construction of tensegrity presents challenges, since the structure will not be stable and rigid until all its members introduce the desired pre-stressing forces in the correct ratio. The design is closely linked to the sequence of connecting members (cables and compression struts) and the use of pre - stressing forces. Compared to the vertical tensegrity of multi - layer prism construction, the configuration of multi-layer arch-shaped tensegrity structures is more difficult due to the arch-shaped design, which includes the structure's self-weight. The upper layer of the arch-shaped structure tends to deflect downwards so that the pre- stress level, which can provide the necessary stiffness to reduce the downward deflection due to the structure's self-weight, must be properly determined. The results of the study on the sequence of construction of vertical multi-layer prism tensegrity should be extended to the construction of non-vertical multi-layer prism tensegrity. In particular, the study on the application of form-finding results to the construction of multi-layer arch-shaped prism tensegrity, taking into account critical issues such as the method of temporary support during construction, difficulties in connecting consecutive layers and details of the connection to avoid collision of compression members, must be studied.

1.3 Objectives

The objectives in this study are:

1. To investigate effect of sequence of construction on the final configuration of multi-layer arch-shaped prism tensegrity
2. To investigate effect of selfweight on final configuration of multi-layer arch-shaped prism tensegrity

1.4 Scope of Work

Chapter One describes the background, problem statement and objectives of this study.

Chapter Two presents the review of various form-finding methods of tensegrity by previous researchers. Existing tensegrity structures are studied. The construction sequence of irregular single layer prism tensegrity structure is reviewed.

Chapter Three describes the procedure of form-finding of tensegrity, selection and testing of materials, and determination and validation of construction sequence through physical modelling of irregular multi-layer prism tensegrity.

Chapter Four presents the results and discussions of the physical models constructed. The determination and validation of construction sequence of the physical models are discussed.

Chapter Five presents the conclusions and recommendations of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Type of tensegrity structure

Tensegrity structure come with many types and configuration.There are three categories of tensegrity structures which are prism tensegrity,diamond tensegrity and zig-zag tensegrity. Karl Ioganson invented prism tensegrity in Moscow in 1921. It called prism tensegrity because it can be regarded as a twisted prism consisting of two triangular faces twisted with respect for one another. The tensegrity of the prism has been designed with a constant length of one set of tendons and struts and the length of another set of tendons.The triangular faces are parallel and face - to - face, the top ring and bottom ring indicate the structure level. Connected diagonal cable from top to bottom ring. The struts are diagonally connected vertically between the top and bottom ring.Figure 2.1 show an example of prism tensegrity structure.

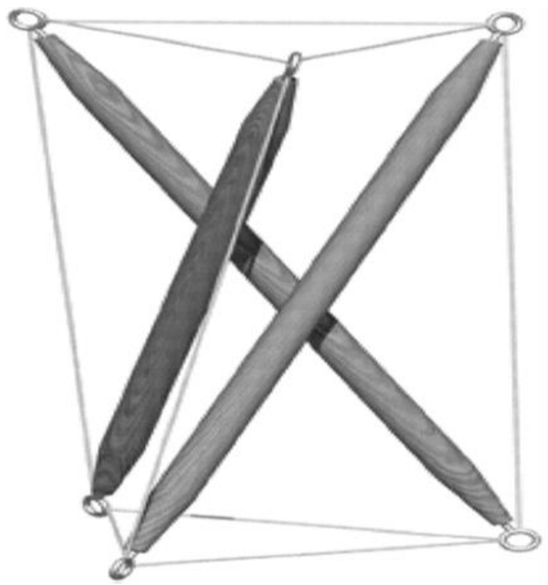


Figure 2-1 An eample of prism tensegrity (Bansod et al..,2014)

The diamond tensegrity are characterized by the fact that each triangle of tendons is connected to the adjacent one via a strut and two interconnecting tendons. Figure 2.2 shows an example of diamond tensegrity

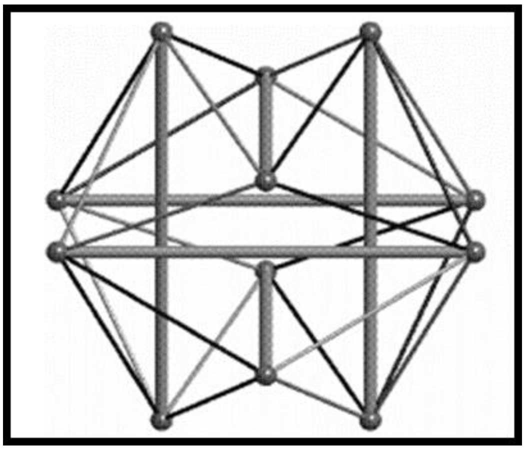


Figure 2-2 An example of diamond tensegrity (Bansod et al.., 2014)

The zigzag tensegrity are counterpart of diamond tensegrity. Although both diamond and zig-zag contain 6 strust,but what make them difference is that diamond tensegrity has four tendon triangles while zigzag tensegrity has eight of them. Figure 2.3 shows an example of zig-zag tensegrity structure

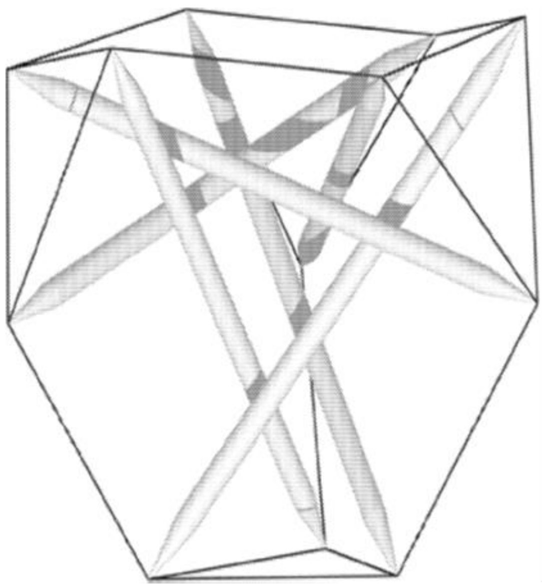


Figure 2-3 An example of zig-zag tensegrity

In this study,we focus on prism tensegrity.This is because the prism tensegrity can form various shape with a spherical geometry such as dome, spheroid, column, arch, tower by using multi-layer prism tensegrity (Mohammad,2016). The multilayer prism tensegrity characteristic, which allows the reduction of individual size and the total mass of compression elements, makes it a lightweight structure compared to ordinary structure (Buckminster ,1962). Figure 2.4 shows some example of multilayer prism tensegrity.

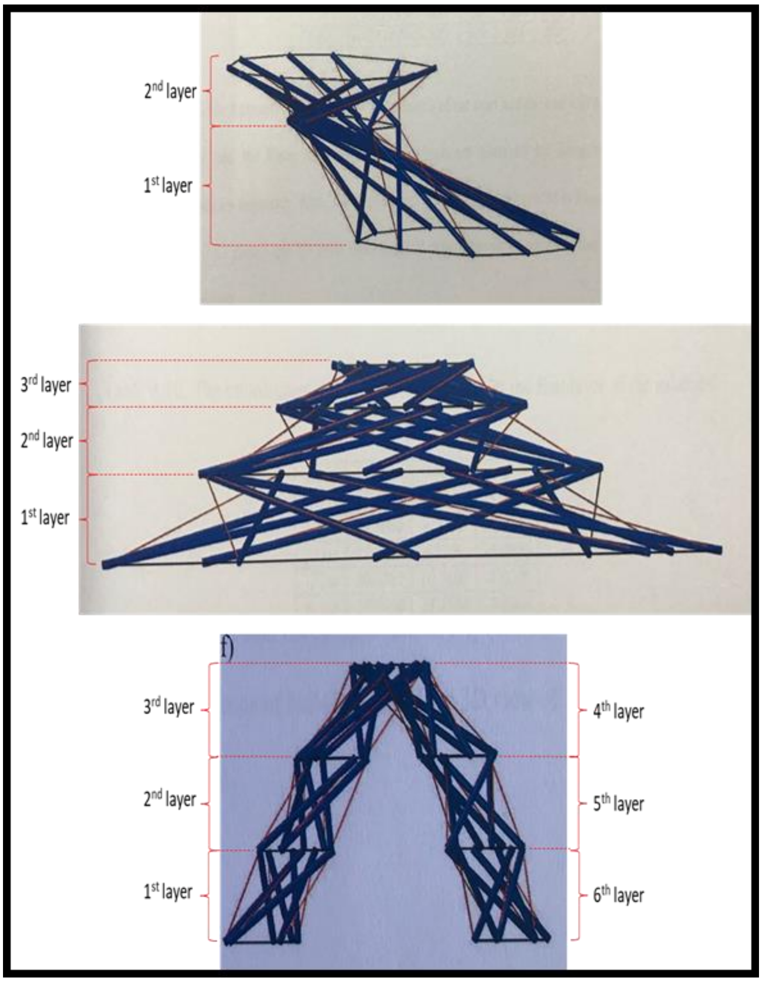


Figure 2-4 Example of multi-layer tensegrity structures (Mohammad,2016)

2.2 Form finding tensegrity structures

In order to achieve self - equilibrium, a tensegrity structure needs to be determined by geometrical configuration or known as tensegrity structure form – finding. Many researchers have various methods of finding tensegrity structures. (Tibert A.G. and Pellegrino, 2003) classified and reviewed seven form-finding methods of tensegrity structures into two major categories of kinematic methods and static methods. There are three methods of analytical solutions, non-linear programming and dynamic relaxation that fall under the kinematical methods. Four methods are classified according to static methods, which are analytical solutions, method of force density, energy method and reduced coordinates. The first category of methods, kinematical methods, determines the geometry of a tensegrity structure by maximizing the length of the struts while keeping the cable length constant. Due to its simplicity, the analytical solution of cinematic methods has an advantage. However, when many variables are required to define the configuration, the formulation becomes impossible. Non - linear programming has a similar disadvantage compared to the analytical solution, where the number of equations of constraints increases as the number of elements increases. For larger tensegrity systems, non-linear programming is not suitable. The dynamic relaxation method has good convergence properties for a few node systems.This method is, however, ineffective if the number of nodes in the system increases, which restrict the method in irregular structural forms. The second category of methods, static methods, establishes a relationship between the structure's balance configurations and its members' forces. Both the analytical solution and the method of force density establish linear nodal equations of balance in terms of force densities and equations for nodal co-ordinates are resolved. The advantage of the force density method is that it is appropriate if the lengths of the structure elements are not specified.. The energy method is based on an approach to minimizing energy to produce an identical matrix to the force density method. This method has introduced super-stable structures for tensegrity. The reduced coordination method achieves a set of rigid bodies' equilibrium configurations by solving a reduced set of equilibrium equations. The advantage of this method is that the shape of the structure is better controlled.

Many other researchers have also introduced new methods and improved previous forms of tensegrity structures. Li et al. (2006) studied a form-finding method based on the kinetic dynamic relaxation method. A suitable selection of related rigidities is used to determine the strength or length of certain elements. This method can create new, more intricate and creative tensegrity configurations. Zhang et al. (2006) presented the method of adaptive strength density for the determination of tensegrity structures. This method is based on the analysis of the own value and the spectral decomposition of the balance matrix in relation to the nodal co-ordinates. This method can search for new configurations by changing the initial set of force densities and nodal coordinates. Koohestani et al. (2013) presented a new form-finding method using the combined formulation of the equations of balance and geometric compatibility, which is a counterpart to the force density method. This method is appropriate for medium-sized and irregular models. However, if its solution is not guided to super-stable configurations, the method has a disadvantage. Ehara et al. (2010) presented a form-finding method by sequentially solving mixed integer programming problems using a numerical method based on the ground structure method. In this method, cable and strut connectivity information is not required in advance when the desired configurations are achieved. Zhang et al. (2014) presented a method of form-finding based on the structural rigidity matrix. The structure's self- balanced and stable state is achieved by using the structure's rigidity matrix and potential energy to converge the structural configuration.

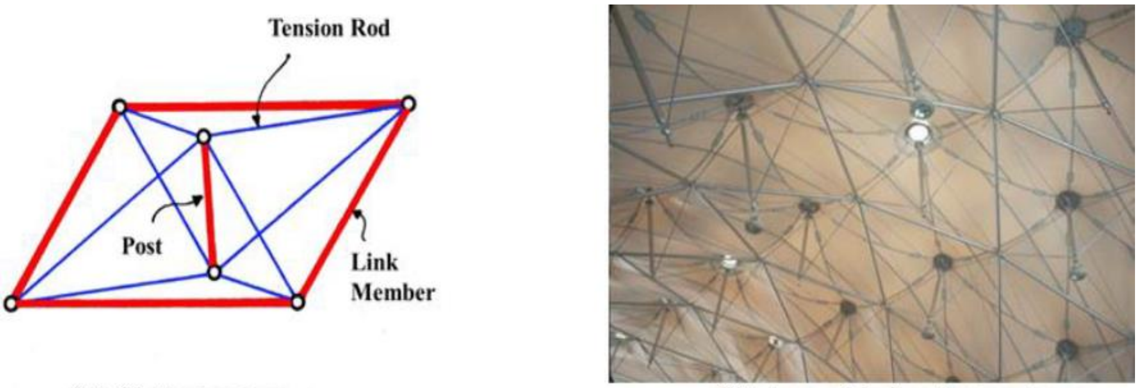
This method is highly efficient for regular and irregular structures of tensegrity. Lu et al. (2015) used the iteration of matrixes as a form-finding method for self-stress and coordinates. This method can be applied to irregular structures of tensegrity that meet certain geometric forms. Mohammad(2016) presented a form-finding method that combines the condition of the longitude relationship and the balance of forces. This method can be used to configure multi-layer tensegrity structures accurately and quickly. This method also achieves new configurations of prism tensegrity such as branching prism tensegrity. A computer tool is also developed that can design regular and irregular tensegrity of prisms with immediate results.

2.3 Development and construction of lightweight prestressed skeletons

Kawaguchi(2018) has worked on the development of lightweight structures, in particular prestressed frame structures, including tension truss and skeletons of Tensegrity. He briefly examines three examples of prestressed frame structures in which he was deeply involved in design and construction. No hydraulic or mechanical jackets were used for the introduction of prestress in these projects. Only manual power and operation were used. He has theoretically and practically worked on the following three-dimensional lightweight structures:

2.2.1 Tension Truss(1991)

The architect, Akira Fujii and Ken'chi Kawaguchi were asked to offer a very light skeleton as an annex to the existing old building. One of the options for lightweight skeleton for such purpose was so-called space frame system, three-dimensional truss skeleton. However, it was already known that space frames were still too redundant and members could be reduced further. It was then decided to search for a new type of lightweight skeleton between space frames and tensegrities. In practice, tensegrity has not yet been used as a structural skeleton, but is known as a very light skeleton stabilized by the prestress.



(a) Unit structure (b) Assembled unit structures

Figure 2-5 Tension truss system

Finally, Kawaguchi successfully proposed the structure of the unit shown in Figure 2.5 and called it "tension truss," although it was earlier called "TST (Truss structure stabilized by cable tension)" (Hangai et al. 1992). This was one of the earliest achievements of a three - dimensional steel frame. The unit structure has one self-equilibrium state and with this stress-state the eight radial members are prestressed in tension while four edge members and one center strut are prestressed in compression. Because to this prestress state, thin tension members can carry compression, without being suffered from buckling, before they slack. Tension steel rods and compression member are used. A set of small turnbuckle was inserted in every tension member and the pre-tension level was controlled by special torque wrenches, which used to turn the buckles. The pre-tension level was only about one ton, which can be easily introduced at the construction site by workers with small torque wrenches. For each unit structure for main pre-tensioning, one upper longitudinal tension rod was operated, since each unit has only. However, secondary adjustment of shorter tension rod are needed based on the results of stress distribution monitoring at the site. The final prestress level measured at the site agreed with what was designed, satisfactorily. Since eight tension rods and four compression pipes meet in one joint, the ball joints, which are usually used for so-called system trusses, were effectively used. The dome was used for 10 years as an annex and demolished in 2001.

2.2.2 White Rhino (I) (2001)

The architect A.Fujii and Ken'chi Kawaguchi were asked to design a new covered space for their institute's experimental centre. They proposed to build typical skeletons of tensegrity as structural components to support the covered space roof. It was a great challenge because no one succeeded in using typical tensegrity frames as practical structural elements for a building. This building became the world's first example in which the structural components used typical tensegrity frames. Since it has two membrane horns, which are pushed up by floating struts, it was called "White Rhino" and later "White Rhino I".

(a) Exterior view (b) Interior view

Figure 2-6 Tension truss dome completed in 1991

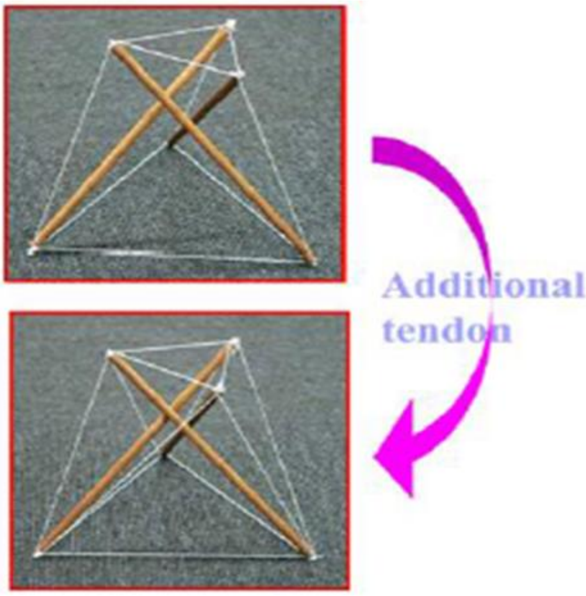


Figure 2-7 Simple and additional tension members

Figure 2-8 Mock-up for manual prestress introduction

Tensegrity skeletons have two main difficulties in applying them to structural components. They are extremely low frame rigidity and control of highly interwoven modes of the pre-stress in the frame.

Ken'chi Kawaguchi found the procedure to overcome these problems during the study of tensegrities without changing the peculiar appearance of tensegrity skeletons. The idea was to add to the skeleton some extra thin tension members. If this process is carried out properly, the skeleton's structural performance is dramatically improved and the problem above are solved. The process is quite simple and stable, and then there is no concern about the control of the pre-stress. This approach was applied by Ken'chi Kawaguchi to the truncated triangular pyramid tensegrity, which takes the form of a skewed triangle prism with a smaller upper triangle and a larger lower triangle. After confirming the skeleton's structural behavior with numerical simulations and models, the author designed and built two skeletons of tensegrity supporting a membrane roof with floating struts

Figure 2-9 Two truncated triangular prism skeletons during construction

Figure 2-10 Manual tension introduction

Figure 2-12 White Rhino 1 (interior view)

Figure 2-11 White Rhino 1 (exterior view)(completed in 2001)

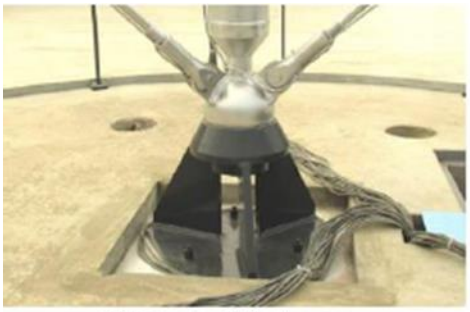
Ken'chi Kawaguchi therefore insisted on the manual introduction of the pre-stress in the tension members by turnbuckle operation, although people in the construction company proposed the use of hydraulic jack. The pretension limit that can be introduced by manual process is approximately 3 tonnes. The other tendons have been selected to operate on their turnbuckles. They were shortened by approximately 8 cm during the tension introduction and finally reached 3ton, while the tension level of other tension members was more than 10ton.

2.2.3 White Rhino (II)

K. Imai, the architect and Ken'chi Kawaguchi were asked to create a common space for a new university campus. They have decided to construct more advanced tensegrity skeletons than the White Rhino I (Kawaguchi et al. 2017). Two new skeletons of tensegrity have been designed, a tower tensegrity and a truncated pentagonal tensegrity pyramid. Two truncated triangular pyramids with other members were used for the tower tensegrity and connected to each other. Another strut was added in this intermediate connecting region so that 12 tension rods around the strut perform a cube as an eye-catch. Either end of the tower was designed as a free - rotation pin joint connected to the base or the membrane roof so that the tensegrity skeleton was not induced by a bending moment. For the truncated pentagonal pyramid, four additional tendons were added instead of five, since the fifth tendon slacked even under the dead load very early. Ken'chi Kawaguchi insisted once again on manual pre-stressing with turnbuckles in the tension members for the construction of these tensegrity skeletons. They tested the procedure in a laboratory and found that the maximum tension level introduced by hand was approximately 8 tonnes. However, they cannot expect the best condition for the workers on the less stable scaffoldings on the construction site. Therefore, the maximum voltage level was limited to around 4ton. Then they had to plan the assembly very carefully so that the designed tension level, in which some tendons had to reach the final 30ton pretension, could only be achieved by manual work. It was successfully planed and properly realized. During the construction, especially during the introduction of tension into the additional tendons, the skeleton is greatly deformed as the tendons are shortened by turnbuckles. This involves a relatively large angle change in the joints. The joints must therefore be designed to adapt to such a large geometric change. A few strain measurements are attached to each member, tension and compression and are used to monitor skeleton stress. Stress in all members was monitored and recorded at the site and used effectively during construction for the pre-stress control. They will also be used to continuously monitor the stress in the skeleton, including the effect of climate change.

(a) Test in a lab. (b) The real work at the site

Figure 2-13 Structural components of membrane structure



(a) Foot of the tower

(b) Top of the tower

(c) Foot of the pentagon

(d)End of the a tendon

Figure 2-14 Details of tensegrity skeletons

Figure 2-15 Exterior view of White Rhino (II) (completed in 2017)

2.2.4 La Plata Stadium

The La Plata Stadium in Argentina uses a different configuration of tensegrity compared to that of the White Rhino. The configuration of tensegrity of the La Plata Stadium shapes like a dome. The tensegrity roof network features tensioned steel cable hoops at three different levels with vertical struts (tensegritywiki). Figure 2.16 and Figure 2.17 show the interior view and the schematic roof frame of the building respectively. In the aspect of the construction process, only images during the construction phase of the building are available without any detailed descriptions. Figure 2.18 shows the images during the construction phase of the building.

Figure 2-16 Interior view of the La Plata Stadium

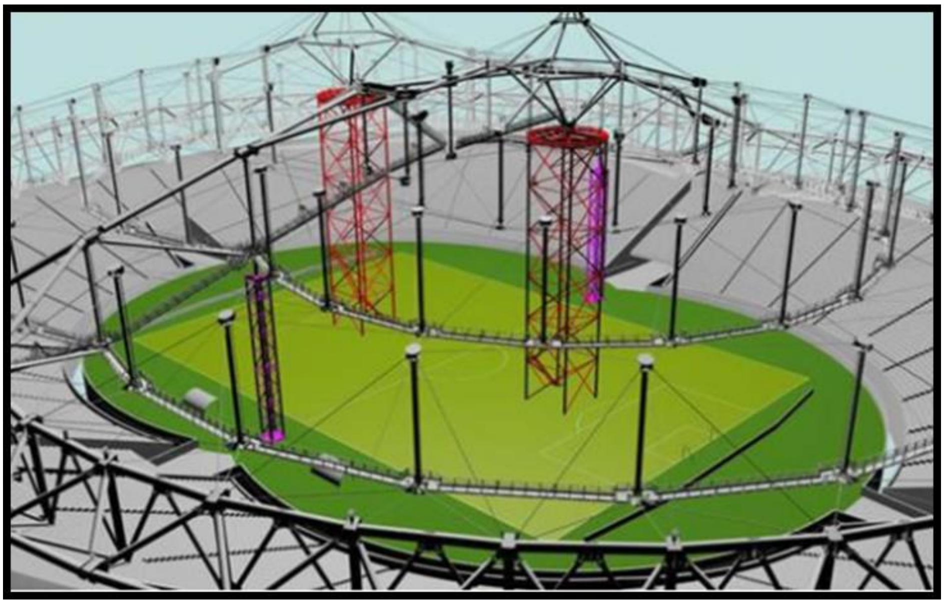


Figure 2-17 Schematic roof frame of the La Plata Stadium

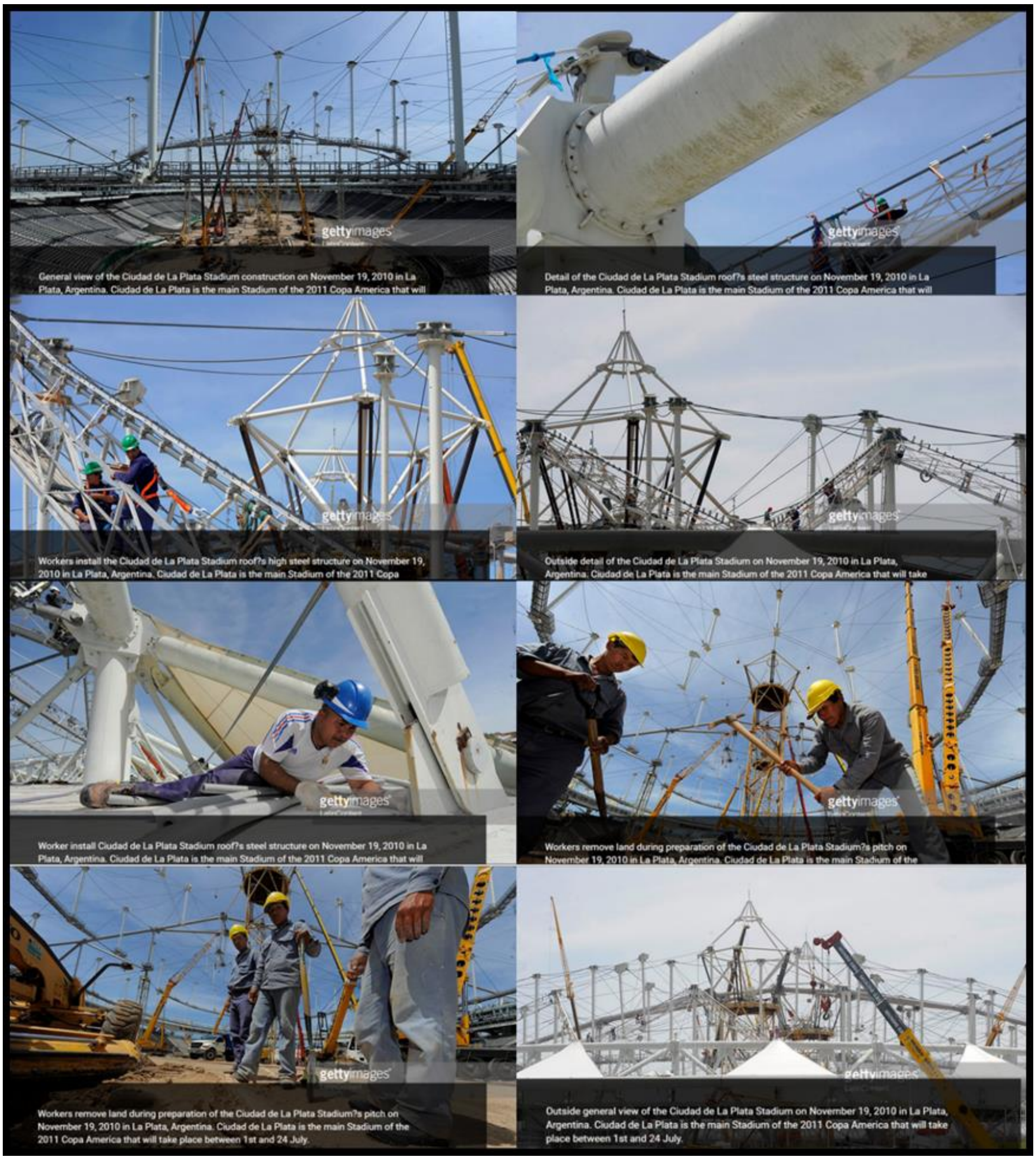


Figure 2-18 Images during the construction phase of the La Plata Stadium

2.2.5 Kurilpa Bridge

The Kurilpa Bridge in Brisbane, Queensland, Australia is the world's first tensegrity pedestrian and cycle bridge. The bridge was completed and opened to pedestrian in October 2009 (www.arup.com). The tensegrity bridge consists mainly of composite steel and concrete deck structure. Other members include series of steel masts and cables, integrated array of steel ties, flying struts and steel-framed tensegrity canopy (www.oasys-software.com). Figure 2.19 shows the completed structure.

Figure 2-19 The Kurilpa Bridge in Australia comleted in October 2009

In order to ensure that the large complex structure can be completed with the correct geometry, the components of the bridge are prefabricated to the desired dimensions. During the connections of the members, adjustment is not required to achieve the desired geometry. Various scenario planning and sophisticated analysis has been carried out by Arup to check every stage of the construction. Figure 2.20 shows the modelling and design of the bridge at different construction stages. The modelling is proved to be accurate when two spans of the bridge met precisely in the middle (www.oasys-software.com).

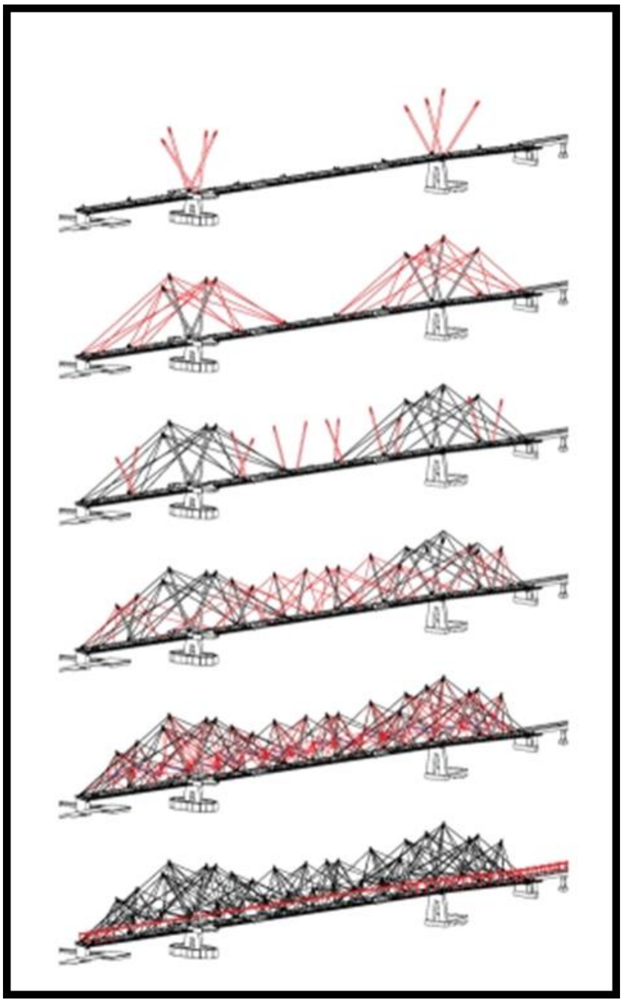


Figure 2-20 The modelling and design of the bridge at difeerent construction stages