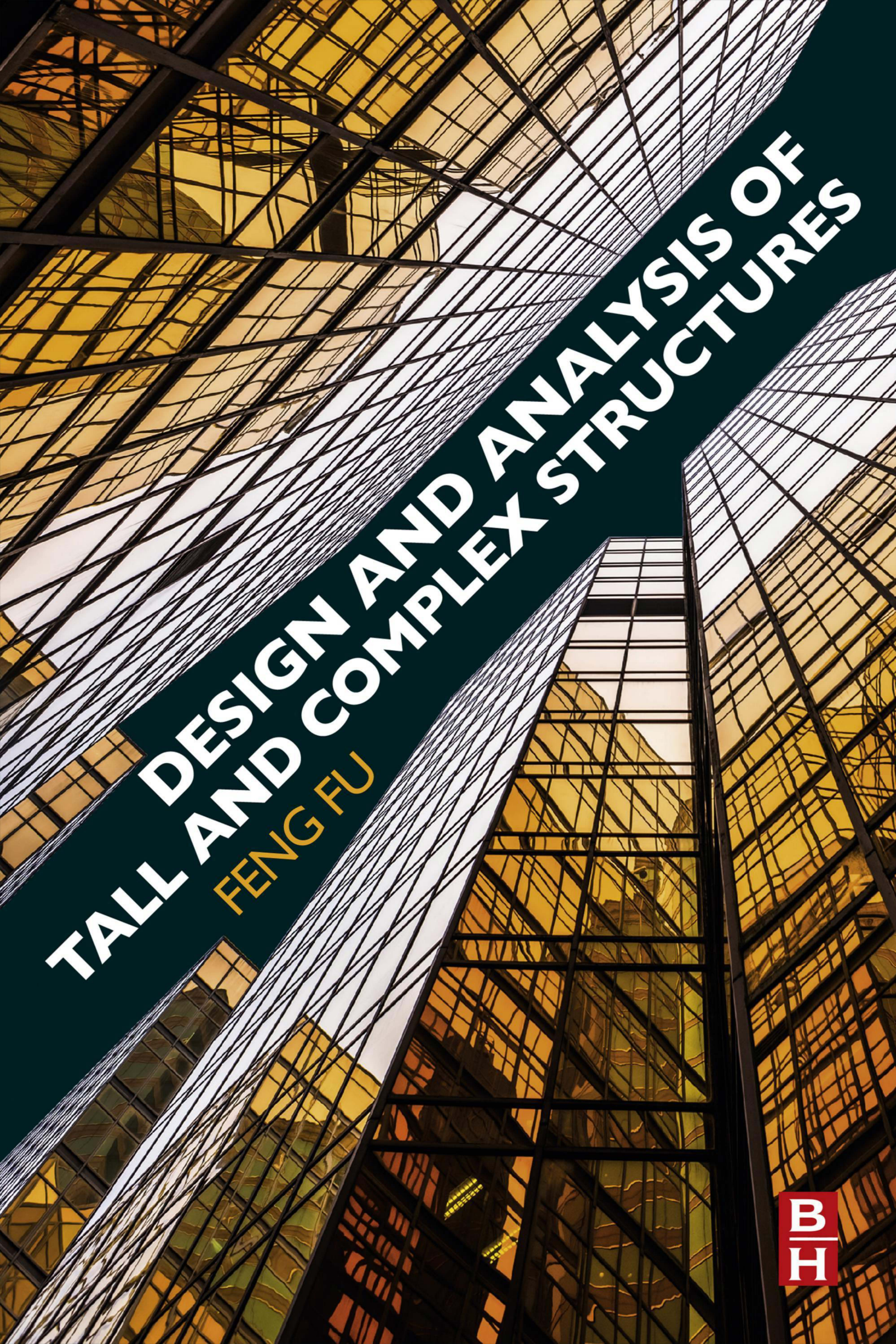

DESIGN AND ANALYSIS OF TALL AND COMPLEX STRUCTURES

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DESIGN AND ANALYSIS OF TALL AND COMPLEX STRUCTURES

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CONTENTS

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He is currently a lecturer in Structural Engineering in City, University of London, following his work at the University of Bradford. Before his academic careers, he has worked for several world leading consultancy companies and was involved in the design of several prestigious construction projects worldwide. He worked in the advanced analysis team in the WSP Group Ltd., London, following his work as a structural engineer in Waterman Group Ltd., London. Before starting his PhD in the UK, he also worked as a structural engineer for one of the best design companies in China, Beijing Institute of Architectural Design (Group) Co., Ltd. In this book, the author takes up for discussion seven tall building projects designed by these three companies.

During his professional engineering experience, he worked with many world-class architects and designed and analyzed all kinds of complex and challenging structures around the world, such as tall buildings, long-span space structures, and bridges.

Dr. Fu has extensive research experience in the area of progressive collapse, structural fire analysis, and blast analysis of tall buildings and long-span structures. He also conducted his research in the area of tensegrity structures and steel and composite structures. His currently research interests also include fluid and structure interaction of offshore structures such as offshore wind turbine and oil platform. He is specialized in advanced numerical modeling and has developed several modeling programs using different programming languages. He is currently working on a €1,438,020.85 research project funded by the European Commission Research Fund for Coal and Steel (RFCS), project number STABFI 751583, "Steel cladding systems for stabilization of steel buildings in fire." He is a PhD supervisor. He is also a peer reviewer for more than 22 international journals and 4 books of internationally renowned publishers. He has published more than 30 technical papers and two textbooks:

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"Structural Analysis and Design to Prevent Disproportionate Collapse, March 10, 2016 Forthcoming by CRC Press, ISBN 9781498706797."

PREFACE

In the past decades, with the development of construction technology and computer analysis methods, extensively tall and complex structures, such as Burj Khalifa, Taipei 101, the Bird's Nest, etc., have been built. The demand from the construction market requires that a civil engineer has the ability to design and analyze these challenging structures. The author has been working in the industry and the academia for many years. As a professional engineer, I have been working on a variety of tall and complex structures, such as the Shard, the tallest building in West Europe, the scheme design of Nakheel Tower (1-km-tall building, designed to be the tallest building in the world, project is on hold), etc. I noticed that most practicing engineers as well as current college or university students lack the knowledge on the design and analysis of tall and complex structures. Therefore, a textbook conveying the knowledge of design and analysis of this type of structures is increasingly important.

The aim of this book is to provide engineers and students with knowledge on the design principles and analysis methods of tall and complex structures, the effective way to model these types of structures using the conventional commercial software, and the theories and design principles that underpin the relevant analysis. This book has been written to serve as a textbook for college and university students and also as a reference book for practicing engineers.

This book discuses almost all types of tall building systems and other complex structural forms such as long-span structures, tensile structures, tensegrity structures, offshore oil platforms, offshore wind turbine, etc. It covers the structural design problems, such as lateral stability analysis, earthquake analysis, wind engineering, foundation design for tall buildings, nonlinear geometric analysis and form finding method for tensile structures and tensegrity, multiphysics modeling for fire safety, fluid structure interaction for offshore structures, etc.

Another feature of this book is that most of the design principles and analysis methods are demonstrated using case studies and modeling examples of existing prestigious projects around the world, such as the tallest buildings in the world: the Jeddah Tower (the tallest building in the world), the Twin Towers (in New York, demolished by 9/11 attack), 432 Parke Avenue in New York (the tallest residential building in the world), Shanghai Tower

(632-m tall, the tallest mega-frame building in the world), Guangzhou International Finance Center (432-m tall, the tallest diagrid building in the world), China Zun Tower (528 m), Petronas Tower (378 m), Georgia Dome (the first tensegrity dome in the world), Allianz Tower in Milan, etc.

This book also introduces several projects designed by the author's previous employers, which include The Shard (the tallest building in Western Europe), One World Trade Center (541.3-m tall, the tallest building in the western hemisphere), 432 Park Avenue (425.5-m tall), Hearst Tower (182-m tall) by WSP group, NEO Bankside Tower by Waterman Group, Poly International Plaza, and China Zun Tower (528-m tall) by Beijing Institute of Architectural Design Group Co., Ltd.

The book also emphasizes on the features of major commercial programs used in the current design practice (such as SAP2000, ETABS, Abaqus, ANSYS, Rhino, Revit, and AutoCAD), helping the engineers to understand an effective way to model complex structures.

One of the highlights of this book is the introduction of the cutting edge technology used in the current construction industry, the Parametric Modeling and Building Information Modeling method.

In addition, this book also incorporates a vast number of project photographs across the world. Majority of them were taken by the author, which help the reader to have a better understanding of the topics introduced in this book.

Feng Fu

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The author expresses his gratitude to Computer and Structures Inc., ANSYS Inc. and/or its subsidiaries, Autodesk Inc., and Robert McNeel & Associates for having given him the permission to use the images of their product.

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I am thankful to all reviewers who have offered their comments. A very special thanks is due to Kenneth P. McCombs from Elsevier for his assistance in the preparation of this book.

Some of the models used in this book are built by me and some are based on the models set up by the MSc and final year students under my supervision. I am very appreciative of my final year and MSc students: Mrs. Hasine Rezaee, Mr. Ervin Duka, Mr. Shahzeb Khan, Mr. Elhashmi Galeisa, Mr. Jorge Caro Yika. Mr. Enammul Miah, Mr. Shariq Naqvi, Mr. Wing Sing Tsang, and Mr. Mauro Jorge Campos.

Thanks to my family, especially my father Mr. Changbin Fu, my mother Mrs. Shuzhen Chen, and my wife Dr. Yan Tan for their support that made this book possible.

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CHAPTER ONE

Introduction

1.1 AIMS AND SCOPE

In the past decade, an increasing number of tall buildings and complex structures such as the Burj Khalifa in Dubai, the Bird's Nest Stadium in Beijing, and the London Aquatic Center were built. These projects demand that the civil and structural engineers have the ability to handle the increasing difficulty in designing even more complicated projects such as tall buildings or structures with complex geometries. The effective design of these types of structures is based on a clear understanding of the behavior of the structures, relevant analysis theory and method, knowledge of effective numerical modeling software, and of specific design principles. However, it has been noticed that, in the construction industry, most structural engineers find themselves lacking the relevant knowledge. In most universities, the basic design modules are taught to students. However, it is hard to find a module that has the systematic introduction on the design and analysis of tall and complex structures. Therefore, a book in this area is imperative.

The main purpose of this book is to provide students and design practitioners detailed knowledge of advanced design and analysis methods of tall and complex structures, such as tall buildings, long-span structures, tensile structures, tensegrity structures, offshore oil platforms, and offshore wind turbines. It also introduces major modeling programs (such as SAP2000 [1], ETABS [2], Abaqus [3], and ANSYS [4]) and the software to generate the structural geometry (Rhino [5], Revit [6], AutoCAD [7], and MicroStation [8]) used in structural design practice. It demonstrates the design knowledge through prestigious projects across the world, such as Jeddah Tower (1008-m tall), Shanghai Tower (632-m tall), etc. It also demonstrates the latest technologies used in design such as the BIM (building information modeling) and parametric modeling technique.

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1.2 THE MAIN DESIGN ISSUES OF TALL AND COMPLEX STRUCTURES

The major design issues of tall buildings are the lateral stability system and the gravity system for the superstructure as well as for the foundation design. The primary design target is to provide sufficient stiffness to tall buildings to resist lateral or gravity loadings. It should also be ensured that a correct foundation be selected, which can securely transmit loads from the superstructure to the soil. Chapters 2–5 of the book cover such design issues.

For complex structures, one of the major design issues is how to set up a complex structural geometry. Due to the complexity, the innovative technology such as the BIM and parametric modeling techniques become the key solutions to it. Another design issue of complex structures is the capability to analyze complex structural problems such as fluid and structure interaction, geometrical nonlinear analysis, form finding, multiphysics modeling, etc. In addition, the designers should also understand the underpin analysis theories of some special types of structures, such as the offshore structures and tensile structures, as their design and analysis methods are different from the conventional structures. All the design issues for complex structures are covered in Chapters 6–8 of this book.

1.3 STRUCTURE OF THE BOOK

Chapter 1 is the introduction to the book.

Chapter 2 gives the fundamental principles of designing tall buildings. It begins with a history of world's tall buildings, then a brief description is given of the major loadings that need to be considered during the design stage. It is followed by a detailed introduction to the floor system and the vertical support system. The next section starts with a detailed discussion of the earthquake design, covering the structural analysis methods for evaluating earthquakes, energy dissipation, structural regularity, and measures to reduce earthquake response, such as using damping systems. The following section provides information on wind loading, enlightening the readers on the fundamentals of wind loadings, enlisting the major design requirements for the occupant comfort design. After this section, discussions on progressive collapse, fire safety design, and blast design are made. In the latter part of this chapter, the foundation design, construction method, as well as the shortening effect and cladding system are dealt with. Chapter 2 is the most important chapter for the topic of tall buildings, as it attempts to cover all the major design issues of tall buildings.

A detailed introduction of the lateral stability system is made in Chapters 3–5. Chapter 3 covers the shear wall and core wall system, the outrigger and belt truss system, and the buttressed core system. The case study of the tall building projects such as the Shard and the Jeddah Tower is discussed in this chapter. Chapter 4 introduces one of the widely used lateral stability systems, the Tube system. It gives a detailed description on the different tube systems, such as the tube-in-tube, framed tube, braced tube, bundle tube, and the hybrid tube system. The case studies of the Twin Towers and One World Trade Center (the replacement of the Twin Towers) are made. In the final part of Chapter 4, two super-slender buildings are considered as a case study: 432 Parke Avenue (425.5-m tall) and Allianz Tower. Chapter 5 focuses on the bracing system, diagrid system, and the mega-frame system. Different types of bracing systems, such as the concentric bracing and the eccentric bracing are introduced, followed by the three-dimensional (3D) truss system used in tall buildings. The diagrid system is described in great detail. A case study of Guangzhou International Finance Centre (432-m tall), the tallest diagrid structure in the world, is made. The latter part of the chapter deals with the moment resisting frames and mega-frame structures. The mega-frame structure is demonstrated using two case studies, the Shanghai Tower (632-m tall, the tallest mega-frame building in the world) and the China Zun Tower (528-m tall).

Chapter 6 deals with complex structures. It gives detailed examples of the existing complex structures in the world, which covers the opera house, train station, hotel, aquatic center, and cable car supports. This gives the readers a clear picture of the different types of complex structures. The major design considerations for complex structures, such as the design of space structure, arches, as well as support and connections are made. Real project examples are also given. It is followed by a brief introduction of the analysis methods for complex structures. The highlights of this chapter are the introduction of the BIM and parametric modeling, which are the cutting-edge technologies used in the construction industry. In the final part of this chapter, there is a brief description of the development of the API (application program interface) and GUI (graphical user interface).

Chapter 7 presents the design and analysis of two special types of structures: tensile structures and tensegrity structures. Detailed analysis theories for form finding and static analysis, such as the nonlinear finite element method, force density method, dynamic relaxation method are introduced, including some important design issues such as wrinkling of the membrane. The way to model membrane structure in ANSYS and Abaqus is also demonstrated. The analysis methods for tensegrity are demonstrated using the Georgia Dome as a prototype, which is modeled using the design-orientated program SAP2000.

Chapter 8 introduces the design and analysis of offshore structures, including offshore oil platforms and offshore wind turbines. The incidents of offshore structures are demonstrated. Detailed introduction of major loadings and design guidelines are made. The wave theories to model the fluid and structure interaction are also elaborated. In particular, the design guidelines on offshore structures are described. This chapter is endeavored to give the reader a fundamental understanding of how to design and analyze offshore structures.

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CHAPTER SEVEN

Design and Analysis of Tensile Structures and Tensegrity Structures

Abstract

In this chapter, the design and analysis of two special types of structures: tensile and tensegrity structures are explained. It starts with the introduction of tensile structure, including different membrane materials, different types of support. This is followed by discussion of major loadings need to be considered for tensile structural. Then, the general design considerations are illustrated which covers some of the important design issues such as wrinkling of the membrane. Detailed analysis theories for form finding and static analysis are illustrated. They are nonlinear finite element method, force density method, and dynamic relaxation method. The way to model membrane structure in ANSYS and Abaqus are also described. In the final two sections of this chapter it covers the topic of tensegrity structures. Design and analysis methods are examined. The analysis methods for tensegrity structure are demonstrated using Georgia Dome as a prototype, which is modeled using design orientated program SAP2000.

Keywords: Tensile structures, Tensegrity structures, Form finding, Geometrical nonlinearity, Nonlinear finite element method, Force density method, Dynamic relaxation method

7.1 INTRODUCTION TO TENSILE STRUCTURES

Tensile structure is one of the unique complex structures. Its structural members can only carry tension but there can be no compression or bending. It normally consists of exterior fabric material with its framework such as cables. The fabric and the cables are maintained in tension in all directions to provide stability. Membranes are one of the common fabric material used in the tensile structure.

A membrane is tensioned between rigid structural elements such as steel frames or flexible structural elements cables. The membrane itself can resist external loading only through increasing tension in the membrane, which results compression and bending in supporting elements. To achieve adequate stiffness, its surface curvatures must be relatively high. Therefore,

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doubly curved forms are conventional in design as it provides greatest stability. As this type of material can only carry tension but no compression or bending, its surface shape must be generated through form finding to find the equilibrium position of a structure for a given stress state.

7.1.1 Type of Fabric Material

There are several different kinds of membrane materials such as polytetrafluorethylene (PTFE)-coated fiberglass, polyvinylchloride (PVC)-coated polyester fabric, silicon-coated glass, etc. Ethylene-tetra-fluorethylene (ETFE) film is another type of membrane material; it can be used as either single layer or cushion form (which is inflammable). The two famous stadiums for 2008 Beijing Olympic Birds Nest and Water Cube have used ETFE membrane. In Water Cube, the inflated cushions provide good insulation and beautiful aesthetic effect. Through the volume control of inflated air, the transparency of the membrane can be changed, therefore the natural light can be effectively used, and in addition, the reflection of sound can also be controlled.

The material of membrane structure has unique feature in terms of insulation, light transmission, and fire protection. Therefore, the selection of the membrane material is important in the design of this type of structure. Among them, PTFE, PVC, and ETFE are widely used with a wide range of tests performed; therefore, they are the preferable material for an engineer to choose. For ETFE material, the stains can be simply washed off by the rain. Although the ETFE is susceptible to punctures, these can be easily fixed with ETFE tape.

7.1.2 Type of Support

The maximum span of the fabric itself can achieve 30 m. To cover longer span, the fabric should be supported by cables (Figs. 7.1 and 7.2) or steel frames (Fig. 7.5). These cables are further supported to the main supports (Fig. 7.1A) or directly anchored to the foundation (Fig. 7.1B). For the main support, there are different types, such as mast support, compression rings, beams, arch support, or hanging by cables. They are going to be explained here.

7.1.2.1 Supported by Hanging Cables

As shown in Fig. 7.1, in O_2 arena, the membrane is directly supported by cables, these cables are further supported by hanging cables which are supported back to masts (Fig. 7.1A), which will result huge compression force to be resisted by these masks. Therefore, the masks are normally supported by heavy concrete block (Fig. 7.2B), which shows another

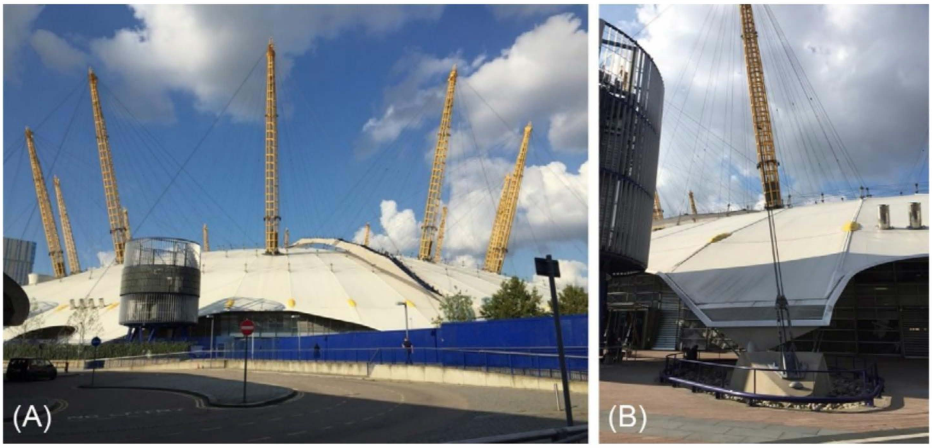

Fig. 7.1 (A) Tensile membrane structure, the O_2 dome, London, UK and (B) the anchorage of the cable. *(Photo taken by the author.)*

Fig. 7.2 A tensile membrane canopy of a toll station at Highway of Beijing International Airport, Beijing, China: (A) overview of the entire structure, (B) details of mast connection to concrete foundation support, and (C) details of cable support. *(Photo taken by the author.)*

membrane structure with a similar support system. In this shape of structures, the membranes are anchored back to the foundations through cables to maintain its shape (Figs. 7.1B and 7.2C).

This kind of support is quite common. Fig. 7.2 is another example of this type of support. It shows a tensile membrane canopy of a toll station on a highway to Beijing International Airport.

7.1.2.2 Supported Directly by Mast

Most tensile structures are supported by some forms of compression or bending elements, such as masts (Fig. 7.3), compression rings, or beams. Fig. 7.3 is another example of membrane structure. It is at the Entertainment Center in Astana, Kazakhstan designed by Architect Foster + partners. The whole membrane structure is supported on a large compression masts which consists of three truss columns to resist the huge compression force come from the supported membrane structures (Fig. 7.4).

7.1.2.3 Supported by Steel Frames

As shown in Figs. 7.5 and 7.6 steel frames are used to support the large inflammable cushion membrane panels.

7.1.2.4 Supported by Arches

Arch support is one of the typical supports for membrane structures (Fig. 7.7). This is because by using the arch support, saddle curvature can

Fig. 7.3 Membrane structure Khan Shatyr Entertainment Center, Astana, Kazakhstan. *(Photo taken by the author.)*

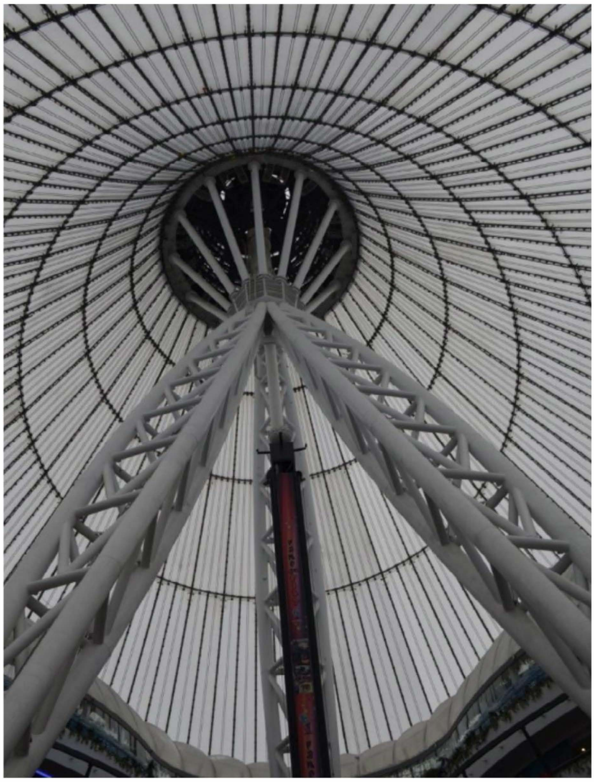

Fig. 7.4 Interior of Entertainment Center in Astana, Kazakhstan. *(Photo taken by the author.)*

Fig. 7.5 Membrane roof in Manchester Victoria Train Station, Manchester, UK. *(Photo taken by the author.)*

Fig. 7.6 Membrane structure in Eton Project, Cornwall, UK. *(Photo taken by the author.)*

Fig. 7.7 A bridge with arch supported membrane canopy at Greenwich, London, UK. *(Photo taken by the author.)*

be formed in between the support of arch, which allows adequate resistance to buckling of the membrane.

7.1.3 Introduction of Different Projects Using Membrane Material

In order to give the readers a clear explanation of membrane structure, in this section, different projects across the world are using the membrane material that will be discussed. Different membrane material and supporting structures are chosen for clear demonstration of membrane structures.

7.1.3.1 Khan Shatyr Entertainment Center in Astana Kazakhstan

As shown in Figs. 7.3 and 7.4, Khan Shatyr is a giant transparent membrane structure in Astana, Kazakhstan. This project was completed on December 9, 2006. The Khan Shatyr Entertainment Center was designed by an UK architect Foster + Partners and UK structural engineer Buro Happold.

The height of the structure is 150 m, it has a 200-m elliptical base covering 140,000 m^2. As shown in Fig. 7.4, the area is larger than 10 football stadiums, is an urban-scale internal park, shopping, and entertainment venue with squares and cobbled streets [1].

The fabric roof is constructed from ETFE-cushions. It can also be seen in Fig. 7.4 that the fabric roof is suspended on a network of cables, they are further supported by a central mask. The transparent membrane allows sunlight through, working with air heating and cooling systems, it can maintain an internal temperature between 15 and 30°C in the main space and 19–24°C in the retail units.

7.1.3.2 Eden Project (Cushion Membrane)

As shown in Fig. 7.6, Eden Project is located in Cornwall, England. It is designed by architects Nicholas Grimshaw & Partners. The project was built by McAlpine as a joint venture. It is featured in its two biome—the Rainforest Biome and the Mediterranean Biome, each of them consist of several domes which are joined in the middle by the link building. The cladding panels are made from the thermoplastic ETFE large cushion panels, up to 9 m across, were made by several layers of thin ETFE film, which are sealed around their perimeter and inflated. These panels are supported on steel space structures using tubular steel, forming hexagonal shape frame. These cushions provide good thermal insulation to the structure. It can be seen in Fig. 7.6 that the structure is completely self-supporting, with no internal supports. Owing to its lightweight, wind uplift has been considered, therefore, the domes are tied into the foundations with ground anchors.

7.1.3.3 O_2 Arena Dome

As shown in Fig. 7.1, the O_2 arena hosted the 2012 Summer Olympics Games. It is an indoor arena covered by the tensile membrane dome using PTFE-coated glass fiber supported by the hanging cables. Its structure was designed by BuroHappold. It is supported by high-strength cables spanning from outer edge to the center, which are supported by 12 100-m-high yellow steel support towers. As shown in Fig. 7.1, the cables are anchored back to concrete block, to support the fabric.

According to Ref. [2], the arena provides 100,000 m^2 of enclosed space. The structure is 365 m in diameter, with a circumference of 1 km and a maximum height of 50 m.

It was the largest structure in the world when it was built. It can be seen that for such a large span structure, membrane material would be the first option due to its super lightweight.

7.1.3.4 Jeju World Cup Stadium

As shown in Fig. 7.8, the Jeju World Cup Stadium located on Jeju Island, with a 35,657-person capacity. It was built in the city of Seogwipo on Jeju Island in South Korea. It was designed resembling the shape of the mouth of a volcano and its roof in the shape of nets of traditional fishing boats in Jeju [3]. The stadium was built 14-m below ground level to endure strong winds. It used the FGT-800 membrane material. FGT series are the glass fiber B yarn clothes impregnated with fluoroplastic PTFE and then sintered. The B yarn has the specific strength even excellent than steel. It has the resistance of high temperature up to 700–800°C and can resist ultraviolet rays. This kind of membrane also has the anti-adhesion and water-repellent features. Therefore, it is a good option for stadium roof.

As we can see that the membrane structures are also supported on the arch which is supported by the cable hanging from six large masks, the arch itself is also anchored back to the mass concrete blocks at the two ends of the structure.

Fig. 7.8 Jeju World Cup Stadium, Seogwipo, Jeju, South Korea. *(Photo taken by the author.)*

7.1.3.5 Birds Nest Stadium, Beijing

As shown in Fig. 7.9, the Beijing National Stadium was completed in early 2008. It has a gross floor area of 254,600 m^2 with seating capacity for 91,000 including 11,000 temporary seats. CITIC Internationals Contracting Inc. was the major construction contractor. The structural engineering, mechanical, and electrical engineering, fire safety engineering, and acoustic designs were made by Ove Arup & Partners.

The National Stadium's main structure is an enormous saddle-shaped elliptic steel structure weighing 42,000 t. The stadium extends 333 m from north to south and 294 m from east to west, with a height of 69.2 m [4]. It uses the ETFE cushion membrane as the roof structure. As shown in Fig. 7.10, it provides a half transparent but water-resistant roof, allow sunshine to penetrate through, but reduce the intensity of the ultraviolet from the sun.

7.1.4 Pros and Cons of Using Tensile Structures

From the explanation of Section 7.1.3, it can be seen that there are plenty of benefits in using tensile structures. Most membrane structures have high sun reflectivity and low absorption of sunlight. They also have benefits such as flexible design aesthetics, good translucency, excellent durability and low maintenance, and cost effective. In addition, daylight is maximized in building interiors, thus reducing the costs for electric lighting.

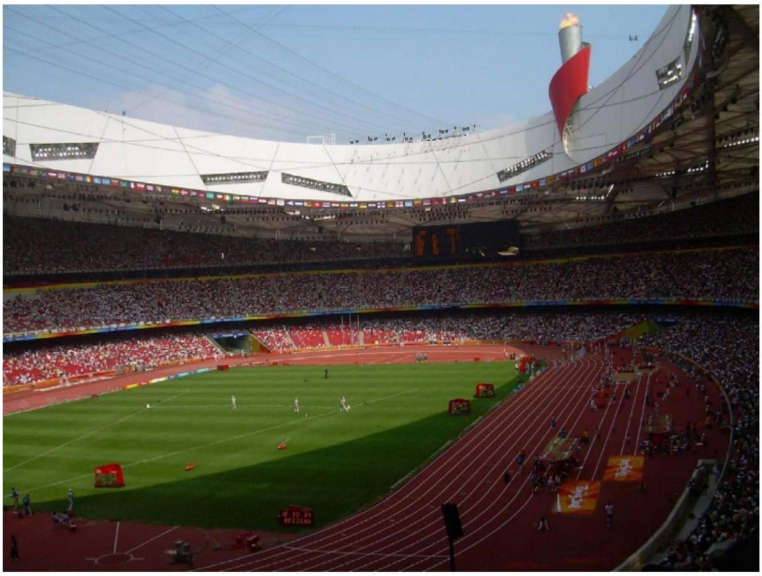

Fig. 7.9 Interior of Birds Nest Stadium in Beijing, China. *(Photo taken by the author.)*

Fig. 7.10 Membrane roof of Birds Nest Stadium in Beijing, China. *(Photo taken by the author.)*

In term of structural design, the lightweight membrane is a cost-effective solution that requires less structural steel to support the roof compared to conventional building materials, therefore, it is ideal to use in long-spans structures. Owing to its flexible feature, it can also be used as a deployable structure.

However, there are also some disadvantages of using membrane structures. Owing to the lightweight of the structure, wind becomes critical for loading, and several accidents of membrane structure can be damaged due to wind that have been reported.

7.1.5 Design Code for Membrane Structures

Currently, there are not many design guidance for membrane structures cross the world. In China, CECS 158:2004 [5] "Technical specification for membrane structures" is one of the detailed design code for membrane structure. It covers the basic design specifications, structural analysis methods, fabrication, construction, procedures for approval, and structure maintenance. It is one of the most detailed design codes for membrane structures.

The European Standard, EN 13782:2005 [6] "Temporary structures Tents-Safety," covers the safety requirements for tents during design, calculation, manufacture, installation, maintenance, operation, and examination for temporary installed tents of more than 50-m^2 ground areas. The contents cover fundamental terms and definitions, the general requirements for design, principles of numerical analysis, the design actions, the verification of stability, and equilibrium, the ground anchorages, the other structural components, the special design and manufacture criteria, the manufacture and supply, the examination, the competence, procedures for approval, examination and tests, and the aerodynamic coefficients for round-shape tents.

There is another European design guidance, EN 15619:2008 + A1:2010 "Rubber or plastic coated fabrics—Safety of temporary structures (tents)—Specification for coated fabrics intended for tents and related structures" [7]. It covers the level of performance for different fabrics.

Membrane structure has been widely used in Japan for long time, especially inflammable membrane structures. MSAJ/M-03:2003 "Test methods for membrane materials (coated fabrics)—qualities and performances [8]" describes the testing procedures for membrane materials.

In the United States, the ASCE Standard 55-10 "Tensile Membrane Structures" [9] covers the design approach and the prescriptions for an appropriate fabrication and erection of the structure. It includes the properties of membrane materials, the connections details, load combinations and strength reduction factors. It also suggests recommendations about the use of wind tunnel analysis in order to investigate the wind pressures (where the shape of the membrane does not fall within the limits of the prescriptive load requirements), the flutter at free edges and the resonance of the entire structures.

ASCE Standard 17-96 "Air Supported Structures" [10] and ASCE Standard 19-96 "Structural applications of Steel Cables for Buildings" [11] are the other two design guidance related to the design of membrane structures.

7.2 GENERAL CONSIDERATIONS IN STRUCTURAL DESIGN OF TENSILE MEMBRANE STRUCTURE

Owing to its unique feature, the design and analysis of membrane structure is different from conventional structures. The support, geometry and prestressing of the membrane are three key design considerations. In addition, patterning is another important design process. Structural fabrics are manufactured as flat panels, for this reason, tensile fabric structures cannot be formed without incurring stresses in the surface. The conventional structural fabrics are manufactured with a typical width of 2–3 m, and a maximum width of 5 m [12]. If it is a large structure, multiple panels are needed. The shape of these panels affects the final form and stress distribution of the membrane. Therefore, a specialist design process, patterning, is needed for this type of structure.

The flow chart of the whole design process is shown in Fig. 7.11, which will be introduced in the following sections.

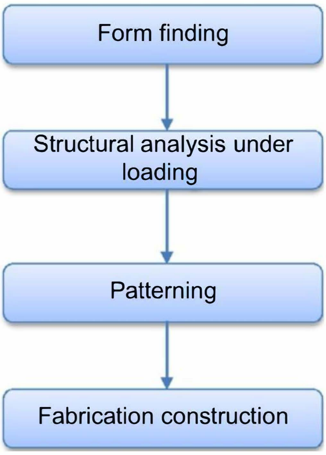

Fig. 7.11 Flow chart of design analysis process of tensile membrane structure.

7.2.1 Design Loading

In this design, the loadings below need to be considered, dead load, snow load, wind load, earthquake load, and thermal loading. The dead loads are mainly from the self-weight of the membrane, as membrane is a super-light material, so it is quite small, around 1 kg/m^2. The membrane roof is not accessible in reality; therefore, the live load can be ignored. Owing to its lightweight, the inertial force is quite small during the earthquake; therefore, the earthquake loading is not a major consideration.

Wind loading is major load which needs to be considered in the design; this is due to its smaller stiffness compared to other kind of structure. Wind is one of the major causes for the failure of membrane structures. The wind load can be resistant through the wrinkling of the membrane. There are quite a few incidents of damage to membrane structure under wind loading that has been reported. Therefore, wind is a dominant load in the design consideration discussed in detail further.

7.2.2 Wind Loading

As mentioned, because membrane structures are lightweight and flexible, wind resistance is critical to their structural design. Wind is a dominant load in the design.

In terms of structural analysis of membrane structure under wind loadings, there are two approaches available to use: quasi-static and dynamic approach.

Quasi-static approach is to assume that the dynamic wind effects can be ignored in designing a membrane structure, so the structure only undergoes deformation, therefore wind load can be considered as static load case. In this case, the wind load can be derived directly using the normal wind code such as EN1991-1-4 [13]. The mean wind load at a certain point on the surface of a structure is computed as the product of a mean dynamic pressure at a specific point, a dimensionless pressure coefficient, and further coefficients.

Dynamic approach membrane structures have a considerably low natural frequency (typically 0.5–1.5 Hz). This damping results from the crimp interchange of the yarns. The high flexibility of membranes leads to considerably large deformations for external loadings, which makes membrane structures susceptible to wind-induced aeroelastic effects. Therefore, to accurately analyze the structure under wind load, the dynamic effect of the wind on the membrane structure needs to be considered. Wind tunnel experiments are necessary to determine the wind load on membrane structures, due to their individual geometry. In addition, numerical approach computational fluid dynamics for the analysis of membrane structures is also necessary. Examples are the works of Saberi-Haghighi [14], Hübner [15], and Glück and Halfmann [16,17]. They analyze membrane-wind interaction through fully coupled fluid-structure interaction simulation, however, with simplified boundary conditions for the fluid analysis. In Ref. [18], Alexander Markus Kupzok also simulated membrane-wind interaction through surface-coupled fluid-structure interaction method.

In real design practice, for large-scale complex membrane structures, the geometry coefficient and wind pressure coefficient under different directions of wind loading is determined using wind tunnel test. However, for simple membrane structure, different design codes such as "Temporary structure Tents Safety" [6], gives the aerodynamic coefficients for round-shape tents for wind design.

7.2.3 Wrinkling

Owing to its low compressive strength, wrinkles can be formed in membrane material in certain loading conditions. The wrinkle often gives a negative image; therefore, to understand what would result in wrinkle occurrence is important for membrane structural design.

Wrinkling theory was the iterative materials properties (IMP) model firstly developed by Miller and Hedgepeth [19,20]. They presume that if a simulation of a membrane element is deemed to be wrinkled, the geometric strain in the direction perpendicular to the direction of the wrinkles, due to out-of-plane deformation of the material, can be modeled by introducing a variable efficacious Poisson's ratio for the element. Hence, the standard "taut" modulus matrix, predicated on Hooke's law for plane stress and given by.

$$M_t = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1}{2}(1-\nu) \end{bmatrix} \tag{7.1}$$

was replaced by "wrinkled" modulus matrix.

$$M_w = \frac{E}{4}\begin{bmatrix} 2(1+A) & 0 & B \\ 0 & 2(1-A) & B \\ B & B & 1 \end{bmatrix} \tag{7.2}$$

Based on above theory, Guo [21] gives two methods to make wrinkle analysis:

1. Tensile field theory method

when the principle strain. $\varepsilon_1 > 0, \varepsilon_2 \leq 0$ wrinkle occurs

2. Finite element static buckling analysis method of membrane

Using FE analysis package such as LS-DYNA, a buckling analysis of membrane can be performed.

The main objective of wrinkle analysis is to find the regions affected by wrinkles and the direction of wrinkles.

7.2.4 The Initial Geometrical Equilibrium—Form Finding

Before analyzing under the loading condition, the membrane and its reinforcing members (cables) should be prestressed to provide adequate stiffness. Therefore, a certain shape of the structure can be formed. Without prestress, the structure does not have adequate stiffness to resist the external loading. For this reason, initial geometrical equilibrium of the structure position need to be found before the load can be applied to the structure, this process is called form finding. Through the form finding, the adequate stiffness can be achieved. Therefore, no wrinkling will be formed under the normal loading.

According to Ref. [22], there are certain assumption made when perform form finding:

1. small strain behavior in a model undergoing large deformations, and
2. the form-finding system significantly more flexible than the form-found shape while still maintaining the desirable relative element stiffness.

There are several form-finding theories discussed in Section 7.3.

7.2.5 Patterning of Tensile Fabric Structures

Patterning is a unique design stage for tensile fabric structures. In the patterning design stage, the three-dimensional surface of the fabric members (membrane), found by means of form finding is flattened obtaining a two-dimensional cutting pattern for the fabric. This process is generally based on mathematical studies, which is included to determine the arrangement of planar fabric panels when the panels are assembled, the desired 3D form to be achieved, ensuring that the stress distribution is as close as possible to that intended during form finding. Fabric usage should also be minimized, so that the membrane can be fabricated.

Based on Ref. [12], the patterning process can be divided into the following steps:

Step 1: Seam definition concerns the division of the form-found membrane surface into panels. The divisions are defined by seams which generally take the form of sewn and/or welded overlapping panels of fabric.

Step 2: Flattening, developing a portion of the 3D form-found membrane surface into the 2D plane.

Step 3: Stress reduction, using iterative methods to the flattened panel geometry to reduce stresses.

Step 4: Compensation, concerns the shrinking of the pattern to account for tensioning of the membrane during construction.

Step 5: Pattern assembly, can be included in patterning schemes to calculate the final geometry and stresses in the constructed membrane.

There are two numerical analysis methods used for patterning: dynamic relaxation method (DRM) and force density method (FDM), which is explained in Section 7.3.

7.3 STRUCTURAL ANALYSIS OF TENSILE MEMBRANE STRUCTURE

Analysis of cable-membrane structure is a geometrical nonlinear problem due to its large deformation when resisting the external loading. Therefore, this type of structure is very sensitive to the geometry shape.

In the analysis, the structure can be idealized into the elements and nodes. The membrane can be discretized into a system of nodes and 2D finite elements, traditionally, triangle elements are chosen for the simulation of membrane, as shown in Fig. 7.12.

As shown in Fig. 7.13, cables can be simulated using 1D finite elements such as cable elements or tension-only elements, both consist of two nodes with six degrees of freedom.

The equilibrium position of each node under loading condition can be searched iteratively using different numerical tools such as DRM and FDM discussed here.

7.3.1 Nonlinear Finite Element Method

For each node of the cable-membrane structure, the equilibrium equation of a node under external loading can be seen in Ref. [23] and Eq. (7.3).

$$\left([K_E]^t + [K_G]^t\right)\{\Delta U\}^t = \{P_0\}^t + \{\Delta P\}^t + \{R\}^t \tag{7.3}$$

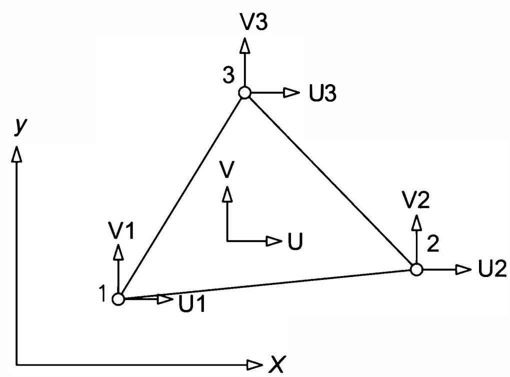

Fig. 7.12 2-D triangular elements.

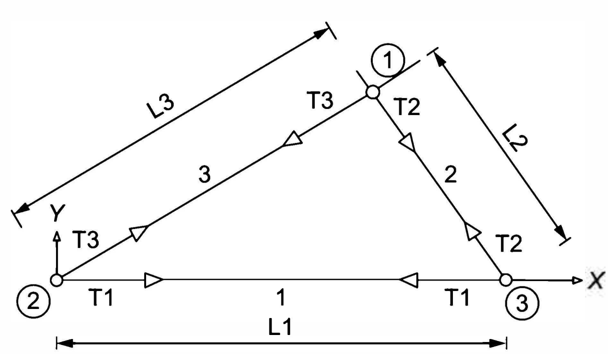

Fig. 7.13 Triangular membrane element and cable elements.

where

$[K_E]$ is the elastic stiffness matrix,

$[K_G]$ is the geometrical stiffness matrix,

$\{\Delta U\}^t$ is the increment of displacement of the nodes,

$\{P_0\}^t$ is the initial nodal force,

$\{P\}^t$ is the external loading force on the node, and

$\{R\}^0$ is the residual force.

At the form-finding stage, there is no external loading, therefore,

$$\left([K_E]^t + [K_G]^t\right)\{\Delta U\}^t = \{R\}^t \tag{7.4}$$

Eq. (7.4) is the basic governing equations for form finding of tensile cable membrane structure using the nonlinear finite element method.

7.3.2 Force Density Method in Form Finding

The force density method (FDM) was first introduced by Schek [24]. In this method, the force/length ratios or force densities are defined for each branch of the cable net and membrane structure. The associated node coordinates of the structure are obtained by solving the topological branch-node matrix [24]. This method makes a simple linear "analytical form finding" possible. This method is used in tensile membrane structures to find the equilibrium shape of a structure consisting of a network of cables and membrane.

7.3.2.1 Cable Net

For cable net, the form-finding equations can be analytically determined by using the force density ratio for each cable element [25]. The basic principle is introduced here.

For any joint i, its equilibrium in the x direction can be represented as.

$$\sum_{k=1}^{n_i} \frac{X^i - X^k}{L_{ik}} t_{ik} = F^i \tag{7.5}$$

where

n_i is the number of cables connected to joint i,

t_{ik} is tensile force in the cable,

L_{ik} is the length of cable, and

$X^i - X^k$ is the coordinate difference of joint i and joint k for cable ik in the X direction.

If $q = t/L$, where t and L are the cable force and length of a cable element, respectively, therefore, for joint i.

$$\sum_{k=1}^{n_i} \left(X_j^i - X_j^k \right) q_{ik} = F_j^i \tag{7.6}$$

If there are n nodes and m cables, the equilibrium equation in the X direction for each node can be deduced:

$$[C]^T [U][L]^{-1}\{t\} = \{F_x\} \tag{7.7}$$

where

$\{F_j\}$ is the load vector,

$[U]$ is the coordinate difference matrix,

$[C]$ is the topology matrix of this network, and $[U]$ and $[C]$ will be explained in the following sections.

If we call $Cs = [C\ C_f]$ branch-node matrix [24], which gives the positions of nodes (vertices) which connect the cables (edges) of a cable network. Cs is constructed following the below rules:

$C(i,j) = -1$ (when j is the smaller node number of element i).

$C(i,j) = 1$(when j is the lager node number of element i).

$C(i,j) = 0$ (for other situation).

where i and j are the joint numbers, from 1 to n_t and

$$n_t = n + n_f$$

where

n is the number of free nodes, these nodes are not constrained, and

n_f is the number of fixed nodes, these nodes are supported.

Therefore, $[C_s]$ can be further divided into $[C]$ and $[C_f]$.

So the coordinate's difference of all the connected joints in the cable net can be obtained using the branch-node matrix C and C_f.

$$\{u\} = [C]\{x\} + \left[C_f\right]\left\{x_f\right\}$$
$$\{v\} = [C]\{y\} + \left[C_f\right]\left\{y_f\right\}$$
$$\{w\} = [C]\{z\} + \left[C_f\right]\left\{z_f\right\}$$

where

x, y, z are the vector for the coordinate of free joints, and

x_f, y_f, z_f are the vector for the coordinate of fixed joints.

In the X direction.

$$\{u\} = [C]\{x\} + \left[C_f\right]\left\{x_f\right\}$$

If the length of the element is $[l]$ and the internal force of the element is $\{t\}$, external loading is $\{F_x\}$, and convert vector $\{u\}$ into $m \times m$ matrix $[U]$, $[U]$ is the coordinate difference matrix:

$$[C]^T[U][L]^{-1}\{t\} = \{F_x\} \tag{7.8}$$

The force density.

$$\{q\} = [L]^{-1}\{t\}$$

$[L]$ can be worked out through $\{x\}$.

Therefore,

$$[C]^T[U]\{q\} = \{F_x\} \tag{7.9}$$

Because.

$$[U]\{q\} = [Q]\{u\}$$

where $[Q]$ is the diagonal matrix for $\{q\}$.

Therefore,

$$[C]^T[Q]\{u\} = \{F_x\} \tag{7.10}$$

So

$$[C]^T[Q][C]\{x\} + [C]^T[Q]\left[C_f\right]\left\{x_f\right\} = \{F_x\} \tag{7.11}$$

If we let $[D] = [C]^T[Q][C]$ and $[D] = [C]^T[Q][C_f]$, $[D]$ is the generalized Gaussian transformation of $[C]$.

So

$$[D]\{x\} = \{F_x\} - \left[D_f\right]\left\{x_f\right\} \tag{7.12}$$

Eq. (7.12) can be used to determine the node coordinate for all the free nodes by using following equations:

$$\{x\} = [D]^{-1}\left\{\{F_x\} - \left[D_f\right]\left\{x_f\right\}\right\} \tag{7.13}$$

Similarly, we can obtain.

$$[D]\{y\} = \{F_z\} - \left[D_f\right]\left\{y_f\right\} \tag{7.14}$$

$$[D]\{z\} = \{F_z\} - \left[D_f\right]\left\{z_f\right\} \tag{7.15}$$

Therefore.

The coordinate for the nodes in the y direction can be:

$$\{y\} = [D]^{-1}\{\{F_y\} - [D_f]\{y_f\}\} \tag{7.16}$$

The coordinate for the nodes in the z direction can be:

$$\{z\} = [D]^{-1}\{\{F_y\} - [D_f]\{z_f\}\} \tag{7.17}$$

Therefore, based on above procedures, the equilibrium shape of a cable net can be determined.

7.3.2.2 Membrane Elements

The basic formulation of cable nets can be extended to the analysis of the membrane structures. As it is described, membrane can be discretized into a system of number of 2D triangular membrane elements. For each triangle element the stress inside can be expressed as [25].

$$\{\sigma\} = \{\sigma_0, \sigma_0, 0\}^t \tag{7.18}$$

As shown in Fig. 7.14, for any joint i, of the triangular element, the prestressed force within the membrane element m produce a tensile force to that joint which can be expressed as.

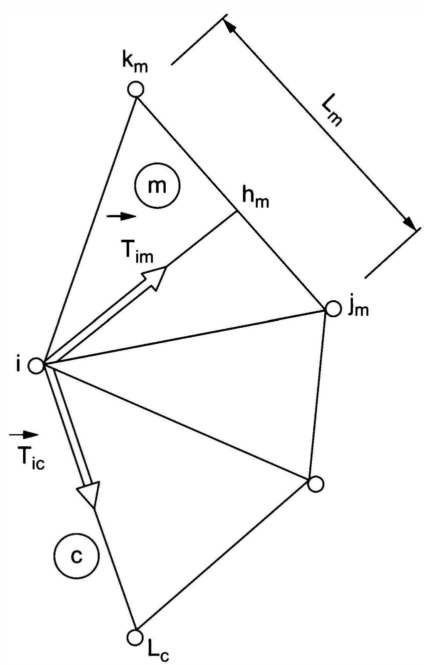

Fig. 7.14 Equilibrium of joints.

$$T_m = \frac{1}{2} L_m t \sigma_0 \frac{h_m}{H_m} \tag{7.19}$$

where

H_m is the length of the perpendicular bisector, and

t is the thickness of the membrane.

The area of the membrane element.

$$S_m = \frac{1}{2} L_m H_m$$

Therefore,

$$T_m = q_m L_m^2 i h_m$$

where q_m is the force density of the membrane elements.

7.3.2.3 Equilibrium of Joints

As shown in Fig. 7.14, for any joint i, the prestressed force in cable element c produce a tensile force to that joint which can be expressed as.

$$T_{ic} = q_c L_c$$

Therefore, the equilibrium of joint i can be expressed as.

$$\sum_{m=1}^{k} q_m L_m^2 i h_m + \sum_{n=1}^{j} q_c L_c = 0. \tag{7.20}$$

where K and j are numbers of membrane elements and cable elements connected to joint i.

Based on Eq. (7.20), the equilibrium of all the joints of.

7.3.3 Dynamic Relaxation Analysis Method

The load analysis of cable-membrane structures is a geometrical nonlinear problem due to their large deformation. The dynamic relaxation method (DRM) is an iterative process that is used to find static equilibrium. The theory of this method was first described by Day [26]. In this method, a dynamic solution is used for a fictitious damped structure to achieve a static solution. The stability of the method depends on the fictitious variables (such as mass and damping) and time step.

Dynamic relaxation is based on the Newton's second law of motion and stress-strain relations of the structural components under consideration.

For motion in the x direction:

$$F_i = M_i \ddot{X}_i \tag{7.21}$$

If a tensile structure is not in equilibrium, there will be some residual force R acting on the node. The static configuration of an elastic system can be treated as a consequence of a previous dynamic state, by presuming an artificial dynamic system which could be expressed as.

$$R_i^t = [M]\ddot{X}_i^t + [C]\dot{X}_i^t \tag{7.22}$$

where

[M] is the artificial mass matrix, oscillating around their equilibrium position,

[C] is the artificial damping matrix, it will dissipate the energy until a steady equilibrium state is reached, X is the displacement,

$\dot{X}_i$ is the velocity,

$\ddot{X}_i$ is the acceleration, and

R_i is the residual of internal and external forces.

$$\ddot{X}_i^t = [M]^{-1}\{R_i^t - [C]X_i^t\} \tag{7.23}$$

For a small time interval Δt, the equation can be rewritten in central difference form.

For velocity:

$$\dot{X}_i^{t+\Delta t/2} = \dot{X}_i^{t-\Delta t/2} + \Delta t \ddot{X}_i \tag{7.24}$$

Substitute Eqs. (7.6) into (7.4), therefore,

$$R_i^t = M_i \frac{\left(\dot{X}_i^{t+\Delta t/2} - \dot{X}_i^{t-\Delta t/2}\right)}{\Delta t} + C_i \frac{\left(\dot{X}_i^{t+\Delta t/2} + \dot{X}_i^{t-\Delta t/2}\right)}{2} \tag{7.25}$$

Further, rearrange Eq. (7.7), we get the nodal velocity that.

$$\dot{X}_i^{t+\Delta t/2} = \dot{X}_i^{t-\Delta t/2}\left\{\frac{M_i/\Delta t - C_i/2}{M_i/\Delta t + C_i/2}\right\} + R_i^t\left\{\frac{1}{M_i/\Delta t + C_i/2}\right\} \tag{7.26}$$

Therefore, the displacement of nodal coordinates at time $t+\Delta t$ can be worked out as

$$X_i^{t+\Delta t} = X_i^t + \Delta t \dot{X}_i^{t+\Delta t/2} \tag{7.27}$$

For the first iteration.

Therefore, the current nodal residuals $R_i^{t+\Delta t}$ can be worked out, and a new iteration starts.

Based on the above equations, the DRM can be divided into the following steps:

1. Setting the displacement of the node X and residual R at their initial value at $t=0$
2. Using displacement X and Eq. (7.23) to work out $\ddot{X}_i^t$ at time t
3. Calculate the new velocities $\dot{X}_i$ at time $t+\Delta t/2$ using $\dot{X}_i^{t+\Delta t/2} = \dot{X}_i^{t-\Delta t/2} + \Delta t \ddot{X}_i$ Eq. (7.24)
4. Calculate the residuals force R at time $t+\Delta t/2$ using $R_i^t = M_i \frac{\left(\dot{X}_i^{t+\Delta t/2} - \dot{X}_i^{t-\Delta t/2}\right)}{\Delta t} + C_i \frac{\left(\dot{X}_i^{t+\Delta t/2} + \dot{X}_i^{t-\Delta t/2}\right)}{2}$ Eq. (7.25)
5. Calculate the new velocities $\dot{X}_i$ at time $t+\Delta t/2$
6. Using the velocity $\dot{X}_i$ to Calculate the new displacement X at time $t+\Delta t/2$
7. Go back to step 2
8. Repeating the above steps unless the residual R close enough to zero

The iterations proceed until the required convergence, is determined by the allowable residual forces are smaller than the required value, has been achieved [27].

7.4 MODELING EXAMPLES OF TENSILE MEMBRANE STRUCTURE

Owing to its flexibility, membrane structure is difficult to model without helping the advanced analysis software. In this section, the modeling example of form finding for membrane structure will be shown using two popular general purpose software ANSYS and Abaqus.

7.4.1 Modeling Example of Form Finding for Membrane Using ANSYS

We have introduced several form-finding theories, here, the form finding will be performed using general purpose software ANSYS. There are several steps to set up the membrane model in ANSYS [28]

1. Set up the geometrical model
2. Using *link10* element to model Cable
3. Using *shell41* element to model membrane, in the *Option*, choose *Tension Only*

4. Meshing the membrane elements using triangular mesh
5. Applying the constrain by
   Load > Apply > Displacement > on Keypoints,
6. Apply the prestress force to the membrane through decreasing the temperature by
   Load > Apply > temperature > on area > then choose the membrane,
   Choose temperature value −0.375°C
7. Analysis using static large displacement analysis procedure
8. Checking the stress distribution of the membrane

7.4.2 Modeling Membrane Elements Using Abaqus

In Abaqus, the membrane can be modeled using several different elements available in Abaqus:

M3D4 membrane element which is a four-node quadrilateral element,
M3D8R, an eight-node quadrilateral membrane, and
M3D3 membrane element which is a three-node triangular element.

These elements are surface elements that transmit in-plane forces only and have no bending stiffness so they could not resist moments. Therefore, they are ideal to model membrane.

It is necessary to prestress these elements before any analysis is carried out. The mesh for the square membrane consists of triangular or square elements.

Uniform biaxial prestress force is applied to the membrane elements directly using the.

**INITIAL CONDITIONS, TYPE = STRESS* option.

This option should be used before applying any of the **STEP* options, to account for the geometric stiffness induced by the prestress.

The nonlinear calculation procedures should be used. Before the eigenvalue extraction calculations, a nonlinear static analysis step is carried out by using the **STEP, NLGEOM* option after the **INITIAL CONDITIONS* option.

In the above static analysis step, the applied initial prestress is maintained by restraining the outer edges of the membrane. Then, in the next step (*frequency extraction step*), the boundary conditions are changed to the actual ones, by using *BOUNDARY, OP = NEW option.

If vibration of the membrane is to be checked, frequency analysis step needs to be defined, using linear analysis step, number of eigenvalues can be extracted with the choice of *eigensolver*. There are two solution methods for solving eigenvalues can be used in Abaqus: the subspace iteration method and the Lanczos method. The Lanczos eigensolver is faster and more effective for models with many degrees of freedom.

7.5 INTRODUCTION TO TENSEGRITY STRUCTURES

Tensigrity is a structural system which was developed in the past 50 years. The concept of 'tensegrity' was first invented by architect B. Fuller [29]. The word tensegrity comes from two words "Tension + Integrity = Tensegrity". He came up with an idea of "nature relies on continuous tension to embrace islanded compression elements." In Fuller's idea, for this type of structure, stresses are evenly distributed throughout the entire structure rather than accumulating at certain points, therefore, maintain the balance of tension members.

7.5.1 Difference Between Tensegrity Structure and Tensile Structure

Most of the tensegrity structures are covered with membrane material, therefore, it sometimes is confused with tensile structures. The major difference between tensegrity structure and tensile structure is that it is a self-equilibrium structure, a system composed of continuous prestressed cables (in tension) and individual compression struts, as shown in Fig. 7.15, with the cables attached to the compression struts. Therefore, different to tensile structures, it consists tensional members as well as compression members, however, the compression member is part of the self-equilibrium system. On the contrast, for tensile structures, compression member such as masts are primarily work as the support structures to the entire tensile cable nets.

7.5.2 Application of Tensegrity Structure in Construction Projects

Tensegrity structure is widely used in long-span space structures in civil engineering, this is due to its super lightweight features, making a clear span of more than 200 m easily achievable which outperform other long-span structures such as double-layer grid and single-layer lattice domes. As shown in Fig. 7.16, the first long-span space structure using project using Fuller's tensegrity structure concept is a "cable dome" in the circular roof structures of Gymnastic and Fencing Arenas for the Seoul Olympic Games in 1986, designed by Geiger [30]. However, many arguments have been made on this

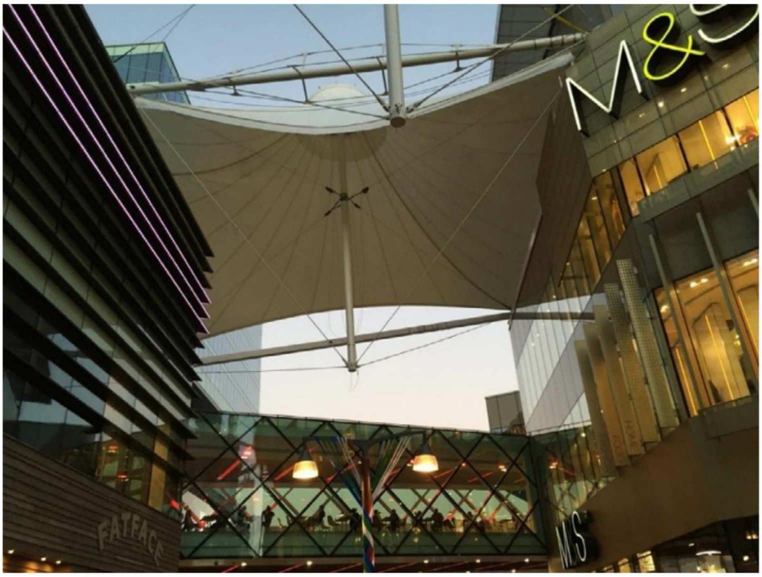

Fig. 7.15 Unit tensegrity structure in Westfield Shopping Center, Stratford, London, U.K. *(Photo taken by the author.)*

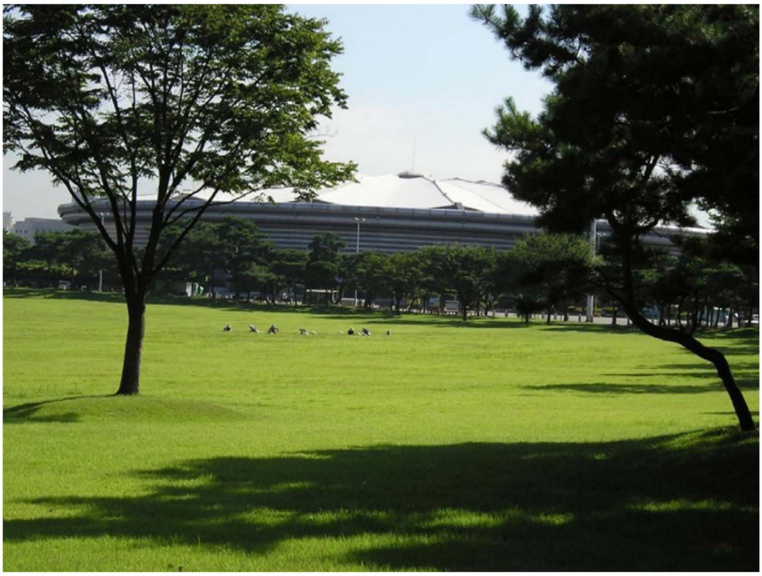

Fig. 7.16 Fencing Arena for Seoul Olympic Games, Seoul, South Korea. *(Photo taken by the author.)*

structure, as most engineers did not recognize it as an actual tensegrity system, because the compression ring is not inside the set of cables. In 1992, Levy [31,32] further improved the layout of the cable dome and built the Georgia Dome in quasi-elliptical shape for Atlanta Olympic Games, which is considered to be the first tensegrity dome built in the world.

Except in long-span structures, tensegrity concept have been used applications in fields such as sculpture, architecture, aerospace engineering, marine engineering, and biology [33]. Owing to its flexible and easily controllable feature, it is also used in active and deployable structures.

7.6 STRUCTURAL ANALYSIS OF TENSEGRITY STRUCTURES

Similar to tensile structure, the tensegrity structure is a geometrical nonlinear system, large deformation need to be considered. Tensegrity structure is a type of statically indeterminate structure, it also requires an initial form-finding procedure to create a state of self-equilibrium. There are several methods in form finding, similar to tensile structures, force density and DRM are also widely used in tensegrity structures.

In spite of that researchers have also discovered certain tools in form finding. Paper [34] presents a novel numerical form-finding procedure which only needs the type of each member, with both equilibrium geometry and force densities are iteratively calculated. A condition of a maximal rank of the force density matrix and minimal member length were included in the form-finding procedure to guide the search of a state of self-stress with minimal elastic potential energy.

In Ref. [35], a review for form-finding methods for tensegrity structure has been made. They are three so-called kinematical methods which include DRM, static method including FDM, energy method, and reduced coordinate method. The most popular methods used in design and analysis will be explained in this section.

7.6.1 Force Density Method in Form Finding

The FDM can be extended in analyzing the tensegrity structures, where similar equation as it introduced in cable-membrane structures can be used:

$$[C]^T[Q][C] = \{F_x\}$$

where $[C] = [C_{ij}]_{n\times m}$ is the topology matrix of this network, following the same rule as it is described in Section 7.3.

As it is a self-equilibrium system, in the form-finding stage, no external loading is applied. Therefore, the equation:

$$[D]\{x\} = \{F_x\} - [D_f]\{x_f\}$$

can be changed into.

$$[D]\{x\} = -\left[D_f\right]\left\{x_f\right\}$$

When determining the [Q], we need to be clear that the cables are always in tension and the struts are always in compression; therefore, the elements in the matrix is not always positive, singularity maybe found.

when $[D] \neq 0$, we will have nontrivial solution. $[D] = 0$, we will have trivial solution.

7.6.2 Dynamic Relaxation Analysis Method

As discussed in Section 7.3.3, dynamic relaxation is based on Newton's second law of motion and the iteration of it over many time steps, it has been used for form finding of pure tensile structures such as cable nets. It is later been used to tensegrity structures.

René Motro [36] proposed to apply the DRM to tensegrities, this marked an important step in form finding of tensegrity structures. When applying it to tensegrity structures, it is one of the so-called kinematical method by Tibert and Pellegrino [35]. In this method, the lengths of the cables are kept constant, while the strut lengths are increased until a maximum is reached. Alternatively, the strut lengths may be kept constant while the cable lengths are decreased until they reach a minimum, in summary, an initial layout member lengths are gradually altered until an equilibrium condition is reached.

In a form-finding analysis, one can prescribe for each element of the structure a constitutive relationship of the type:

$$t = t_0 + ke \tag{7.28}$$

where

t is the axial force,

e is the extension, t_0 is the desired prestress, and

k is a fictitious small axial stiffness.

Nodal equations of equilibrium are used to compute out-of-balance forces from which the current acceleration can be obtained through.

$$M\ddot{x} + D\dot{x} + Kx = f$$

where

K is a stiffness matrix,

M is a mass matrix,

D is a damping matrix,

f is the vector of external forces, and

$\ddot{x}$, $\dot{x}$, x are the vectors of acceleration, velocity, and displacement from the initial configuration, for simplicity, and the velocities and displacements are initially set to zero in the analysis.

Motro [36] applied the DRM to the form finding of the triangular tensegrity prism. The lengths of the cables were held constant while the struts were gradually elongated, until a state of prestress was set up in the structure. This analysis converged when the ratio between length of the strut to the length of the cable are 1.468.

As in Ref. [37] form finding through DRM depends on member stiffness, damping, and length ratio. Among them, the stiffness property assignment is crucial to the relaxation procedure. As tensegrity structures consist of both rigid and nonrigid members (struts and cables). At the beginning of the analysis two member stiffness parameters need to be defined: EA (tensile) and EA (compressive). At latter loading application stage during the analysis, this will ultimately decide the element's deformation under external load and hence the displacement of the nodes. Experiments show that the least successful procedures are those in which the relative difference in stiffness between the members is the greatest. Gustav Fagerström [37] suggests that not only relative stiffness differences between members but also absolute stiffness in relation to overall structure dimension and topology govern the properties of a tensegrity assembly.

Different to the form-finding processes in pure tensile structures, it is important to set appropriate interrelation between tension and compression members in the assembly. It is necessary to specify that elements are to be in pure compression and pure tension, respectively. To achieve this, in Ref. [37] for each relaxation cycle, if a compression member switches into tension or a tension member switches into compression, the forces acting on that member are re-set to zero. This can solve the problem of unwanted forces that are present.

7.6.3 Nonlinear Dynamic Finite Element Method

This method is to set up the nonlinear finite element equation for the tensegrity structures [38]. This procedure is to set up the basic nonlinear finite element equation for the entire structure, using stiffness of matrix method, and then using different numerical method such as Newton-Raphson approach to solve the equation.

7.6.3.1 Nonlinear Finite Element Analysis Equations

In the procedure of the determination of the initial equilibrium, the coordinate can be firstly presumed with an ideal distribution of the prestressed force which means it can be in any form of shape. Nevertheless, the node in the structural grid will not be balanced under this condition, imbalance force will be resulted, hence, it results in displacement of the node. Thus, the coordinate and the prestressed force need to be adjusted step by step until the whole structure is balanced.

The formula to determine the initial equilibrium is.

$$\left([K_L]^0 + [K_{NL}]^0\right)\{\Delta U\}^0 = -\{P\}^0 + \{R\}^0 \tag{7.29}$$

where

$[K_L]^0$ is the initial linear stiffness matrix,

$[K_L]^0$ is the initial nonlinear stiffness matrix,

$\{\Delta U\}^0$ is the variation of the coordinate,

$\{P\}^0$ is the prestressed force, and

$\{R\}^0$ is the residual force or imbalance force at each node.

After the determination of the initial equilibrium of the structure, the structure can be further analyzed under the load conditions. The fundamental equation for static analysis is.

$$([K_L] + [K_{NL}])\{\Delta U\} = -\{P\} + \{R\} \tag{7.30}$$

where

$[K]$ is the total stiffness matrix,

$\{U\}$ is the displacement vector of the node,

$\{P\}$ is the external load vector, and

$\{R\}$ is the residual force.

7.6.3.2 Newton-Raphson Approach to Solve the Equation

The Newton-Raphson approach can be used for solving the above two equations. The total load is divided into small increments and the calculation procedure is divided into correspondent steps, and for each increment a new $[K]_i$ is used. The nonlinearity is therefore treated as piece-wise linearity and a constant $[K]_i$ is used in all increments. After each iteration, the "unbalanced" portion of the external force is estimated and applied in the next increment.

For each step:

$$[K]_i\{\Delta U\}_i = \{\Delta P\}_i \tag{7.31}$$

$$\{U\}_i = \{U\}_{i-1} + \{\Delta U\}_i \tag{7.32}$$

where

$[K]_i$ is the stiffness matrix when $n = i$,

$\{\Delta U_i\}$ is increment of the displacement when $n = i$,
$\{\Delta P\}_i$ is imbalance load when $n = i$,
$\{U\}_i$ is displacement when $n = i$, and
$\{U\}_{i-1}$ is displacement when $n = i - 1$.

As $\{\Delta U\}_i$ is obtained, $\{\Delta F\}_i$, the increment of the internal force when $n = i$ can be therefore obtained. For each step, the internal force can be obtained as

$$\{F\}_i = \{F\}_{i-1} + \{\Delta F\}_i \tag{7.33}$$

where $\{F\}_i$ is the internal force of member $n = i$, $\{F\}_{i-1}$ is the internal force of member $n = i - 1$, and $\{\Delta F\}_i$ is the increment of member when $n = i$.

When all the steps are completed, the increment of the displacement and the increment of the internal force in a different step will be added together, so the final result can be obtained.

$$\{U\} = \sum_{i=1}^{n} \{\Delta U\}_i = \{\Delta U\}_1 + \{\Delta U\}_2 + \cdots + \{\Delta U\}_n \tag{7.34}$$

$$\{F\} = \sum_{i=1}^{n} \{\Delta F\}_i = \{\Delta F\}_1 + \{\Delta F\}_2 + \cdots + \{\Delta F\}_n \tag{7.35}$$

7.6.4 Case Study of Georgia Dome

As shown in Fig. 7.17, Georgia Dome is a decommissioned domed stadium located in Atlanta, Georgia, United States. The dome is supposed to be demolished in 2017. It was completed in 1992. The stadium seated

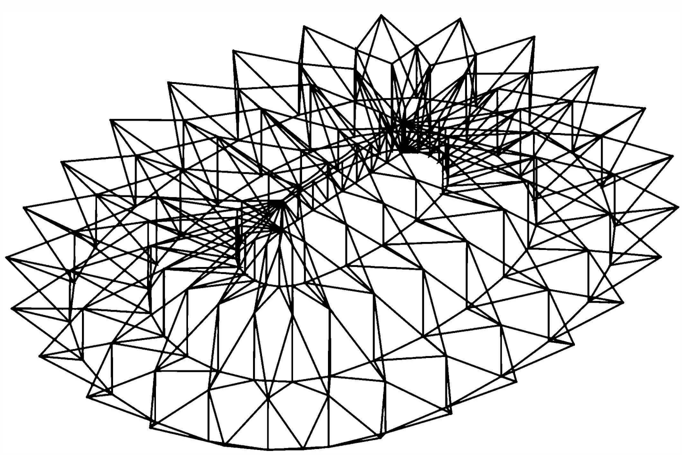

Fig. 7.17 3D AutoCAD Drawing of Georgia Dome.

74,228 for football, and could hold approximately 80,000 for concerts, and 71,000 for basketball [39].

7.6.4.1 Structural System of Georgia Dome

The dome was the largest cable-supported dome in the world and as mentioned in the earlier section, it is considered to be the first tensegrity dome in the world. The dome was designed by Levy [31,32]. On top of the tensegrity skeleton, it was covered by Teflon-coated fiberglass fabric and with an area of 34,800.000 m^2. It was the largest membrane structure in the world before the completion of Millennium Dome, London in 1999.

From Fig. 7.18, it can be seen that the longitudinal length of the dome is 239.35 m, the transvers length of the dome 186.97 m. As shown in Fig. 7.17, the dome can be divided into four layers, each layer composes of vertical compression struts connected by diagonal ridge cables. These cables are joined into a center cable truss, as shown in Fig. 7.20. It can be seen that the center truss is constructed using nine vertical compression struts connected by diagonal cables and cables as the top and bottom cord. The reason is evident, as the center truss needs to resist the huge tension forces come from the ridge cables. At the perimeter, these ridge cables are anchored back into a large concrete compression ring beam (7.9-m wide and 1.5-m deep). Therefore, the ring beam and the dome compose a self-equilibrium system. This fulfilled the design philosophy of Fuller for nature relies on continuous tension to embrace islanded compression elements.

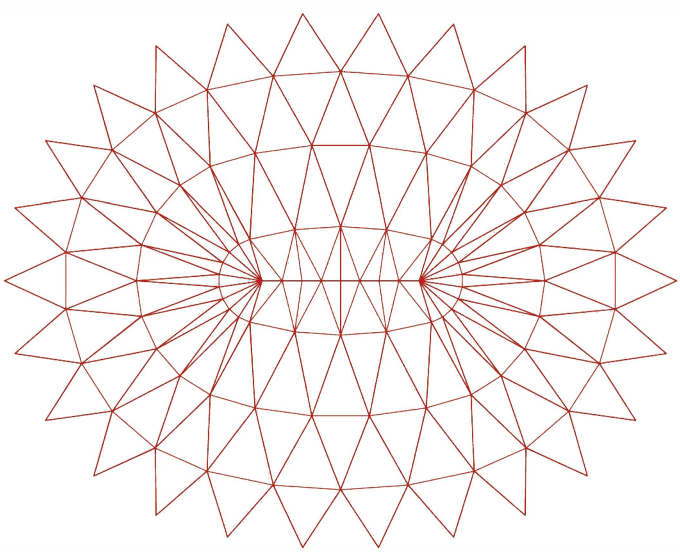

Fig. 7.18 Plan view of Georgia Dome.

To accommodate the complex connection between the compression struts and tension cables, a special joints are designed by Levy [31,32]. This type of connection can resist the huge tension force come from the cables, as well as the compression forces from the compression struts.

7.6.4.2 3D Modeling of Georgia Dome Using SAP2000

In this section, the nonlinear dynamic finite element method discussed in Section 7.6.3 was used to analyze the tensegrity structure Georgia Dome. The analysis was implemented in SAP2000. As SAP2000 can perform geometric nonlinear analysis, which also have the cable element, which can also define the prestress force of the cable and the perform form-finding analysis.

The model was first built using AutoCAD. As shown in Fig. 7.17, a 3D AutoCAD model was built, then imported into SAP2000, as shown in Figs. 7.19 and 7.20.

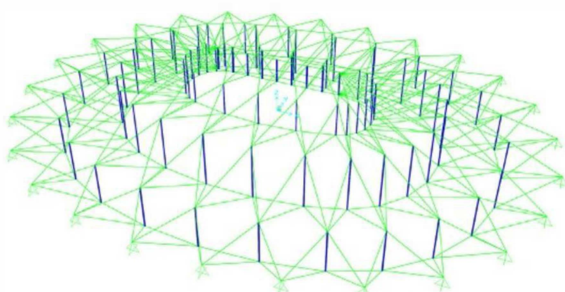

Fig. 7.19 3D SAP model of Georgia Dome. *(SAP2000 screenshot reprinted with permission of Computer and Structures.)*

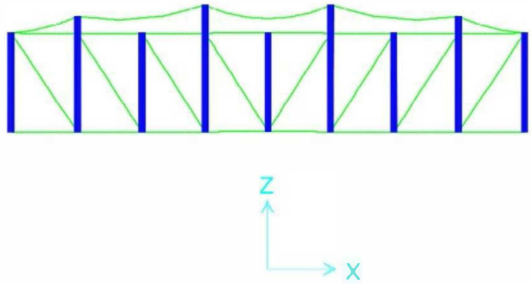

Fig. 7.20 Center Truss of Georgia Dome. *(SAP2000 screenshot reprinted with permission of Computer and Structures.)*

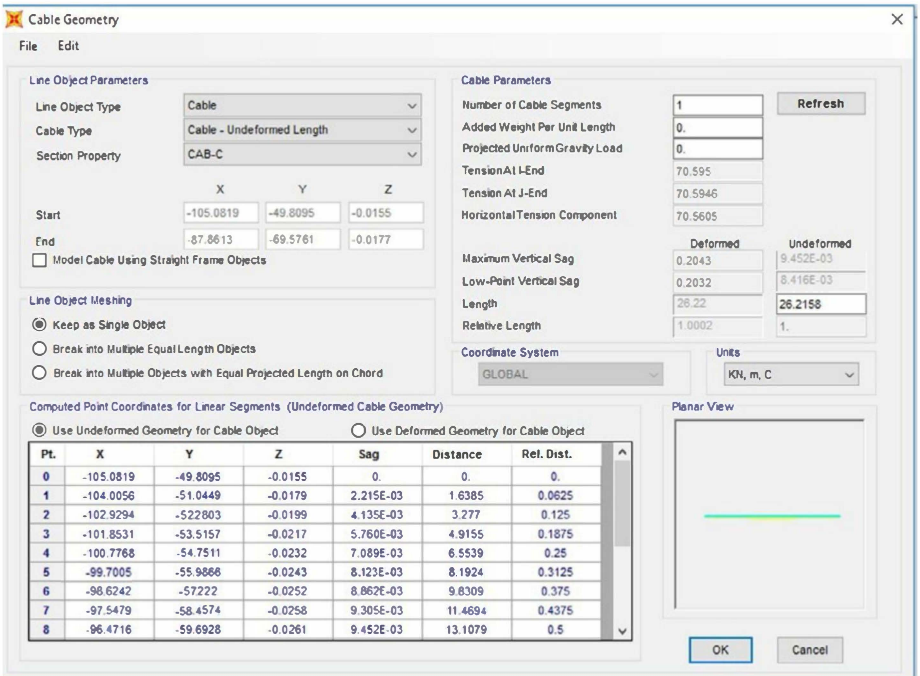

Fig. 7.21 Defining cable element. *(SAP2000 screenshot reprinted with permission of Computer and Structures.)*

7.6.4.2.1 Defining Cables and Struts

After the dome has been imported into the SAP2000, the cable element can be defined (Fig. 7.21) as well as the compression struts. The size of the cables and struts are based on Levy (1989, 1991).

7.6.4.2.2 Defining Prestress Force for the Cable

Then select the cables, choose Assign → Cable Loads → Target Force, then define the initial prestress forces for the cables. The initial prestress force of a cable is calculated using below empirical formula:

$$F = \sigma \times A \times 60\%$$

where

F is the initial prestress force,
σ is the yield stress of the cable, and
A is the cross-sectional area of the cable.

7.6.4.2.3 Form Finding

When all the structural members are set up, there are two analysis steps, one is form-finding analysis, another is the analysis under the actual loading in

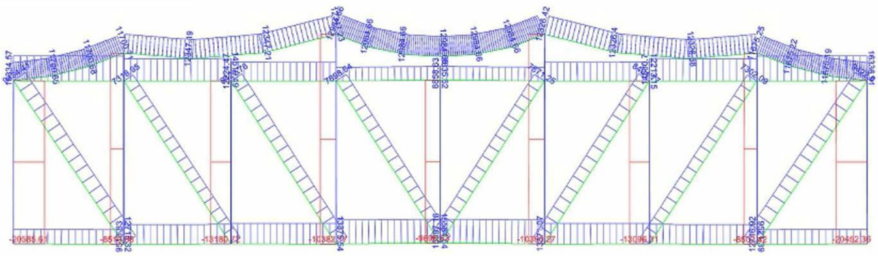

Fig. 7.22 Result of form finding for center cable truss. *(SAP2000 screenshot reprinted with permission of Computer and Structures.)*

SAP2000, one can define the *target load case* step for nonlinear form-finding analysis, however, remember to include the dead load when running the target load case, as the self-weight of the structure need to be inclusive in the form-finding analysis. Fig. 7.22 shows the analysis result, which shows the tensile and compression force distribution in the cable truss, the unit is in kN.

7.6.4.2.4 Analysis Under Loading Case

After the form-finding analysis completes, one can perform an analysis under the loading case, however, when defining the load cases such as wind or live load, make sure to choose the option "*Continue from State at the End of Nonlinear Case.*" Fig. 7.23 shows the analysis result of the dome under the live load. In this case study, 0.6 kN/m^2 live load was applied to the dome, which shows the tensile and compression force distribution in the cable truss, the unit is in kN. It can be seen that when the live load is applied, the tensile force inside the cables are reduced. The tensigrity structure primarily relies on the prestress force to resist the external loading. Therefore, a proper form finding is important, as it will optimize the right level of the prestress force.

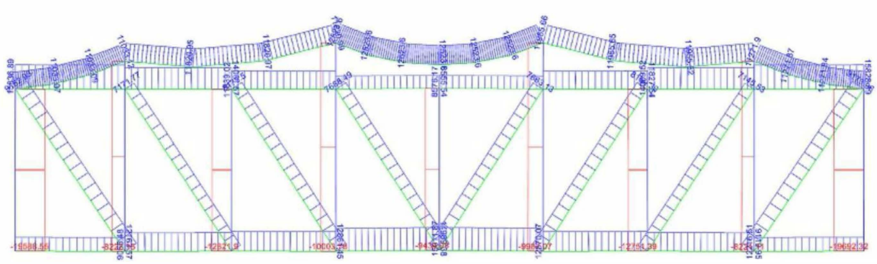

Fig. 7.23 Result of analysis under live load for center cable truss. *(SAP2000 screenshot reprinted with permission of Computer and Structures.)*

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