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Non-linear static analysis and design of Tensegrity domes

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Abstract. In this paper, a non-linear structural analysis software with pro-processing and post-recessing function is proposed by the author. The software incorporating the functions of the structural analysis and geometrical design of Tensegrity structures. Using this software, Cable Dome is analyzed as a prototype, a comprehensive study on the structural behavior of Tensegrity domes is presented in detail. Design methods of Tensegrity domes were proposed. Based on the analysis, optimizing design was performed. Several new Tensegrity domes with different geometrical design scheme are proposed, the structural analysis of the new schemes is also conducted. The analysis result shows that the proposed new forms of the Tensegrity domes are reasonable for practical applications.

Keywords: tensegrity; non-linear; prestressed force; self-equilibrium.

1. Introduction

Recently, there are increasing applications of Tensegrity structures in construction industry, aerospace industry and biotechnical industry. This newly developed structural system is developed from the concept of Fuller (1975), ‘nature relies on continuous tension to embrace islanded compression elements’. It is composed of continuous prestressed cables and individual compression bars. It is a self-equilibrium system. The characteristic of the structure is its prestressability, which is the property to maintain an equilibrium shape with all cables in tension. It is capable of large displacement, belonging to the class of flexible structures. Therefore, it offers excellent opportunities for physically integrated structure and controller design.

As the self-weight of such kind of structure is the smallest compared to other types of space structure such as space frame and space shell systems, it has been widely used in the long span domes. Geiger (1986) was the first person to make use of Fuller’s thought and designed an innovative structure ‘cable dome’. It has been successfully put into practice in the circular roof structures of Gymnastic and Fencing Arenas for the Seoul Olympic Games in 1986. In 1992, Levy (1989, 1991) further improved the layout of the cable dome and built the Georgia Dome in quasi-elliptical shape for Atlanta Olympic Games.

Another application for Tensegrity structure is the smart structural systems. It is to endow flexible structures with control engineering. In the research of Elton *et al*. (1997), the infinitesimal mechanisms

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of Tensegrity structures have become an advantage for deployable and shape-controlled structures for easy manipulation. It can be also used as space telescopes and flight simulators.

It worth noting that, recently, the concept of Tensegrity structure has been adopted by the biologists to study the structural behavior of the cell. Some scientists as Ingber (1993) start to use Tensegrity structures to explain how different type of cells resists shape distortion. Canadas *et al*. (2002) conducted a cellular Tensegrity model to analyse the Structural viscoelasticity of the cytoskeleton.

The research toward the structural behaviour and design method of the Tensegrity structures was started about two decades ago. Motro (1992) and Hanaor (1993) conducted extensive research on the geometrical type selection of Tensegrity system. Some researchers also conducted the research on the numerical analysis of the system. Kebiche *et al*. (1999) performed the geometrical non-linear analysis of Tensegrity systems. Sultan *et al*. (2001) discussed the prestressability problem of Tensegrity structures. Williamson *et al*. (2003) discussed the equilibrium conditions of a Tensegrity structure. Through the research of the researchers, an algorithm considering the geometrical non-linearity is widely developed, and the dominant role of initial equilibrium state and prestressed force is also widely recognized.

As Tensegrity structures are prestressable system, the geometrical configuration of the Tensegrity structure is difficult, unless suitable conceptual tools are employed. Few programs are available for this purpose. A method which is called ‘formex configuration processing’ is proposed by Nooshin (1975) to provides the conceptual tools that are needed for convenient handling of space structure configurations. A correspond software called Formian is also designed by Rebielak (2000) which has been used for the shaping of cable dome in circular layout. However, the research is not sufficient. The geometrical configuration methods proposed so far are still quite complicated for practical applications in the industry.

For application purpose, it is necessary for the designers to find a convenient way for the structural and geometrical design of the Tensegrity structures. A better understanding of correspondent structural features with different layout is also important. An ideal structural configuration design can reduce the cost of the structure.

For this purpose, a non-linear analysis program is proposed by the author. Using this program, the initial equilibrium of prestressed force can be determined, and then the non-linear geometrical static analysis can be performed. Using the general purpose package AutoCAD as a platform, the software also incorporates the pro-processing and post-processing functions. With these functions, a 3-D Tensegrity model can firstly be designed using AutoCAD program; then the DXF file of the model can be converted into text files with the format required by the proposed program of the author or any other general purpose finite element package such as SAP, ANSYS, ABAQUS. Therefore, the structural analysis of the model can be performed. After the analysis, the result file of the analysis can be transformed back into the DXF file, the analysis results such as the internal force and the displacement of the 3-D model can be post-viewed in AutoCAD as well as shown in Figs. 3-4. As AutoCAD is a commercial software widely used by the structural engineer, therefore the design of the Tensegrity dome becomes convenient.

As stated by Castro and Levy (1992), the dead load of the roof is very low, seismic loads do not affect the cable design and must be considered only for the design of the supporting column that supports the compression ring. Therefore, only static analysis is performed in this paper. Using the proposed program, the first Tensegrity dome project—Cable Dome is analyzed as a prototype. A comprehensive study on the structural behavior of Tensegrity domes is presented. Based on the analysis, optimizing design was performed, several new types of the Tensegrity Dome are designed and proposed by the author, analysis shows that they all have reasonable structural configurations.

2. Structral analysis and geometrical configuration method

The Tensegrity structure is a non-linear geometrical system. It is unable to resist loads before it is prestressed. It can only become stable and stiff with the existence of internal prestressed force.

For the structural analysis, it assumed that:

(a) Cables are regarded to be perfectly flexible; they can sustain only tensile force and are devoid of any flexural rigidity;

(b) The deadweight of struts is taken as concentrated nodal forces shared equally at its two end joints;

(c) Loads on cable, such as self-weight, is distributed uniformly along the curve of the cable which is assumed to be a parabola; and

(d) The materials of both cables and struts have linear elastic stress–strain relationship, and their strains are small.

The structural analysis can be divided into two phases: the first phase is the initial equilibrium of the prestressed force; the second phase is static analysis. The proposed program is designed based on above numerical method. The two phases are presented below:

2.1. Boundary conditions

It is important to determine the boundary conditions before the analysis. For the instance of Levy's Georgia Dome, a compression ring beam along the outer edge of the roof is supported on radically sliding bearing pots by 52 columns projecting up from the seating structure below. Twenty six attachment points spaced about 25 m on centre around this compression ring serve as the springing points for the cable dome. Therefore, for the boundary conditions, it is assumed that the dome is pin supported at the edge of the roof.

2.2. Determination of the initial prestressed force

When the boundary condition is determined, the distribution and magnitude of the prestressed force applied to the Tensegrity structure will determine the initial equilibrium state of the structure. Iterative method is used in the program to determine the initial geometrical equilibrium state of the structures.

In the procedure of the determination of the initial equilibrium, the coordinate can be firstly presumed with an ideal distribution of the prestressed force as it was recommended by Castro and Levy (1992) that an initial prestress averaging 30% of cable capacity was needed to rigidize the structure. However, the nodes of the structure could not be balanced under this condition, imbalance force will be resulted, hence, the displacement of the nodes will also be resulted. Thus, the coordinate and the prestressed force need to be adjusted step by step by the program using non-linear iterative method until the whole structure is balanced. The formula to determine the initial equilibrium is

$$[K]^0\{\Delta U\}^0 = -\{P\}^0 + \{R\}^0 \tag{1}$$

Where $[K]^0$ is initial stiffness matrix

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

$\{P\}^0$ is Prestressed force

$\{R\}^0$ is the Residual force

2.3. Static analysis

After the determination of the initial equilibrium of the structure, the load is applied, the static analysis can be performed. The fundamental formula for static analysis is:

$$[K]\{U\} = -\{P\} + \{R\} \tag{2}$$

Where $[K]$ is the total stiffness matrix

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

$\{P\}$ is the Load vector

$\{R\}$ is the residual force

The Newton Raphson approach is used here for solving the solution of the equation. 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 non-linearity 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 until the convergence of the iteration.

For each step:

$$[K]_i \{\Delta U\}_i = \{\Delta P\}_i \tag{3}$$

$$\{U\}_i = \{U\}_{i-1} + \{\Delta U\}_i \tag{4}$$

Where $[K]_i$ Stiffness matrix when $n = i$

$\{\Delta U\}_i$ Increment of the displacement when $n = i$

$\{\Delta P\}_i$ Imbalance load when $n = i$

$\{U\}_i$ displacement when $n = i$

$\{U\}_{i-1}$ 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:

$$\{F\}_i = \{F\}_{i-1} + \{\Delta F\}_i \tag{5}$$

Where $\{F\}_i$ the internal force of member $n = i$

$\{F\}_{i-1}$ the internal force of member $n = i-1$

$\{\Delta F\}_i$ the increment of member when $n = i$

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

$$\{U\} = \sum_{i=1}^{n} \{\Delta U\}_i = \{\Delta U\}_1 + \{\Delta U\}_2 + \cdots + \{\Delta U\}_n \tag{6}$$

$$\{F\} = \sum_{i=1}^{n} \{\Delta F\}_i = \{\Delta F\}_1 + \{\Delta F\}_2 + \cdots + \{\Delta F\}_n \tag{7}$$

Apart from the non-linear structural analysis of the Tensegrity structures, the geometrical design can also be performed on the basis of AutoCAD. The pre-processing and post-processing functions of the program were based on the redevelopment of AutoCAD using Autolisp language. As cable and strut have different mechanical properties, the key issue of the pre-processing and the post-processing program is to identify these two different types of members. A very simple and effective method is used in the program. When designing the 3-D Tensegrity model, different type of members such as ridge cable, diagonal cable, hoop cable and strut are sorted into different layer with different colours, when decoding the DXF file, the program can automatically sort the different member into different group according to their colours. The strut members are grouped into truss element group, which can resist tension and compression force. And the cable members are grouped into cable element group, which can only resist tension force. After structural analysis, the post-processing program can convert the analysis result file back into 3-D models with different colours to denote different type of members. The internal force and the nodal displacement can be viewed in AutoCAD.

The whole analytical procedure of the software can be described as: 3-D Structural model design---conversion of model figure into text data files---non-linear computing and analysis---result files---conversion of text data file back into 3-D model---post-view of force and displacement of the model.

3. Structural behaviour of the cable dome

As shown in Fig. 1, Geiger's Cable Dome is the first built Tensegrity structures, The Gymnastic and the Fencing Arenas for the Korean Olympics are circular cable domes having diameters of 119.7 m and 89.9 m, respectively. The cable dome spans the space using continuous tension cables and discontinuous compression posts as shown in Fig. 2. Loads are carried from a central tension ring through a series of radial ridge cables, tension hoops, and intermediate diagonals until they are resolved in a perimeter compression ring. The tension hoops are 14.47 m apart. For the Fencing Arena there are two tension hoops and for the Gymnastic Arena there are three. The ridge and diagonal cables separate

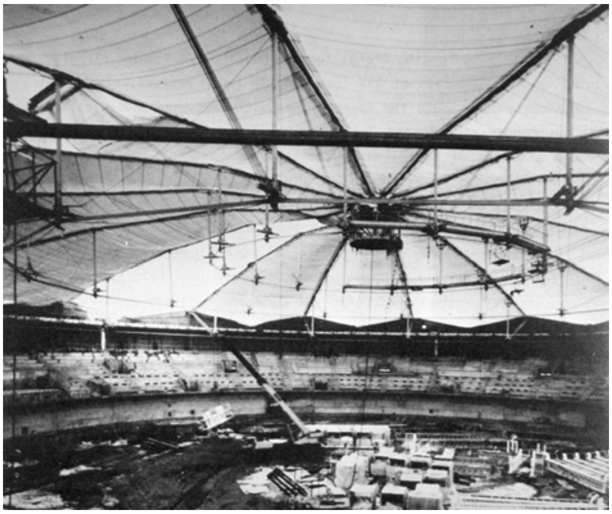
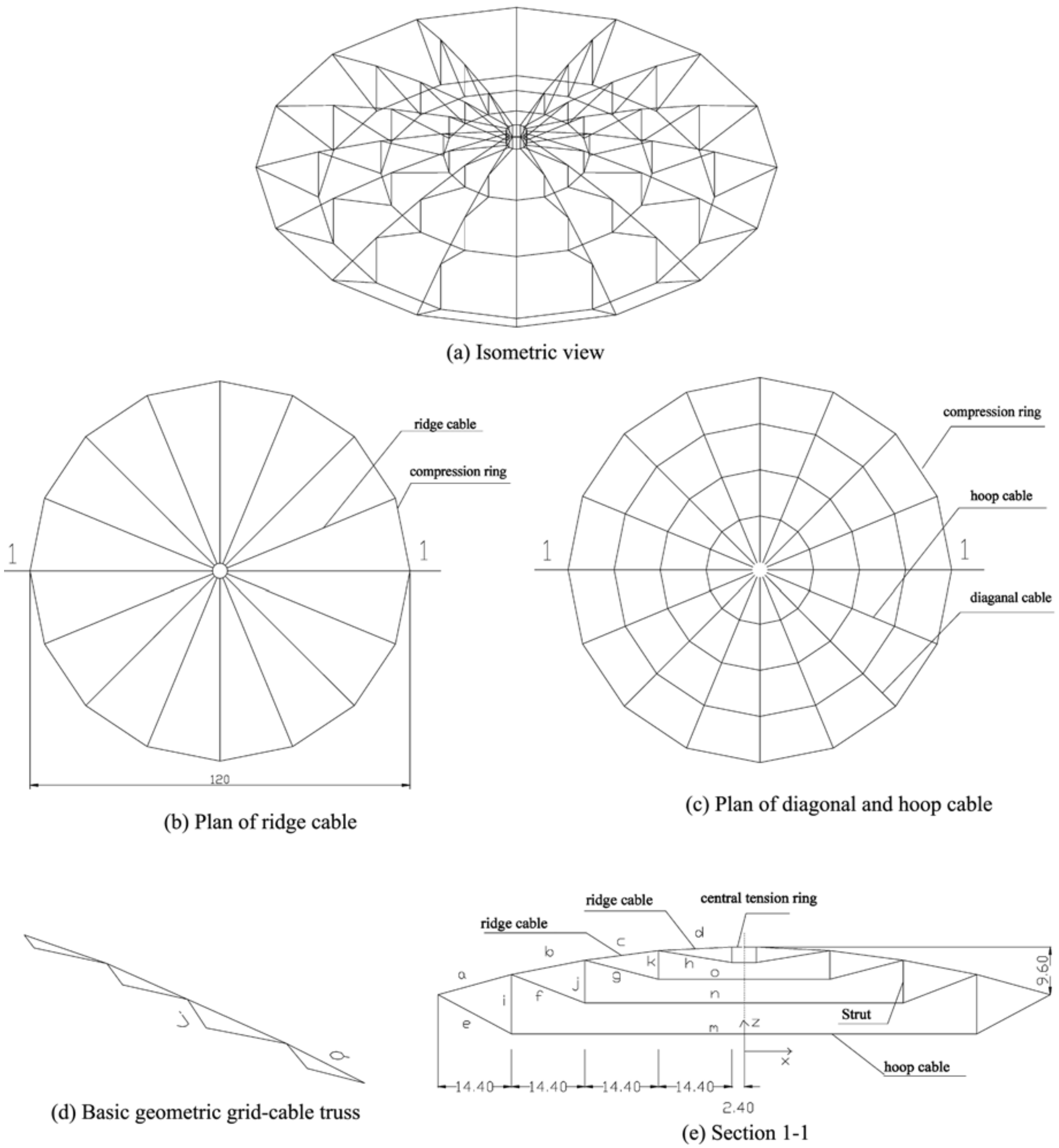


Fig. 1 The Gymnastics Arena interior, under construction (Geiger 1986)



(a) Isometric view

(b) Plan of ridge cable

(c) Plan of diagonal and hoop cable

(d) Basic geometric grid-cable truss

(e) Section 1-1

Fig. 2 Geiger's Cable Dome

the roof into sixteen equal segments, they form as a cable truss as shown in Fig. 2(d). For roofs with equal segments, equal hoop spacing, equal loading on tributary areas and corresponding vertical geometry, the corresponding members of cable domes of different diameters carry the same load as one moves from the center of the dome outward. By analogy, the dome behaves as two cantilever trusses (as shown in Fig. 2(d)), not quite touching at the center. This gives rise to significant repetition of details and allows for the use of castings at the connection points where posts and cables meet. As a consequence, the two rings of the Fencing Arena share the same castings at the top and bottom of the posts and the Gymnastics Arena requires another set of castings for the top and bottom of the posts of the outermost hoop.

In this paper, the Gymnastic Arena is analyzed using the proposed nonlinear analysis program. The structural behavior of cable dome is therefore discussed.

3.1. The structural layout and material used for analysis

The model of the cable dome was built using the proposed program with the actual dimension of Gymnastics Arena. Fig. 2 shows the structural layout and dimension of the model of Cable Dome. In order to clarify the geometrical relationships between different members of the model, different letters are used to denote different members. In Fig. 2(e), letter a, b, c and d denote the ridge cable in each layer; letter e, f, g, h denote the diagonal cable in each layer; letter l, m, n denote the tension hoop cable in each layer, while letter i, j, k, l, denote the compression strut in each layer, all ascending from the bottom to top.

The following materials are used for the structural analysis: 5 mm high strength tensile wires for cables with a tensile strength of 1670 N/mm^2 and Q345 circular tubes for struts with a yielding strength of 345 N/mm^2. Uniform superimposed load of 0.6 kN/m^2 is applied to the top surface of the dome. The diameter of the span is 120 mm.

The following cross sectional areas of the cables are used for the structural analysis in the paper. For ridge cables in a, b, c, d layers, the areas are 80 cm^2. For diagonal cables in e, f, g, h layers, the areas are 60 cm^2. For tension hoop cables in l, m, n layers, the areas are 100 cm^2. The following cross sectional areas of the strut was employed. For struts on i layers, the areas are 107 cm^2. For strut in j, k, l layers, the areas are all 52.4 cm^2.

Table 1 Comparison of structural types

Structural type	Steel wt (kg/m^2)	Nominal steel. wt (kg/m^2)	Max. vertical displacement (mm)
Cable dome	18.2	31.4	161
Type 1	24.3	42.4	124
Type 2	21.3	34.8	148

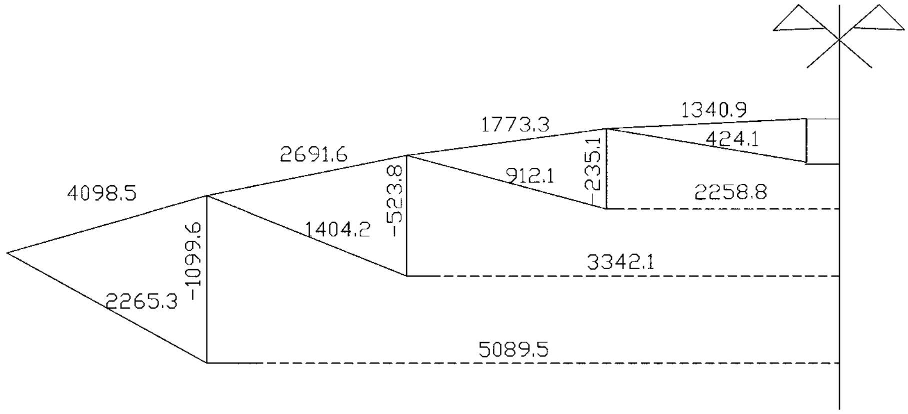


Fig. 3 The initial prestressed force equilibrium state of the cable dome (kN)

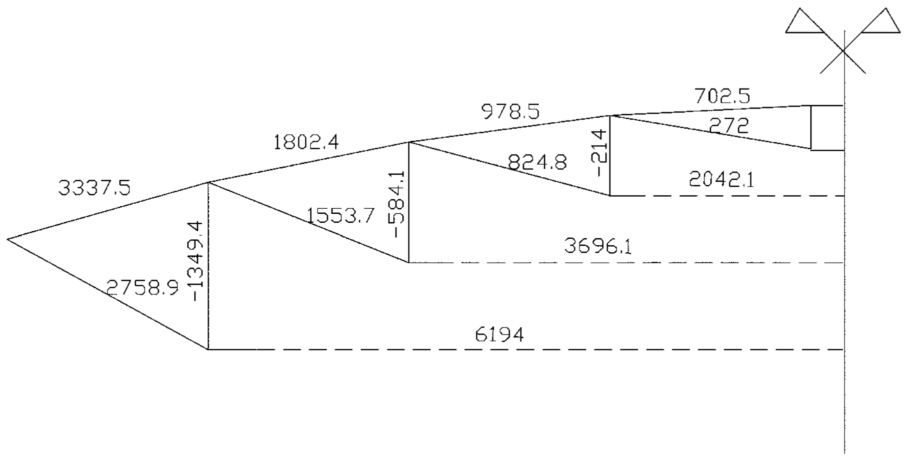


Fig. 4 The internal force of the members under vertical load (kN)

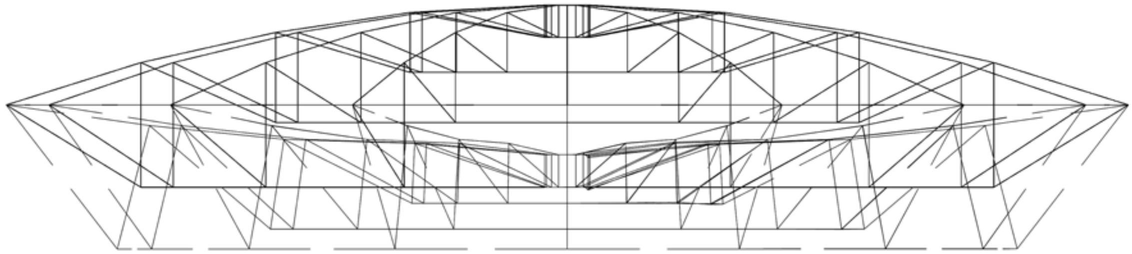


Fig. 5 Deformation of the Cable Dome model (100 times amplified from the original size)

3.2. The structural behavior of cable dome

From the structural analysis the internal force of the members, the steel consumption and the maximum displacement can be obtained by the proposed software as shown in Table 1 and Figs. 3, 4 and 5. The structural behaviour of the Tensegrity dome is described below.

3.2.1. The influence of the prestressed force

Fig. 6 shows the variation of bearing force of ridge cable in d layer under different prestressed force level 1000 kN, 3000 kN, 5000 kN, it can be seen that when the load increase the force of the ridge cable decrease, when it decrease to 0, the cable become slack. The variation of forces with loading is basically linear. It can be concluded that the higher the prestressed force, the greater the slack load. As stated in the later part, the mode of the failure is determined by the slack of the ridge cable in d layer, therefore, increase prestressed force can increase the bearing capacity of the cable dome.

Fig. 7 shows the changing of the vertical displacement under the different prestressed force level. It is assumed that the structure is under 100 kg/m^2 Load. It can be seen that the higher the prestressed force the less the vertical displacement.

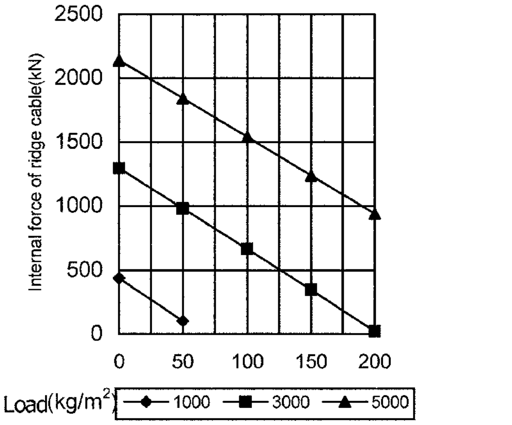


Fig. 6 Slacken force of ridge cable in d layer under different prestressed force level

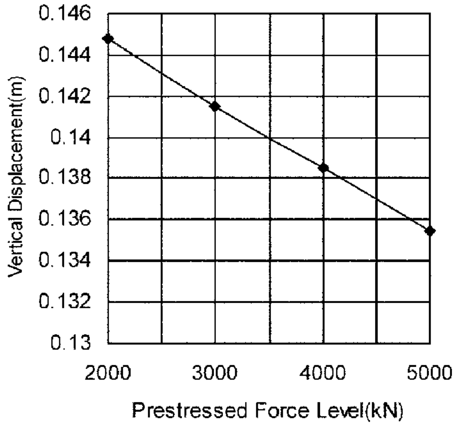
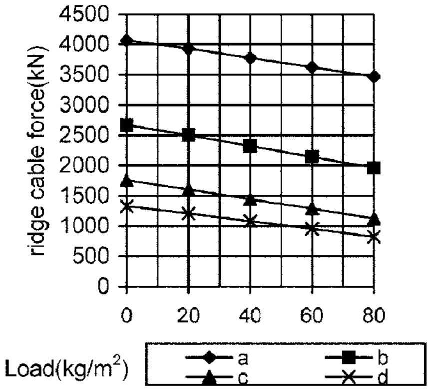
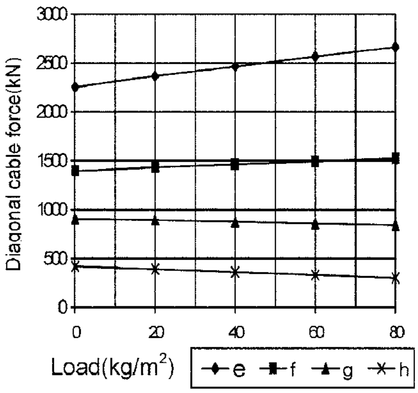


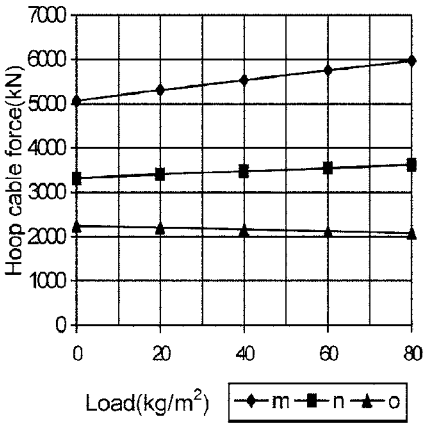
Fig. 7 Vertical displacement v.s. prestressed force level



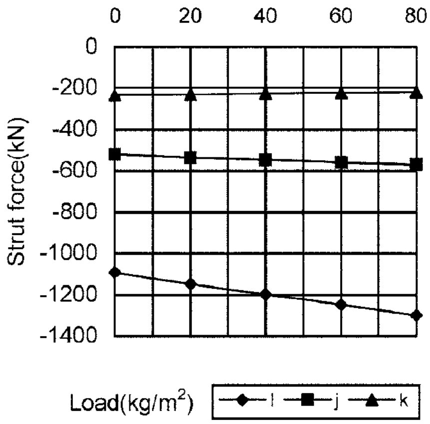
(a) Ridge cable force v.s. Load



(b) Diagonal cable force v.s. Load



(c) Hoop cable force v.s. Load



(d) Strut force v.s. Load

Fig. 8 Load and force relationship

3.2.2. The internal force v.s. load relationship

The analysis result of the structure under the vertical imposed load is shown in Fig. 8.

Fig. 8(a) shows the load and force relationship of the ridge cable in a, b, c, d layers, it can be seen that when the load increase the force in every layer decrease, when it decrease to 0, the cable become slack. The variation of forces with loading is basically linear.

Fig. 8(b) shows the load and force relationship of the diagonal cable in e, f, g, h layers, it can be seen that the variation of forces in diagonal cables depends on its position. For outer and lower layer, it increases, while for inner and upper layer, it decreases.

Fig. 8(c) shows the load and force relationship of the hoop cable in m, n, o layers. Forces in hoop cables m, n increase with the load, and the force in hoop cable in layer o decrease.

Fig. 8(d) shows the load and force relationship of the strut cable in i, j, k layers. It can be seen that the force of the strut in different layers are all decrease as the load increase.

3.2.3. Mode of failure

From the structural analysis of the cable dome, it can be seen that, when the load keeps increasing, the forces in the ridge cables in d layer, the diagonal cables in h layer and the hoop cables in o layer all decrease. When the load attains certain value, the force of the ridge cables will decrease to zero, and thus the cables become slack. However, the forces of hoop cables in other layer and part of the diagonal cables are still increasing. The structure can still maintain its bearing capacity, but the deformation is increasing significantly. If the load increases further until one of the diagonal cables on h layer also becomes slack, then failure occurs to the whole structure. Therefore, the failure mode of cable dome is the slackening of the ridge cable and diagonal cable in the central section of the dome. The slack of the cable in the central section determines the bearing strength of the structure.

3.2.4. The way to increase the bearing capacity

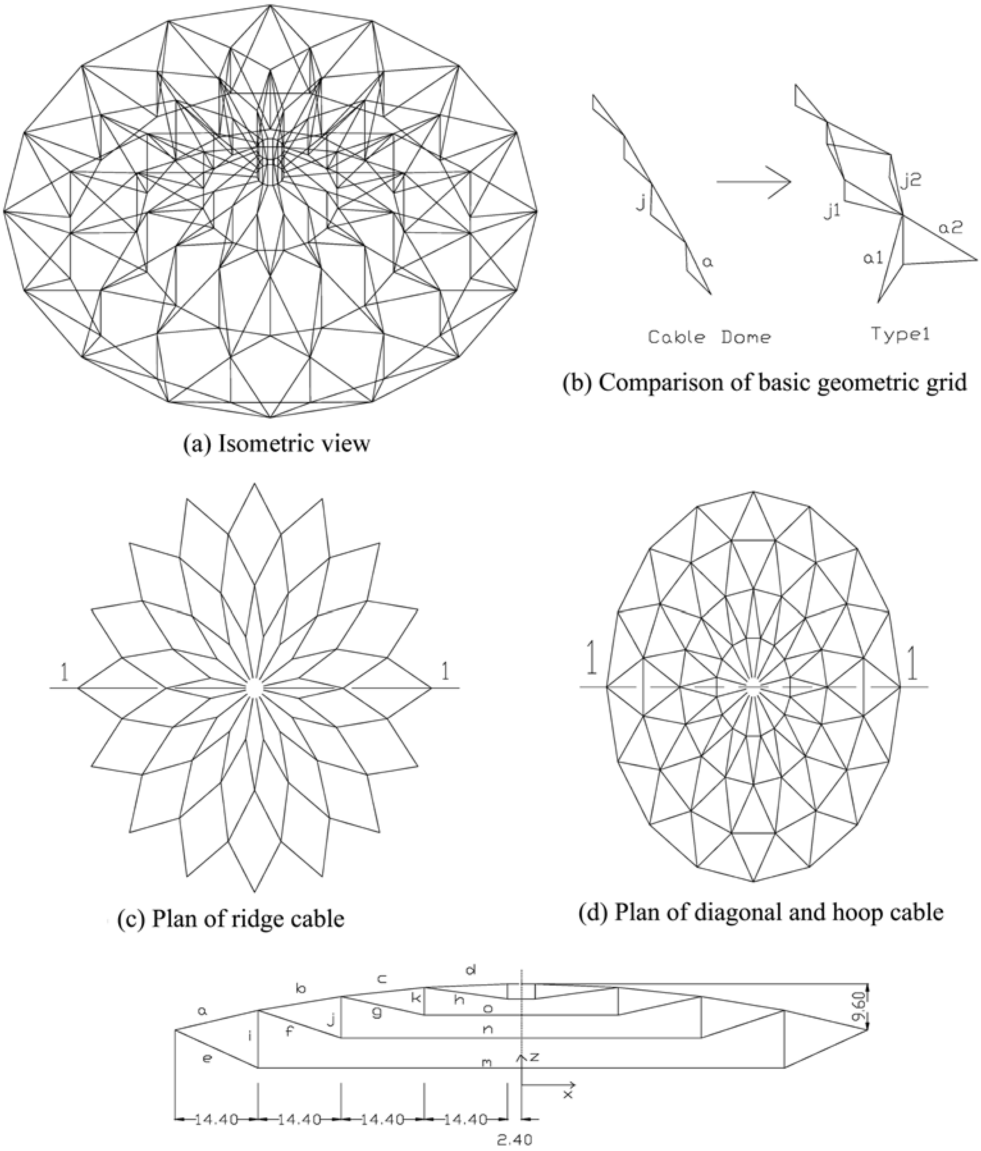
From the analysis it can be concluded that the inner and upper layer of the central section of the dome is the weakest in the whole structure. Therefore, an efficient way to increase the bearing capacity is to increase the prestressed forces in the ridge and diagonal cables on the inner and upper layer of the central section of the dome as it can delay the slacking of the central cable.

4. Proposed structural types

Based on the structural behavior of the cable dome, several structural schemes of Tensegrity domes are designed and analyzed by the author. For the purpose of comparison, the span of type 3 is the same as Levy's Georgia Dome with the same materials, and same materials are chosen as well. All the remaining schemes are designed in a circular plan with the same span of 120 m as Geiger's Cable Dome with the same materials. The schemes are analyzed under the same load as well.

4.1. Structural Type 1 in circular layout

Fu (2005) proposed that, the circular Cable Dome designed by Geiger demonstrates some significant advantages. The ways of forming networks in wedge shape of the cable dome is simpler than the triangulated networks. The number of cable elements is less, and hence less weight. As there are less cables connecting at a node, the construction of a joint is more or less easy. The advantages of such



(a) Isometric view

(b) Comparison of basic geometric grid

(c) Plan of ridge cable

(d) Plan of diagonal and hoop cable

(e) Section 1-1

Fig. 9 Structural Type1

network are shown on circular domes, since the construction of the joints in each layer is the same, so the types of joints are less. However, the stiffness of cable dome is smaller when compared with the triangulated dome system, especially in the horizontal direction. There are no links between the top chords joints in the circumferential direction of the cable dome. For triangulated networks, all the top chord joints are connected by the ridge cables, thus a greater horizontal stiffness can be obtained. Based on this finding, all the three new structural types of Tensegrity domes are designed using triangular network.

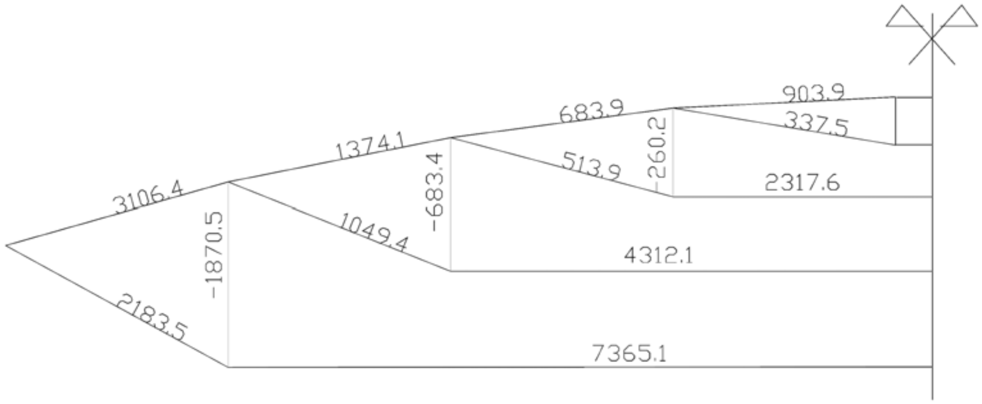


Fig. 10 The internal force of the members under vertical load (kN)

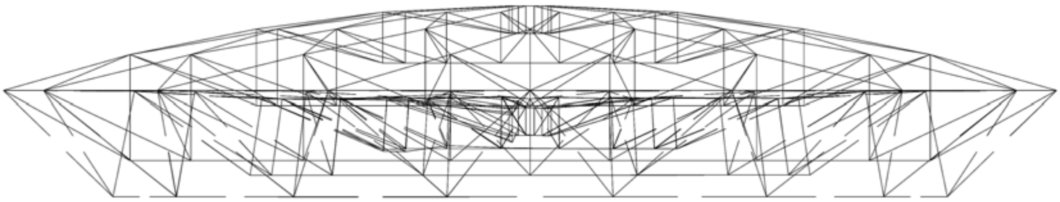


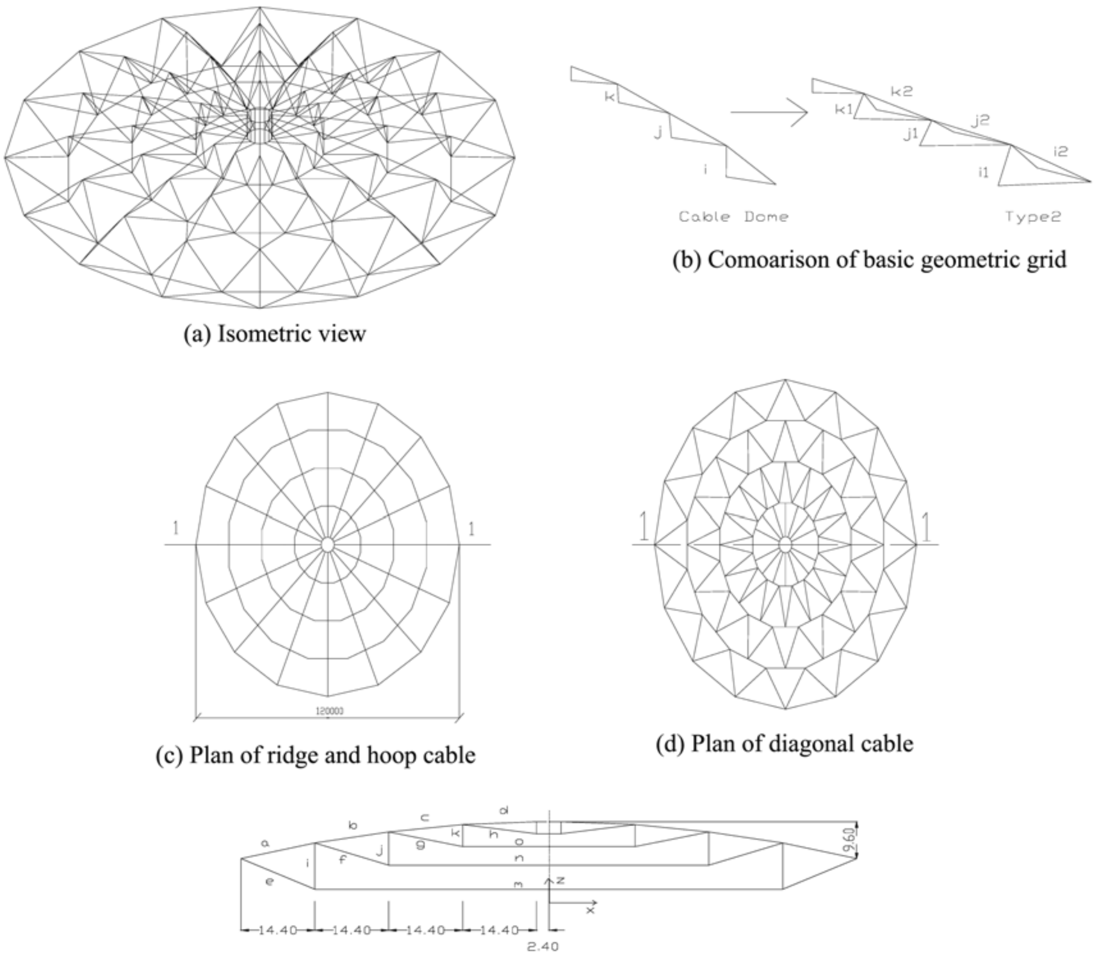
Fig. 11 Deformation of the proposed model (100 times amplified from the original size)

The structural type 1 is in circular layout, it is composed of ridge cable, diagonal cable, hoop cable, strut, compression ring and central tension ring, the difference between type 1 and Cable Dome is shown in Fig. 2(d) and Fig. 9(b). In Geiger's cable dome design, ridge cable, diagonal cable, strut are in the same plan, just like a planar truss. But in Type 1, strut **j** is divided into two struts **j1** and **j2**, and ridge cable **a** is divided into **a1** and **a2**. Therefore a triangular network is built. With this improvement the out plane stability of the cable truss is increased. The analysis results are shown in Fig. 10 and Fig. 11. As shown in Table 1, compared with Cable Dome, the maximum displacement is decreased so the stiffness of the dome is increased.

The layout and dimension of the dome is shown in Fig. 9. In Fig. 9, the same letters as in Fig. 2 are chosen to denote the members in the different layer. The cross sectional area of structural member are taken as follows: For ridge cables - 60 cm^2, for diagonal cables - 40 cm^2, for tension hoop cables -130 cm^2, for strut in i layer - 137.5 cm^2, other struts - 59.6 cm^2.

4.2. Structural Type 2 in circular layout

Type 2 is in circular layout dome as well. The difference between type 2 and Geiger's Cable Dome is the struts (shown in Fig. 12(b)). It can be seen that in type 2, the strut has been divided into two diagonal struts rather than Cable Dome to form the triangular network. So the amount of the strut is twice of Geiger's Cable Dome and therefore the amount of the diagonal cables is twice of Geiger's Cable Dome. The analysis results are shown in Fig. 13 and Fig. 14. As shown in Table 1, the stiffness of the type 2 is also increased.



(a) Isometric view

(b) Comoarison of basic geometric grid

(c) Plan of ridge and hoop cable

(d) Plan of diagonal cable

(e) Section 1-1

Fig. 12 Structural Type 2

Fig. 12 shows the layout and dimension of the dome, where, the same letters are chosen to denote the different layer of member as Cable Dome. The cross sectional areas of structural members are taken as follows. For ridge cables - 80 cm^2, for diagonal cables - 30 cm^2, for tension hoop cables 110 cm^2, for strut in layer i - 89.4 cm^2, other struts - 49.8 cm^2.

4.3. Structural Type 3 in elliptic layout

As few elliptic layout Tensegrity dome was built so far, it is important to study the design method of the dome with elliptic layout as well. In this section, a model with elliptic layout is designed. As shown in Fig. 15, the model is built up by central cable truss (as shown in Fig. 15(d)), diagonal cable, ridge cable, hoop cable and struts. From Fig. 15(b) it can be seen that, the ridge cables are distributed radiate from the central truss. As discussed in Fu (2005) the central part of the structure is the weakest, and the way to increase the bearing capacity is to enhance the bear capacity of the central member, therefore,

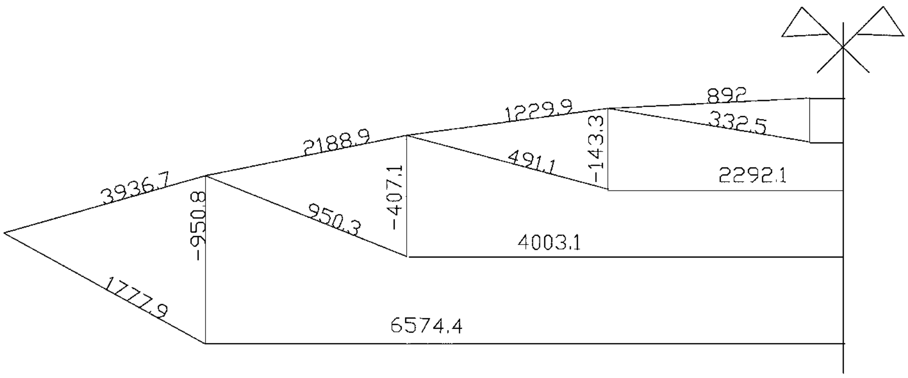


Fig. 13 The internal force of the members under vertical load (kN)

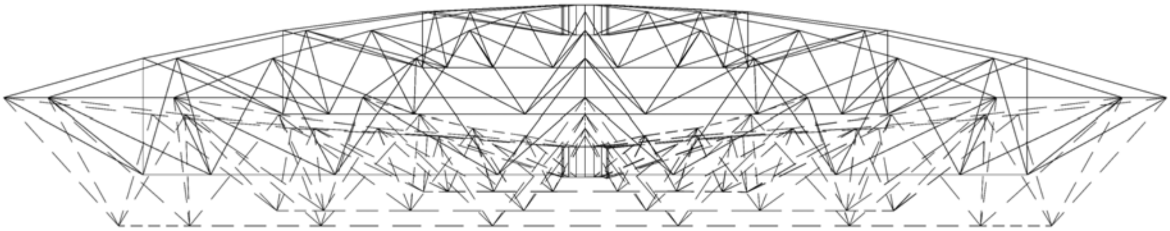


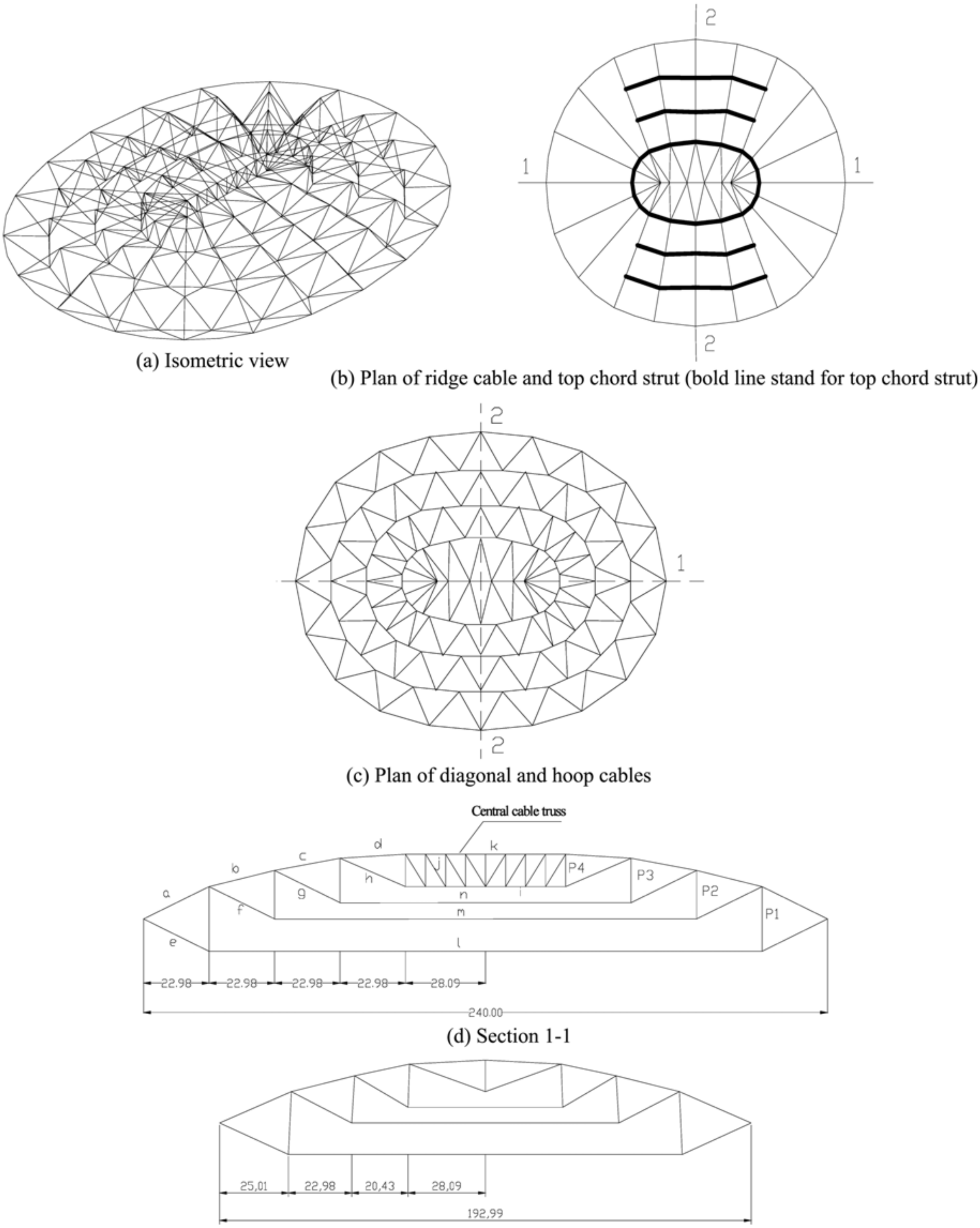
Fig. 14 Deformation of the proposed model (100 times amplified from the original size)

rigid steel bar (as shown in Fig. 15(b)) is used in the central part in order to provide greater stiffness and greater bearing capacity. As the similar grid design of Type 2 is used, the diagonal cables are decreased to two for each connection, rather than four cables as Georgia Dome, and there are no struts connected to the connection as well. Therefore, the complexity of the fabrication of the connection is also reduced. The design principle can be concluded as: strengthen the central section and to simplify the semi-circular sections.

In Fig. 15, a, b, c, d denote the ridge cable in each layer; e, f, g, h denote the diagonal cable; l, m, n denote the tension hoop cable, i, j, k denote the cable in the central cable truss, while P1, P2, P3, P4 denote the compression strut, all ascending from the bottom to top. In order to be compared with Georgia Dome, the span is the same as 240 m. The material for the members and the imposed load remains same as well.

The following cross sectional area of the cables are used for the structural analysis in the paper. For ridge cables in a, b, c, d layers, the areas are 100 cm^2. For diagonal cables in e, f, g, h layers, the areas are 80 cm^2. For tension hoop cables in l, m, n layers, the areas are 200 cm^2, for the cable in the central cable truss, i, j, k, the area are 80 cm^2. respectively. For struts in P1, P2, P3, P4 layer, the areas are 127.8 cm^2, for the strut on the top chord in the central part, the areas are 308.5 cm^2.

From the structural analysis the unit steel weight and the displacement of the scheme is obtained by the proposed program. The unit steel weight used is 31.5 (kg/m^2). Fig. 16 is shows the deformation mode of the model, the maximum vertical displacement is 700 mm. Compared with analysis result of Georgia Dome by Fu (2005), which has unit steel weight as 23.3 (kg/m^2) and maximum vertical displacement as 706 mm, the proposed model is reasonable for application practice in the construction design.



(a) Isometric view

(b) Plan of ridge cable and top chord strut (bold line stand for top chord strut)

(c) Plan of diagonal and hoop cables

(d) Section 1-1

(e) Section 2-2

Fig. 15 The proposed model

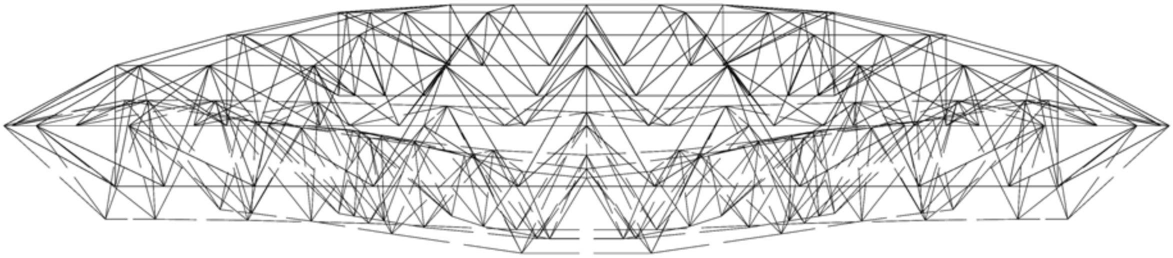


Fig. 16 Deformation of the proposed model (100 times amplified from the original size)

5. Comparison of the structural types

The structural types in circular layout have been proposed by the author are compared with the prototype – Geiger's Cable Dome in terms of steel weight, nominal steel weight and maximum vertical displacement in Table 1. As the cost of the cables is approximately twice the cost of the steel sections, the weight of the cable is multiplied by 2 and then added to the weight of the steel sections to give the nominal steel weight of the corresponding structural type. This will reflect the cost of the structure in a more objective sense.

From Table 1, it can be seen that structural types 1, 2 all demonstrate a low steel consumption. Although their steel consumption is a little bit greater than Cable Dome, but it has a greater stiffness. Therefore, the structural types proposed by the author are practical. It is expected to be put into practice in the future.

6. Conclusions

From above research it can be concluded that:

1. A software to design and analyze the structural behavior of the Tensegrity dome is proposed by the author. It can perform non-linear analysis of the structure with convenient pre-processing and post-processing functions.
2. The presressed force is an influential factor to the Tensegrity dome, the higher the prestressed force, the smaller the displacement and the higher the bearing capacity.
3. The failure mode of Tensegrity dome is characterized by the slackening of the ridge and diagonal cables in the central section of the dome.
4. The efficient way to increase the bearing capacity is to strengthen the central section of the dome by means of increase the prestressed forces in the ridge and diagonal cables on the inner and upper layer of the central section of the dome or for the dome with elliptic layout, using rigid steel bar at the central part of the dome. It can be concluded as strengthen the central section and to simplify the remaining sections
5. The 3 structural types proposed by the author have different features, they are all reasonable for practical application and can be used in the design of Tensegrity Dome.

References

Canadas, P., Laurent, V. M., Oddou, C., Isabey, D. and Wendling, S. (2002), "A cellular tensegrity model to analyse the structural viscoelasticity of the cytoskeleton", *J. Theoretical Biology*, **218**(2), 155-173.

Castro, G. and Levy, M. (1992), "Analysis of the Georgia Dome Cable Roof ", *Proc. of the Eighth Conf. of Computing in Civil Engineering and Georgraphic Information Systems Symposium*, ASCE, ed. by Barry J. Goodno and Jeff R. Wright. Dallas, TX, June 7-9.

Fu, F. (2005), "Structural behavior and design methods of Tensegrity domes", *J. Constr. Steel Res*., **61**(1), 23-35.

Fuller, R. B. (1975), *Synergetics Explorations in the Geometry of Thinking*, Collier Macmillan Publishers, London.

Geiger, D., Stefaniuk, A. and Chen, D. (1986), "The design and construction of two cable domes for the Korean Olympics, shells, membranes and space frames", In: *Proc. of IASS Symposium*. Osaka, **2**, 265-272.

Hanaor, A. (1993), "Developments in tensegrity systems: An overview," In: H. Nooshin, Editors, *Proc. of the 4th Conf. on Space Structures*, University of Surrey, 987-997.

Hidenori, Murakami (2001), "Static and dynamic analyses of tensegrity structures. Part 1. Nonlinear equations of motion", *Int. J. Solids Struct.*, **38**(20), 3599-3613.

Ingber, D. E. (1993), "Cellular tensegrity: Defining new rules of biological design that govern the cytoskeleton", *J. of Cell Science*, **104**(Pt 3), 613-627.

Kebiche, K., Kazi-Aoual, M. N. and Motro, R. (1999), "Geometrical non-linear analysis of tensegrity systems", *Eng. Struct.*, **21**(9), 864-876.

Levy, M. (1989), "Hypar-tensegrity dome", *Proc. of Int. Symp. on Sports Architecture*, Beijing, 157-162.

Levy, M. (1991), "Floating fabric over georgia dome", *Civil Engineering ASCE*, 34-37.

Motro, R. (1992), "Tensegrity systems: The state of the art", *Int. J. of Space Structures*, **7**(2), 75-81.

Nooshin, H. (1975), "Algebraic representation and processing of structural configurations", *Int. J. of Computers and Structures*, June.

Rebielak, J. (2000), *Structural System of Cable Dome Shaped by Means of Simple Form of Spatial Hoops, Lightweight Structures in Civil Engineering*, Warsaw, Poland: Micro-Publisher Jan B.

Sultan, C., Corless, M. and Skelton, R. (2001), "The prestressability problem of tensegrity structures: Some analytical solutions", *Int. J. Solids Struct.*, **38**(30-31), 5223-5252.

Skelton, R. E. and Sultan, C. (1997). "Controllable tensegrity, a new class of smart structures", SPIE, San Diego, pp. 12.

Williamson, D., Skelton, R. E. and Han, J. (2003), "Equilibrium conditions of a tensegrity structure", *Int. J. Solids Struct.*, **40**(23), 6347-6367.

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