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Structural evaluation of a foldable cable-strut structure for kinematic roofs

Jianguo Cai [*1,2], Qian Zhang [1a], Yiqun Zhang [2b], Daniel Sang-hoon Lee [3c] and Jian Feng [1d]

[1] *Key Laboratory of C & PC Structures of Ministry of Education, National Prestress Engineering Research Center, Southeast University, Nanjing 210096, China*
[2] *Key Laboratory of Electronic Equipment Structure Design, Ministry of Education, Xian 710071, China*
[3] *Institute of Architecture and Technology, The Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation, Copenhagen 1435, Denmark*

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Abstract. The rapidly decreasing natural resources and the global variation of the climate push us to find intelligent and efficient structural systems to provide more people with fewer resources. This paper proposed a kinematic cable-strut system to realize sustainable structures in responding to changing environmental conditions. At first, the concept of the kinematic system based on crystal-cell pyramid (CP) cable-strut unit was given. Then the deployment of the structure was studied experimentally. After that, the static behaviors in the fully deployed state under the symmetric and asymmetric load cases were investigated. Moreover, the effects of thermal loading and the initial prestress distribution were also discussed. Comparative studies between the proposed structure and other deployable cable-strut system under three times of design load cases were carried out. Finally, the robustness of the system was studied by removal of one passive cable at one time.

Keywords: kinematic roof; cable-strut structures; deployment; mechanical behavior; robustness

1. Introduction

Some kinematic structures can be found from nature, such as the extensible worm, foldable leaves and wing of insects, expanding virus capsid, and human body (Kovács *et al*. 2004, Pellegrino 2001). There are also many small-scale deployable/foldable structures in the daily living equipments, such as fans, umbrellas, and chairs etc. It can be found that the deployable/foldable structures have the ability to move between a folded state to a deployed state (De Temmerman 2007, Cai *et al*. 2015a). Therefore, in the last two decades, deployable structures are often used as antennas, booms and solar sails in the space (Pellegrino 2001, Gantes 1996, Bai *et al* 2017). On the other hand, it had been mainly used for tents, shelter, bridges, building skins and retractable roof structures (Chen *et al*. 2015, 2016, Cheng *et al*. 2015, Filipov *et al*. 2015, Fu 2006, Li and Wu 2017, Liu *et al*. 2017, Raheem 2014, Sareh and Guest 2015, Yan *et al*. 2015, Zhou *et al*. 2014).

Now 50% of the world population lives in an urban environment and they produce more than 75% of all CO2 emissions. By 2050, there will be 70% of the population will live in cities. Moreover, the rapidly decreasing natural resources and the global variation of the climate are also insistent problems, which push us to find intelligent and efficient structural systems to provide more people with fewer resources (Friedman *et al*. 2011). This leads to a sustainable engineering structural system. Sustainable solutions using kinetic systems in architecture are explored for their inherent advantages in responding to changing environmental conditions.

Some kinetic solutions in architecture have been implemented with a specific focus on sustainability. A deployable scissor system, which is used to cover and heat of an Olympic swimming pool during the cold season, was proposed with ability that it could be assembled in only a few days (Escrig *et al*. 1996). Block (2013) proposed an interactive kinetic architecture with structures that tend to become alive, as organisms with a skeleton, muscles, tendons, a skin, senses and a brain. Kokawa (1996, 1997) developed a cable scissors arch system, which can transform from a straight line configuration to an arch configuration. Then a proposed novel concept of planar scissor-hinge structures was introduced by Akgün *et al*. (2010, 2011). The new kinetic structures incorporate a new primary element, the so-called Modified Scissor-Like Element that enables them to exhibit higher geometric transformation capability. The most of these studies are based on the concept of scissor-like elements (Cai *et al*. 2014, 2015b). However, Liew *et al*. (2008) have stated that the system consists of scissor-like elements has low structural load bearing capacity. Recently, Wang and Li (2003) pointed out that cable-strut systems, which consist of bars and cables, have higher structural efficiency than conventional space trusses. Therefore, the cable-strut system is chosen as a candidate for the development of a kinematic cover structures.

The deployment of folding of the cable-strut system has

∗Corresponding author, Professor,
E-mail: caijg_ren@hotmail.com; j.cai@seu.edu.cn
[a] Ph.D. Candidate, E-mail: qianzhang@seu.edu.cn
[b] Associate Professor, E-mail: yiqunzhang@xidian.edu.cn
[c] Associate Professor, E-mail: Daniel.Lee@kadk.dk
[d] Professor, E-mail: fengjian@seu.edu.cn

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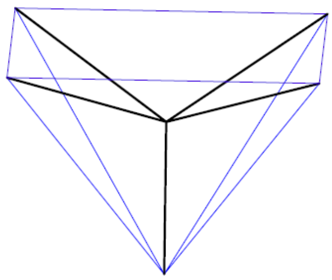
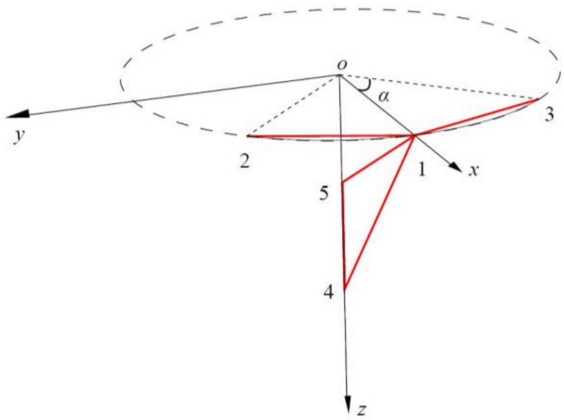
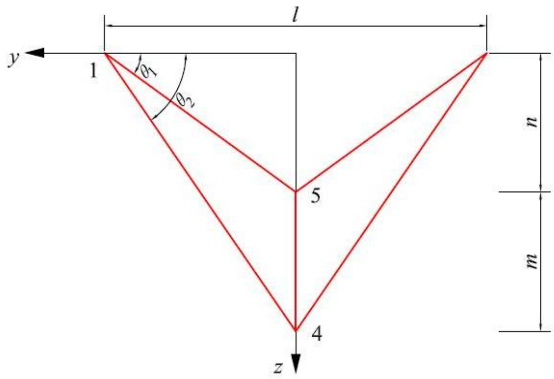


Fig. 1 The basic unit



(a) Elements at joint 1



(b) Elevation of the unit

Fig. 2 Sketch of CP unit

been studied by many researchers. Based on the remove of self-stress modes, two folding methods of cable-strut systems were proposed by Samili and Motro (2005). Vu *et al*. (2006a) explained the basic design concept of deployable cable-strut system. The nonlinear finite element analysis of four prototypes was carried out to study the structural behavior. They also proposed some viable alternative forms of deployable cable-strut system by using shape grammar in computer programming (Vu *et al*. 2006b). Recently, a novel deployable cable-chain system was developed by Li *et al*. (2011) based on the mechanism of linkages restrained by cables. Various structural forms such as barrel vaults, geodesic domes and their combinations were also studied. A new type of deployable cable-strut system was proposed by Cai *et al*. (2016). The mechanical behavior of this system was also investigated (Cai *et al*. 2018, 2019). However, in this study, the basic cable-strut element is complex. Therefore, the design of the joints of the deployable system is a big challenge. Then we should find a simple cable-strut element but has a good structural efficiency.

A basic crystal-cell pyramid (CP) unit, which is shown in Fig. 1, has been proposed by Wang (1998). The unit is formed by two pyramids with the same top polygon. The outer pyramid is composed of four inclined cables and four top cables, while the inner pyramid consists of four inclined struts and four top cables. The pyramid connects with each other through the central strut. The topology of this cable-strut is simple. The mechanical behavior of a foldable shelter based on a single CP unit was studied by Cai *et al*. (2012). The result shows the system has good structural performance. In this paper, a double layer lattice system based on CP units will be proposed as a kinematic roof structure for swimming pools or a deployable roof structure for long-span transitional shelters. The mechanical behaviors of the system under different load cases will be also studied. Moreover, the effect of pre-stress levels, temperature effects and cable losses on the structural behavior will also be discussed in this paper.

2. Foldable cable-strut structures

2.1 Basic unit

In each CP unit, only one state of self-stress exists and there is no inner mechanism state when it is fully unfolded. In order to make the state of self-stress more general, a CP unit, which consists of a regular polygon top with N edges, is studied in this section. Based on the force equilibrium condition, the self-stress state of CP unit can be obtained. It is assumed the axial force of the bar, which is connected to node i and node j, is q_{ij}. From Fig. 2, the force equilibrium equations of the joint 1 are given as

$$q_{12}\cos(a/2)-q_{13}\cos(a/2)=0 \tag{1}$$

$$q_{14}\cos\theta_2+q_{15}\cos\theta_1+q_{12}\sin(\alpha/2)+q_{13}\sin(\alpha/2)=0 \tag{2}$$

$$q_{14}\sin\theta_2+q_{15}\sin\theta_1=0 \tag{3}$$

where $a=\frac{2p}{N}$, $\tan q_1=\frac{2n}{l}$ and $\tan q_2=\frac{2(m+n)}{l}$, m the length of the vertical strut, n the rise of the inner pyramid and l is the span of the CP unit.

From Eq. (1), it can be found that

$$q_{12}=q_{13} \tag{4}$$

The relation between forces of top cables and inclined cables can also be obtained from Eq. (1) to Eq. (3) as

$$q_{14}(\cos q_2-\sin q_2/\tan q_1)+2q_{12}\sin(a/2)=0 \tag{5}$$

From Eq. (4), it can be found that the forces of all inclined cables are equal. Then the vertical equilibrium of Node 4 can be given by

$$q_{45} = -N \times q_{14} \sin\theta_2 \tag{6}$$

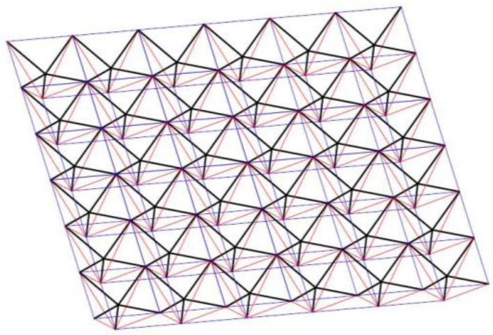
Based the above analysis, the state of self-stress of proposed system can be calculated by Eqs. (3), (5) and (6).

2.2 The kinematic roof system

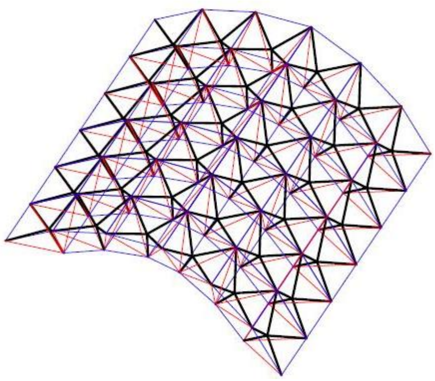
When the CP units are arranged in the two perpendicular directions of the horizontal plane, an additional layer of cables should be added to connect the apex joints of CP units to form the kinematic roof structure. When the length of this additional cables *l*’, which connect the apex joints of adjacent CP units, is equal to the length of the top cables of the CP unit *l*, a kinematic truss system is obtained as shown in Fig. 3(a). If the length of this additional cables *l*’ is smaller than the length of the top cables of the CP unit *l*, a kinematic barrel vault system is formed as shown in Fig. 3(b). The span *S* and the rise *H* of the barrel vault system can be obtained from Fig. 4 as

$$\frac{l'}{2} = \frac{l}{2}\cos\left(\frac{\varphi}{2k}\right) - (m+n)\sin\left(\frac{\varphi}{2k}\right) \tag{7}$$

$$R = \frac{l}{2\sin\left(\frac{\varphi}{2k}\right)} \tag{8}$$



(a) Planar truss system



(b) Barrel vault system

Fig. 3 The foldable grid system formed by CP unit

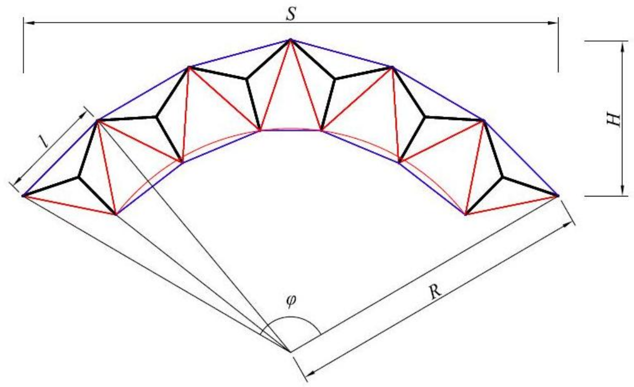


Fig. 4 The geometrical parameters of the barrel vault system

$$S = 2R\sin\frac{\varphi}{2} \tag{9}$$

$$H = R - R\cos\frac{\varphi}{2} \tag{10}$$

where R and φ are the radius and central angle of the circumscribed arc, k is the number of basic CP units.

2.3 Deployment of the system

The system proposed in Section 2.2 can be active by struts and cables. However, the number of actuators is large if struts are selected as active members. Therefore, cable driving is chosen. The deployment process of the basic CP unit is given in Fig. 5. It can be found that during the deployment process, inclined cables with red color are regarded as driving cables, and the length of these red cables are shortened constantly. Top cables with blue color and struts with black color are passive elements. For the struts, the length is not changed. For the passive cables, they are slack in the fully folded state. And they are become taut in the fully deployed state. In this configuration, cables and struts are not stressed if the system movement stops just when the passive cables become taut. However, a cable-strut system should have prestress if it needs stiffness to take external loads. Therefore, the driving cables should be further shortened at the end of system movement to obtain the prestress. The prestress distribution can be obtained using Eqs. (3), (5) and (6).

3. Experimental study of the deployment

In order to valid the concept of the kinematic cable-strut system, a prototype was constructed. The planar deployable truss system with nine basic units is selected as shown in Fig. 6. Every column and row has three CP units. The length of upper cables of each CP unit l is 1500 mm, the length of the vertical strut m is 250 mm and the rise of the inner pyramid n is also 250 mm. The area of the cross-section of struts is 144.5 mm^2 with the diameter of 25 mm and thickness of 2 mm. The area of the cross-section of cables is 19.6 mm^2.

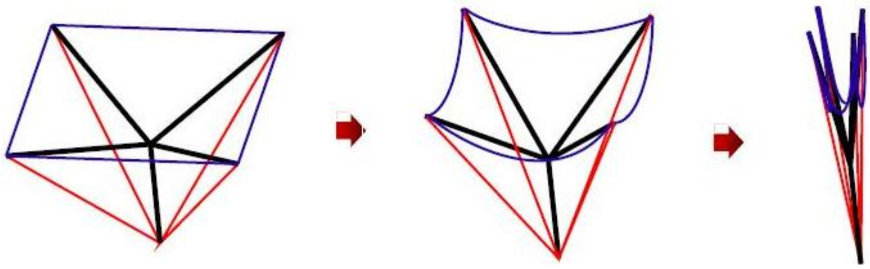
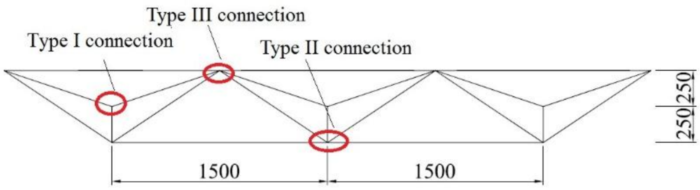
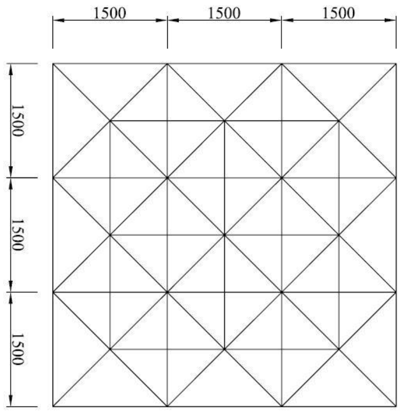


Fig. 5 Folding process of CP unit



(a) Side view



(b) Plane view

Fig. 6 The dimensions of the model

The biggest challenge of the prototype is the design of the connections between active and passive elements. Furthermore, the connection design has a strong relationship with the cost of the joint manufacture. These were overcome and working models were built for the proposed systems. There are three types of connections that were designed and built in this prototype.

The Type I connection, which is given in Fig. 7, is used to connect the cables can slide through the pulleys easily. As show five struts including four inclined struts and one vertical strut. This kind of joint provides the revolute connections for the four inclined struts and rigid connection for the vertical strut. The Type II connection is designed to connect the active cables by pulleys so that n in Fig. 8, the passive cables can be connected by the connection with the thread joint. Two ends of the passive cables are casting with

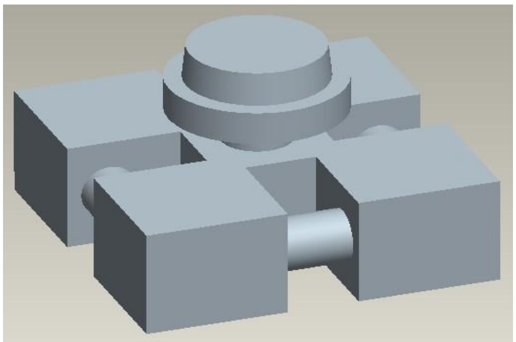


Fig. 7 Type I connection

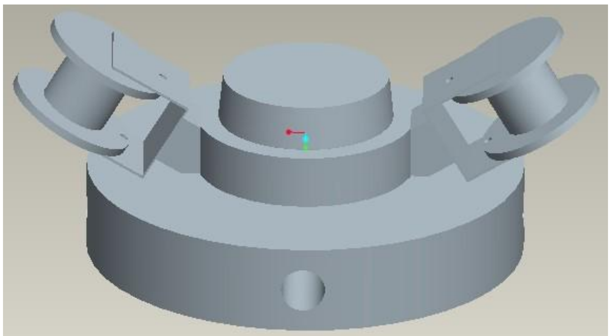


Fig. 8 Type II connection

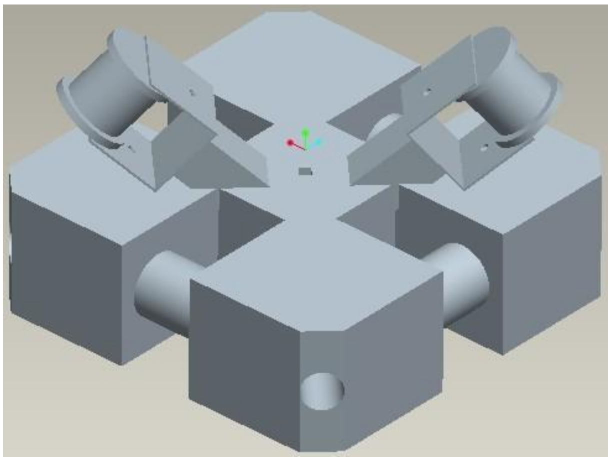


Fig. 9 Type III connection

Fig. 10 The prototype of Type III connection

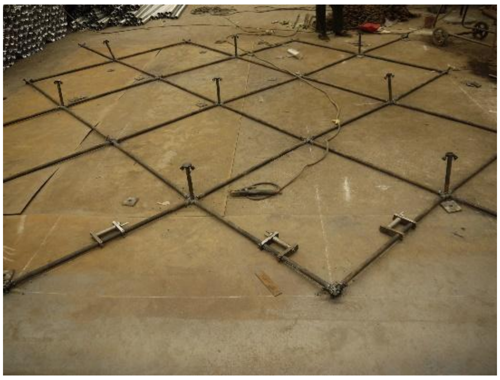


Fig. 11 The tension equipment

(a) Fully folded state

(b) Fully deployed state

Fig. 12 The deployment of the proposed system

positive threads and the connection has negative threads. Two ends of the vertical strut are rigidly connected with Type I and Type II connections. The third type of connection is used to connect four inclined struts, four passive cables and tow active cables. Therefore, this connection, which is shown in Fig. 9, can be seen as the combination of Type I and II connections. The prototype of Type III connection is given in Fig. 10.

In the prototype, the total length of passive cables is 1480 mm including the length of the thread at the two ends, which is 28 mm. One end of the active cable is a thread to joint with a Type III connection at the boundary unit. The other end of the active cable is rolled in tension equipment, which is fixed in a strut as given in Fig. 11. The tension equipment is used to shorten the active cables during the deployment process of the system. At construction sites, the connections are located firstly and then inclined struts are connected followed by construction of vertical struts. Finally, the cables are arranged at the folding state. The deployment of the proposed system is shown in Fig. 12. It can be found that the proposed kinematic cable-strut system is feasible.

4. Numerical study of mechanical behavior in the fully deployed configuration

4.1 Finite element model

When the cable-strut system is deployed, it is designed to resist external loads, such as dead loads, wind loads, snow loads and thermal loading, etc. In this section, the mechanical behavior of the structure given in Section 3 in the fully deployed configuration is studied. In the simulation, the lower nodes of four corner CP units are fixed. The dead load, snow load and thermal loading are considered. The value of the deal load is 0.5 kN/m^2. Two kinds of snow loads are investigated. One is that the snow load is applied in the full span and the other is that the snow load is only applied in the half span of the structure. The thermal loading is assumed to be from -30℃ to 30℃.

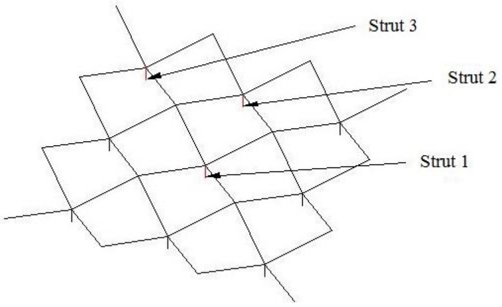
The software, ANSYS, is chosen for the numerical study. The Young's modulus of steel struts is 2.0×10^5 N/mm^2. A elastic perfectly-plastic material model is used for the steel struts with the yield stress of 235 MPa. A elastic material model is used for the cables with the Young's modulus of 1.9×10^5 N/mm^2. Element LINK 8 and LINK 10 are selected to simulate struts and cables, respectively. The initial prestress force in the active cables (inclined cables) is 3000 N, and the distribution of the other element forces is given in Table 1.

4.2 Structural behavior under dead and snow loads

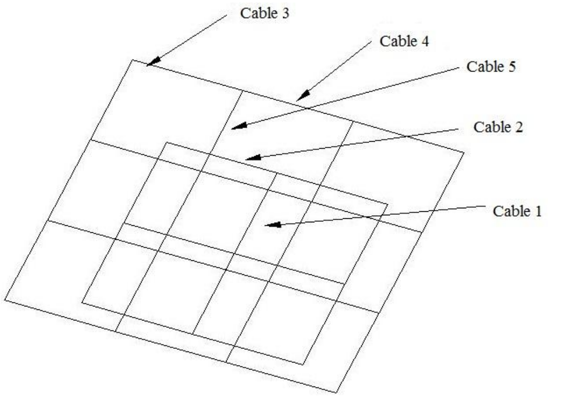
Two design load cases, load case 1 with the dead load and full-span snow load and load case 2 with the dead load and half-span snow load, are considered in the structures. The typical elements and nodes are selected to evaluate the element stress and nodal displacements. As shown in Fig. 13, three vertical struts, five passive cables, three upper

Table 1 Distribution of self-stress state of each element in CP unit

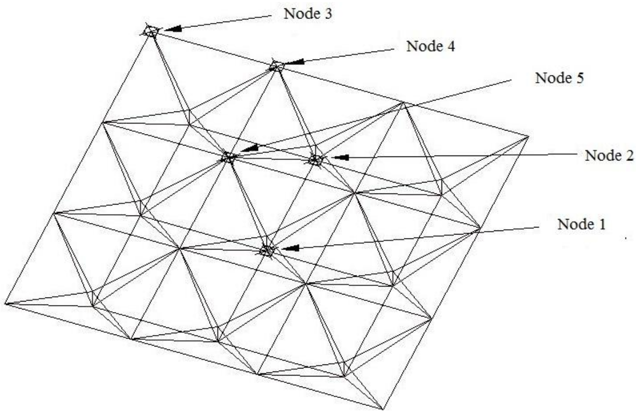
Member	Vertical strut	Inclined strut	Inclined cable	The upper passive cable	The lower passive cable
Initial force/N	-5116.8	-5575.9	3000	1918.8	0



(a) Typical struts

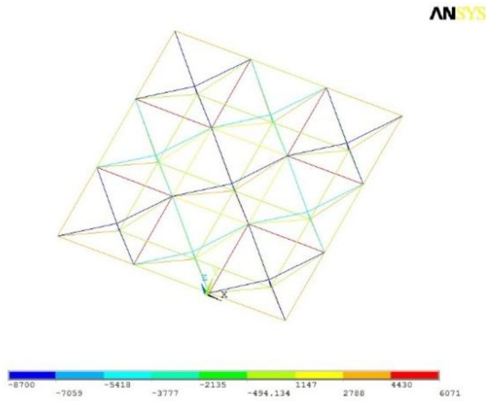


(b) Typical cables

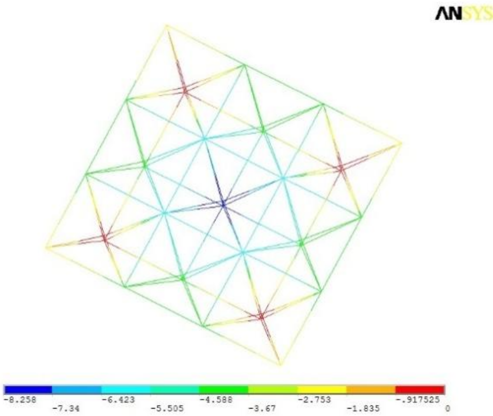


(c) Typical nodes

Fig. 13 Typical members



(a) Axial forces (N)



(b) Nodal displacements (mm)

Fig. 14 Results under the symmetric load case

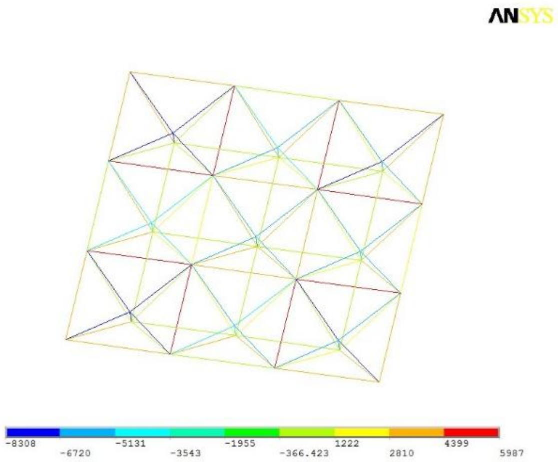
nodes and two lower nodes are chosen.

The element axial forces and nodal displacements under the symmetrical loads (load case 1) are given in Fig. 14. It can be found that the element forces and nodal displacement is symmetrical under load case 1. The struts of the corner and central CP units have higher axial forces than struts of other units. The cable forces of corner CP units are also larger than cable forces of other units. From the boundary to the centre of the system, the nodal deflection increases from 0 to 8.258 mm.

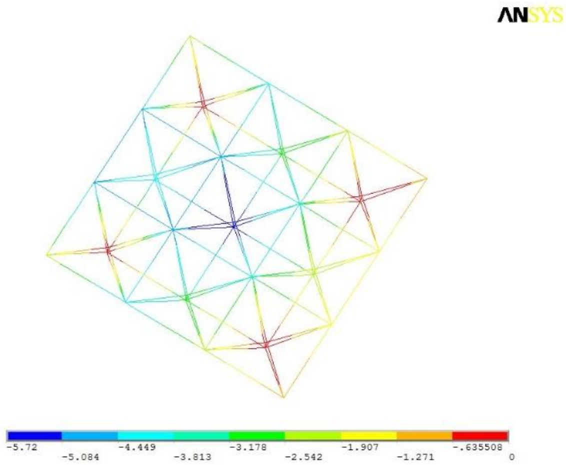
4.3 Effects of thermal loading

When the cable-strut structure is used as a roof system, fires will leads to the thermal loading. More generally, the thermal loading can be obtained by the temperature variation ΔT from the reference temperature, which is because of the environment temperature deviation. In this study, the thermal loading only caused by the environment temperature will be considered. ΔT is assumed to be between -30℃ and 30℃. Thermal loading plays an important role on the mechanical behavior of arches, columns and tensegrity structures. However, there are few studies on thermal loading effects on cable-strut system.

Fig. 16 shows that the curves between the nodal displacements and thermal loading. It can be found that the nodal displacement has a linear changing trend with thermal loading. The absolute value of displacement of node 3 decreases while others increase with the rise of environment temperature. The stiffness of cable-strut system is mainly replied on the prestress level. Then we should investigate the effects of thermal loading on the self-stress distribution



(a) Axial forces (N)



(b) Nodal displacements (mm)

Fig. 15 Results under the asymmetric load case

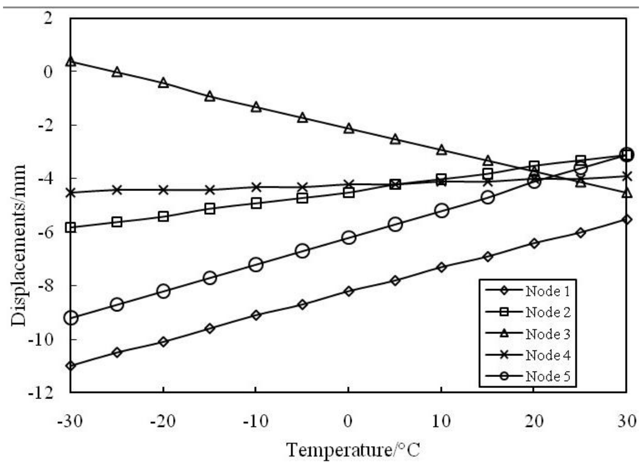
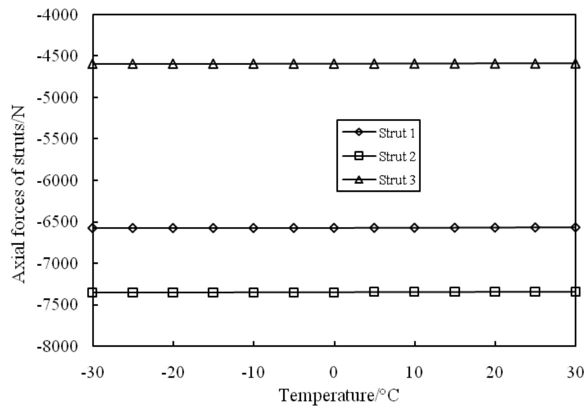
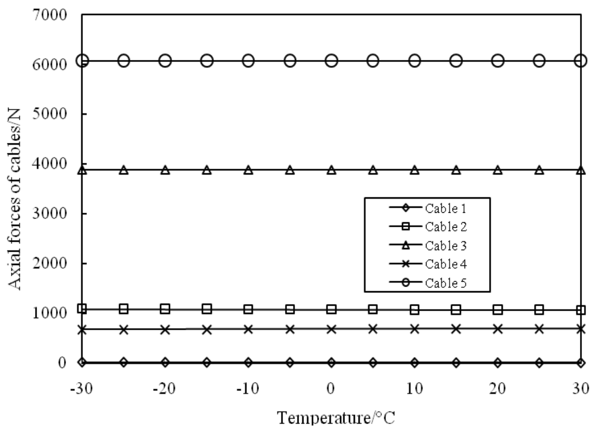


Fig. 16 Nodal displacements under thermal loading

of the cable-strut system. The element axial forces of typical cables and struts are given in Fig. 17. It can be found the cable and strut forces are almost not changed under the thermal loading. It denotes the environment temperature changes considered in this section has slight influence on the self-stress level of the system.



(a) Strut axial forces



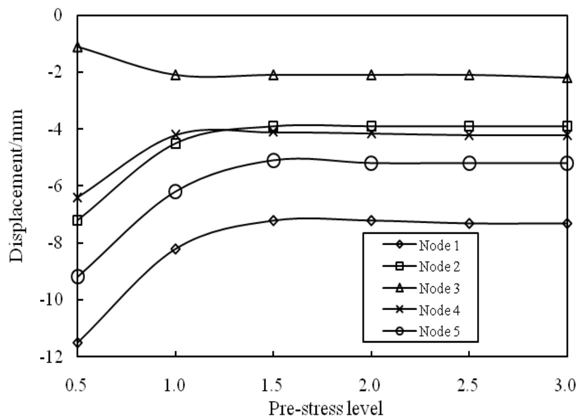
(b) Cable axial forces

Fig. 17 Axial forces of the struts and cables thermal loading

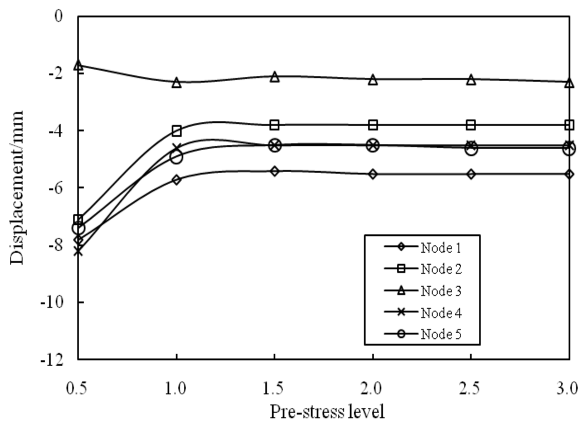
4.4 Effects of the initial prestress distribution

In this section, effects of the initial prestress level will be studied. The prestress distribution given in Table 1 is chosen as the basic prestress value. Then the prestress level ratio is defined as the value of the element stress divided by the basic value given in Table 1. Six prestress level ratios, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 are considered. The relationship between nodal displacements and prestress level ratios is shown in Fig. 18. It can be found that the most nodal displacements decrease with the increase of prestress level when the ratio is lower than 1.0. But after that, the initial prestress has little influence on the nodal displacement. This also indicates that the initial prestress distribution of the basic model is the optimal value.

The relationship between the axial forces of cables and struts and prestress levels are given in Fig. 19. It can be seen from this figure that by increasing the pre-stress level, the axial forces of struts increase linearly. Moreover, as the upper cables are prestressed to the greater level, there is less stress transferred to the lower cables (Cable 1 and Cable 2). Thus the level of tension stress in the lower cables is actually reduced as more stresses are taken by the highly prestressed upper cables with the rise of the prestress level. It means that the influence of the pre-stress level on the axial forces of elements except the lower passive cables is significant.

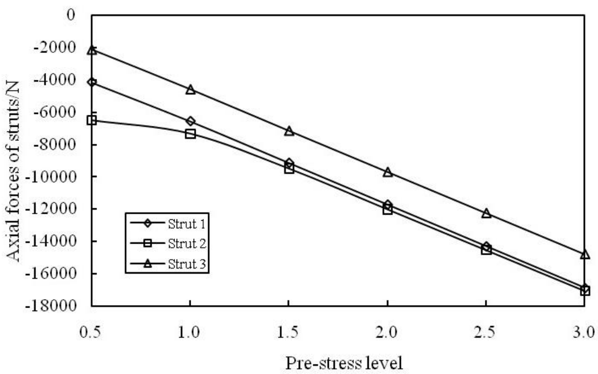


(a) Load case 1

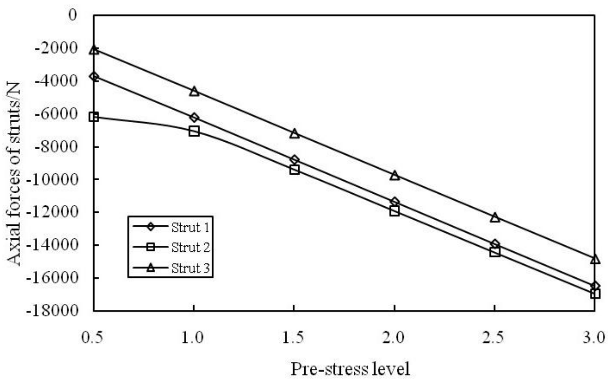


(b) Load case 2

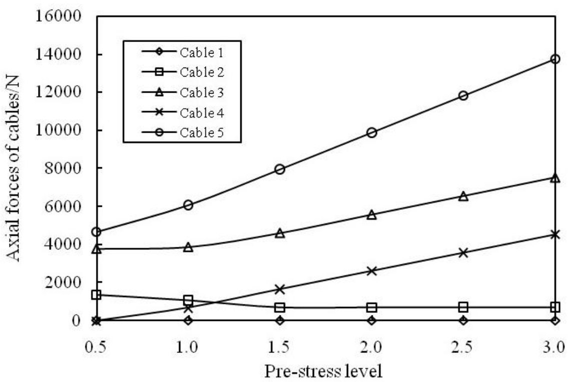
Fig. 18 Nodal displacements with different pre-stress levels



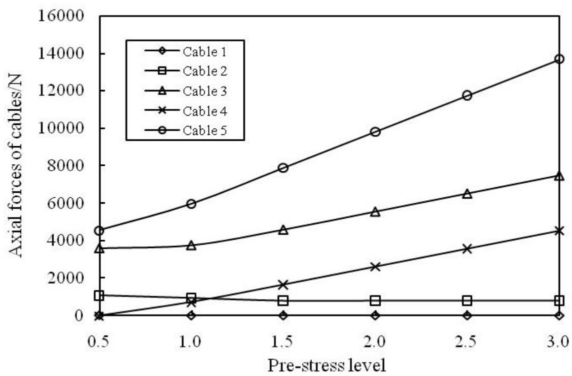
(a) Struts under load case 1



(b) Struts under load case 2



(c) Cables under load case 1



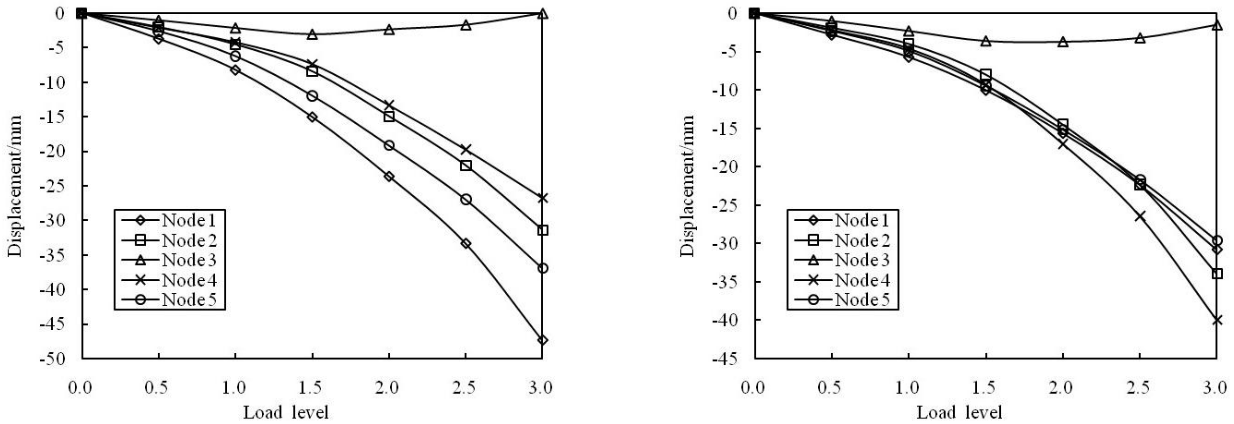
(d) Cables under load case 2

Fig. 19 Axial forces with different pre-stress levels

4.5 Effects of the load level

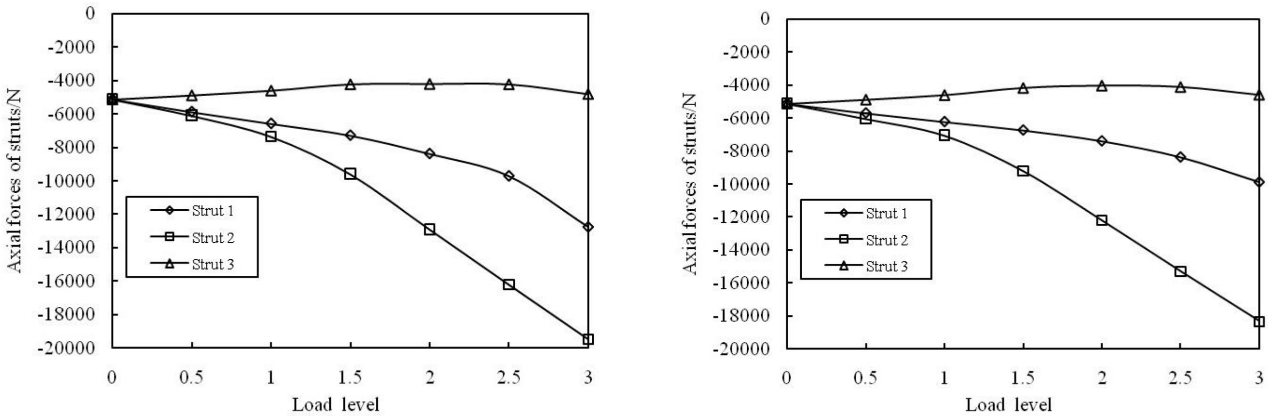
In practice, the system may bear greater loads than the design load. In the other hand, Cai *et al*. (2016) have studied a deployable cable-strut structure based on di-pyramid (DP) cable-strut units. Then three times of the design load are applied to study the structural behavior of this kinematic cable-strut structure. To compare these two cable-strut system, the span, geometry, materials and cross-section of members are all the same.

The nodal displacements under both load cases are given in Fig. 20. It can be found that the change trends of nodal displacements under both load cases are similar. The displacement of node 3 increases firstly and then decreases with the increase of the load level. The displacements of other nodes increase with the increase of the load level. For the symmetric load case, Node 1, which is located at the center of the system, has the maximal nodal displacement, 47.3 mm. But for the asymmetric load case, because of the half-span snow load, the maximal nodal displacement, 39.9 mm, occurs at Node 4. For the cable-strut system with DP units, the maximal nodal displacements are 86.7 mm and



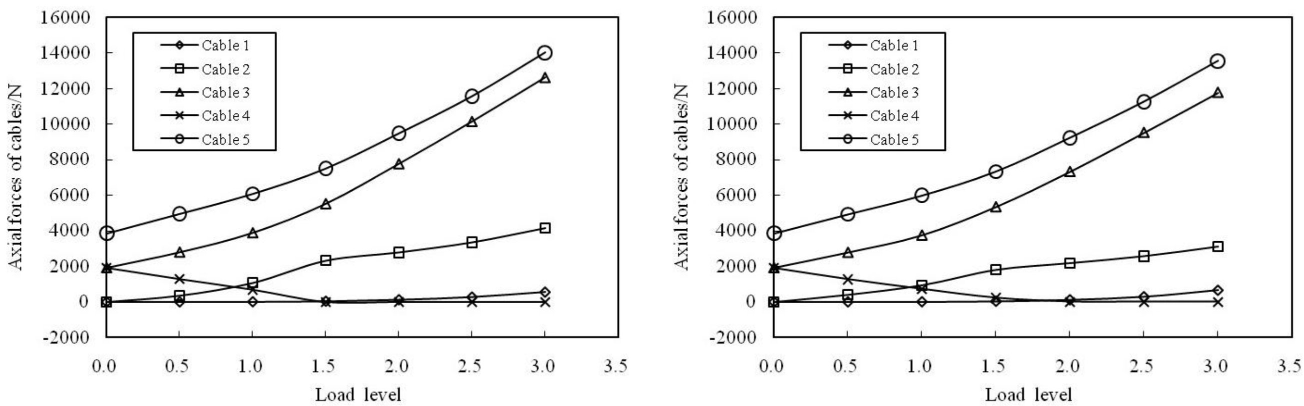
(a) Load case 1 (b) Load case 2

Fig. 20 Nodal displacements under three times of design loads



(a) Load case 1 (b) Load case 2

Fig. 21 Axial forces of struts under three times of design loads



(a) Load case 1 (b) Load case 2

Fig. 22 Cable forces under three times of design loads

57.6 mm for load case 1 and load case 2, respectively.

The axial forces of struts under the symmetrical and asymmetric load cases are shown in Fig. 21. It can be found that under both load cases, the axial force of Strut 3 remains unchanged while the others are increasing with the increase of the load level. The axial force of Strut 2 is the maximal because it is located at the boundary of the structure. The maximal axial stresses of Strut 2 are 135 MPa and 127 MPa for both load cases. For the cable-strut system with DP units, the maximal axial stresses of struts are 212 MPa and 157 MPa, respectively.

Fig. 22 shows the relations between cable forces and

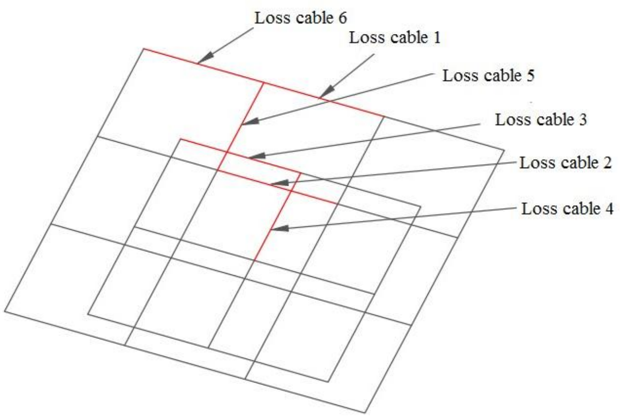
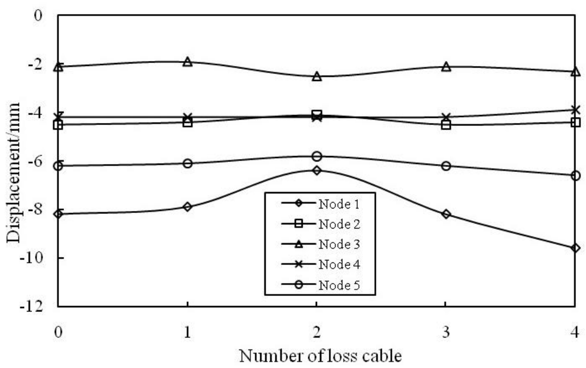


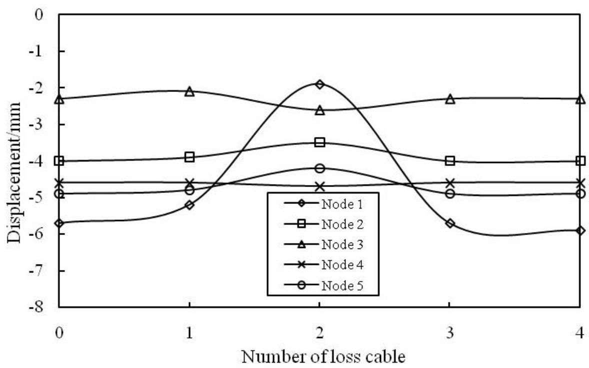
Fig. 23 Numbers of loss cables

load levels. It can be seen that under both load cases, Cable 4 has an unloading behavior after the cable force becomes zero at about 1.5 times of design loads. Other cable forces increase with the increasing of the load level. Especially, Cable 3 and Cable 5 have an intense growth of cable forces. Cable 5 has the largest forces, 14022 N and 13561 N for load case 1 and load case 2. For the cable-strut system with DP units, the largest cable forces are 12895 N and 11802 N.

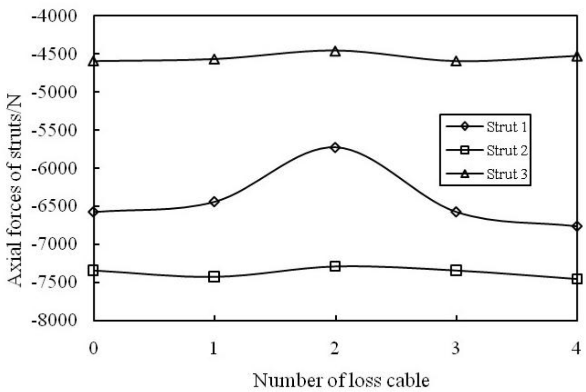
It can also be found from the previous studies, the proposed kinematic cable-strut system has a good structural behavior than the deployable cable-strut structure based on DP units.



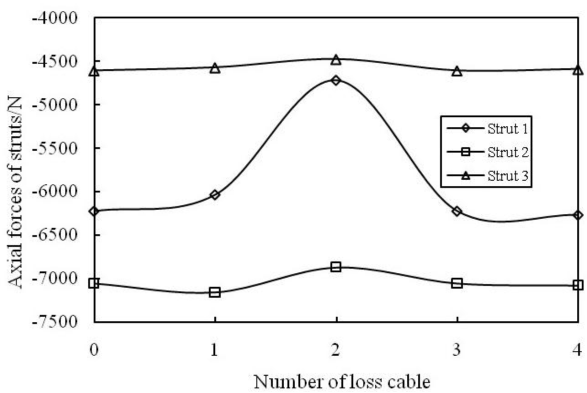
(a) Nodal displacements under load case 1



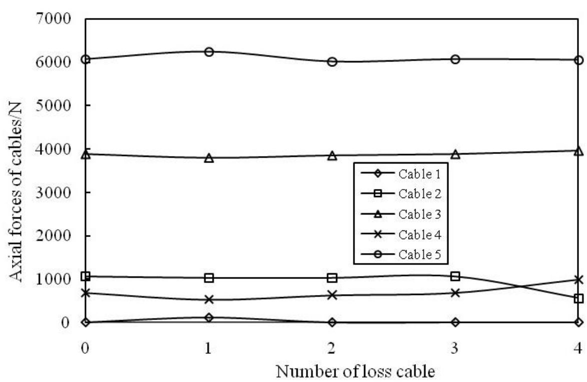
(b) Nodal displacements load case 2



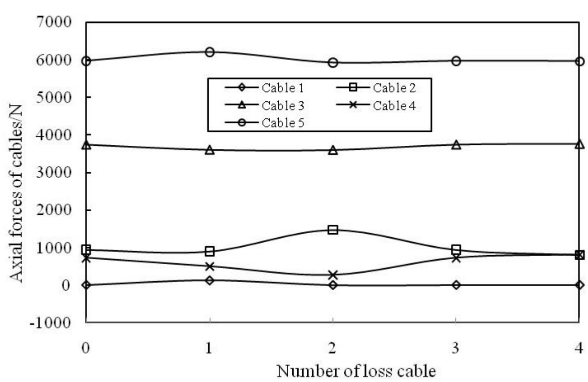
(c) Strut forces under load case 1



(d) Strut forces load case 2



(e) Cable forces under load case 1



(f) Cable forces load case 2

Fig. 24 Structural behavior after the removal of cables

5. Robustness of the system

After the accident of 9/11, more and more researchers studied the robustness and progressive collapse analysis of structures. However, the robustness of cable-strut system are rarely discussed in the literatures (Li *et al*. 2011). Normally, the degree of statical indeterminacy of cable-strut system is lower. Furthermore, highly prestressed cables are more susceptible to failure, and thus the effects of cable loss are studied in this section. It should be noted that in the proposed system, the inclined cables are active cables and they are continuous. If one of the cables is disconnected, the system would collapse. Then only the passive cables are seen as candidates of invalid elements. In respect of the geometrical symmetry, the loss of six cables is considered for the study (Fig. 23).

In this study, the prestress and external loads are firstly applied to the system. After that, the cable is killed to simulate the rupture of cables. A cable is killed at one time. Then each cable is removed one at a time, to explore the effect of sequential cable loss on the global integrity of the structure. From the numerical simulation, it can be found that the role of Cable 5 and Cable 6 is important. If Cable 5 or Cable 6 is removed, the corner CP unit becomes a mechanism, which leads to the failure of the system. After the removal of cables, the structural behaviors under both load cases, such as the nodal displacements and axial forces of struts and cables, are illustrated in Fig. 24. It should be noted that the results of the intact structure are also given in this figure for comparison. The horizontal coordinates are the number of the removal of cables. Moreover, '0' denotes the intact structure.

It can be seen from Fig. 24 that after the removal of Cable 2, the displacement of Node 1 decreases from 8.2 mm to 6.4 mm for load case 1 and from 5.7 mm to 1.9 mm for load case 2. Meanwhile, the axial force of Strut 2 decreases from 6575 N to 5729 N in load case 1 and from 6221 N to 4715 N in load case 2. It can also be found that the effect of the removal of other cables on the structural behavior is slight.

6. Conclusions

The experimental and numerical studies of a kinematic cable-strut roof structures was carried out in this paper. The mechanical properties of the CP unit were firstly introduced. Then a foldable planar truss system and a foldable barrel vault system were proposed for the kinematic cable-strut roof. And the previous one was chosen as studied example. After that, the deployment of the foldable planar truss was investigated experimentally. The static behavior of the kinematic roof structure in the fully deployed state under the symmetric load case, the asymmetric load case and thermal loading was studied numerically. The results show that the half-span snow load leads to the asymmetrical structural performance. The nodal displacements are greatly influenced by thermal loading but the cable and strut forces are almost not affected by the environment temperature variation considered in this paper. Moreover, the influence of initial prestress distribution was also investigated. It can be found that the prestress level of the basic model is optimal. It has great influence on the axial forces of elements except the lower passive cables. The comparison between the proposed kinematic structure and the cable-strut system based on DP units shows that the proposed system has a better structural performance. Finally, the robustness of the system was studied. The removal of cables of corner CP units will leads to the collapse of the structure. Furthermore, the nodal displacements and strut forces may be changed significantly after the removal of some passive cables. It should be noted that the degree of freedom of the proposed system is large during the folding and deploying. Then the movement of the structure is hard to control. An advanced connection, such as gear joints, should be researched to realize the synchronous deployment of the system.

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