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Progressive collapse analysis of Geiger type cable domes with partial CFRP cables

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Abstract

Carbon fiber reinforced polymer (CFRP) has the advantages of light weight, high strength, corrosion resistance, fatigue resistance, etc., and has a promising application prospect in long-span prestressed space structures. In order to study the rational placement of CFRP cables in cable domes and the ability of cable structure with partial CFRP cables to resist progressive collapse, progressive collapse analysis was carried out on Geiger cable dome structures with a span of 71.2m and with partial ridge or diagonal cables using CFRP cables. The simulation results show that: (1) when CFRP cables are used as outer ridge cables and a single CFRP outer ridge cable is broken, the maximum vertical displacement of the joints is close to 10m, which is 1/7 of the span of the structure, and the structure collapses partially. When the CFRP cables are used as middle or inner ridge cables, the damage degree of cable domes caused by breaking of a single CFRP cable is smaller than that of caused by breaking of single CFRP cable located in outer ridge cable. (2) When CFRP cables are arranged on the diagonal cables, the structural dynamic response caused by single CFRP cable breaking is small. When CFRP is arranged on the outer diagonal cable and a single CFRP cable is broken, the maximum vertical displacement of the joints is about 0.5m, which is 1/144 of the span of the structure. (3) When CFRP cables are used as entire diagonal cables, the structural failure caused by a single CFRP is similar to that caused by a single CFRP broken when CFRP cables are used as outer diagonal cables. For the Geiger type cable dome structure, the CFRP cables can be preferentially arranged in the diagonal cable positions.

Keywords: cable dome, CFRP cables, progressive collapse, CFRP positions.

1. Introduction

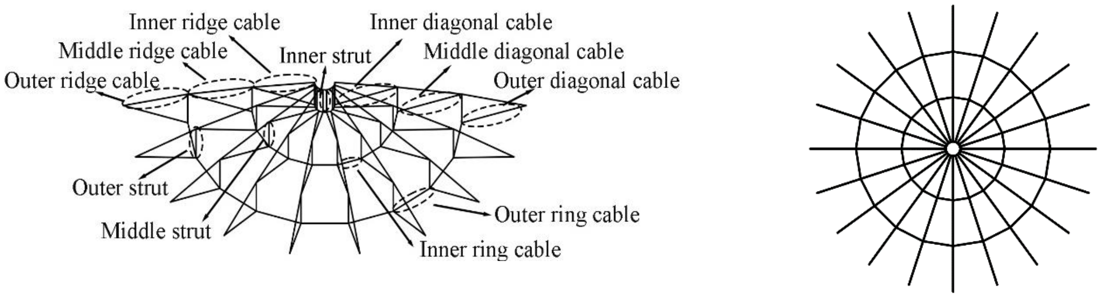
Cable domes have the advantages of light weight, beautiful shape, reasonable force and good economy, and have been favored by engineers in recent years [1]. However, the redundancy of cable dome structures is low, and it is easy to cause the progressive collapse of the structure when the key members are broken. Zhu Mingliang et al. [2] analyzed the dynamic collapse of the sunflower-type cable dome structure and pointed out that the failure of the ring cable would cause the progressive collapse of the structure. Zong Zhongling et al. [3] conducted a cable instant breaking test on the sunflower type cable dome test model, indicating that the cable at different positions has different influence on the structure. Lu Jinyu et al. [4] proposed a novel self-equilibrium cable-strut tensile structure called torus-dome, and analyzed the response of the remaining structure after the rupture of the cable in different parts. Zhang Weijing et al. [5] conducted a collapse test study of cable breakage under multiple working conditions on the Geiger type cable dome test model, and the results showed that the failure of a single outer ring cable would lead to progressive collapse of the structure.

Carbon fiber reinforced polymer (CFRP) is a kind of composite material with excellent mechanical properties, which has the advantages of high strength to weight ratio, excellent corrosion resistance and durability [6-7]. At present, CFRP cable is only used in Sanya Stadium in China instead of the traditional steel cable for the inner ring cross cable [8]. In order to further promote the application of CFRP cable in cable dome structure, and considering that CFRP cables are not suitable for use in ring cables, which are the key member of anti-collapse, in this paper, an actual Geiger type cable dome structure project is taken as the object, and part of the ridge or diagonal cables with CFRP cable are used. The progressive collapse simulation of the cable dome structure with partial CFRP cables is carried out to study the rational placement of the CFRP cables and the dynamic response characteristics of the structure caused by the rupture of single CFRP cable.

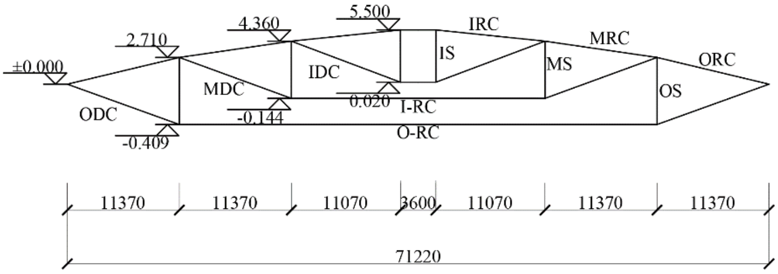
2. Finite element model of Geiger cable dome

2.1. Introduction of structural model

An actual Geiger type cable dome is selected as the object, with a span of 71.2m, a height of 5.5m and a ring direction of 20 equal parts. The cable dome comprises two ring cables, from the outside to the inside, namely the outer ring cable (O-RC) and the inner ring cable (I-RC); There are 3 rings of ridge and diagonal cables. The ridge cables from inside to outside are inner ridge cables (IRC), middle ridge cables (MRC) and outer ridge cables (ORC), and the diagonal cables from inside to outside are inner diagonal cables (IDC), middle diagonal cables (MDC) and outer diagonal cables (ODC). Each circle is equipped with 20 struts, respectively, the inner struts (IS), the middle struts (MS), the outer struts (OS). The height of the struts from inside to outside are 5.3m, 5.8m, 6.8m respectively. An inner pull ring with a radius of 1.8m is arranged in the center of the structure. The structure axonometric drawing, floor drawing and sectional drawing are shown in Figure 1.



(a) (b)



(c)

Figure 1: Structural diagram of cable dome: (a) axonometric drawing, (b) floor drawing, (c) sectional drawing.

Part cables of the cable dome adopts CFRP cable with a density of 1600 kg/m^3, elastic modulus of 1.72×10^5 MPa, and ultimate tensile strength of 2500MPa. Member specifications are shown in Table 1 and material properties are shown in Table 2. Details of other design parameters and component dimensions are provided in reference [9].

Table 1: Member specifications and initial prestress of cable dome structure

Member Type	Specification	Area/mm^2	Initial Prestress/kN
IRC	Φ38	853	394.34
IDC	Φ32	605	127.58
MRC	Φ48	1361	517.05
MDC	Φ38	853	243.50
ORC	Φ56	1844	761.17
ODC	Φ65	2488	582.38
I-RC	3Φ40	3318	731.09
O-RC	3Φ65	7466	1751.5
IS	Φ194×8	4674	-42.68
MS	Φ194×8	4674	-81.02
OS	Φ219×12	7804	-189.58

Table 2: Material properties used for structural analysis

Member Type	Materials	Density (kg/m^3)	Modulus of Elasticity (MPa)	Ultimate Tensile Strength(MPa)
Cables	CFRP	1600	1.72×10^5	2500
	Steel	7850	1.8×10^5	1600
Struts	Steel	7850	2.06×10^5	345

Dead load of the roof structure is 0.25 kN/m^2, and live load is 0.5 kN/m^2. The upper surface load is applied to the upper joints of the strut as a joint load, and the bridleway's self-weight is applied to the lower joints of the strut. The specific load values are shown in Table 3.

Table 3: Load values in structure

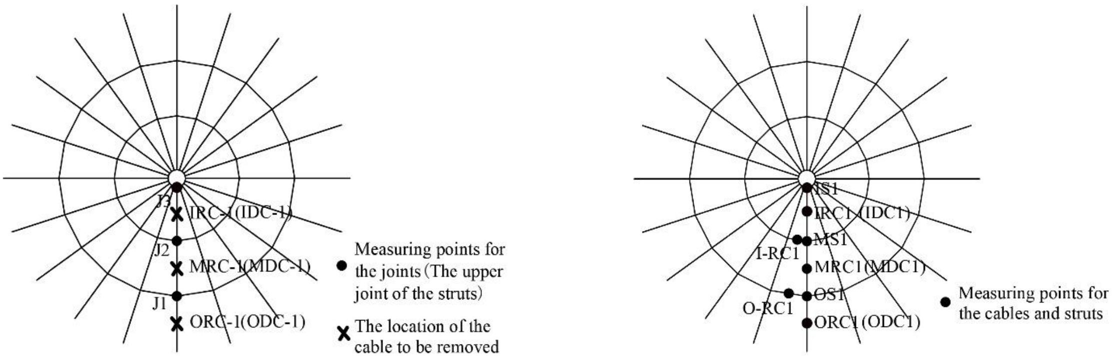
	Load sources	Value of load
Dead load	Roof practice	0.25 kN/m^2
	Bridle path(The first round)	2kN
	Bridle path (The second round)	10 kN
	Bridle path（The third round）	15 kN
Live load	Accumulation of snow etc.	0.5 kN/m^2

2.2 Structure modelling

Using finite element software ABAQUS, the progressive collapse analysis of Geiger type cable dome structure with partial CFRP cables was carried out by nonlinear dynamic analysis method. Beam element is used for struts and Truss element is used for cables, regardless of the flexural stiffness of cables. The initial strain method is adopted to apply the prestress to the cables. Considering Rayleigh damping, the support is simplified as a fixed hinged support, and the load combination of 1.0 × dead load +0.5 × live load is used for analysis. During the analysis, the results of the complete structure are transmitted to the model of the removed cable through the result transmission function of the software, so as to realize the progressive collapse analysis of the model of the removed single cable.

3 Progressive collapse analysis

In order to prevent the progressive collapse of the structure after the application of CFRP cables and to determine the reasonable location of the CFRP cables, the progressive collapse of the structure with the CFRP ridge and diagonal cables at different positions is analyzed when a single CFRP cable is removed. The location of the removed CFRP cable is shown in Figure 2.



(a) (b)

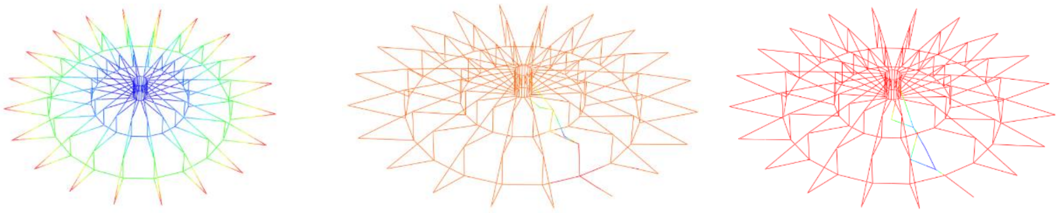
Figure 2: The position of cable to be removed and measuring points: (a) the members to be removed and measuring points for the joints, (b) measuring points for the members.

In order to judge the damage degree of cable dome structure after the rupture of a CFRP cable, two control indexes are used in this paper. 1) Vertical displacement of joints. After the cable is broken, if there are joints with vertical displacement greater than $L/250$ but less than $L/30$ (L is the span of the cable dome structure), then the local failure of the structure is judged. If there are joints with vertical displacement greater than $L/30$, the collapse area needs to be calculated. 2) Collapsed area. If the collapse area enclosed by the joints whose vertical displacement is greater than $L/30$ is greater than 30%

of the roof area, it can be judged that the progressive collapse of the whole cable dome structure occurred. Otherwise, the local collapse of the cable dome structure occurred.

3.1 Removal of a CFRP ridge cable

CFRP ridge cable rupture can be divided into three cases: (1) Rupture of the outer ridge cable ORC-1; (2) Rupture of the middle ridge cable MRC-1; (3) Rupture of the inner ridge cable IRC-1. When the outer ridge ORC-1 breaks, the structure collapse process is shown in Figure 3.

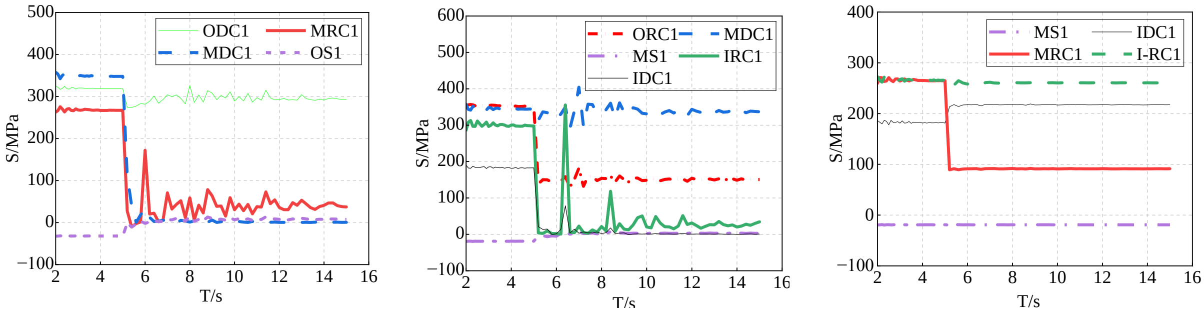


T=5.0s T=5.2s T=15s

Figure 3: Collapse process diagram of structure after removal of a CFRP outer ridge cable.

It can be seen from the Figure that when T was 5.0s, the rupture of ORC-1 occurred. When T was 5.2s, the structure oscillated violently, the struts where the initial failure members were located were inclined and torsional, and the internal force redistribution occurred in the structure. The outer strut OS1 attached to the broken member felled to the center side of the structure after losing the constraint of the cable. The toppling of OS1 caused the MRC1 and MDC1 connected to OS1 to lose their constraints and relaxed, which eventually leads to the entire cable relaxation. When T was 15s, the structure was basically stable under the energy dissipation of damping, and the internal force redistribution was completed.

When single CFRP MRC-1 or IRC-1 is removed, the structure collapse mode is similar to that when single CFRP outer ridge cable is broken, but the change amplitude of cable stress and joint displacement is small. The internal force changes of adjacent cable under three working conditions are shown in Figure 4.



(a) (b) (c)

Figure 4: Internal force changes of adjacent members after removal of different ridge cables: (a) outer ridge cable; (b) middle ridge cable; (c) inner ridge cable.

As can be seen from Figure 4: (1) The breakage of ORC-1 or MRC-1 will lead to partial relaxation of the cables in the structure: When ORC-1 was broken, the cable forces of MRC1 and MDC1 decreased rapidly. After a short period of structural stability, the internal force of MRC1 and MDC1 decreased by more than 90%. The internal force reduction of the remaining cables is within 50% except for the ones where the broken cables are located. (2) When MRC-1 was broken, MS1 lost its support and toppled over, resulting in a rapid decline in the cable force of IRC1 and IDC1 connected to it, and the final cable force dropped by more than 90%. The tipping of the middle strut has little effect on MDC1. Due to the breakage of MRC-1, the OS1 constraint is reduced, and there is a slight tilt to the ORC1 side, resulting in a decrease in the cable force of ORC1 by 63%. (3) When IRC-1 was removed, only the cable force of MRC1 dropped significantly, reaching 66.5%, and the internal force fluctuation of the remaining cable was small. (4) In the three working conditions, the cable force of most cables in the structure decreases, and the cable force of some cables rises but the amplitude is small, and there is no cable break during the whole process.

Table 4: Joint displacement after a CFRP cable is removed (m)

Joint	Initial	ORC-1	Initial	MRC-1	Initial	IRC-1
J1	-0.05	-9.91	-0.05	-0.01	-0.05	-0.03
J2	-0.10	-8.48	-0.10	-8.34	-0.10	-0.08
J3	-0.11	-0.18	-0.11	-0.14	-0.12	-0.09

Under the three working conditions, the displacements of joints J1, J2 and J3 are shown in Table 4 (" - "indicates downward direction). As can be seen from Table 4: (1) After the single CFRP outer ridge cable ORC-1 was broken, the vertical displacements of joints J1 and J2 increased sharply, with the maximum vertical displacements reaching 9.91m (*L*/7) and 8.48m (*L*/8), respectively, exceeding that of *L*/30 (2.37m). Except for joints J1 and J2, the vertical displacement of other joints is smaller than that of *L*/30, and the maximum vertical displacement of joints J3 is only 0.18m. The area enclosed by joints with vertical displacement greater than *L*/30 is 6.7% of the total area of the roof, and the structure collapses locally. (2) After the single CFRP middle ridge cable MRC-1 was broken, the vertical displacement of joints J2 increases sharply to 8.34m (*L*/8), exceeding *L*/30. The vertical displacement of joints J1 and J3 is small, not exceeding 0.2m. The area enclosed by joints with vertical displacement greater than *L*/30 is 2.3% of the total area of the roof, and the structure collapses locally. (3) When the inner ridge cable IRC-1 of a single CFRP was broken, the joints displacement changed within 0.1m, and no local damage occurred to the structure. The final collapse area of the structure is shown in Figure 5.

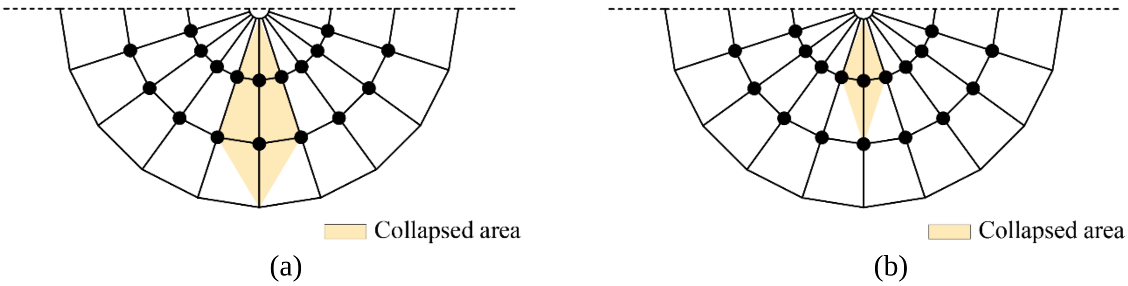


Figure 5: Diagram of the final collapse area of the structure after removal of a CFRP cable: (a) outer ridge cable; (b) middle ridge cable;

3.2 Removal of a CFRP diagonal cable

CFRP diagonal cable rupture can be divided into three cases: (1) Rupture of the outer diagonal cable ODC-1; (2) Rupture of the middle diagonal cable MDC-1; (3) Rupture of the inner diagonal cable IDC-1. After the failure of ODC-1, the structure collapse process is as follows: When T was 5.0s, ODC-1 was broken. When T was 5.6s, outer strut OS1 tilted, the two adjacent middle ridge cables relaxed, and the two struts rose slightly upward, and internal force redistribution occurred in the structure. The inner ring of the structure sank downward. When T was 15s, the structure was basically stable under the energy dissipation of damping, and the internal force redistribution was completed. The collapse process is shown in Figure 6.

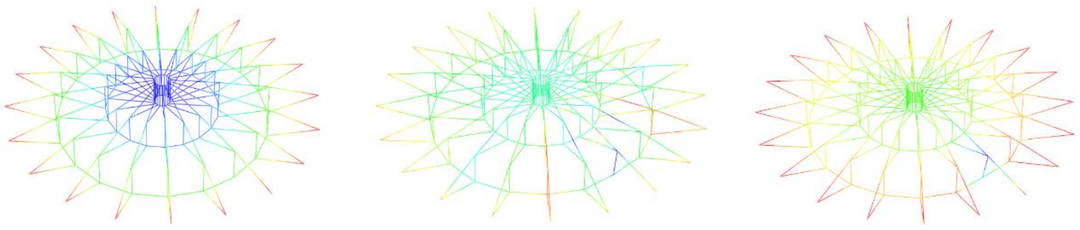
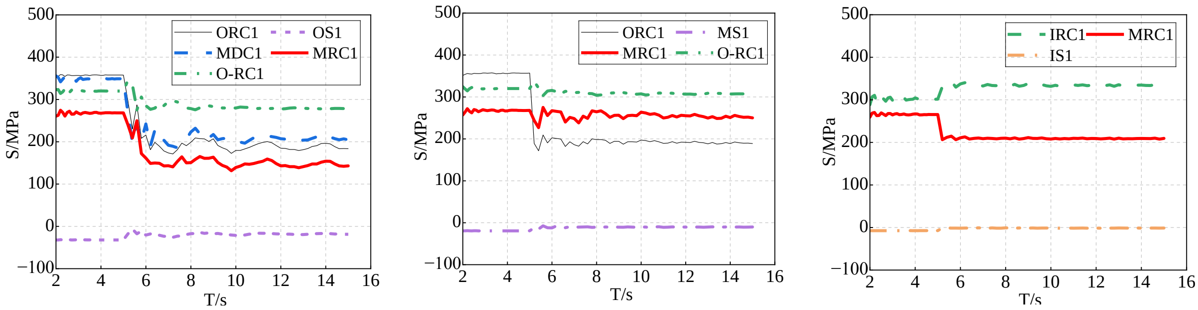

T=5.0s T=5.6s T=15s

Figure 6: Collapse process diagram of structure after removal of a CFRP outer diagonal cable.

When a single CFRP middle diagonal cable MDC-1 or a single CFRP inner diagonal cable IDC-1 is broken, the structure collapse mode is similar to that when a single CFRP outer diagonal cable ODC-1 is broken, but the change of cable stress and node displacement is small. The internal force changes of adjacent cable under three working conditions are shown in Figure 7.



(a) (b) (c)

Figure 7: Internal force changes of adjacent member after removal of different CFRP diagonal cables: (a)outer diagonal cable; (b)middle diagonal cable; (c)inner diagonal cable.

As can be seen from Figure 7, after a single CFRP outer diagonal cable ODC-1 was broken, the outer strut OS1 slightly inclined due to the loss of lower support, resulting in the relaxation of the connected cable, but the cable force change range was within 50%, and the cable force reduction of ORC1, MDC1 and MRC1 was 49%, 42% and 47%, respectively. The O-RC1 cable has the smallest reduction in cable force, at 13%. After a single CFRP middle diagonal cable MDC-1 is broken, the middle strut MS1 has a slight tilt, and the adjacent cables has a small relaxation. The cable force drop of ORC1 is the largest, reaching 57%, and the cable force drop of other cables is within 10%. After a single CFRP inner diagonal cable IDC-1 was broken, the IRC1 cable force increased by 11%, which did not exceed the broken cable force. In general, the fracture of a single CFRP diagonal cable has little effect on the cable force in the structure.

Table 5: Displacement change of the joints after the cable is removed (m)

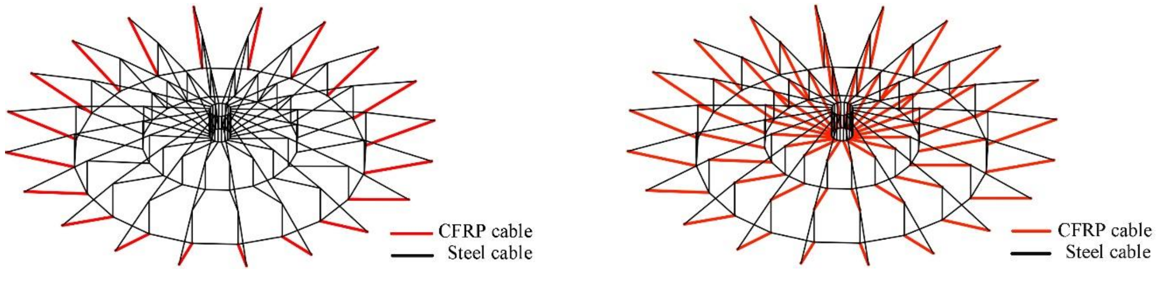
Joint	Initial	ODC-1	Initial	MDC-1	Initial	IDC-1
J1	-0.05	-0.46	-0.05	0.12	-0.05	-0.03
J2	-0.10	-0.22	-0.09	-0.27	-0.09	0.01
J3	-0.11	-0.20	-0.11	-0.17	-0.11	-0.13

As can be seen from Table 5, the displacement of the complete structure before cable breakage is small. (1) After the single CFRP outer diagonal cable ODC-1 is broken and the structure is stable, the displacement of joints J2 and J3 is small, less than $L/250$ (0.28m), and the displacement of joints J1 is slightly larger, the maximum value is 0.46m, less than $L/30$ (2.37m) but greater than $L/250$ (0.28m), and the structure is partially damaged. (2) After the single CFRP middle diagonal cable MDC-1 is broken, joints J1 rises upward and joints J2 and J3 fall down. The vertical displacement of joints in the structure is small, all of which are less than $L/250$ (0.28m), and the structure does not have local damage. (3) After a single CFRP inner diagonal cable IDC-1 was broken, the vertical displacements of nodes in the structure were small, all less than $L/250$ (0.28m), and no local damage occurred in the structure.

3.3 Comparison of two kinds of CFRP diagonal cables arrangement

According to the above calculation results, when a single CFRP diagonal cable is broken, the change of joint displacement and cable force of the structure is smaller than that when a single CFRP ridge cable is broken. It can be seen that the fracture of CFRP diagonal cable has less impact on the structure than that of the ridge cable.

In order to promote the application of CFRP cables in cable domes, the progressive collapse resistance of the cable dome structure with all the diagonal cables being CFRP cables and the cable dome structure with only the outer diagonal cables being CFRP cables is compared. The arrangement of CFRP cables in the structure is shown in Figure 8.



(a) (b)

Figure 8: Arrangement of CFRP diagonal cables: (a) outer diagonal cables; (b) all the diagonal cables.

In order to study the advantages and disadvantages of using all the diagonal cables and using single ring diagonal cables, the displacement response of the structure after the breaking of the corresponding CFRP outer diagonal cable under the two replacement methods is compared with the change of adjacent cable forces. The structural displacement changes under the two modes are shown in Table 6.

Table 6: Change of joint displacement of different CFRP cable domes after removing the outermost cable (m)

Joint	With CFRP outer diagonal cable	With all CFRP diagonal cables
J1	-0.46	-0.47
J2	-0.22	-0.21
J3	-0.20	-0.20

As can be seen from Table 6, there is no significant difference in the displacement response of the structure after ODC-1 fracture under the two different arrangement methods of using CFRP outer diagonal cables and using all CFRP diagonal cables.

Table 7 shows the internal force changes of ORC1, ODC1, MRC1 and MDC1 cables after the corresponding single CFRP outer diagonal cable is broken under the two arrangement methods.

Table 7: Change of cable stress after removing the outer CFRP diagonal cable (MPa)

Member name	Replace the outer diagonal cable			Replace all diagonal cables		
	before	after	change	after	before	change
ORC1	358	183	-49%	356	187	-47%
ODC1	319	423	+33%	317	407	+28%
MRC1	268	143	-47%	268	145	-46%
MDC1	349	205	-41%	346	207	-40%

As can be seen from Table 7, when a single CFRP outer diagonal cable is broken, the change of cable force of cable dome with all CFRP diagonal cables is slightly smaller than that of the cable dome with CFRP outer diagonal cables. The cable force of ODC1 is increased by about 30%, but it does not reach the breaking cable force of the cables. The cable force of ORC1, MRC1 and MDC1 all decreased within 50%. Under the two conditions, after ODC-1 is broken, the internal force difference of adjacent cables is very small.

The above results show that the collapse resistance of the cable dome with all CFRP diagonal cables is similar to that of the cable dome with CFRP outer diagonal cables. In order to apply more CFRP cables in the cable dome, the CFRP cables can be arranged in all the diagonal cable positions.

4. Conclusion

1. When the ridge cables at different positions are CFRP cables, the failure of single CFRP ridge cable will not cause the progressive collapse of the whole cable dome structure. When a CFRP outer ridge cable is broken, the maximum vertical displacement of the joint is close to 10m, which is 1/7 of the span, and the collapse area of the structure is 6.7%.

2. When the diagonal cables at different positions are CFRP cables, the overall response of the structure caused by the failure of a single CFRP diagonal cable is small, and the structure will not collapse progressively. When the CFRP outer diagonal cable is broken, the maximum vertical displacement of the joints is about 0.5m, which is 1/144 of the span, and only local damage occurs.

3. For the Geiger type cable dome structure, the structural response caused by the breaking of the cable on the outside is greater than that of the cable on the inside, and the structural response caused by the breaking of the ridge cable is greater than that of the diagonal cable.

4. In the two cases of using CFRP outer diagonal cables and using all CFRP diagonal cables, the structural response after the fracture of a single diagonal cable is similar. Therefore, when the CFRP cables are applied in the Geiger cable dome, the CFRP cables can be arranged in all the diagonal cable positions.

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