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Mechanical features of cable-supported ribbed beam composite slab structure

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Abstract. Cable-supported ribbed beam composite slab structure (CBS) is proposed in this study. As a new cable-supported structure, it has many merits such as long span availability and cost-saving. Inspired by the previous research on cable-supported structures, the fabrication and construction process are developed. Pre-stress design method based on static equilibrium analysis is presented. In the algorithm, the iteration convergence can be accelerated and the calculation result can be kept in an acceptable precision by setting a rational threshold value. The accuracy of this method is also verified by experimental study on a 1:5 scaled model. Further, important parameters affecting the mechanical features of the CBS are discussed. The results indicate that the increases of sag-span ratio, depth of the ribbed beam and cable diameter can improve the mechanical behavior of the CBS by some extent, but the influence of strut sections on mechanical behavior of the CBS is negligible.

Keywords: cable-supported ribbed beam composite slab; spatial structure; pre-stress; fabrication; mechanical features; sag-span ratio

1. Introduction

The support system of the floor and roof such as columns and walls will affect the utilization efficiency of the indoor space. Sometimes, the column-free or wall-free indoor space is highly demanded in public buildings such as gymnasiums, airline terminals, special workshops, etc. How to make such structures to effectively span a long distance has always been a hot topic. In general, researches are focused on two aspects: to use the lightweight and high-strength building materials, or to utilize pre-stressed or pre-tensioned structural elements and systems.

The cable-supported spatial structure system (Yan *et al*. 2015) combines the merits of both the rigid structures such as shell, grid structure and the flexible structures such as cable network structures (Kmet and Mojdis 2015, Ouni and Kahla 2014) and it usually forms a self-balanced system with the help of the pre-stressed cables. Due to high-efficient mechanical features, the cable-supported structures have been widely used in the public buildings around the world. Beam string structure, truss string structure, cable-supported barrel vault structure and suspend-dome are all popular cable-supported structures.

Systematical study has been carried out to the beam string structure and truss string structure (Masao and Kurasiro 1985, Zhao *et al.* 2015). Masao was the first scholar to raise the concept: traditional structures such as simply supported beam, arch or truss could span a longer distance and save more materials by introducing strengthening members such as struts and strings in certain places. The suspend-dome structure proposed in the 1990's by Kawaguchi *et al.* (1993, 1999) is composed of the upper single-layer latticed shell, middle struts and lower cables. The out-plane stability of the single-layer latticed shell structure is greatly improved by using the vertical struts, loop and radial cables appropriately. With rational mechanics and elegant configuration, the suspend-dome structure has been one of the most popular structures among the engineers and architects. Chen *et al*. (2010) and Qiao *et al.* (2012) introduced struts and cables to the cylindrical grid shell structure and proposed a new cable-supported structure, namely, the cable-supported barrel vault structure. The out-plane stability of cylindrical grid shell structure can be improved, and the horizontal thrust at the supports can be reduced significantly because of the action of the struts and strings. The highlight of the cable-supported barrel vault structure is that the horizontal thrust of the supports can be almost eliminated by optimization design. As a result, this kind of grid vault can be well applied without the giant thrust balancing elements.

This study will bring together these previous cable-supported structures and traditional concrete floor or roof such as steel-concrete composite floor (Silva *et al*. 2014, Mello *et al.* 2008), steel-deck composite floor (Lee *et al.* 2014, Silva and Thambiratnam 2009), hybrid composite floor plate system (Abeysinghe *et al.* 2013), space grid-concrete slab composite structure (Varela and Battista 2011), put forward a new prototype of the cable-supported structure system, namely, Cable-supported ribbed Beam composite Slab structure (CBS). The remainder of this paper is organized as follows: Section 2 describes the basic concept and fabrication processes of the CBS. Section 3 proposes the pre-stress design method of the CBS.

Theoretical analysis is performed with FEM to calculate

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the reasonable pre-stress level required. Subsequently, a 1:5 scaled physical model based on the calculation prototype is fabricated to verify the theoretical model. Further, the effects of four relevant parameters are studied in order to better figure out mechanical features of the CBS.

The contribution of this paper is mainly on putting forward the CBS, proposing the standard fabrication and pre-stress design method. Moreover, the parametric study results will also figure out the mechanical characteristics of CBS further, which is helpful to design economical and safe CBS. All of these works of this paper will provide theoretical foundation and actual experience for the implementation of the new-style CBS in the practical project.

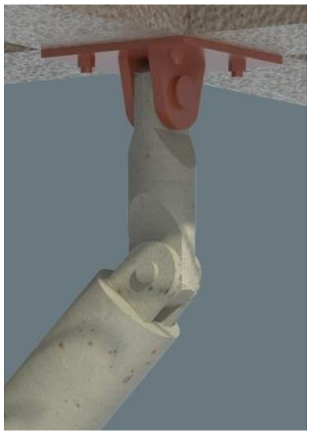

Fig. 2 Strut junction

2. Fabrication

The CBS consists of the upper concrete slab, middle struts and lower cables. Since the lower pre-stressed cable can act on the upper slab through the struts, the struts behave as the flexible supports of the upper slab. Due to this configuration, CBS can span a long distance when used in the floor and roof systems, and the utilization efficiency of the indoor space can be enhanced significantly.

The fabrication of a standard unit of CBS is shown in Fig. 1. The upper reinforced concrete slab, ribbed beam, the middle steel struts, and the lower cable are all prefabricated and assembled together on site. Most of the connections and joints are of traditional and simple configuration. Two special connections are illustrated in Figs. 2 and 3. Fig. 2 shows the connection between the strut and the ribbed beam, which includes two rotational axes in different directions. The lower pin can adjust the angle of strut so that the strut can be connected to another strut or cable easily, while the upper one can rotate about the longitudinal direction of the cable and help transfer the cable force from one end to the other. The two ends of each cable are fixed to the beam, the anchorage of cable end is shown in Fig. 3.

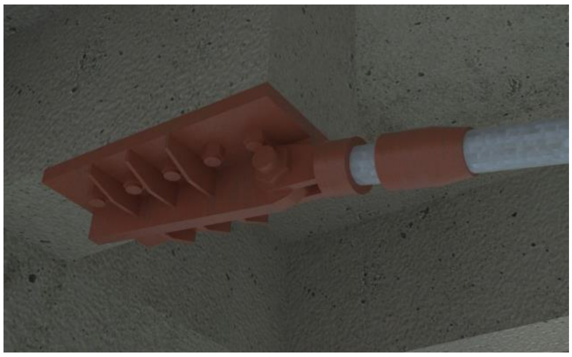

Fig. 3 Anchorage of cable end

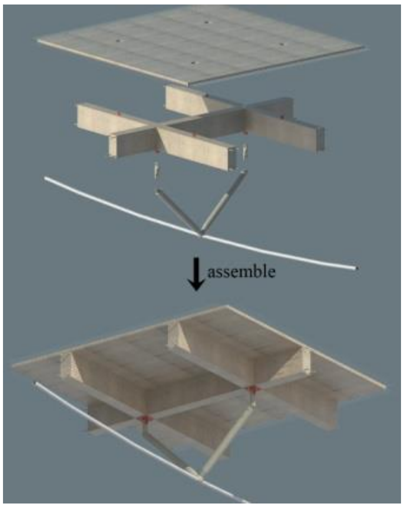

Fig. 1 Unit fabrication

Based on the construction methods of other cable-supported structures and the features of CBS, three main aspects of the CBS construction are highlighted. Firstly, the standard slabs, beams, struts, cables and joints are prefabricated, then assembled on site. Secondly, casting concrete between prefabricated slabs and beams is performed. This makes the bond firmer. Thirdly, one end of the span of CBS is fixed and the other end is free to slide horizontally. With this configuration, the cable force can act on the upper slabs through struts efficiently, and the horizontal actions can be released as well.

As shown in Fig. 1, each prefab element can be assembled into one integrated structure. The four angle steel elements on beams are inserted into the four holes in the slab, and then the concrete is cast into the holes. This fabrication method ensures the shear forces can be transferred smoothly between beams and slabs.

The major construction steps of CBS are as follows:

Step 1. The first span CBS construction. The beam elements are assembled first. The temporary and movable scaffold can support the current span CBS, after the current one is finished, it can be moved to the next span construction and reused. The steel bar cages are set up among prefab beam elements, which are marked red circles in Fig. 4.

Step 2. Casting concrete into steel bar cages, and connecting prefab beam elements. The struts and cables are installed under the upper beams first, followed by pre-stressing the cables. The upper beams and the lower cable-supported system will form a complete self-balancing structure system. Steps 1 and 2 are shown in Fig. 4.

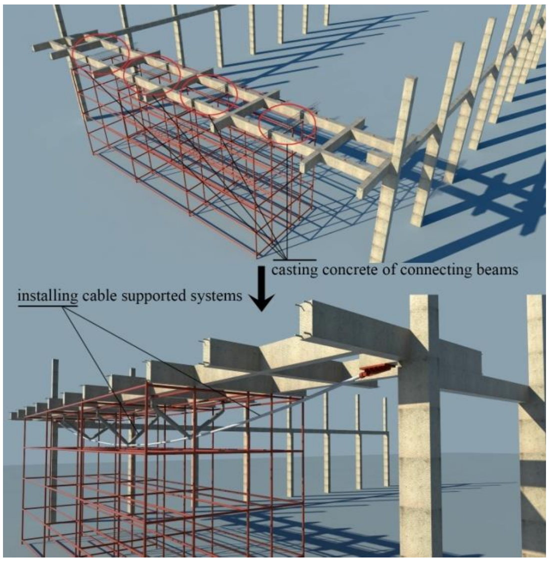

Fig. 4 Step 1 and construction

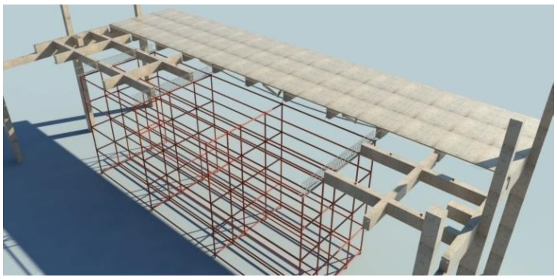

Fig. 5 Step 3 construction

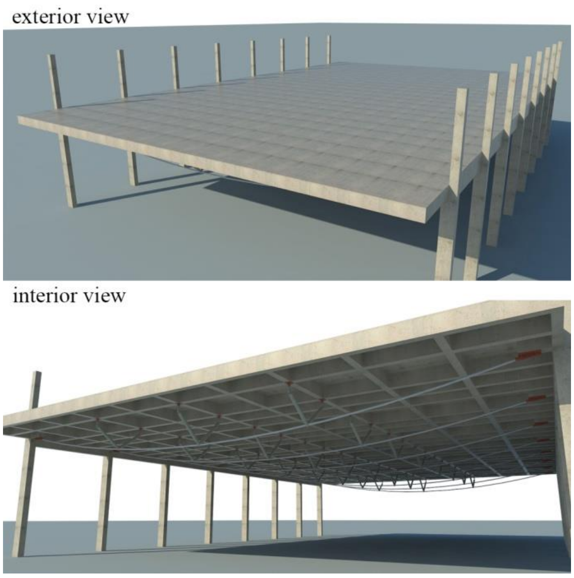

Fig. 6 Final step rendering

Step 3. As shown in Fig. 5, the slabs are paved on top of the beams, and the angle steel elements are inserted into the holes in the slabs. After casting concrete into the holes and the belts among the slabs, one complete span CBS construction is finished. The same process is implemented for the next span until all of spans are constructed.

Final step. After finishing the construction, the temporary scaffold is removed, and the floor becomes an integrated and stable structural system. Fig. 6 shows a final rendering of CBS with large interior space.

3. Prestress design

3.1 Numerical simulation procedure

The proper design of pre-stress is the key of the CBS. It determines both the rigidity and the load-bearing capacity of the CBS. Therefore, it is very important to figure out the precise and appropriate pre-stress value. The principle of the CBS pre-stress finding mainly includes three aspects. First, the pre-stress can make the CBS (without paving slabs, namely, in the state of construction step 2) deform upwards, and the maximum deformation should be limited to less than span/600 (Chen and Qiao 2010). Secondly, after pre-stressing the cable and paving slabs, namely, in the state of construction step 3, the upward deformation decreases. In general, the appropriate pre-stress should keep the upward deformation not less than zero. Thirdly, if the pre-stress is determined according to the two rules above but still cannot meet the demands of the load-capacity and rigidity, the rigidity of the upper ribbed beam and slab system should be increased and the sag-span ratio of the CBS may be too large.

As shown in Fig. 7, a standard span of CBS is taken to illustrate the detailed pre-stress design process. The cable pre-stress is first set to zero, $Tp = 0$. With the weight of the CBS being all loads in the state of construction step 2, the deformation of the structure can be worked out. As the deformation control point of the CBS, the mid-span point vertical displacement is recorded as d' (All of the deformation discussed in this paper is based on a zero state which is drawn in dash line and shown in Figs. 13 and 14, and the displacement above this zero state is positive, below is negative.) and F' is the cable force. Then the structure is reanalyzed. This time the cable pre-stress is set to F', namely, $Tp = F'$. Under the same condition, the mid-span point vertical displacement and cable force can be determined again which are respectively d and F. D is the preset value of the maximum upward displacement of the mid-span point. If $d \neq D$, $Tp = F' + F' \times (D-d) / (D-d')$ will be applied to the cable, and the structure will be recalculated. This process will be repeated until $d = D$ when the cable pre-stress design value $T = F$. Note that the geometric nonlinearity of the structure must be considered in the calculation process. The computation can be performed using some general FEM software such as ANSYS, Midas/Gen, etc. The iteration calculation workflow is shown in Fig. 8.

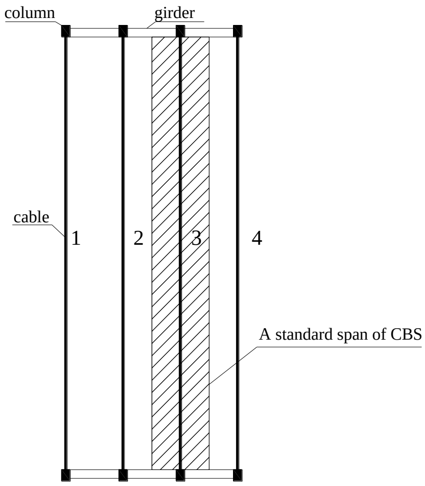

Fig. 7 Cable disposition

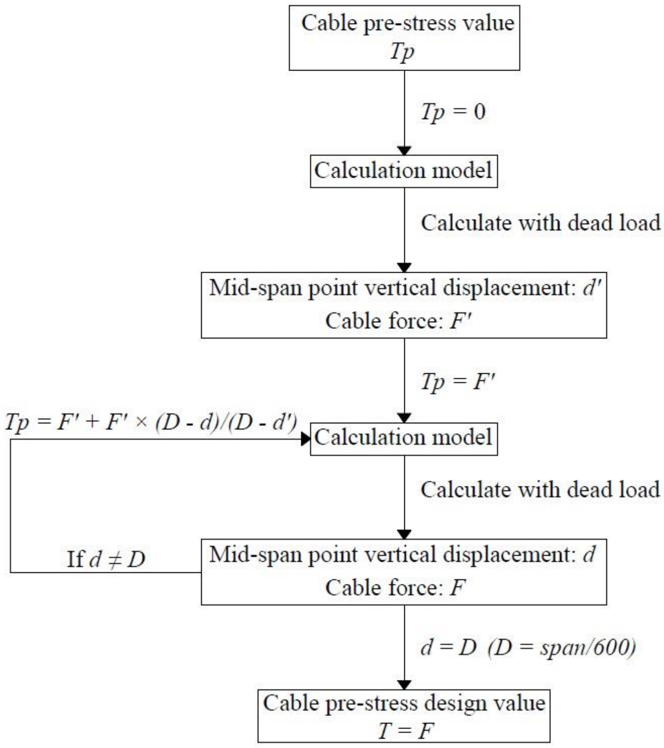

Fig. 8 Pre-stress finding iteration workflow

3.2 Example analysis

The new gymnasium of Hebei Normal University in China is chosen as the prototype of the calculation model in this study. The beam string structure adopted on the second floor of this new gymnasium is a very similar structure to the CBS. They have the similar mechanical features and fabrication. In the analysis, this building is redesigned using CBS. For this gymnasium, there are 13 standard spans and each span is 42.25 m long. The standard span is composed of 10 standard units which is shown in Fig. 1. The key dimension of the model is shown in Fig. 9. Note the strut is V type as shown in cross section 2-2, the circular steel tube with section of 159 mm×10 mm (external diameter × thickness) is adopted, and the cable is the steel strand with section of 80 mm in diameter. The tensile strength of the steel strand is 1570 MPa, so the bearing capacity of the cable is no less than 7800 kN.

Using the design method proposed in section 3.1, the numerical simulation is carried out by using FEM software Midas/Gen, and a rich element library is provided in Midas/Gen, which can simulate the actual structure accurately. The plate element is used to simulate the RC

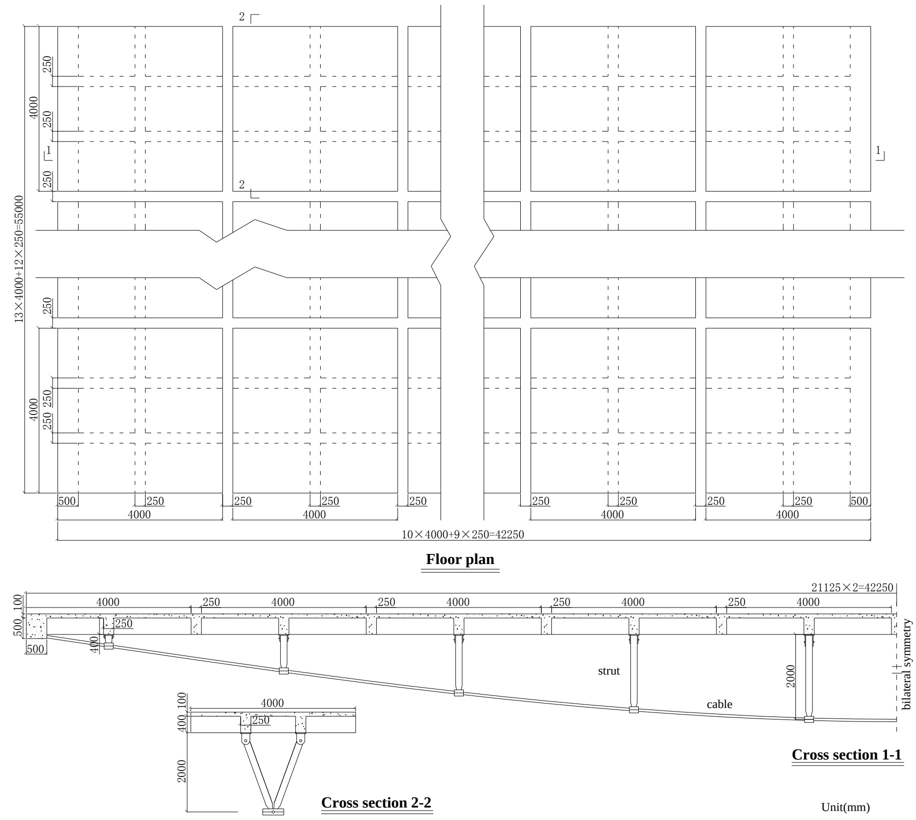

Fig. 9 Model's key size drawing

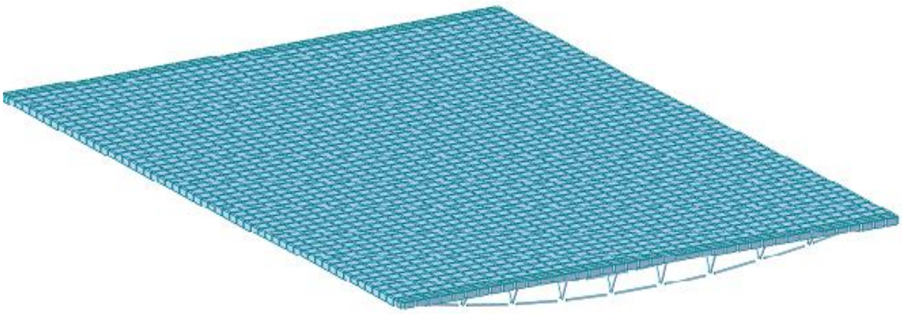

Fig. 10 FEM model of CBS

slab, the beam element is used to simulate the ribbed beam and strut. But for the strut, the in-plane rotation constraint of the beam element was released so that the struts can deform or rotate in accordance with the physical model. Moreover, the rigid coupling is used between the rib beam and slab for co-working and deformation consistency. The boundary condition of FEM model is set according to the actual situation, namely rigid connection in the one end, and slidable pin support in the other end. The FEM model is shown in Fig. 10.

Sometimes it is difficult to converge to the completely precise preset value *D*, which is shown in Fig. 11, although the vertical displacement *d* keeps fluctuating from the nth iteration step, it is getting close to the objective *D*, therefore a threshold value involved with precision is usually assigned to accelerate the iteration convergence, namely the tiny error ±*t* is set and shown in dash line in Fig. 11. In this example analysis, 0.05 is taken as the threshold value, which means ±5% error is allowed. The iterative process is shown in Fig. 12.

It is seen in Fig. 12 that the iteration converges at the 6th step, and the mid-span point vertical displacement value is 67.6 mm. Compared with the target value *D* = *span / 600*, the error of the mid-span vertical displacement is about 4%. Actually at the 5th iteration step, the corresponding displacement value is 63.8 mm, and the error is 9.4%, which is also acceptable as the pre-stress design value.

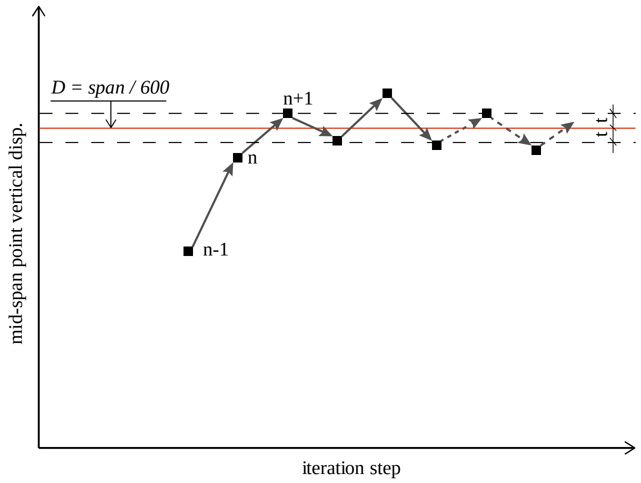

Fig. 11 Convergence analysis

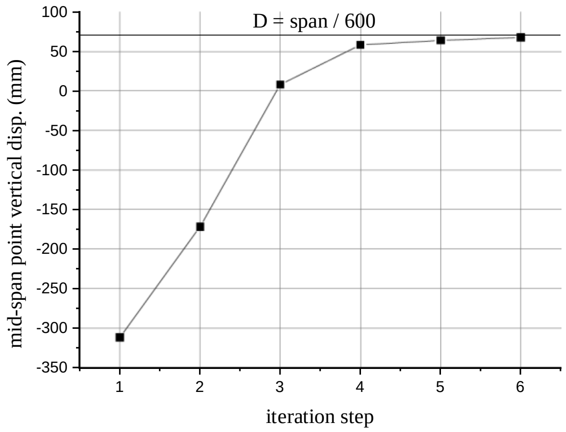

Fig. 12 Iteration process

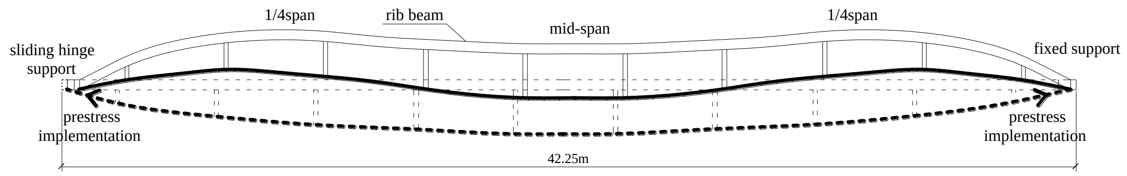

Fig. 13 Final deformation in step 2

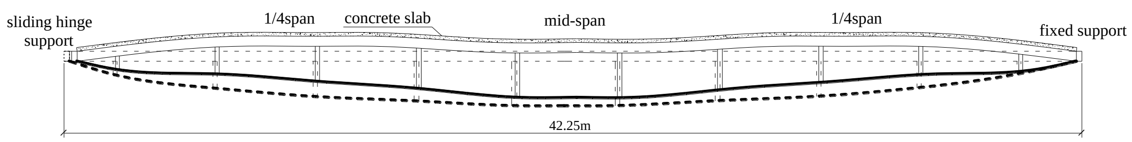

Fig. 14 Final deformation in step 3

In order to verify the rationality of the pre-stress design value calculated above, with this pre-stress applied to the cable, the deformation of the structure in the state of construction step 3 described in section 2 is calculated. Apparently, the rational pre-stress may be a range of values, and the smaller values are preferred. Here the 5th iteration value is tried and the corresponding pre-stress design value is 1900 kN. The deformation of the structure is illustrated in Fig. 13. In construction step 3, the prefab concrete slabs will be paved on top of the ribbed beams. Because of the extra dead load of the slabs, the CBS in the construction step 2 equilibrium state will deform downwards, and the

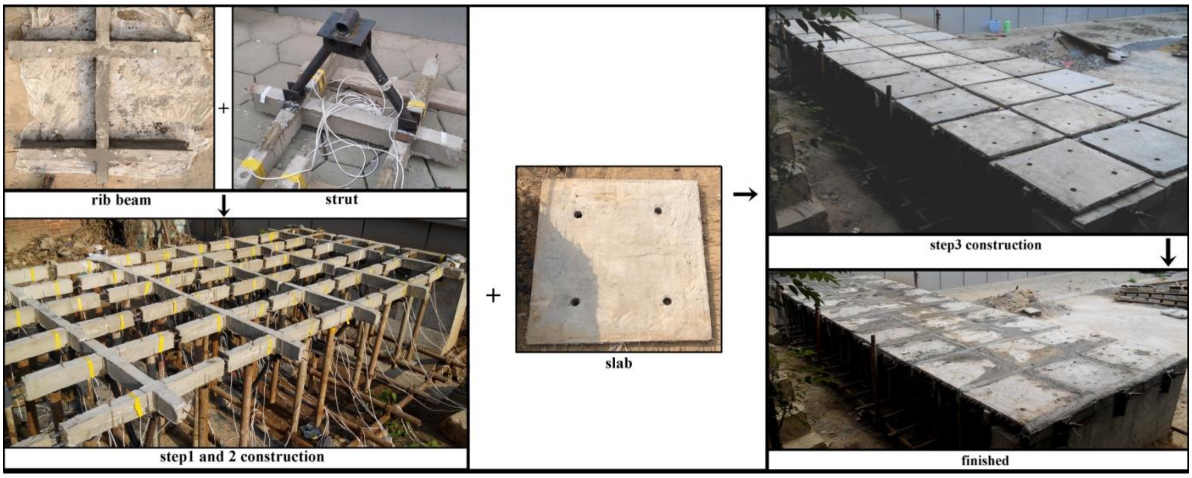

Fig. 15 Scaled physical model

Fig. 16 Indicator distribution and cable force testing

Table 1 Vertical disp. comparison between theory and experiment

Item	Theoretical value	Practical value	Error (%)
Step 2			
Cable force (kN)	76	81.17	6.8
Mid-span vertical disp. (mm)	12.76	13.26	3.9
Left1/4 span vertical disp. (mm)	13.52	13.8	2.1
Right1/4 span vertical disp. (mm)	13.52	13.97	3.3
Horizontal disp. (mm)	1.52	1.58	3.9
Step 3			
Cable force. (kN)	101.32	111.05	9.6
Mid-span vertical disp. (mm)	3.08	2.68	-13.1
Left1/4 span vertical disp. (mm)	4.24	3.90	-8
Right1/4 span vertical disp. (mm)	4.24	3.81	-10.2
Horizontal disp. (mm)	0.82	0.77	-6.1

final deformation of the CBS is shown in Fig. 14. The vertical displacement of the mid-span point is positive 15.4 mm which is still above the zero state, and can meet the demand of reasonable pre-stress design value described in section 3.1. Moreover, the internal force of the cable also increases because of the dead load of the concrete slabs. The calculated value is 2533 kN, which is 633 kN bigger than the tension 1900 kN in construction step 2.

3.3 Experimental study

In order to verify the accuracy of the analytical results, the experimental study is carried out in this section.

(I) Scaled physical model

Based on the prototype in section 3.2, a 1:5 scaled model is designed and fabricated. The scale factors can be determined according to the similarity constant and similarity ratio relationship in static loading experiment of engineering structure (Li 2004). For the geometric dimension shown in Fig. 9, the ratio of scaled model to the full scale model is 1:5. For the cable tension and structural displacement, the ratio of scaled model to the full scale model is respectively 1:25 and 1:5. These two scaled analytical values are shown in Table 1. The scaled physical model and its construction process are shown in Fig. 15.

Note that the key of the construction is to control the deformation, namely, the displacements of the critical positions. Therefore the displacement values monitored must be controlled as close to the corresponding analytical values as possible. If the actual tension applied to the cable deviates from the corresponding analytical value too much and the displacements recorded are still not close to the analytical values, the tensioning must be stopped for trouble shooting.

(II) Data measurement

In the experiment, the cable forces are collected by INV3080B-BCF cable force tester, which is shown in the bottom right of Fig. 16. The displacements are measured by the dial indicators, and for each standard span CBS, four indicators are respectively placed at two 1/4 span points, mid-span point, and sliding hinge support, which are shown in the left and top right of Fig. 16.

(III) Experimental results analysis

The scaled physical model was constructed according to the fabrication and construction process introduced in section 2. The data were collected and recorded, and compared with the theoretical data, the results are shown in Table 1. Note that error = (practical value - theoretical value) / theoretical value.

When tensioning the cable in the step 2, the deformation of the structure is very close to the analytical values, and the errors are all less than 4.0%. Also in step 2 the actual cable force is larger than the analytical value and the error is only 6.8% which is acceptable. Moreover, in the construction step 3, the maximum error of cable force is 9.6%, and the displacement is -13.1%, which are both in an acceptable range. It indicates the theoretical analysis method proposed is rational.

4. Parameter study

Four important parameters, including the sag-span ratio, depth of ribbed beam, strut's section diameter and cable's section diameter, may affect the mechanical characteristics of the CBS. The CBS prototype in section 3.2 is selected as the calculating model, and the mechanical features in the normal service condition are investigated. According to the Chinese load code GB5009-2012 (2012), the fundamental load combination 1.2 × dead load + 1.4 × live load is applied to the CBS. Note that with the same span, the different sag-span ratios can be obtained by setting the different cable sags. Also, the displacement is recorded according to the rule described in the section 3.1, namely, the displacement above the zero state is positive, while down is negative.

4.1 Study on Sag-span ratio

Keeping the other variables constant, the influence of the different sag-span ratio on mechanical characteristics of the CBS is analyzed. Here seven sag-span ratios of 0.03, 0.04, 0.05, 0.06, 0.07, 0.08 and 0.09 are considered. The main results are shown in Figs. 17-20.

As shown in Fig. 17, since the deformation goes below the zero state, all the displacements are negative. As the sag-span ratio increases, the ordinate value also increases, which means the actual deformation of the structure decreases. It is observed from Figs. 18-20 that both the maximum moment of the ribbed beam and the cable force decrease but the strut force increases with the increase of the sag-span ratio. The shape of the CBS will change with the variation of the sag-span ratio. In general, the increase of the sag-span ratio means the intersection angle between the strut and cable decreases, which will make the cable force transfer to the strut more efficiently and lead to the increase of strut force. Also, the flexible supporting action of struts on the upper ribbed beam and slab system is enhanced which can help to reduce the deformation of the structure as well as the moment of ribbed beams to some extent.

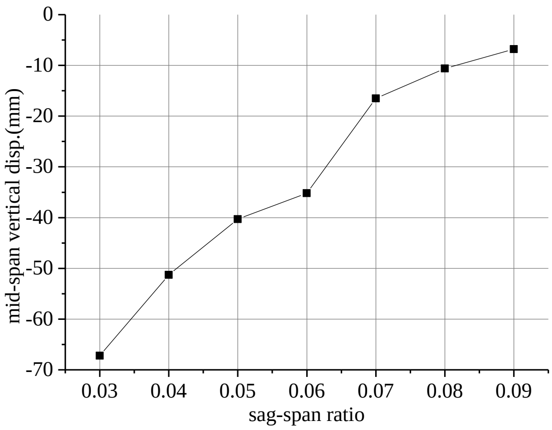

Fig. 17 Influence of sag-span ratio on displacement

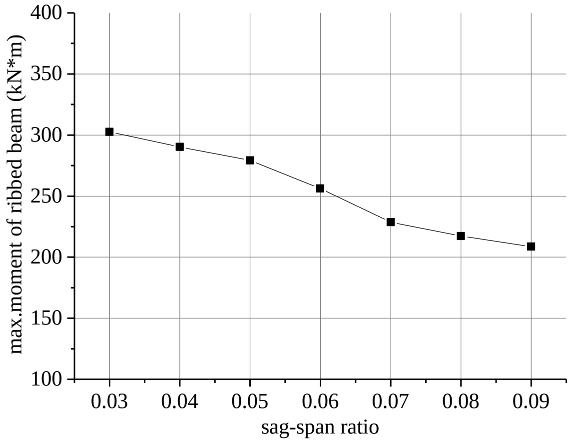

Fig. 18 Influence of sag-span ratio on moment

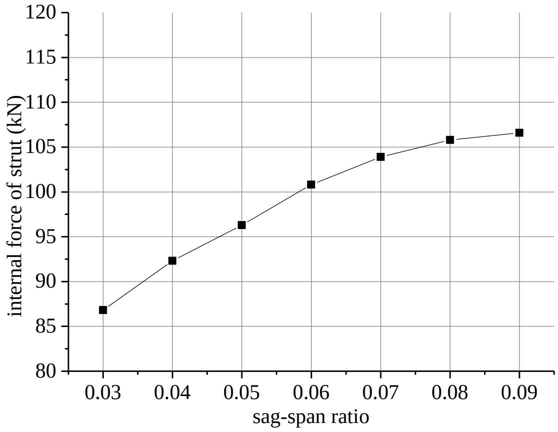

Fig. 19 Influence of sag-span ratio on strut force

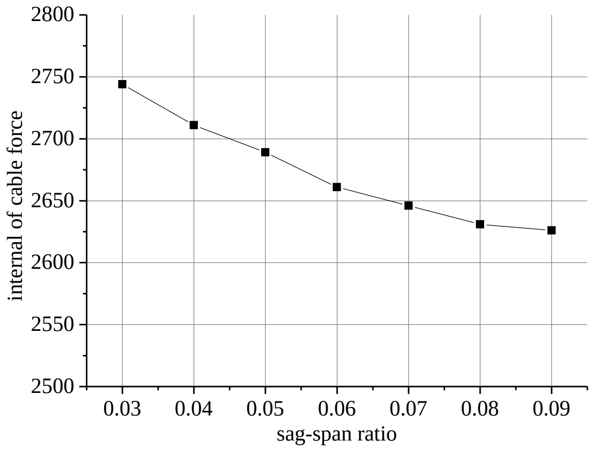

Fig. 20 Influence of sag-span ratio on cable force

Because of the decreasing intersection angle, the cable forces transfer unevenly in each parts and also lose a lot due to the increasing friction. Consequently, the cable force tends to decrease. Overall, the increase of the sag-span ratio can improve the mechanical behavior of the CBS. However larger sag-span ratio often means a larger cable sag which will occupy more interior space, and sometimes it is not desired. Generally on the premise of meeting the demand of architecture, reasonably larger sag-span ratio is recommended.

4.2 Study on depth of ribbed beam

Keeping the other variables constant, the influence of the depth of the ribbed beam on mechanical characteristics of the CBS is analyzed. Here seven depth of 350 mm, 400 mm, 450 mm, 500 mm, 550 mm, 600 mm and 650 mm are considered. The main results are shown in Figs. 21-24.

As can be seen from Fig. 21, with the increasing of the depth of the ribbed beam, the deformation decreases, but once the depth is larger than 550 mm the deformation begins to increase. It is obvious in Figs. 22-24 that all of the maximum moment of ribbed beam, strut force and cable force increase as the depth increases. Increasing the depth of the ribbed beam can improve the rigidity of the CBS, which will help to reduce the deformation of the structure. On the other hand, the weight of the structure is also increased and this may counteract the effect induced by the improvement of the rigidity.

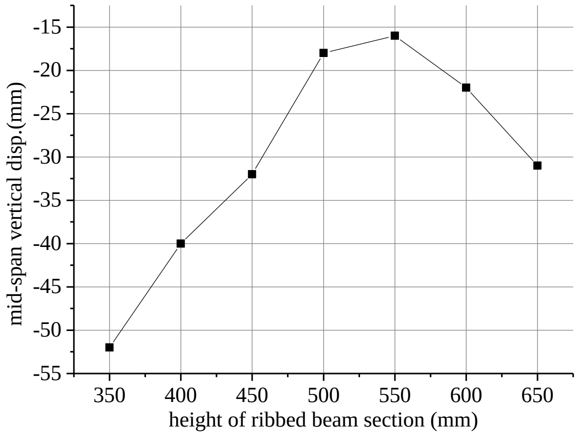

Fig. 21 Influence of beam depth on displacement

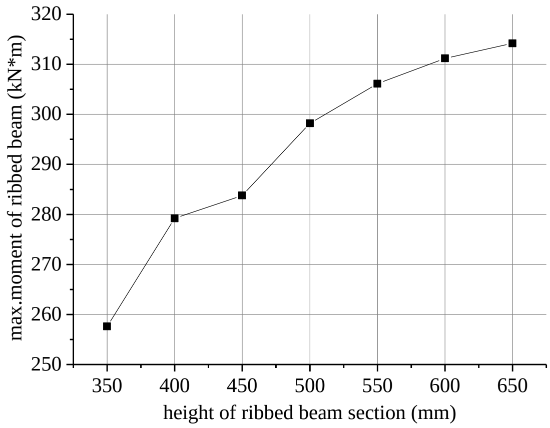

Fig. 22 Influence of beam depth on moment

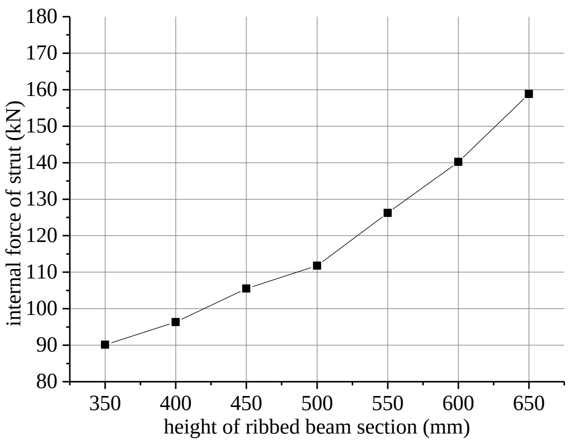

Fig. 23 Influence of beam depth on strut force

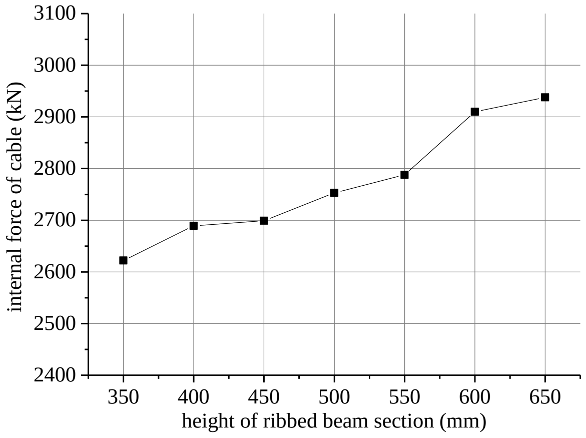

Fig. 24 Influence of beam depth on cable force

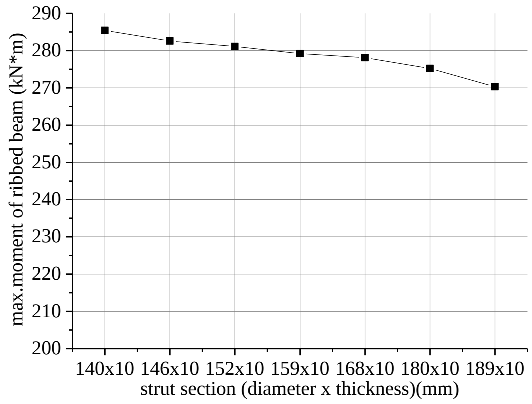

Fig. 26 Influence of strut section on moment

Therefore, when the depth is increased too much, the deformation does not reduce any more but begins to increase instead. To sum up, increasing the depth of the ribbed beam can improve the rigidity of the CBS, but this helpful effect is limited because of the increasing weight of the structure.

4.3 Study on size of strut section

Keeping the other variables constant, the influence of the strut's section diameter on mechanical characteristics of the CBS is analyzed. Here seven sections of 140×10, 146×10, 152×10, 159×10, 168×10, 180×10 and 189×10 are considered, and the results are figured out and shown in Figs. 25-28.

It is seen from Figs. 25 and 26, both the deformation and maximum moment of the ribbed beam are reduced as the strut section increases. This is because increasing the strut section can enhance the flexible supporting action of the strut on the upper ribbed beam and slab system which will be helpful to reduce the deformation and moment. But this improvement is not strong as the maximum decreasing value of displacement and moment are respectively about 4.4 mm and 15 kN, and maximum change rate are respectively about 10% and 5%.

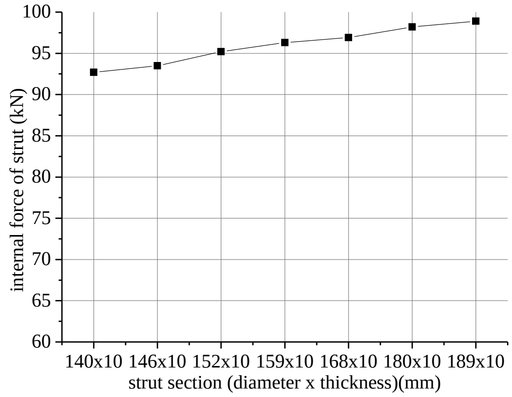

Fig. 27 Influence of strut section on strut force

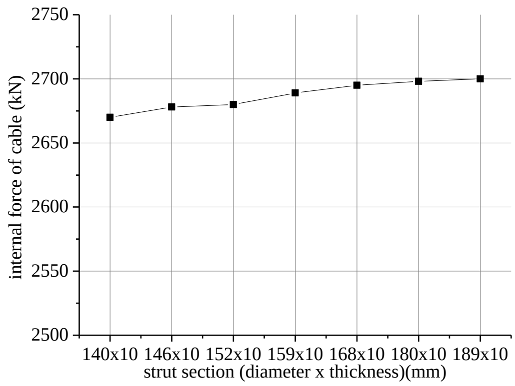

Fig. 28 Influence of strut section on cable force

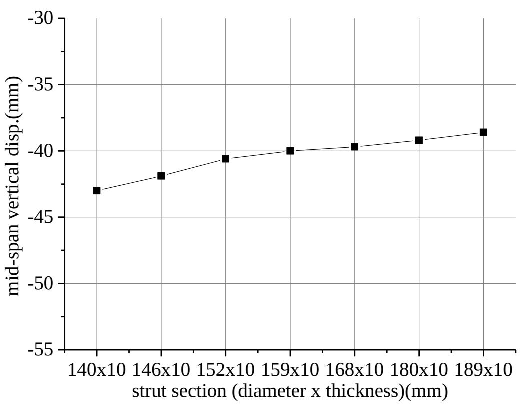

Fig. 25 Influence of strut section on displacement

It is clear in Figs. 27 and 28, both the strut force and cable force increase as the strut section increases, which is caused by the increase of the struts' weight and the variation of the rigidity of the structure. Likewise, the variation is small as the maximum increasing value of strut force and cable force are respectively around 6.2 kN and 3 0kN, and maximum change rate are respectively about 6% and 1%.

4.4 Study on cable diameter

Keeping the other variables constant, the influence of the cable's section diameter on the mechanical characteristics of the CBS is analyzed. Here seven diameters of 60 mm, 70 mm, 80 mm, 90 mm, 100 mm, 110 mm and 120 mm are considered, the main results are figured out and shown in Figs. 29-32.

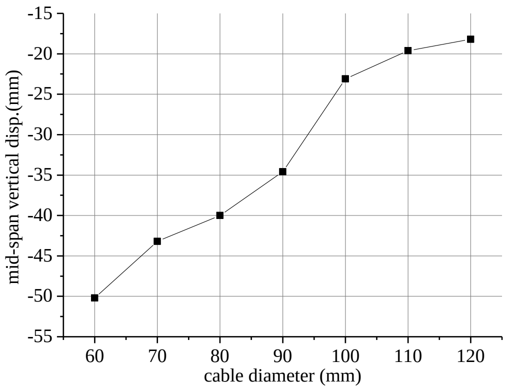

Fig. 29 Influence of cable diameter on displacement

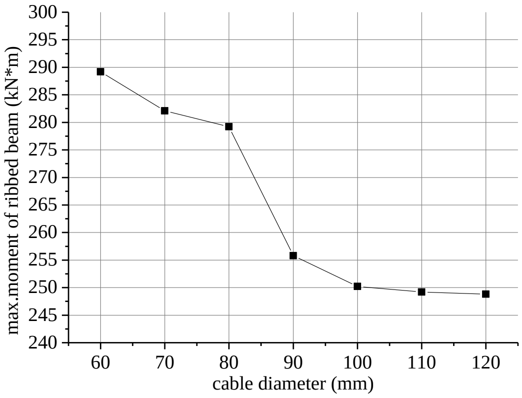

Fig. 30 Influence of cable diameter on moment

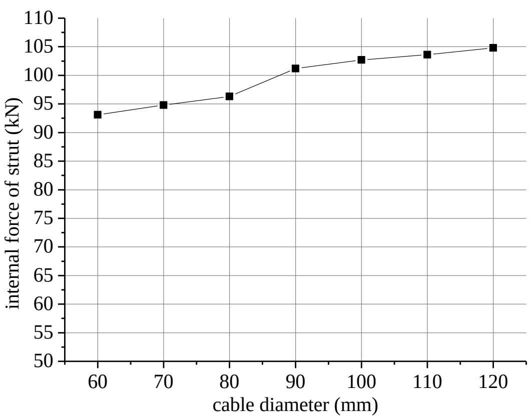

Fig. 31 Influence of cable diameter on strut force

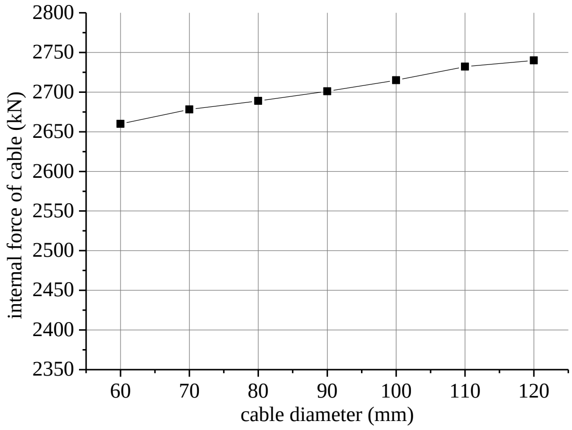

Fig. 32 Influence of cable diameter on cable force

It is observed from Figs. 29 and 30, both the deformation and maximum moment of the ribbed beam decrease as the cable diameter increases. This is because increasing the cable diameter can fortify the constraint imposed on the lower end of the strut so that the flexible supporting action of the strut on the upper ribbed beam and slab system is enhanced. This will help to reduce the deformation and moment. However, it is seen clearly from the slope change that this helpful effect will not change any more after certain limit is reached. Because of the increasing weight of the cable and the enhanced constraint, both the strut force and cable force will increase as the cable diameter increases, which is clearly shown in Figs. 31 and 32. If the variation is not significant as the slopes of curves are gentle, the maximum increased value of cable force and strut force are limited (respectively around 11.7 kN and 80 kN and maximum change rate are respectively about 11% and 3% in the case study). To sum up, increasing cable diameter can improve the behavior of the CBS on the whole, but this helpful effect is not significant and will diminishes after the limitation is reached.

5. Conclusions

As a new cable-supported structure, the CBS is put forward in this study. For the CBS, the standard fabrication, construction process and pre-stress design method are proposed. The experimental study on a 1:5 scaled model is performed to verify the rationality of the theoretical research method. Furthermore, four important parameters which may affect the mechanical features of the CBS are discussed. Based on the discussion, below conclusions are drawn.

- The CBS is composed of reinforced concrete slabs, ribbed beams, steel struts, steel strands and joints. All of these elements are prefabricated and then assembled on site. The construction process includes three main steps. Step 1, assembling the first span of the CBS beam elements. Step 2, connecting beam elements by casting concrete on site and installing the lower cable-supported system. Step 3, paving the slabs and finishing the first span construction, then repeating the same process in the next span.

- The pre-stress design method based on static equilibrium algorithm is proposed. The controlling value of the vertical displacement of the mid-span point, which is the key of the pre-stress finding and often set to be span/600. Using the rational threshold value can accelerate the iteration convergence in the process of force calculation and keep the result within an acceptable range. This analytical method is verified by the experimental study on a 1:5 scaled model.
- Increasing the sag-span ratio can improve the mechanical behavior of CBS, but the larger cable sag will often occupy more interior space. In general, on the premise of meeting the demand of architecture, the reasonably larger sag-span ratio is recommended. The increasing of the depth of the ribbed beam can enhance the rigidity of the CBS, but this helpful effect is limited because of the concurrent increasing of the weight. The influence of the strut section on the behavior of CBS is negligible. The increasing cable diameter can improve the behavior of the CBS, but this helpful effect is also limited and it does not increase any more after the cable diameter reaches a certain value.

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References

Abeysinghe, C.M., Thambiratnam, D.P. and Perera, N.J. (2013), "Dynamic performance characteristics of an innovative hybrid composite floor plate system under human-induced loads", *Compos. Struct.*, **96**(4), 590-600.

Chen, Z.H. and Qiao, W.T. (2010), "Analysis on cable supported concrete roof structure and its basic characteristics", *Build. Struct*., **40**(11), 22-25.

Chen, Z.H., Qiao, W.T. and Yan, X.Y. (2010), "Cable supported barrel vault structure system and research on mechanics characteristics", *J. Adv. Steel Constr.*, **6**(3), 867-878.

GB5009-2012 (2012), Load Code for the Design of Building Structures, China Building Industry Press; Beijing, China.

Kawaguchi, M., Abe, M. and Hatato, T. *et al.* (1993). "On a Structure System "Suspen-dome"", *Proc. of IASS Symposium*, Istanbul, 523-530, 5.

Kawaguchi, M., Abe, M. and Tatemichi, I. (1999). "Design, tests and realization of "Suspen-dome" System", *J. IASS*, **40**(131), 179-192.

Kmet, S. and Mojdis, M. (2015), "Adaptive cable dome", *J. Struct. Eng*., **141**(9), 1-16.

Lee, K., Lee, S.H., Kim, G.C. and Woo, S.S. (2014), "Global vertical resonance phenomenon between steel building and human rhythmic excitations", *J. Constr. Steel Res*., **92**, 164-174.

Li, Z.X. (2004), *Theory and Technique of Engineering Structure Experiments*. Tianjin University Press, TianJin, China.

Masao, S. and Kurasiro, T. (1985), "A study on structural behaviors of beam string structure", *Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, B.1*, Tokyo, Japan, 280-284, 6.

Mello, A.V.A., Silva, J.G.S.D., Vellasco, P.C.G.D.S., Andrade, S.A.L.D. and Lima, L.R.O.D. (2008), "Dynamic analysis of composite systems made of concrete slabs and steel beams", *J. Constr. Steel Res.*, **64**(10), 1142-1151.

Ouni, M.H.E.I. and Kahla, N.B. (2014), "Active tendon control of a Geiger dome", *J. Vib. Control*, **20**(2), 241-255.

Qiao, W.T., Chen, Z.H. and Zhao, M.S. (2012), "Test study on basic static characteristics of cable supported barrel vault structure", *J. Adv. Steel Constr.*, **8**(2), pp.199-211.

Silva, J.G.S.D., Andrade, S.A.L.D. and Elvis, D.C.L. (2014), "Parametric modelling of the dynamic behavior of a steel–concrete composite floor", *Eng. Struct*., **75**(75), 327-339.

Silva, S.S.D. and Thambiratnam, D.P. (2009), "Dynamic characteristics of steel–deck composite floors under human-induced loads", *Comput. Struct.*, **87**(17-18), 1067-1076.

Varela, W.D. and Battista, R.C. (2011). "Control of vibrations induced by people walking on large span composite floor decks", *Eng. Struct*., **33**(9), 2485-2494.

Yan, R.Z., Chen, Z.H., Wang, X.D., Liu, H.B. and Xiao, X. (2015), "A new equivalent friction element for analysis of cable supported structures", *Steel Compos. Struct*., **18**(4), 947-970.

Zhao, X.Z., Yan, S. and Xu, Z.Y. and Wu, A.H. (2015). "Research and application of beam string structures", *Struct. Eng. Int*., **25**(1), 26-33.

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