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Development and analysis of a long-span retractable roof structure

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ABSTRACT

A long-span retractable roof structure based on the beam string structure (BSS) and scissor mechanisms was presented in this paper. The BSS are placed parallel to each other and they are connected with the linear scissor mechanism. During the folding or unfolding, the structure just has one degree of freedom. The geometry of the retractable roof structure was firstly given. Then structural analysis of an integrated model of the unfolded configuration was conducted. Furthermore, the structural behavior of the structure in the semi-open configuration is also investigated. Finally, using the translational and rotational springs to model the elastic support of the strut, an analytical model for the lateral buckling of the BSS during the motion is developed. Based on the virtual work principle, the formulation of the critical load is obtained. Then a detailed parameter analysis of the BSS with a straight beam is undertaken.

1. Introduction

In recent years, space structures have been developed rapidly all over the world. And string (cable) structures can be found in many large space structures [1–3]. String structures are divided into two types [4]: hybrid tension structures and thoroughbred tension structures, such as membrane structures [5], cable nets [6] and cable–strut structures [7,8]. Beam string structure (BSS) is a typical type of hybrid tension structures, which is composed of upper beams, lower steel cables and struts. Applying pretension force to lower steel cables causes the structure to deform to an invert arch, which decreases the deflection of the structure greatly.

Due to the above advantages, BSS has been widely used in stadiums, public halls, and airplane hangers, such as Green Dome Maebashi [4], Urayasu Municipal Sports Center [4], Shanghai Pudong International Airport Terminal [9], Guangzhou International Convention and Exhibition Center [10], Harbin Exhibition Sports Center [11], Shanghai Yuanshen Arena [12], and National Gymnasium Roof Model [13]. There are also many researches on the BSS [9–14], like static and parameter analyses, form-finding analysis, dynamic analysis, and model test.

Retractable roofs are cover structures that can transform from one configuration to another, usually referred to as the open and closed configurations. Although small-sized retractable roofs have been developed, the long-span retractable roof is still a problem [15]. Moreover, in a building, especially in a long-span building, there is a large desire for the provision of very large spaces for sports or other events, which could provide complete protection from inclement weather to audience and players, but which could remain open if the weather was good [16]. Based on the above advantages of beam string structure and the mature design theory and construction level for BSS, it is a good candidate for the long-span retractable roof structure.

In this paper, a new type long-span retractable roof based on the beam string structure and the scissor mechanism is developed. The independent beam string structures are connected with the scissor mechanism. During folding or unfolding, the structure just has one degree of freedom. The geometry of the retractable roof structure was firstly given. Then the static behavior under different load combinations of the unfolded and semi-open structure is also investigated. Finally, using the translational and rotational springs to model the elastic support of the strut, an analytical model for the lateral buckling of the BSS during the motion is developed.

2. Geometry of the retractable roof

The structure presented in this case study is a retractable roof structure used in stadiums, convention and exhibition center, public halls etc. Many different designs and concepts using scissor mechanisms have already been proposed for deployable or mobile structures. Most of these designs were based on scissor-grid structures as described in Reference [17]. However, scissor-grid structures always have to be handled as a whole, which limits their size and weight. Therefore, we suggest that the system with parallel linear beam string structures can be used as an interesting alternative. And the separate beam string structures are connected with the scissor mechanism. The deployed and semi-open configurations are shown in Fig. 1. The scissor mechanism in the unfolded configuration is overlapped to form a line. The structure can also be folded to a small compact bundle.

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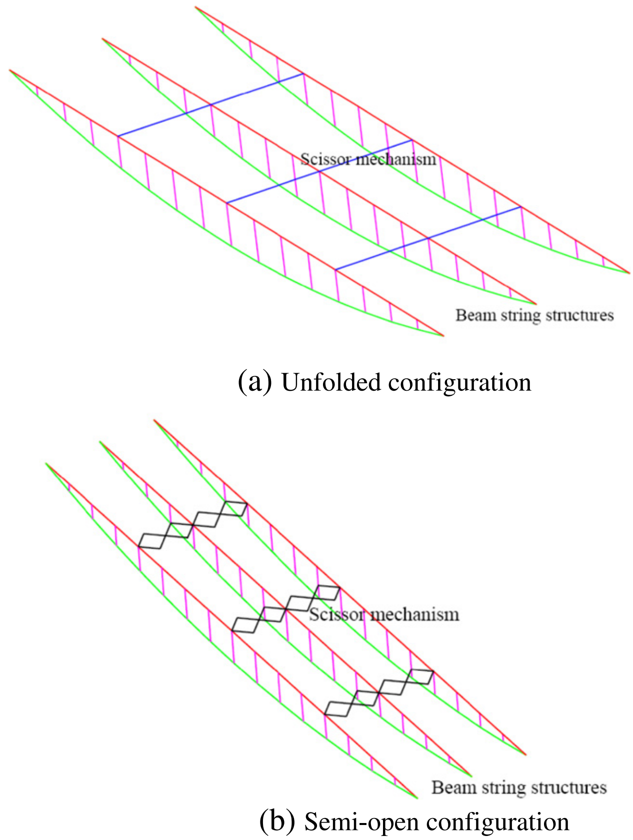

Fig. 1. The retractable roof based on beam string structures and scissor mechanisms (a) unfolded configuration (b) semi-open configuration.

The span of the BSS of the case is 72 m, and the sag of the cable is 4 m. The length between the parallel beam string structures in the fully closed configuration is 9 m. The other geometry information of one single piece of the BSS is shown in Fig. 2.

3. Static analysis of the unfolded structure

3.1. Loads and load combinations

The completely closed roof and the semi-open roof in this case are required to withstand full wind and live/snow loads and their combinations. These loads and load combinations are determined in accordance with the Chinese Codes. Both the dead and live loads are assumed to be 0.5 kN/m^2. In their closed and semi-open configuration and for wind coming from the transverse direction, which is perpendicular to the plane of beam string structures, the structure can be compared to a flat roof structure as described in the Chinese Code. So the wind loads for the closed and semi-open roofs are $-$0.284 kN/m^2 and $-$0.25 kN/m^2, respectively.

Eight load cases are considered for the Ultimate Limit State analysis as (1)1.2Dead + 1.4Live; (2)1.35Dead + 1.4 × 0.7 Live; (3)1.2Dead + 1.4Wind; (4)1.2Dead + 1.4Live + 1.4 × 0.6Wind; (5) 1.2Dead + 1.4 × 0.7Live + 1.4Wind; (6) 1.2Dead + 1.4Live(asym); (7)1.2Dead + 1.4Live(asym) + 1.4 × 0.6Wind; (8)1.2Dead + 1.4 × 0.7Live(asym) + 1.4Wind. And seven cases for the Serviceability Limit State Analysis are given as: (1) Dead + Live; (2) Dead + Wind; (3) Dead + Live + 0.6Wind; (4) Dead + 0.7Live + Wind; (5) Dead + Live(asym); (6) Dead + Live(asym) + 0.6Wind; (7) Dead + 0.7Live(asym) + Wind. The self weight of the structure is included in all cases.

Table 1
Overview of the support forces in the unfolded configuration.

	F_x(kN)	LC	F_y(kN)	LC
Min	−2796	1	261	6
Max	2796	1	652	1

3.2. Finite element model

The Finite Element Analysis software ANSYS is employed in all structural analyses that have taken into account the geometrical nonlinearity. The steel truss and beam are simulated by element BEAM 188, the steel strut is simulated by element BEAM 44, and the tension-only element LINK 10 is employed to model cable in the structure. The section for the beam of BSS is H1200mm × 600 mm × 24 mm × 35 mm, and the section for the scissor mechanism is H250mm × 100 mm × 4 mm × 6 mm. Steel pipes of 245 mm in diameter and 8 mm in thickness are used as the strut of the BSS. All the above elements are made of steel with an elastic modulus of 206 GPa. The type of the cables with an elastic modulus of 180 GPa is PES7-301.

The two scissor-bars of a unit are interconnected at the scissor-hinge. At the scissor-hinge, four elements (BEAM 188) are connected to one translational point, representing the location of the scissor-hinge in global 3-D space. To simulate the effect of the scissor-hinge, an additional rotational point is created. The two beam elements of one scissor-bar are connected to the one rotational point, and the two beam elements of the other scissor-bar are connected to the other rotational point. This way the two beam links of each scissor-bar can be rigidly connected to each other, while the rotation of the two scissor-bars is decoupled.

3.3. Ultimate limit state analysis

The minimum and maximum values of the reactions are given in Table 1. The maximum stresses in the elements are given in Table 2. The σ(N) denotes the stress caused by the axial forces, and σ(M) is the bending stress. The elements in which these values are found are depicted in Fig. 3.

The highest support forces are found for LC1 and LC6, which are the dead and live loads. Maximum tension force in the cables of the BSS is 2738 kN, which occurs when the structure is subjected to LC1. The maximum stress of the struts occurs in the LC1. This is because the directions of the wind load and the live load are opposite. The worst load for the scissor is LC6, which is the asymmetric live load. Bending in the scissor-bars is caused by the interaction of the bars at the scissor-hinges. Therefore, the highest bending and the highest axial

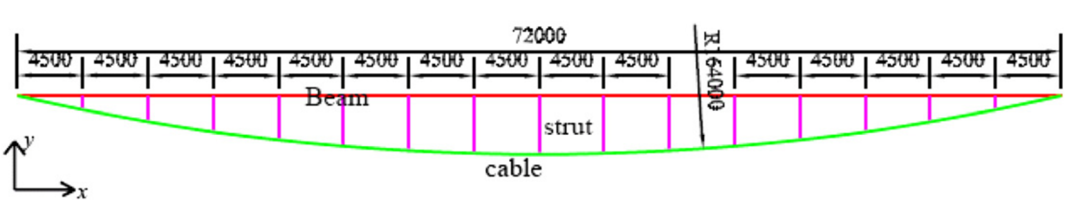

Fig. 2. Geometry of the BSS.