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Form-finding of a mixed structure with cable nets and tubular trusses

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ABSTRACT

This paper presents the main results of the form finding analysis, model testing and on-site investigation on a mixed structure consisting on a system of steel tubular trusses coupled with a spatial cable net. Firstly, the combining method of force density and finite element is proposed for the form finding analysis of the mixed structure. Then, experimental tests are carried out on a scaled model in order to assess the different levels of pretension to be introduced in the cable system. Finally, the result of the on-site assessment activity carried out to monitor the real force level acting on different cables is presented and the comparison between the inspection results and the design target is made. The construction of the mixed structure has been successfully carried out and completed on the basis of the work presented in this paper.

1. Introduction

The mixed structure described in the present paper, consisting of a 3D cable net and a shell-like steel tubular truss structure was chosen as the main image of the newly built China Maritime Museum (Fig. 1.1a–b) in Lingang city — PRC. The maximum height of the structure is 58 m while the height of the cable net structure is 40 m. Each portion of the cable nets is formed by the presence of couples of shorter transverse cables and longer longitudinal cables (Fig. 1.1c).

As known, for cable net structures, there is a tight relationship between the shape and the condition of equilibrium. For the mixed structure shown in Fig. 1.1, different sequences of cable pre-tensioning and different levels of internal forces would result in a different final geometry.

The aim of the form finding process is to determine a desirable shape together with the corresponding internal force distribution [1]. Model testing is an effective tool in order to check the feasibility of the structure and the effectiveness of the pre-tensioning sequence. Through the on-site inspection activity on the completed structure, the correspondence between the expected theoretical level of internal force distribution from the process of form finding and the real values can be determined.

For cable nets, many methods of form finding analysis have been proposed such as force density method [2], dynamic relaxation method [3], geometrically nonlinear finite element method [4], etc. In this paper, a method combining force density and finite element is proposed for the mixed cable-net and steel truss structure. For the measurement and inspection of cable forces, oscillating frequency technique and three point bending method are commonly used [5], although both of them would be inappropriate for the cable net shown in Fig. 1.1, because the first one is only suitable for a single cable while the second is suitable for slender cables. In this paper, the EM principle and the corresponding sensor [6–8] are adopted in model test and on-site inspection.

2. The combining form-finding analysis method for the mixed structure

The geometrical layout of the mixed structure is initially determined by architectural reasons, even if the final shape of the cable-net can just be confirmed on the basis of a numerical form-finding analysis. It has to be noticed that the cable net in the mixed structure is connected to a rigid tubular truss system; therefore when its shape is determined the corresponding cable forces under fixed boundary conditions can be determined through the application of the force density method. Then the corresponding forces of the boundary cables can be applied to the tubular trusses and its internal forces and deflections can be solved by linear finite element method under the previously given geometry by the architects. As a result of this process, the final system of internal forces in the whole structure is strictly self-equilibrated under the shape of cable nets found by force density method and the geometry of tubular trusses previously given by the architects. Such self-equilibrating state can be defined as the “initial state” of the structure. This so-called combining form-finding analysis method is very simple and efficient, but together with this method the construction process analysis may need to be carried out carefully.

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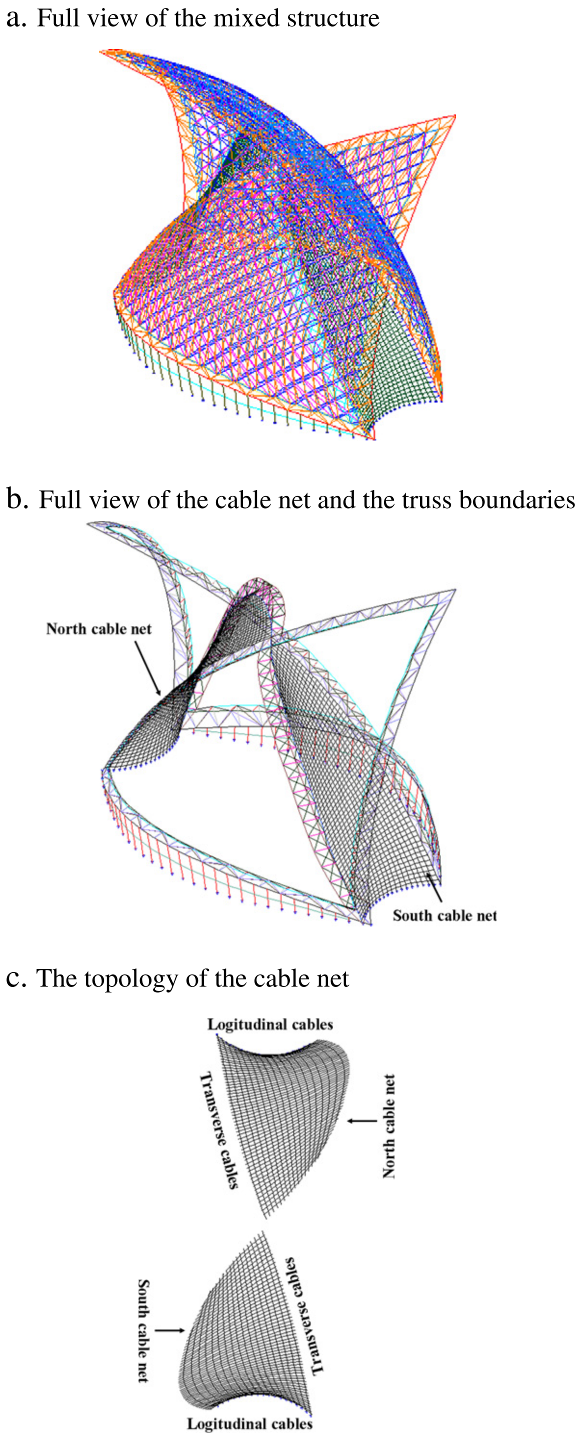
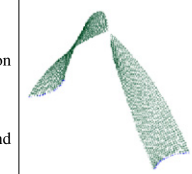
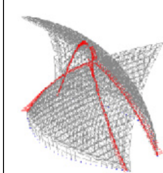
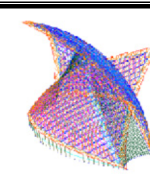


Fig. 1.1. Mixed structure of China Maritime Museum. a. Full view of the mixed structure. b. Full view of the cable net and the truss boundaries. c. The topology of the cable net.

If the tubular trusses are stiff enough, the trusses supply a "rigid frame" for the cable nets and the pre-tensioning will cause negligible deformations. Otherwise the pre-deforming, which can compensate the deflections of tubular trusses caused by the pre-tensioning, should be computed through the construction process analysis and considered in the manufacture of the trusses [1].

The procedure of the combining form-finding analysis method for the mixed structure is listed in Table 2.1.

Table 2.1
Procedure of formfinding for the mixed structure.

Method	Description	Model
Force density method	• Fix all nodes connected to truss members. • Find the shape and corresponding pre-tension distributions of the cable nets by the force density method with given fixed boundaries and pre-tensions.	
Linear finite element method	• Fix all nodes linked to the cable nets only. • Reactions at the boundaries of the cable nets are reversely applied to the rigid trusses, which are shown as red arrow lines in the right figue. • Linear FE analysis is performed to obtain the force distribution of the trusses under the given geometry.	
Geometric nonlinear finite element method	• Based on the formfinding of the mixed structure, geometric nonlinear FE analysis is performed to obtain the force and displacement distribution under different loading combinations.	

The force density method is a very efficient form-finding tool for cable nets. Fig. 2.1 shows a node k connected with m cable members in a cable net. The equilibrium equation of node k can be expressed as:

$$\sum_{j=1}^{M_k} \frac{x_{Xi}^{k} - x_{Xi}^{k'}}{L_j} s_j = \sum_{j=1}^{M_k} \left(x_{Xi}^{k} - x_{Xi}^{k'} \right) q_j = f_{Xi}^{k} \quad (i = 1, 2, 3) \tag{1}$$

where s_j and L_j are the internal force and length of member j, $x^{k'}{}_{Xi}$ is the coordinate of node k' in X_i direction, f_{Xi}^{k} is the external force of node k in X_i direction, $q_j = s_j / L_j$ is defined as the force density of member j.

In Eq. (1), boundary node coordinates are previously given and the unknown variables are inner node coordinates and force density in

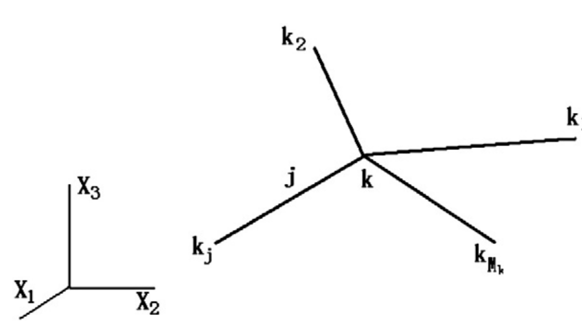


Fig. 2.1. Joint and cable members in cable nets.