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Engineering Structures 29 (2007) 529–541
ENGINEERING STRUCTURES
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Structural behaviors of an arch stiffened by cables

Minger Wu[a,*], Mutsuro Sasaki[b]

[a] *Department of Building Engineering, Tongji University, 1239 Shiping Road, Shanghai 200092, China*
[b] *Department of Architecture, Hosei University, 3-7-2 Kajino-cho, Koganei, Tokyo 184-8584, Japan*

Received 13 January 2006; received in revised form 26 May 2006; accepted 31 May 2006
Available online 18 July 2006

Abstract

In this paper, the static and dynamic behavior of a cable-stiffened arch is investigated by means of numerical and experimental methods. The pre-tension introducing experiment, the loading experiment and the free vibration experiment are carried out and the experimental results are compared with the numerical analysis. From the pre-tension introducing experiment, it is shown that pre-tension of a cable can be effectively introduced through using length-adjustable struts and a reversed process method. In the loading experiment, the loading ability of the cable-stiffened arch is examined and it is found that the buckling load of the experimental model increases greatly when cable is used. Natural frequency and mode damping ratio from the first mode to the fourth mode are measured by means of the free vibration experiment. Damping ratio increases greatly when cable is used. It is also found that the amplitude of displacement and the pre-tension of cable have influences on the damping ratio.

Keywords: Tension structure; Cable structure; Cable stiffened structure; Pre-tension introduction; Loading experiment; Damping ratio

1. Introduction

The usages of tension elements, such as membrane, cables, tension rods and so on, can be classified into three categories. The first one is that tension elements are used as main structural elements in "tension-only" structures, for example, cable nets or tension membrane structures. The shape of a "tension-only" structure should be carefully designed so that pre-tension can be introduced into every part of the structure. The soap experimental method, which was used by F. Otto in shape-finding design in previous times, now can be carried out by using numerical calculation. The second usage of tension elements is found in "tension–compression" structures in which all elements are pin-jointed and no moment exists. Tensegrity [1] or tensegric structure [2] and tension truss [3] belong to this class, or are typical examples of this class. A "tension–compression" structure becomes stable only when pre-tension is introduced. In order to obtain a "tension–compression" structure which can be pre-tensioned, a shape-finding process is also necessary. The third usage of tension elements can be found in cable-stiffened structures, which is the focus of this paper.

In a cable-stiffened structure, tension elements are used to stiffen a primary stable structure, which can be a column, a beam or even a single layer lattice shell. Structural properties, such as buckling load, stiffness, stabilization, etc., can be improved greatly through stiffening primary structures with tension elements. For example, a stayed column is much more effective in resisting buckling than a simple column [4], or the maximum moment in a beam can be reduced greatly if a beam string structure is used. For large span space structures, tensegric systems can be used to stiffen thin-walled domical domes [5] and supplementary self-equilibrated tension units are effective in stiffening lattice shells to obtain larger buckling load [6]. A pre-stressed dome with cable stiffeners was numerically investigated [7,8], and it was found that the buckling load of the dome increased when stiffeners were used. Many real cable-stiffened structures, a glass grid roof is one example, can be found in [9]. Because the primary structure itself is usually stable, no shape-finding process is necessary in designing a cable-stiffened structure.

Tension elements are usually pre-tensioned so that they can be used as compression elements. Several theoretical methods for calculating self-equilibrated stress mode and analyzing

* Corresponding author. Tel.: +86 21 6598 0644; fax: +86 21 6598 6345.
E-mail address: wuminger@mail.tongji.edu.cn (M. Wu).

0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2006.05.018

pre-tension introducing processes have been suggested [10,11]. It is not easy to get both the shape and tension under control in a real construction process. The deformation of a structure in the pre-tension introducing process will cause the change of tension in other cables. A pre-tension introducing method that will not cause large deformation of the structure and can introduce pre-tension effectively is usually expected.

In general, there are two kinds of methods for pre-tension introduction. The first one, which is here named as method A for convenience, is that pre-tension is introduced one cable at a time and little tension by little tension until the designed pre-tension is reached. Method A depends on the designer's experience in determining the introducing order and the pre-tension value of every introducing step. Though no complicated calculation is necessary for method A, many steps are usually needed and the pre-tension introduction is time-consuming. The second one, i.e. method B, is called the reversed progress method. By considering the final shape in which pre-tension has already been introduced and calculating tension in other cables through slacking off one cable in a reverse order of the pre-tension introducing process, the pre-tension that should be introduced into cables in every step is obtained. Generally, the pre-tension introduction can be finished in one turn. Method B is very efficient though an accurate reversed progress calculation is needed [12].

In order to analyze the structural response under wind or earthquake, the dynamic characteristics of a structure, damping ratio for example, are necessary. There are a few reports on the damping ratio of tension structures, which mainly come from cable-stayed bridges [13,14]. For space structures, few data on natural frequency and damping ratio from direct measurement can be found [15]. Damping ratio of a practical structure is influenced by many factors, such as friction, foundation conditions, roof materials, and so on. Also, measured damping ratio is influenced by measuring methods and data analyzing methods. Until now, few investigations on the damping property of tension structures can be found.

To investigate the basic behavior of a cable-stiffened system, the authors of this paper have carried out numerical and experimental studies on a cable-stiffened column [16]. In this paper, we apply the cable-stiffened system to an arch as shown in Fig. 1. In order to study the suggested cable-stiffened arch, an experimental model with a 1/10 scale of a designed arch is investigated for (1) the pre-tension introducing process, (2) the loading behaviors and (3) the free vibration. In the pre-tension introducing experiment, two models with different introducing systems, i.e. model A for pulling cables and model B for elongating struts, are used. In the loading experiment, several kinds of loading conditions are set and different pre-tensions are used. In the end, the free vibration experiment is carried out in order to obtain the damping ratio of the experimental model. Natural vibrations from the first mode to the fourth mode are stimulated and the corresponding natural frequencies and damping ratios are measured.

Numerical analyses for the pre-tension introducing process simulation and the loading–displacement calculation are carried out using geometrically nonlinear FEM. Results from the experiments and the numerical analysis are compared in the paper.

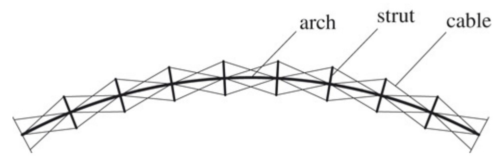

Fig. 1. A cable-stiffened arch.

Before the details of the experiments are described, the numerical method used in this paper is summarized.

2. Numerical method for pre-tension introduction

There are several practical methods to simulate the pre-tension introducing process. For example, the pre-tension introducing process can be analyzed by using temperature simulation. Another useful method is by using stress analysis. First, remove cables or struts that pre-stress (pre-tension or pre-compression) should be introduced from the structure and take their specified pre-stresses as external loads. Then, a standard stress analysis for the reduced system is carried out. Geometrically nonlinear analysis should be used if large displacement is observed within the pre-stress introducing process. The reduced system, from which some elements are removed, may become unstable. In this case, instead of removing elements, we can specify a small axial stiffness for those elements so that the stability of analysis is ensured.

In this paper, the stress analysis method is used for the pre-tension introducing process simulation. Fig. 2 illustrates the procedure in which the linear stress analysis is used.

3. Geometrically nonlinear finite element method

The geometrically nonlinear finite element method is used in this study. The material is assumed to be elastic. Small strain, small rotation and small displacement are satisfied within every incremental step. Under these conditions, geometrically nonlinear formulation can be simplified greatly [17].

Updated Lagrangian formulation is used for the incremental calculation. The incremental equation can be written as

$$(\mathbf{k}_e + \mathbf{k}_g)\,\Delta\mathbf{u} = \Delta\mathbf{f} + \mathbf{r} \tag{1}$$

where $\mathbf{k}_e$ is elastic stiffness matrix, $\mathbf{k}_g$ is geometric stiffness matrix, $\Delta\mathbf{u}$ is incremental displacement vector, $\Delta\mathbf{f}$ is incremental load vector and $\mathbf{r}$ is error of unbalanced force vector at the current state. The elastic modulus of cable is set to zero when the tension of the cable vanishes.

A program based on the geometrically nonlinear finite element method is developed in which the arc length method is employed. Post-buckling analysis of a low-rise arch model shown in Fig. 3, which was given by Harrison [18], is used to check the validity of the developed program. If the loading point is the center of the arch (perfectly symmetrical model), one bifurcation point is observed near the peak of the load–deflection curve from numerical results (see Fig. 4: the