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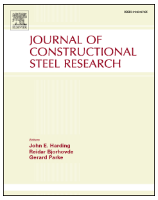

Static behaviour and simplified design method of a Tensairity truss with a spindle-shaped airbeam

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ABSTRACT

To provide solutions for large span structures, the use of a Tensairity truss with a 60-m span, which was studied numerically, is proposed. The influence of the internal pressure and cable tension length on the mechanical properties is investigated for several load cases. A simplified spring model based on the vertical stiffness formula of the inflated airbeam is presented, and a static design principle and a design method are proposed. The results show that the adoption of a steel truss can greatly increase the spanning capacity of a Tensairity structure, and the stiffness and load bearing capacity for the structure increase with the increase in air pressure. However, the structure is very sensitive to wind load, which can be improved by re-tensioning the lower cable. Comparisons between the simplified spring model and the original model show a good correlation for the displacement distribution and overall stiffness at a relatively high internal pressure for all load cases considered. The simplified design method will be an easy way for designers to evaluate the behaviour of Tensairity structures, and can be conveniently applied to practical engineering cases.

1. Introduction

Inflatable membrane structures have been used for a long time owing to their high strength-to-weight ratio. This salient characteristic provides many solutions to long span and spatial structures [1–3]. However, the poor load-bearing capacity drastically limits the application of such structures in civil engineering projects. During the past decade, the concept of Tensairity has developed in a variety of directions for construction applications. Tensairity is a synergetic combination of struts, cables, and an airbeam under a low internal pressure [4]. This type of structure can be seen as a beam string structure, of which the brace rods are replaced with a low-pressure airbeam. Therefore, the basic mechanical characteristics are very similar for both structures, and the brace rods and airbeam will provide elastic support for rigid components.

The Tensairity structure takes full advantage of the compression characteristics of rigid members and the tensile characteristics of flexible cables and low-pressure inflatable airbeams. The tension and compression separation is dexterously realized, and the structural material is fully utilized [4]. Previous researches have focused on Tensairity beams, columns, and arches, demonstrating the widespread application of the Tensairity concept [5–10]. Airbags and flexible cables greatly facilitate the storage, transport, and installation. Moreover, the combination of airbags and built-in lights also enhances the architectural aesthetics at night. The structure is very suitable for temporary bridges, exhibition halls, and protection structures at archaeological sites. Recent advances in Tensairity structure and construction technologies have the potential to provide this structural concept with a wider range of application [11].

In this paper, a Tensairity truss with a spindle-shaped airbeam was studied numerically based on the structural concept described above. Compared to the other studies on Tensairity beams mentioned above, a truss has been used instead of a compression element for the upper chord in this paper to meet the needs of buildings with a long span. And the static behavior and ultimate failure mode of Tensairity truss, which are much different from the conventional ones, are discussed. In particular, the stiffness of the included airbeam is discussed as an elastic foundation, which can be simplified into discrete springs. The development of a simplified spring model to better understand the role of the airbeam is then described. The study also focuses on comparing the static behaviours of a prototype and a simplified model under different types of external loads to verify the accurate prediction of simplified one. Consequently, the design principle is summarized, and the method used to greatly simplify the Tensairity design is elucidated.

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2. Structural design

For this study, a Tensairity truss with a span of 60 m was designed in accordance with the current Chinese code, *Code for Design of Steel Structures* [12], and both the displacement and stress of the components are able to meet the requirements. This structure is composed of three parts: an upper steel truss whose cross section is an inverted triangle with a height of 3 m, a spindle shaped airbeam with a diameter of 6 m at midspan, and a lower steel cable. The geometry and details of the Tensairity truss are shown in Fig. 1. The rigid member of a conventional Tensairity structure is replaced with a steel truss so as to improve the mechanical properties and allow the structure to obtain a stronger span. The airbeam was fabricated using a PVC coated polyester fabric material with a thickness of 1.5 mm. The upper truss is made of steel pipes with Q345B material. The lower cable is made of a stainless steel parallel wire rope, and is connected to the ends of the upper truss. The left end of the structure is simply supported, whereas the right end is free to slide in the span direction. The upper joints of the steel truss is constrained in the lateral direction to prevent the whole structure from rotating. The sectional dimensions of the rigid members and lower cable are listed in Table 1. And the material properties of the rigid members, cables and membranes are presented in Table 2.

3. Analytical method and simplified model

Owing to the tight contact between the inflated airbeam and the other members in the structure, the airbeam can be regarded as a continuous elastic connection of the rigid member and cable. To develop an analytical model to investigate the static behaviour, the elastic coefficient of an inflated airbeam with regard to the contact members was derived in this study. In addition, we improved the mechanical and geometrical relations of the Tensairity structure, which were deduced from [4].

For the interactions between a cylindrical airbeam and the components up and down, a force diagram of the cross section of the airbeam is shown in Fig. 2. The initial cross section of the airbeam is shown as a circular dashed line, with a cross section radius of R_0. The contact pressures of the rigid members and cables acting on the airbeam are simplified into two concentrated forces F. Under the action of the external loads, the distance between the upper and lower vertices of the airbeam is reduced by x, and the downward displacement of the upper vertex is $x/2$. At this point, the airbeam cross section becomes two symmetrical intersectional arcs with a radius of R. In addition, the distance between the centres of the two arcs is L.

The following basic assumptions are satisfied based on the derivation:

(1) In the initial state, the cross-section of the airbeam is assumed to be circular.
(2) The strain of the membrane surface is ignored, and the perimeter of the airbeam section is considered a constant before and after deformation.
(3) During the deformation process, the section of the airbeam consistently maintains a biaxial symmetry.

Table 1
Cross-sections of rigid members and cable (mm).

Components	Upper chord	Lower chord	Other members	Lower cable
Section	$\phi 102 \times 10$	$\phi 133 \times 12$	$\phi 73 \times 3$	$91 \times \phi 5$

Considering that the perimeter of a film surface is equal before and after deformation, the following is obtained:

$$2\pi R_0 = 2(\pi + \varphi)R. \tag{1}$$

According to the displacement compatibility condition, the following can be obtained:

$$R_0 = R\cos\varphi + x/2, \tag{2}$$

$$x = 2R_0 - 2R\cos\varphi = 2R_0\frac{\pi + 2\varphi - \pi\cos\varphi}{\pi + 2\varphi}. \tag{3}$$

The inner volume of the unit length is

$$V = 2R^2\left(\frac{\pi}{2} + \varphi\right) + LR\cos\varphi, \tag{4}$$

$$V_0 = \pi {R_0}^2. \tag{5}$$

According to the equilibrium equation of vertical force, the following is obtained:

$$F = PA = PL = 2PR\sin\varphi. \tag{6}$$

After the structure is constructed, the internal pressure should be monitored to keep a constant value. So the structure system works according to a constant pressure during a slow loading progress. But when the loading process is relatively fast, such as a strong wind or a sudden heavy rain, the pressure control device is unable to keep the internal pressure constant in a very short time. In such a loading process, the structure works with a closed volume in the airbeam, leading to an increase in pressure for downward loading as well as a decrease in pressure for upward loading. In this paper, all the load cases are considered to be fast loading processes, so the internal pressure will change according to load cases. And the air in the airbeam is assumed to behave like an ideal gas, the internal pressure P changes to

$$P = \frac{P_0 V_0}{V}. \tag{7}$$

The following can then be obtained:

$$F = 2P_0R_0\frac{(\pi + 2\varphi)\sin\varphi}{\pi + 2\varphi + \sin 2\varphi}. \tag{8}$$

The vertical stiffness can be obtained through the differential of (1):

$$\frac{\mathrm{d}F}{\mathrm{d}\varphi} = 2P_0R_0\frac{[2\sin\varphi + (\pi + 2\varphi)\cos\varphi](\pi + 2\varphi + \sin 2\varphi) - (\pi + 2\varphi)(2 + 2\cos 2\varphi)\sin\varphi}{(\pi + 2\varphi + \sin 2\varphi)^2}, \tag{9}$$

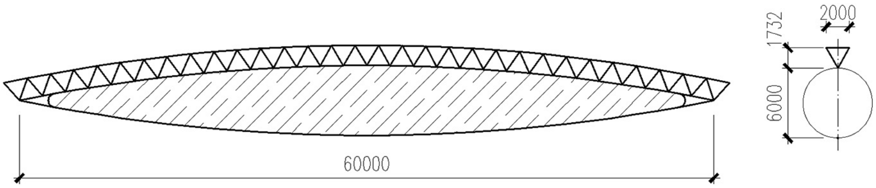

Fig. 1. Dimensions of Tensairity truss (mm).