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Pre-stressing method and structural behaviour of a Tensairity dome with multiple inflated cushions

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ABSTRACT

This paper describes a novel type of Tensairity dome, which is composed of a tensegrity cable dome and several inflated cushions. The cushions and cable dome act as a whole in synergy, and the introduction of compressed air, which is an important part of the structure, extends the tensegrity concept. This study builds an illustrative numerical model and examines the feasibility of the proposed structure. The inflating amount of air for each cushion and influence of the inflating sequence are considered. The effect of the internal air pressure on the structural behaviour is investigated for several different load cases. The results demonstrate that pre-stressing can be introduced by inflating the cushions instead of the tensioning cables, which greatly facilitates the construction. The novel structure exhibits effective stiffness and integrity in several possible conditions, and the internal air pressure of approximately 500–3500 Pa can ensure the tensioning role of the cushions. The air pressure values should be determined according to the environmental conditions of the construction site.

1. Introduction

The tensegrity structure, which was proposed by Fuller [1], is a self-balancing system consisting of continuous tension and dispersed compression elements. Based on the tensegrity concept, Geiger developed a type of cable dome supported by a circular, rigid peripheral component, known as the Geiger form [2], which includes ridge and diagonal cables, cable hoops, struts and a compressed ring. Several typical cable dome constructions have already been constructed globally, including the gymnastics and fencing halls for the Seoul Olympic Games, the Redbird Arena in Illinois, the Florida Suncoast Dome in St. Petersburg, and the National Fitness Centre in Inner Mongolia [3]. Subsequently, Levy improved the structure and developed a new hyper-tensegrity dome system, which was also known as the Levy form. The structure system transforms the ridge cables in the Geiger form system from a radial arrangement into a square grid. Compared to the Geiger form, the structural integrity of the Levy form is significantly enhanced, and the stiffness is particularly improved under asymmetric and local loads. The Levy form was first used in the Georgia dome in Atlanta, which was built in 1992 [4]. However, the construction process of the cable domes mentioned above is quite complicated. During construction, the pre-tensioning process should be controlled with high accuracy. As a result, the construction complexity has become an important factor restricting the popularisation and application of cable domes.

Based on the tensegrity concept, two types of hybrid space structures have been proposed. Kawaguchi developed the Suspen-dome in 1993, which combined the advantages of rigid and flexible structures [5,6], and was constructed by replacing the cable dome upper chords with a single-layer reticulated shell. The use of rigid members can significantly improve the overall stiffness of the cable-strut system and reduce the required pre-stress level in cables, thereby simplifying the construction techniques. Moreover, the cable-strut system can improve the stiffness and stability of the latticed shell. The other type of hybrid space structure is the Tensairity system, which was proposed by Luchsinger [7]. Tensairity is a synergetic combination of struts, cables and an inflated cushion, under a low internal pressure. This structural concept introduces compressed air into the conventional tensegrity system. Therefore, Tensairity takes advantage of the compression of struts, tension of cables and air compression in the inflated cushions. Previous studies have focused on the structural development of Tensairity beams, columns and arches [8–14]. In recent years, Cao et al. [15] proposed two dome types to enlarge the application of Tensairity as a spatial structure.

In order to enrich the application scope of the Tensairity concept, a

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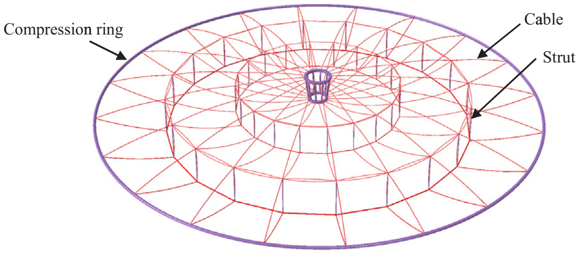
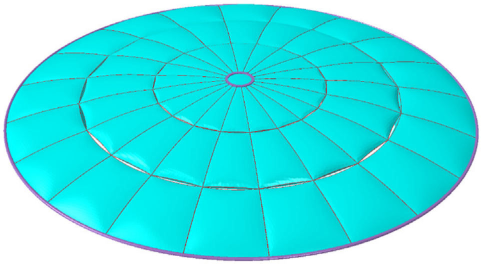
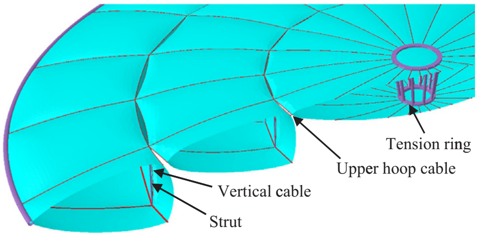


(a) Cable dome



(b) Perspective view



(c) Inner details

Fig. 1. Schematic of Tensairity dome, (a) Cable dome, (b) Perspective view, (c) Inner details.

type of Tensairity dome consisting of a cable dome and several inflated cushions is proposed in this study. The structure combines the inflatable structure and cable-strut system. The entire structure can be pre-stressed by inflating the included cushions, making the introduction of pre-stressing more convenient. In this paper, feasible methods for the pre-stressing introduction into the structure are studied. The inflating amount of air for each cushion and influence of the inflating sequence are investigated. Thereafter, the static performance of the structure under various possible working conditions is analysed using numerical methods. Furthermore, the effects of internal pressures on the mechanical behaviour and pre-stress distribution of the cables and struts are discussed.

2. Tensairity domes

This section proposes a type of Tensairity dome composed of a cable dome and several inflated cushions. As illustrated in Fig. 1, the cushions are completely connected to the cables and rigid members, which are considered to be the membrane boundaries. The entire structure is pre-stressed by the pressured air in the included cushions in order to obtain its load-carrying capacity. Based on the force principle, the cushions are considered as the primary structure for bearing the external loads along with the cable dome, making this structural system quite different from the air cushion structure. The structure combines the advantages of conventional cable domes with pneumatic structures.

However, in order to ensure that the membranes and cables can move together in all load cases, the cushions and cable dome should be connected reliably. In this study, three connection types, as illustrated in Fig. 2, were utilised to fabricate the membrane onto the other members. Following inflation, all the cables could operate in different curved shapes owing to the internal air pressure action. As illustrated in Fig. 1, two upper hoop cables were set among the upper ends of each ring strut as the membrane boundary, in order to ensure that the cushions were completely independent of one another following inflation. In this manner, the cushions were connected to one another only in the position of the upper joints of the struts. Owing to the upper hoop cables, the entire structure could also obtain a greater pre-stress level at the same internal pressure. Moreover, if the membrane was connected to the strut along the length, the strut would undergo bending moment. Therefore, in this design, a series of vertical cables were specifically added between the two ends of each discontinuous strut as the membrane boundaries in order to avoid the bending moment in the struts. However, the vertical struts would run through the cushions, making construction difficult, particularly for the airtightness of the cushions. To solve this problem, the same amount of air tubes as the struts, which were constructed using the same membrane material as the cushions, could be welded to the cushions at the position of the strut ends. Thus, the struts were installed outside the cushions, thereby significantly improving the airtightness.

In this paper, the proposed structure is divided into three states during its lifetime, based on the construction and working process: the zero state, initial state and loaded state. The zero state is also known as the lofting state, in which all components are fabricated in the correct places but not pre-stressed, so there no internal force exists in the structure. The initial state is the structural equilibrium state under the action of the internal air pressure and gravity; that is, the state when construction is completed. The loaded state is the rebalance state of a structure subjected to external loading based on the initial state.

3. Illustrative example

The Tensairity dome example designed in this study is illustrated in Fig. 3, and both the schematic diagram and geometric dimensions are presented for the initial state. The basic structure shape is a Geiger cable dome combined with three different shaped cushions, and the dome is radially segmented into 20 pieces. The span and rise of the dome are 80 and 6.18 m, respectively. The structure system comprises an outer compression ring, inner tension ring, cables, struts and three inflated cushions. In the zero state, all cables in the dome are set in a straight state, while each membrane surface is set in a plane shape. In this model, all members are mutually connected at the ends by means of hinge joints, and 20 joints at the perimeter are fixed in three directions to function as supports. The outmost rigid ring exists as the boundary of an inflated cushion. However, in practical engineering projects, the outmost ring would be made of a steel truss to counteract the structure horizontal forces, and subsequently reduce the support reactions.

Table 1 lists the sectional dimensions of the rigid members and cables. The outer compression ring, inner tension ring and the struts were constructed from steel tubes with Q345B material, according to Chinese codes. The tension cables were made of parallel stainless steel wire ropes. The cushions were fabricated using a PVC coated polyester fabric material with a 1.5 mm thickness. Table 2 lists the material properties of the rigid members, cables and membranes adopted in the structure. In this paper, the membrane material is assumed to follow the linear orthotropic elasticity model [16], the warp direction of which corresponds to the dome radial direction.

The static behaviour of the Tensairity dome was simulated and analysed using the ABAQUS finite element software [17]. In the model, the inner tension ring and outer compression ring were simulated using two-node Timoshenko beam elements (B31), which have six degrees of freedom at each node and consider the shear-deformation effects. The cables and other struts were modelled using two-node linear truss elements (T3D2) without bending stiffness, while three-node membrane elements (M3D3) were adopted for the cushion membranes. After the structure is inflated, the internal air pressure are always monitored to keep constant. Therefore, for a slow loading process, the cushion works in a constant air pressure. But in case of instant load, such as a strong wind or a heavy rain, the pressure control system is unable to keep the