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Experimental deployment behavior of air-inflated fabric arches and a full-scale fabric arch frame

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ABSTRACT

Extensive research efforts have been dedicated to understanding the static behavior of air-inflated fabric arch structures, while little research has been conducted in regard to their dynamic deployment behavior and self-erection feasibility during the construction phase. Deployment difficulties, air flow obstruction, stress concentration and local membrane damage might occur. This paper presents an experimental study on the dynamic deployment performance of four small scale single arches and one full scale arch frame. Pressure sensors were used to achieve instant air state data within arch structures during inflation. Digital videos and digital cameras were applied to simultaneously and continuously capture the arch formation. Control volume finite element analysis was performed to simulate the deployment and reveal membrane stress development. Results show that, in most cases, fabric arches are able to self-deploy when certain levels of pressure are achieved. Only one of them failed to erect properly. Geometric parameters of arches and their initial deflated layouts have significant influence on the deployment pressure. External facilitations, such as partially elevating the arches or providing sliding supports at the base, help to substantially lower the deployment pressure. The control volume method proves to be applicable in simulating dynamic deployment of fabric arches. Stress analysis shows that stress concentration occurs at bending areas and connections during inflation. The full-scale fabric arch frame presents adequate structural integrity in its deployment process.

1. Introduction

Air-inflated fabric tubular structures have received more attention since the Fuji Group Pavilion was presented at the Exp'70 held in Osaka, Japan. A number of experimental studies have been performed on the static load bearing capacity and load-deflection behavior of air-inflated beams, columns and arches for earthbound applications [1–12]. In 1996, NASA sponsored an Inflatable Antenna Experiment (IAE) to validate the deployment sequence of inflatable antenna in space [13, 14]. Unexpected dynamics and deployment was observed in the test. From then on, several dynamic tests were conducted in gravity-free or gravity-negligible environments to study the inflation deployment behavior of inflatable structures [15–19]. Barbero et al. [20] performed full scale testing under earth conditions on deployment of a 4.939 m(Diameter) × 4.641 m(Length) confined inflatable cylinder for temporarily sealing off and protecting tunnels by stopping hazards, such as smoke or flooding. However, few tests focused on the deployment and self-erection feasibility of terrestrial air-inflated slender tubular structures. Russell et al. [21] simulated the deployment of a Z-folded tube under both space and Earth conditions and revealed that the deployment behavior in vacuum and zero-gravity conditions is significantly different from that under atmospheric pressure and gravity. The deployment of tube under Earth conditions shows more erratic behavior. Gong et al. [22] designed a 60 m(Span) × 45.5 m(Height) × 93 m (Length) movable laboratory by integrating air-inflated tube skeletons and air-supported membrane cover as shown in Fig. 1(a). The exterior air-supported membrane serves as load bearing and weather proof cover in service conditions. The tube frames were designed mainly for temporary support of deflated exterior membrane which allowed a large gate opening for transportation of 20 m × 20 m balloons. During construction, the inflation process of exterior air-supported membrane was smooth, while the inflation of interior air-inflated tubes encountered difficulties. Fig. 1(b) shows that the top ring of dome-shaped frame was able to deploy and self-erect, but the surrounding legs were not able to fully unbend even though the pressure in tubes reached 11.0 kPa, over 2 times of design service pressure. Similar problems happened to the

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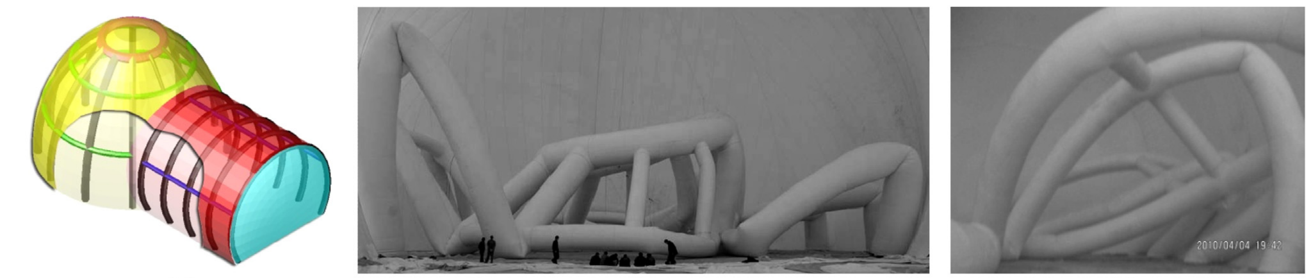


(a) (b) (c)

Fig. 1. Movable fabric laboratory: (a) isometric view of 3D model; (b) performance of dome-shaped frame; (c) performance of Moorish arch frame.

Moorish arch frame at the right part of structure as shown in Fig. 1 (c). Slightly hoisting the bends on the ground did not improve the situation. The slenderness of tubes, constraints from exterior membrane, air flow obstruction, interaction between segments of tubes, seemed contribute to the deployment difficulties.

To learn more about the deployment behavior of slender tubular structures, especially the inflatable arches, a series of inflation tests were conducted in Beijing, China. Four small scale single arches were designed and constructed for the tests and one full scale arch frame for a real-life project was also tested.

The main objectives of the present work are: (1) to provide basic understanding of dynamic behavior of air-inflated arches during deployment and to investigate their self-erection feasibility, (2) to study the influence of geometry parameters on the deploying of arches, (3) to assess the effectiveness of external facilitations that aim at reducing the difficulties of deployment, and (4) to compare small scale tests with full scale tests to reveal the spacial correlations of arch frame during erection.

2. Description of test structures

2.1. Fabric arches

Table 1 presents geometric parameters and front views of all single fabric arches, where, *S, H,* and *d* are the basic parameters of arch, which refer to arch span, arch height, and tube diameter, R_a refers to radius of arch, α refers to arch central angle, *L* refers to arch length, *V* refers to arch volume, *S*/*H* and *L*/*d* refer to span to height ratio and arch length to diameter ratio, respectively.

Each arch was designed with different combinations of arch span, arch height, and tube diameter to cover a wide range of typical project applications. The shapes of M1 and M3 are semicircle. The M2 is a shallow arch and M4 corresponds to a Moorish arch. All arches were designed with flat feet to help them independently stand on the ground. Fig. 2 shows the connection detail of a typical arch base. A larger sized round bottom membrane was welded to each end of the arch. The edge of the round base was rolled up with a cable inside and then welded to the top side of arch membrane to ensure it is air-tight. The welded membrane flange was sandwiched between the top narrow steel plates and a large square steel base plate by self-tapping screw connection. This detail can provide a fully constrained connection to the arch feet since the base plates are heavy and not easily moved. It could be assumed as a fixed connection during inflation. When the target pressure of arches is high, sand bags are placed on top of the base plates to avoid movement.

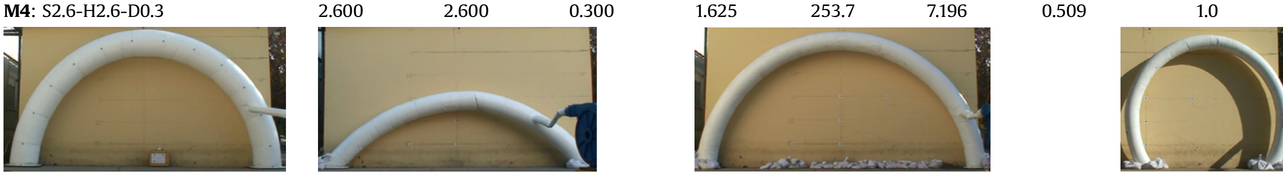
2.2. Fabric arch frame

Fig. 3 shows the fabric arch frame, whose dimensions are 20 m (Span) × 9 m(Height) × 25 m(Length). Comprises 7 arches (Ø1.5 m), 2 continuous base beams (Ø1.8 m) and 12 superstructure tie beams (Ø1.2 m), both ends of the frame are made of twin arches to strengthen its out-of-plane stiffness. Several short membrane straps are welded to both top and bottom faces of the twin arches to tie them together. Three remaining single arches are spread evenly between the twin arches at each end. All tubular members are separated from each other by partially opened diaphragm membranes at the joints. Through a Ø100 mm opening in each diaphragm, gas can freely flow through the arches and beams. Two outlet/inlet hoses (Ø100 mm) are connected to the external side of right base beam. A 300 mm-wide self-balancing membrane strap is connected to the base beams below each arch via aluminum connections to constrain in-plane horizontal outward movement.

All structures are made of KOBOND membrane, which is an impermeable high-tech coated and multi-layer laminated fabric. The substrate is polyester fabric and the surface coating is polyvinylidene fluoride (PVDF). Table 2 presents the basic material properties of KOBOND membrane [23].

Table 1
Geometric parameters of single arches.

Test samples	*S* (m)	*H* (m)	*d* (m)	R_a (m)	α (deg)	*L* (m)	*V* (m^3)	*S*/*H*	*L*/*d*
M1: S5.2-H2.6-D0.6	5.200	2.600	0.600	2.600	180.0	8.168	2.310	2.0	13.6
M2: S5.2-H1.3-D0.4	5.200	1.300	0.400	3.250	106.3	6.027	0.758	4.0	15.1
M3: S5.2-H2.6-D0.4	5.200	2.600	0.400	2.600	180.0	8.168	1.027	2.0	20.4
M4: S2.6-H2.6-D0.3	2.600	2.600	0.300	1.625	253.7	7.196	0.509	1.0	24.0



M1 **M2** **M3** **M4**