Thin-Walled Structures 94 (2015) 446–456

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Dynamic deflation assessment of an air inflated membrane structure

Qingsong Li [a], Xiao Guo [a], Qiang Qing [a], Jinghai Gong [a,*]

[a] Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 6 September 2014
Accepted 9 May 2015
Available online 29 May 2015

Keywords:
Air inflated structure
Membrane structure
Deflation
Simulation
Control volume method

ABSTRACT

As a critical safety performance index, the emergency evacuation capacity of air inflated membrane structures subjected to accidental deflation deserves in-depth study. Although conventional static analysis can be applied to predict its potential collapsed shapes, it cannot provide details of collapse behavior and the internal air state variation. Dynamic analysis is recommended. The focus of this paper is to apply the Control Volume method to deflation simulation of a large-scale air inflated arch frame, which is designed for a temporary pavilion, and to validate numerical analysis results by full-scale testing. Through a series of preliminary studies on air inflated single arches, practical analytical parameters and solutions are concluded regarding proper numerical modeling, pre-stressing, and precision controlling. A full-scale frame is then modeled and simulated. Results appear to agree with experimental tests of the corresponding real-life structure with minor differences in collapse behavior and deflation duration time. Several general guidelines for design and deflation simulation analysis are proposed as a result of research. Feasible measures to ensure emergency evacuation capacity of the air inflated arch frame are adopted in the design based on results of this dynamic assessment.

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1. Introduction

Air inflated membrane structure is a new type of spatial structure, which is composed of airtight membrane members and highly pressurized internal air. It has wide applications in both civilian and military facilities, such as temporary pavilions, spacial habitats and antenna, military warehouses, field tents, hospitals, and etc., for its obvious advantage of being light weight, low cost, reusable, and able to accommodate large spans.

Series of research has been performed on the static load bearing capacity and load-deflection behavior of air inflated members such as air inflated beams, columns, and arches: Steeves [1] derived a linear theory for the behavior of pressure stabilized beams under uniform and concentrated loading for both simply supported and fixed end restraints; Lukasiewicz et al. [2] analyzed the behavior of free-standing cylindrical or toroidal membranes under collapse loads; Main et al. [3,4] developed a method of analysis for inflated fabric beams that is analogous to the shear-moment method; Molloy et al. [5] studied paired leaning arch-shells under snow and wind loads; Thomas et al. [6] presented experimental, analytical and numerical results on the deflection of highly inflated fabric tubes submitted to bending loads; Davids [7] studied in-plane load-deflection and buckling response of pressurized fabric arches of constant circular cross section; Nguyen et al. [8] proposed an analytical approach to study the buckling and behavior of an inflatable orthotropic beam subjected to uniform compression loads under different boundary conditions.

Feasible theories and analytical models were proposed to dynamically simulate the inflation deployment of air inflated structures: Hirt et al. [9] presented an arbitrary Lagrangian–Eulerian method (ALE) for all flow speed; Donea et al. [10] adopted the ALE kinematical description of the fluid domain in finite element analysis of non-linear response of fluid-structure systems exposed to transient dynamic loading; Wang et al. [11] developed a generalized analytical model of an airbag inflation system based on the Control Volume method of classic thermodynamic theory and applied it into the CAL3D occupant dynamics simulation program; Salama et al. [12] further developed the simplified volume inflation model which allows discretized description of gas flow, pressure variation, and resulting nonlinear large deformation throughout domains of the inflatable structure; Olovsson [13] developed a corpuscular method for simulating the flow of a gas mixture and its interaction with flexible structures based on the laws of kinetic molecular theory.

However, very few studies are on dynamic collapse behavior and deflation performance of air inflated structures. As a large span structure that is vulnerable to sharp objects or open flame, its evacuation performance under deflation emergency is critical for safety assessment and deserves further research.

* Corresponding author.
E-mail address: gongjh@sjtu.edu.cn (J. Gong).

http://dx.doi.org/10.1016/j.tws.2015.05.008
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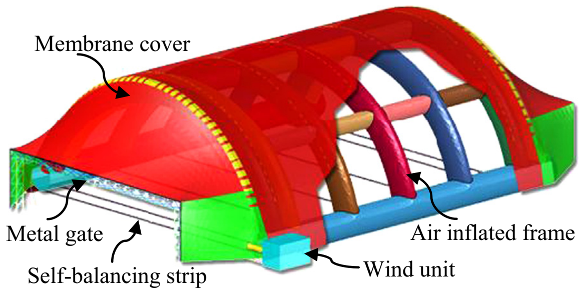

Fig. 1. Air inflated arch frame designed for a temporary pavilion.

Table 1
Basic parameters of air inflated arch frame.

Structure geometry					Membrane properties		
S (m)	H (m)	D_a (m)	D_b (m)	D_t (m)	t_m (m)	ρ (kg/m^3)	E_l/E_h (N/m^2)
20.0	9.0	1.5	1.8	1.2	8.0E−4	1.25E3	9.44E7/7.81E8

In the present work, a large-scale air inflated arch structure designed for a temporary pavilion is studied by both dynamic deflation simulation and experimental test. As shown in Fig. 1, the temporary pavilion is composed of an internal arch frame, exterior membrane cover, two large gates made by light weight metal frames, and a wind blow and control unit with two 100 mm diameter hoses connected to one of the base beams. The air inflated arch frame is designed as the main load bearing system so that large gates can be fully open for access of trucks and other vehicles. Table 1 lists basic design parameters of the frame. Geometric parameters and material properties are from exhibition clearance requirements and related static load bearing capacity analysis [14]. Exterior membrane cover is designed for weather shelter. Light weight metal gates are used for easier operation of the automated door. The structure has no permanent footings to meet requirements of fast erection, easy removal, and being reusable. Temporary anchoring, such as sand bags, mechanical anchors, or soil nailing rebar, and etc., will be applied accordingly to different types of foundations.

where S is the arch span, H is the arch height, D_a is the diameter of arch, D_b is the diameter of base beam, D_t is the diameter of tie beam, t_m is the thickness of membrane, ρ is the density of the membrane, and E_l and E_h are the axial and hoop elastic modulus of the membrane, respectively.

The purpose of this paper is to propose several general guidelines for the design and deflation simulation analysis, to provide more insight into collapse behavior and deflation duration time of the air inflated structure, and to propose feasible measures for the current design to ensure its emergency evacuation under accidental ventilation. It is organized as follows: Section 2 briefly describes the Control Volume algorithm. Section 3 presents preliminary studies on the single air inflated arch regarding the simulation modeling and design parameters. Simulation and experimental test of a full-scale air inflated arch frame is discussed in Section 4. General guidelines and conclusions for both design and simulation are summarized in Section 5.

2. Control volume method

Simulation of the dynamic deflation process is actually an analysis of interaction between gas and membrane. It is the reverse process of deployment simulation. Both of them share similar assumptions and algorithms. The most popular methods for deployment simulation of thin membrane structures are: (1) Arbitrary Lagrangian–Eulerian (ALE) method [9] , (2) Control Volume (CV) method [11,12], and (3) Corpuscular (CPM) method [13]. The ALE and CPM methods considers gas dynamics, which makes them suitable for fast inflation simulation but can be computationally expensive [15,16]. In the present work, the CV method was chosen for its proven capability of dealing with the slow inflation process and its relatively high efficiency in computation. Based on classic thermodynamics [17], the CV method assumes uniform pressure and temperature within each control volume while allowing temporary pressure differences between adjacent CVs. Driven by the pressure differences, gas will flow among all CVs. Every flow is assumed to be an adiabatic, one-dimensional, and quasi-steady flow so that all gas exchanges and instantaneous internal pressures can be solved. According to classic thermodynamics [11,17], the mass flow rate, $\dot{m}_t$, of ideal gas from one CV to another CV, or from the airbag to the environment through an orifice at any time t is given by

$$\begin{cases} \dot{m}_t = BA_e \dfrac{P_t}{R\sqrt{T_t}} \left(\dfrac{P_e}{P_t}\right)^{\frac{1}{k}} \sqrt{2g_c\left(\dfrac{kR}{k-1}\right)\left(1-\left(\dfrac{P_e}{P_t}\right)^{\frac{k-1}{k}}\right)} \\ \text{with} \qquad P_e = max(P_a, P_c), \quad P_c = P_t\left(\dfrac{2}{k+1}\right)^{\frac{k}{k-1}} \end{cases} \tag{1}$$

where, B and A_e are the shape factor and area of the orifice, respectively, g_c is the gravitational conversion constant, k is the specific heat ratio of air, P_t and T_t are the air pressure and temperature within the airbag at time t, P_a is the ambient pressure, P_e is the exhaust pressure in the orifice, and P_c is the critical pressure, at which "choked" or sonic flow occurs [11].

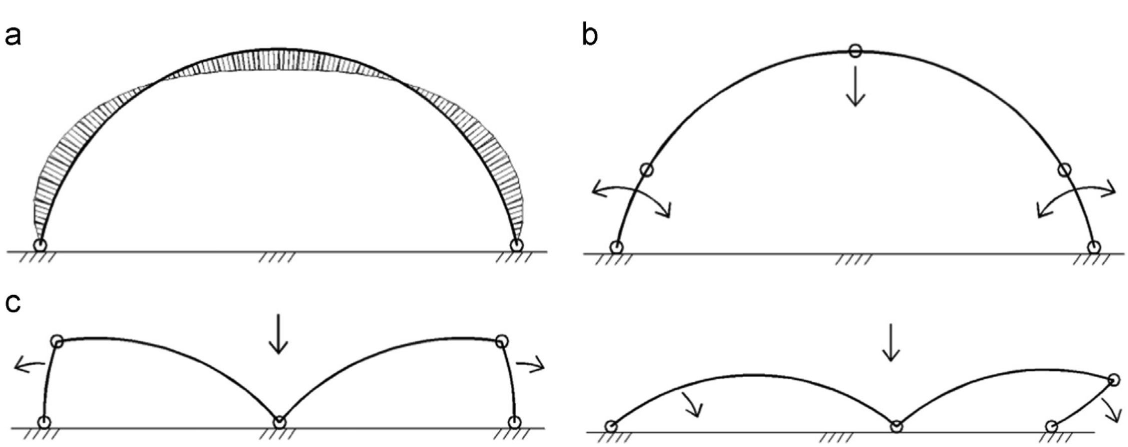

Fig. 2. Collapse prediction of single arch by static analysis, (a) bending moment diagram, (b) potential hinges and movement directions, and (c) potential collapsed shapes.

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