Thin-Walled Structures 129 (2018) 225–236

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Deflation behavior and related safety assessment of an air-supported membrane structure

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ARTICLE INFO

Keywords:
Air-supported structure
Deflation
Safety assessment
Residual pressure
Experiment
Numerical simulation

ABSTRACT

As a large span structure that might serve many occupants, the deflation behavior of an air-supported membrane structure under emergency deflation is of critical importance for safety assessment on occupants' evacuation but has received few studies. This paper presents experimental field tests and numerical simulations on deflation behaviors of a real-life air-supported membrane structure. A numerical model is employed in deflation simulation which considers tension-only membrane based on the vector form intrinsic finite element method for membrane motion analysis and pressure change due to air loss in deflation according to the classic thermodynamics. The correctness and the applicability of the model are verified by good correlation of prediction in response of pressure, displacement, and wrinkling formation and development of the structure with those measured and observed in deflation tests. The study shows that the structure in emergency deflation will lose its high pressure quickly first, and then sustain deflating under low residual pressure for a long time. The model is further used in parametrical analysis on factors that affect deflation progress and a complete deflation simulation to predict the whole collapse process, which is accordingly characterized by two typical phases, the tender deflation stage and the severe deflation stage. In tender stage the structure holds a relatively plump form, while in the severe stage the structure bears low decreasing residual pressure, membrane losses most tension stress so that many elements wrinkle and the structure experiences instability. Due to wrinkling, the residual pressure is found to approximately balance with its vertical loads. As a result, the feasible method proposed based on the residual pressure in deflation is very simple and reliable to predict the deflation duration and evaluate maximum escape area for deflation assessment of the studied structure.

1. Introduction

An air-supported membrane structure derives its structural integrity from internal pressurized air and a tensioned membrane envelope to preserve a reasonable size and shape. It has wide applications especially in buildings of unobstructed open interior space (free of column) that might serve big crowds of people in civilian and military fields (see Kröplin [1], Bell [2] and Bradshaw et al. [3]), such as sporting facility covers, warehousing, construction-site storage, light manufacturing, military logistics operations. Due to its inherent characteristic of pressure-dependence structural stiffness, the inflation system of an air-supported membrane structure must keep supplying air continuously because of unavoidable normal air leakage during its service period [4]. In some offensive cases, this kind of structure may even experience problems like inflation system failure, snow accumulation due to snow removal system failure or water ponding (see Hamilton et al. [5] and Hamilton and Campbell [6]). Perceptibly, it is necessary to open some clean passages for occupants' evacuation, which jeopardizes the structure with accidental ventilation or emergency deflation. An air structure in deflation will no longer have substantial tensile strength, gradually become deformable and flexible, and therefore can no longer bear its designed load, for example the wind. Hence the deflation behavior and duration are of critical importance for safety assessment to provide timely and safe evacuation for occupants. Relative guidelines and precautions have attracted the regulating authorities' increasing attention.

A simple safety assessment method on deflation of air-supported structures has been given in ASCE 17-96 [4] to justify the safety of the structure subjected to deflation regarding the deflation index and the air supply rate of inflation system. In fact, the deflation process that leads to overall collapse of air-supported structures is dominated by dynamic interactions between the internal pressure variation generated by the flow of pressurized air and the membrane motion with change of pressure due to air loss. Changes in structural form also induce changes in pressure loading profile, and vice versa. To this end, the assessment only provides a rough estimation of deflation duration, but no deflation

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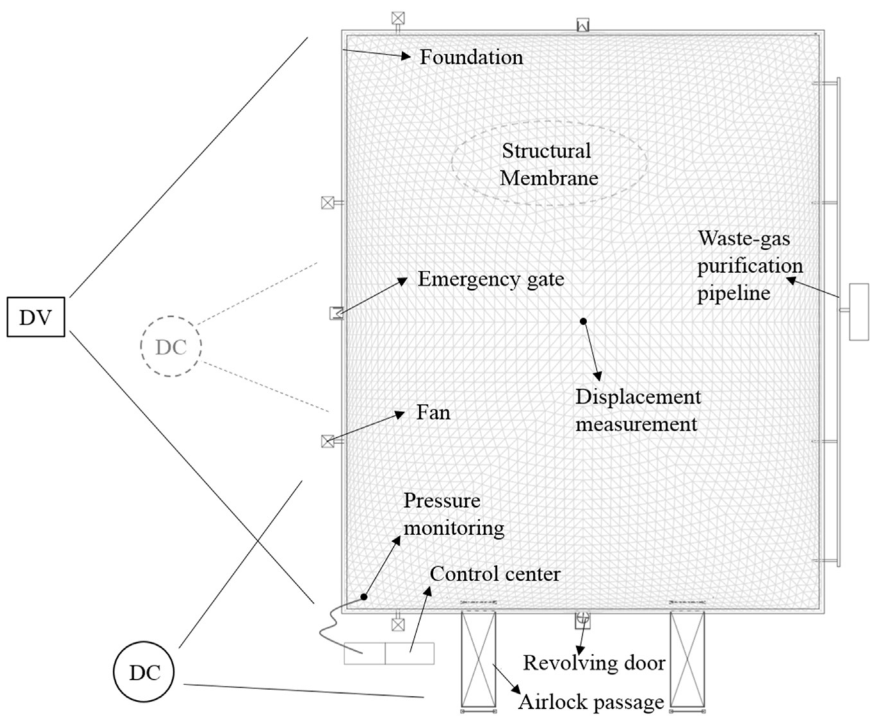
https://doi.org/10.1016/j.tws.2018.01.037
Received 31 May 2017; Received in revised form 17 January 2018; Accepted 24 January 2018
Available online 25 April 2018
0263-8231/

(a)



(b)

Fig. 1. The air-supported structure in study: (a) a side view of the structure; (b) test schematic layout.

details like time history of membrane deflated form and pressure (Li et al. [7]).

The most attractive method for air state analysis in the dynamic interaction simulation attributes to the control volume method that first developed by Wang and Nefske [8], while the explicit integral scheme is mostly involved for membrane motion analysis (such as using the LS-DYNA software). This method focuses on a simple ideal gas flow in a compartment, or to say a control volume, to analyze air state variation like pressure change during the interaction based on classic thermodynamic theory. It was further developed by Salama et al. [9] to allow for the discretized description of gas flow and pressure variation (multiple compartments). Since then, many efforts have been conducted to analyze deployment feasibility of deployable structures with the control volume method (Lampani and Gaudenzi [10], Wang and Johnson [11] and Li et al. [12]). However, so far, few studies have been focused on the service performance after construction and the dynamic collapse behavior of an air-supported structure when subjected to deflation, neither numerically nor experimentally. Li et al. [13] studied deflation processes of inflated arches and an air inflated arch frame with the control volume method and experimental tests. This study indicates that there will be no evident pressure differences among different control volumes under slow air flow, which means that pressure is uniformly distributed within the whole arch frame at any time of the deflation process. The above studies (see [9,11,13]) prove that the control volume method is reliable in air state variation prediction during the dynamic interaction especially in slow air flow case.

An air structure in deflation usually takes large displacement and is flexible and deformable. A non-linear finite element (FE) analysis of similar problem has been presented in Qing and Gong [14], but the numerical difficulties in the linearization of the nonlinear discrete equations were unavoidable, mainly due to ill-conditioned or near-singular tangent stiffness matrices (Rossi et al. [15]). On the contrary, the vector form intrinsic finite element (VFIFE) method, firstly proposed by Ting et al. [16] and Shih et al. [17] based on vector