834. Experimental and numerical investigation on the structural performance of the tensioning air beam system

Ki-Youl Baek[1], **Dae-Jin Kim**[2], **Junbok Lee**[3]
[1]POSCO E&C, Tower1, 36 Songdo-Dong, Yeounsu-Gu, Incheon, 406-732, Republic of Korea
[2, 3]Department of Architectural Engineering, Kyung Hee University
Yongin, Kyunggi-Do, 446-170, Republic of Korea
[2]Corresponding author
E-mail: [1]*kybaek@poscoenc.com*, [2]*djkim@khu.ac.kr*, [3]*leejb@khu.ac.kr*

(Received 1 July 2012; accepted 4 September 2012)

Abstract. An experimental and numerical study on the structural performance of the tensioning air beam system (TABS) is presented. TABS is a hybrid structural system consisting of a membrane air beam, steel frames and cable struts. This system has the advantage of reduced self-weight and is easy to construct while it can improve the load bearing capacity of membrane structures. It maximizes the structural capacities of individual elements, thus can be considered as a very effective system in terms of both structural and economical aspects. In this paper, a test was carried out to examine the structural performance of TABS under different membrane pressure conditions. The material properties of the air beam were obtained from the results of two membrane tensile strength tests, which were performed prior to the main test. A simple numerical model was proposed to predict the structural behavior of TABS and its validity was evaluated by comparing its results with the test values.

Keywords: tensioning air beam system, membrane, bending, nonlinear analysis.

Introduction

Recently, there has been a growing interest in large structures in many countries all over the world. The structural performance and construction cost of the large structure greatly depend on the types of roof structural systems and materials used, thus the selection of the roof structural system and its member design suitable for construction are very important. An air beam is a membrane structure that can be used as a beam member and has dramatically reduced self-weight if compared to general steel frames. However, it has limitations in its shape and generally retains small load bearing capacity.

The air beam was originally developed to protect military facilities at the radar base station right after World War II. In 1960s, Frei Otto first applied it to the construction of private houses, and then Thomas Herzog made a significant contribution to its application to various types of building structures in 1970s. Its prime time began with Osaka Expo'70 where various membrane structures were introduced for the purpose of exhibition. Since then, air beam structures were frequently used to build the roof structures of large sports facilities such as baseball or basketball stadiums, but there has not been much significant progress in terms of its structural novelty.

Tensioning Air Beam System (TABS) is a hybrid structural system which consists of an air beam, cables and frames and combines membrane and tensioning structures. This system has the advantage of reduced self-weight and is easy to construct while it can improve the load bearing capacity of membrane structures. It maximizes the structural capacities of individual elements, thus can be considered as a very effective system in both structural and economical aspects. TABS was first suggested by Luchsinger et al. [1-3] at the EMPA (Swiss Federal Laboratories for Materials Testing and Research) under the name of Tensairity, and several research results on its design equations and structural capacity have been presented, but the interrelation between important variables for design including the air pressure, cable tension and overall capacity of the structural system was not clarified. Hence, there are not sufficient research data required for the application of Tensairity to real structures.

In this study, a structural test was carried out to investigate the structural performance of the TABS under different pressure conditions. The material properties of the air beam were determined by performing membrane tensile strength tests in both a single axis and two perpendicular axes and then applying the least squares method. A numerical model to simplify complicated issues such as a contact problem between membrane and cable elements was suggested to predict the structural behavior of the TABS. The validity of the suggested numerical model was evaluated by comparing its results with the test values.

Membrane Tensile Strength Test

A tensile strength test in two perpendicular axes was performed to determine material properties of membrane made of PVC Poly (vinyl chloride) such as its Young's moduli and Poisson's ratios by following the procedure introduced in the manual of Membrane Structures Association of Japan [4]. The test setup and the details of the test specimen are illustrated in Figs. 1 and 2, respectively. The membrane specimen had a symmetrical shape with respect to both of x (warp) and y (fill) directions, and the width and length of the arm were greater than 16 cm. The corner of the specimen was rounded, and the arm was cut along the slits in order to prevent excessive application of stress to the clamp as shown in Fig. 2. Tensile force was applied by the actuator attached to the clamps in both of the wall and fill directions, and the strains were measured by linear variable differential transducers (LVDTs) installed on the surface of the membrane. The strains were measured for five different sets of tensile forces in the two directions, of which ratios were given as 1:1, 1:0, 0:1, 1:2 and 2:1. This was required to determine the material properties using the least squares method.

The details of the least squares method are as follows. The relations between the applied tensile force and the measured strain can be stated as follows in terms of the membrane elastic modulus (E_{11}, E_{22}, E_{12}), tensile stiffness of membrane ($E_x t$, $E_y t$) and Poisson ratios (ν_x, ν_y). Here, t is the thickness of the membrane.

$$N_x = E_{11}\varepsilon_x + E_{12}\varepsilon_y, \tag{1}$$

$$N_y = E_{21}\varepsilon_x + E_{22}\varepsilon_y, \tag{2}$$

where each variable in these equations has the following relations:

$$E_{11} = E_x t / \nu, \tag{3}$$

$$E_{22} = E_y t / \nu, \tag{4}$$

$$E_{12} = E_{21} = \nu_y E_x t / \nu = \nu_x E_y t / \nu, \tag{5}$$

$$\nu = 1 - \nu_x \nu_y. \tag{6}$$

The least squares method finds its optimum on interval [a, b] when the sum of squared residuals is a minimum as expressed below [5]:

$$\int_a^b \{f(x) - y(x)\}^2 dx \to \min., \tag{7}$$

where $f(x)$ is a continuous function, and $y(x)$ is its approximation. The sum of residuals can be obtained by plugging (1) and (2) into (7):

$$S=\sum(E_{11}\varepsilon_{xi}+E_{12}\varepsilon_{yi}-N_{xi})^2+\sum(E_{21}\varepsilon_{xi}+E_{22}\varepsilon_{yi}-N_{yi})^2. \tag{8}$$

Since E_{11}, E_{22}, E_{12} are linearly independent:

$$\frac{\partial S}{\partial E_{11}}=\frac{\partial S}{\partial E_{22}}=\frac{\partial S}{\partial E_{12}}=0. \tag{9}$$

From these equations, the unknown terms E_{11}, E_{12} and E_{22} can be determined. The Poisson ratios v_x and v_y can be easily computed by putting the calculated E_{11}, E_{12} and E_{22} into (1) to (3).

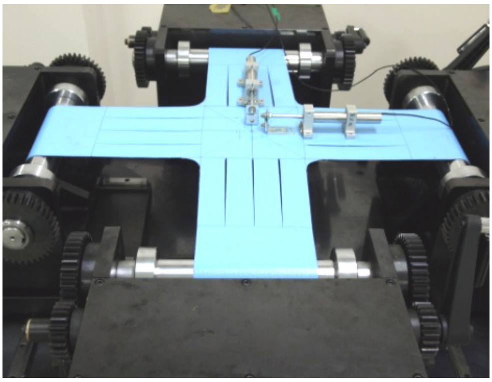


Fig. 1. Test setup to determine material properties of PVC membrane

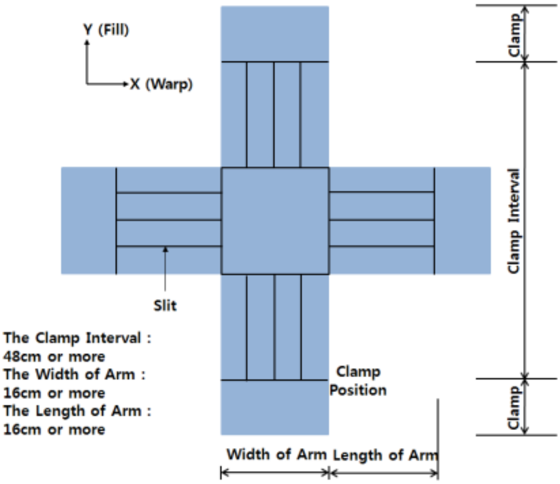


Fig. 2. Details of the membrane test specimen

The tensile strength of the membrane was determined by a single axis tensile strength, which was performed in a similar way to that of the previous tensile strength test in two perpendicular axes. Its setup is presented in Fig. 3, and the test was carried out in both of the warp and fill directions. The results of the test are plotted in Fig. 4. It shows that the breaking strengths of the membrane are 128.0 kN/m and 107.6 kN/m in the warp and fill directions, respectively. In general, the quarter of the breaking strength of membrane is used as its design strength. Therefore, the design strengths (T) of the membrane tested are 32.0 kN/m and

26.9 kN/m in the warp and fill directions, respectively. Since the membrane is assumed to have zero thickness, its design strength and Young's moduli are given in the unit of force per length. The material properties of the membrane obtained from the two tensile strength tests are summarized in Table 1.

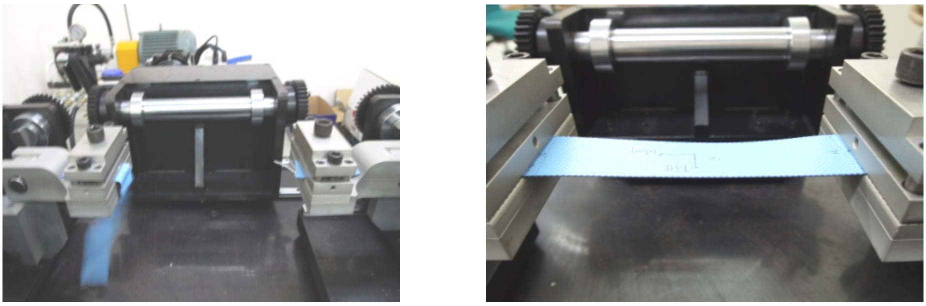


Fig. 3. A single axis tensile strength test setup

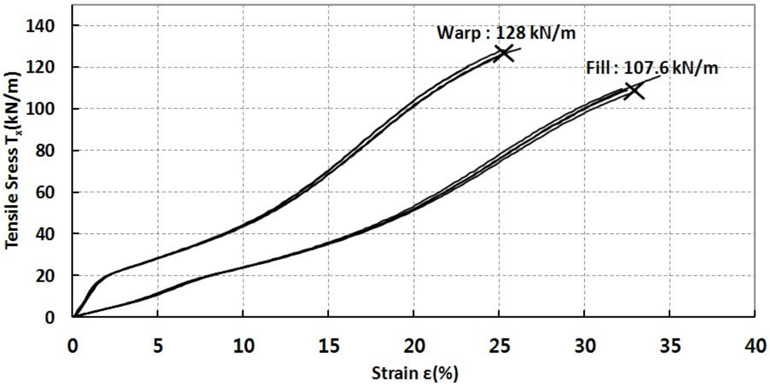


Fig. 4. Details of the membrane test specimen

Table 1. Material properties of PVC membrane

Direction	*E* (kN/m)	*T* (kN/m)	*v*	Weight (g/mm^2)
Longitudinal (Warp)	610.0	32.0	0.22	0.0013
Circumferential (Fill)	424.0	26.9	0.15	

TABS Bending Test

A bending test was performed to investigate the structural performance of the TABS. Four test specimens were manufactured with different membrane pressures, which are 100, 200, 400, 600 mbar and have the same span of 10 m. Tables 2 and 3 list the material properties of the cable and steel square pipe used in the TABS specimens. The size of the steel square pipe was 125×75×2.3 mm. The test setup of the specimen is illustrated in Fig. 5, and its connection details are shown in Figs. 6 and 7. Four cables were used in the TABS specimen as illustrated in Fig. 5, and the slenderness ratio defined by $L/2R$, where L is the length of the membrane and R is its radius, was 20. Both ends of the specimen were hinge supports and their details are shown in Fig. 7. They allow the elongation of cables caused by the volume change due to the increase of membrane pressure. Fig. 6 shows the details of the connection at the middle of the span where two steel square pipes and the cable element are joined together. This type of the connection is required when a long span member is required, thus the square steel pipe has to be cut.

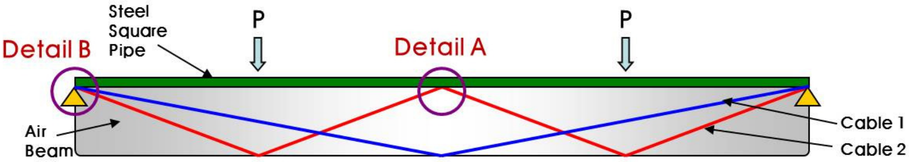


Fig. 5. Bending test setup of a typical TABS specimen

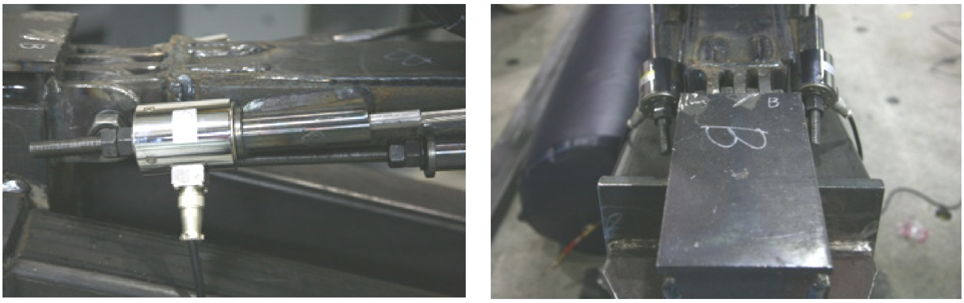


Fig. 6. Connection detail B

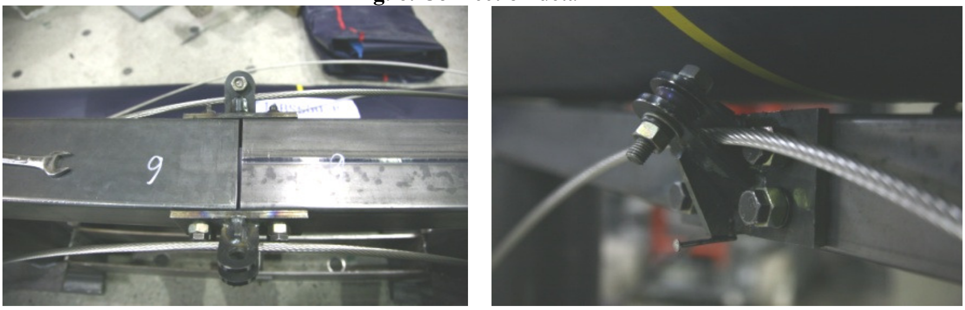


Fig. 7. Connection detail A

Load was applied to the specimen using two hydraulic cylinders, which were installed at the locations, which are 2.5 m away from each end of the specimen, such that the moment at the middle of the span becomes identical to that caused by a distributed load. The magnitude of the load was measured by the load cell attached to the cylinder, and the vertical displacement was monitored by a linear LVDT installed at the midspan of the beam. All of the TABS specimens showed a large deflection, which indicates the ductile nature of the structural performance of TABS. Consequently, in this test, the maximum load is the measured value at the maximum stroke of the LVDT, which is 250 mm, not the one at the ultimate state of the structure.

Table 2. Cable element properties

Diameter (mm)	Section area (mm^2)	Breaking force (kN)	Weight per section (g/m^2)
10	61.3	84.7	0.49

Table 3. Material properties of the steel pipe element

E (GPa)	v	Yield strength (GPa)	Ultimate strength (GPa)
210	0.3	0.24	0.41

Test Results

Fig. 8 shows the results of the bending test on the four TABS specimens. The results in the figure indicate that the load-displacement curves exhibit a linear behavior at the beginning and then their slopes gradually increased. Originally, it was expected that the slope of the load-displacement curve would decrease with increasing load due to the local buckling of the steel square pipe at the loading points. However, it turned out that the slope increases as the load increases as indicated in Fig. 8. This seems to happen because the overall behavior of the TABS specimen was governed by the geometrically nonlinear deformation due to large deformation of the air beam even if local yielding occurred in the steel square pipe. It can be also seen from the plot that the stiffness of the TABS specimen increases as membrane pressure increases. This happens because increase in the membrane pressure stiffens the air beam as expected.

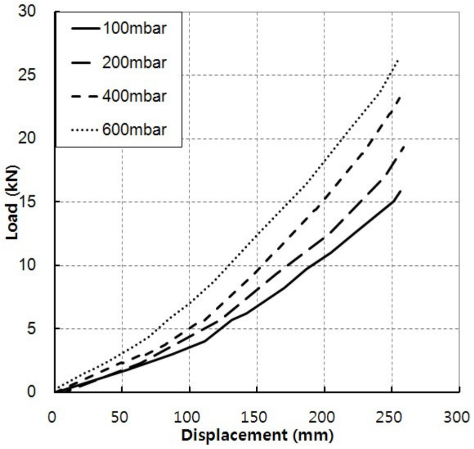


Fig. 8. Load-displacement curves for each TABS specimens

Numerical Modeling for TABS Analysis

An accurate three-dimensional finite element modeling of the TABS requires to deal with complicated issues such as a contact problem between membrane and cable element, but it is highly time-consuming. Thus, a simplified model taking into account the nonlinear behavior of the TABS is proposed, and its predictions are compared with the experimental results discussed in Section 3.1.

The main concept of the simplified model is illustrated in Fig. 9, and it is composed of two beam members representing horizontal beam elements of the TABS, two identical vertical springs representing the stiffness of the entire air beam tightened by the cables and two springs at the middle of the span with axial and rotational stiffness, respectively, representing the connection detail A in Fig 7. Since the air beam continuously supports the square steel pipe, the stiffness of the vertical springs is obtained from the equation of the cable force normal to the surface of membrane [1] and can be expressed as:

$$k_{spring} = 0.16 p \cdot \pi \cdot R \cdot \frac{L}{n} \text{ (kN/m)}, \tag{10}$$

where p is the membrane pressure, and n (= 2) is the number of the springs replacing the air beam with cables. The stiffness of the spring at the midspan was calculated from the sectional and material properties of the connection A. The finite element analysis of the proposed model was performed using the commercial package ABAQUS, [6] and the geometrical and material nonlinearities of the horizontal beam members were considered during the analysis.

The results of the analysis are compared with the experimental results in Fig. 10, which shows a good agreement between them in terms of the initial stiffness and behavior at the stage of large deformation. Also, as the pressure of the air beam increases, the difference between the analytical and experimental results diminishes. This indicates the effectiveness of the spring stiffness represented by (10) becomes higher as the pressure increases.

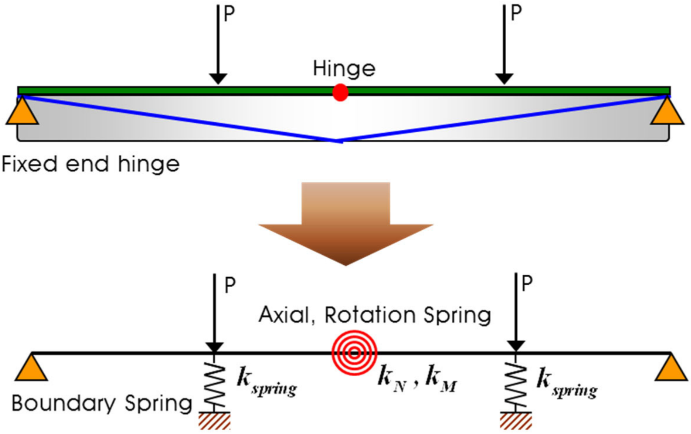
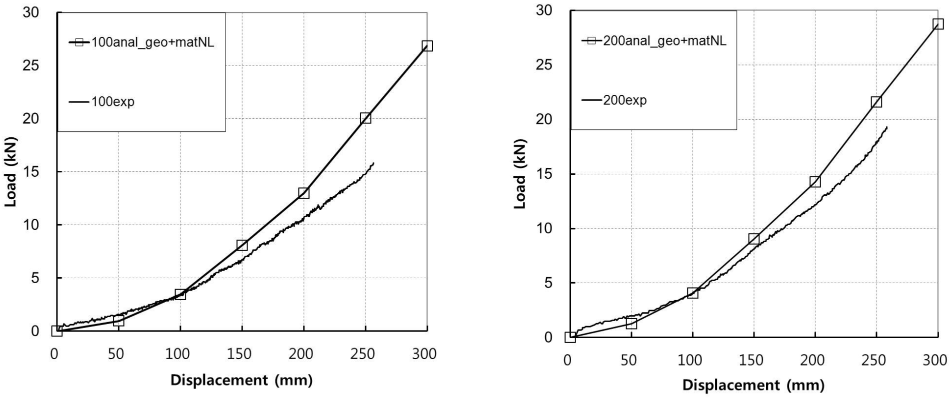
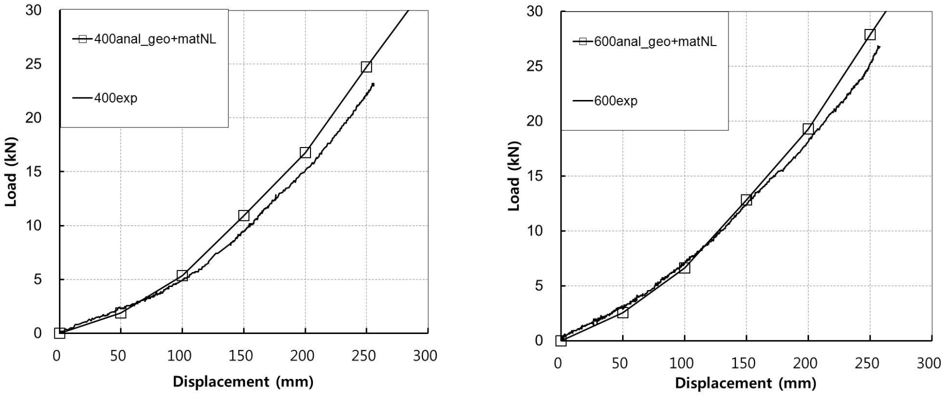


Fig. 9. Simple analytical model to predict the structural behavior of the TABS



(a) 100 mbar

(b) 200 mbar



(c) 400 mbar

(d) 600 mbar

Fig. 10. Comparison between the results of the analysis and experiment for different membrane pressures

Summary and Conclusions

In this study, a structural test was carried out to investigate the structural performance of TABS under different membrane pressure conditions. A simple numerical model was proposed to predict the structural behavior of TABS and its validity was evaluated by comparing its results with the test values. The main conclusions of this study can be summarized as follows:

1) The load-displacement curves of the TABS specimens exhibited a linear behavior at the beginning and then their slopes gradually increased. This seems to happen because the overall behavior of the TABS specimen was governed by the geometrically nonlinear deformation due to large deformation of the air beam.

2) The results of the test showed that the stiffness of the TABS specimen increased as membrane pressure increased. This is because increase in the membrane pressure stiffens the air beam.

3) TABS shows a highly ductile behavior and nonlinear analysis is required to accurately predict its structural behavior. The numerical model proposed in this study turned out to be valid and was able to accurately predict the experimental results.

Acknowledgements

This research was supported by a Grant (Code # ’06 R&D B03) from Cutting-Edge Urban Development Program funded by Ministry of Land, Transport and Maritime Affairs of Korean Government. This support is gratefully acknowledged.

References

[1] **Luchsinger R. H., Pedretti A., Steingruber P., Pedretti M.** The new structural concept Tensairity: basic principles. Progress in Structural Engineering, Mechanics and Computations, A. A. Balkema Publishers, London, 2004.

[2] **Lushinger R. H., Crettol R., Plagianakos T. S.** Temporary structures with Tensairity. Proceedings of Int. Association for Shell and Spatial Structures Symposium, Acapulco, 2008.

[3] **Luchsinger R. H., Crettol R.** Experimental and numerical study of spindle shaped Tensairity girders. International Journal of Space Structures, Vol. 21, Issue 3, 2006, p. 119 - 130.

[4] Test for Young’s Modulus of Membrane. Membrane Structures Association of Japan, 2003.

[5] **Reddy J. N.** An Introduction to the Finite Element Method. McGraw-Hill International Editions, 1993.

[6] ABAQUS. Ver. 6.5-1 Manual.