ANALYSIS OF TENT-LIKE STRUCTURES SUPPORTED BY PRESSURIZED FABRIC ARCHES

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ABSTRACT

This study investigates large tent-like maintenance shelters for vehicles, helicopters, and aircraft. The objective is to design structures that can be transported in lightweight modules and deployed quickly where needed. These structures consist of a skin supported by pressurized arches anchored to the ground. The arches are made of fabric with an air-tight liner and are filled with air at high pressure. Some relatively small structures of this type have been constructed, and the feasibility of large hangars with this configuration is being examined. A finite element analysis is carried out. The arches and skin of the structure are modeled as thin shells, using the computer software ABAQUS. The basic framework consists of six vertical arches, plus two leaning arches at each end that can be raised to allow vehicles and aircraft to enter or exit. Snow and wind loads are assumed to act on the structure, and the static and dynamic responses are determined numerically. Displacements, stresses, and vibration modes and frequencies are computed.

INTRODUCTION

Most air-supported structures require a continuous addition of air to hold up the roof. Other membrane structures possess a rigid framework, sometimes made of steel or aluminum. For ease of transportability and deployment, and to allow a large opening for vehicles or aircraft to enter, the type of structure investigated here, supported by highly-pressurized fabric arches, has some advantages and could become more common in the future. These transportable structures could have various significant applications in addition to serving as vehicle shelters and hangars. One would be as emergency shelters following disasters such as floods, earthquakes, and hurricanes. The compact modules could be trucked or flown to sites where buildings have been destroyed or people have been forced to evacuate their homes, and could be deployed quickly. They could provide a large enclosed space with protection from the elements, and could be transported to wherever they would be needed. The skin of the shelter being developed by the U.S. Army is comprised of panels of PVC coated polyester that are hooked onto the arches (Kronenburg, 1996). The tubes are woven, but braided tubes are also being considered, and candidate materials for future tents include polyesters, nylons, aramids (e.g., Kevlar), extended chain polyethylenes (e.g., Spectra), liquid crystal polymers (e.g., Vectran), and fluorocarbons.

As an aside, it is noted that there has been an increased interest in the use of fabrics in architecture. Recent writings on this topic include books by Berger (1996), Kronenburg (1997), and Shock (1997), and the paper by Monjo-Carri_ and G_mez Guardiola (1998). Properties of some of the fabrics available for these structures are described in Karni (1994). Membrane or fabric structures for use on the moon or Mars also have received some study, e.g., Szilard (1967), Szyszkowski and Glockner (1990), Sadeh and Criswell (1995), and Kronenburg (1996).

Much previous work on pressurized arch-tubes has utilized membrane theory. However, the arches under consideration for the large tents are subjected to high internal pressures, and the bending stiffness of the material becomes important. Therefore a shell theory is more appropriate. The tubes do not fit into one of the standard categories of shells, such as shells of revolution, cylindrical shells, conical shells, axisymmetric shells, or toroidal shells having two constant radii (one for the cross section and one for the midline of the cross sections in the plane of the curved tube). Also, the tubes are not homogeneous or isotropic; they are designed to form into the natural shape of an arch when they are inflated, which requires properties that vary with position.

Some work on single pressurized arch-shells has been carried out by Mohan and Kapania (1998a,b). A three-node, flat, triangular shell element was utilized, which was a combination of the Discrete Kirchhoff Theory plate bending element and a membrane element similar to the Allman element. The follower effects of the pressure load were included in the formulation. Molloy et al. (1998) and Plaut et al. (1998) considered a pair of pressurized arch-shells leaning against each other and attached at the crown. Deflections, buckling loads, and vibrations were investigated using the finite element program ABAQUS (1994). Experiments on two scale models of a fabric shelter supported by pressurized arch-shells were described in Carradine and Plaut (1998). The models were tested in a wind tunnel and also subjected to simulated snow loads.

NUMERICAL ANALYSIS

The shelter considered in this study is supported by ten pressurized arches and is symmetric about its center. Six of the arches are vertical and the last two at each end lean away from the center. A perspective is illustrated in Figure 1. Figure 2 shows the placement of the five arches on the left half of the structure. Along the axis of the structure, the centerlines of the vertical arches are separated by 4m, and the centers of the tops of the leaning arches are separated from each other and the last vertical arch by 1.2m.

The last arch on each end leans at an angle of 40^o with the vertical, and the adjacent arch on each end has a 20^o angle with the vertical, as depicted in Figure 3.

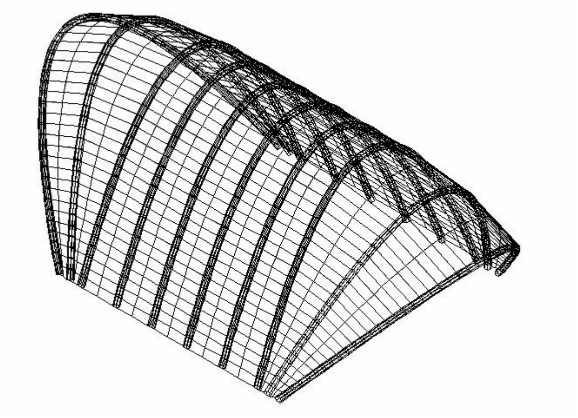


Fig.1 : Perspective of analysis model

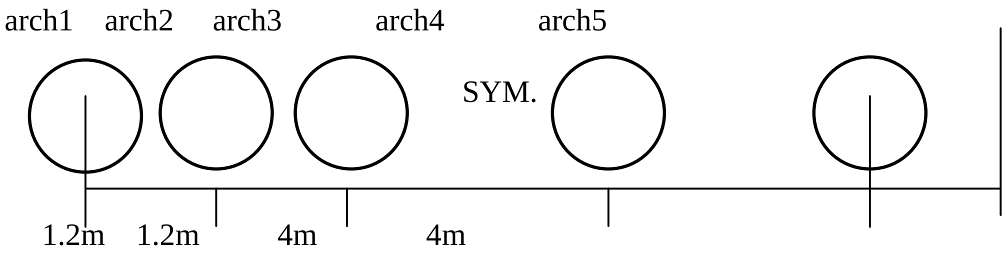


Fig. 2: Placement of the arches on the left half of the structure

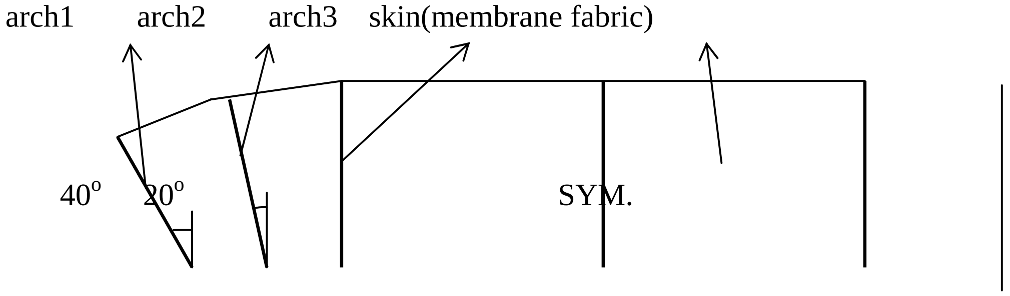


Fig. 3: Elevation of structures(half)

Figure 4 illustrates the geometrical properties of the arches. Their centerline has a parabolic shape, with a height of 17m and a base width of 12.5m. The cross section of each arch is circular and has a radius of 30cm. The coordinate system is oriented with the X axis parallel to the lines connecting the two supports of each arch, the Y axis parallel to the longitudinal axis of the structure, and the Z axis upward. At the supports, the arches are assumed to be fixed, so that they have no deflections or rotations. They have an internal pressure of 500kN.

The arches are connected to each other by the skin of the shelter, as sketched in Fig. 5. The points of attachment are assumed to be located where the slope of the cross section is 45 degrees. The modulus of elasticity is chosen to be 7GPa, Poisson's ratio is 0.3, the density is 1,440kg/m^3, and the thickness is 2.5mm. The material properties are representative of a lightweight fabric such as Kevlar or nylon.

The structure is modeled using the finite element method. ABAQUS (1994) is utilized, with S4R rectangular shell elements for both the arches and the skin. Each arch is represented by 400 elements, and the skin between adjacent arches is discretized into 100 elements, as shown in Fig. 1. The total number of degrees of freedom is 27,234.

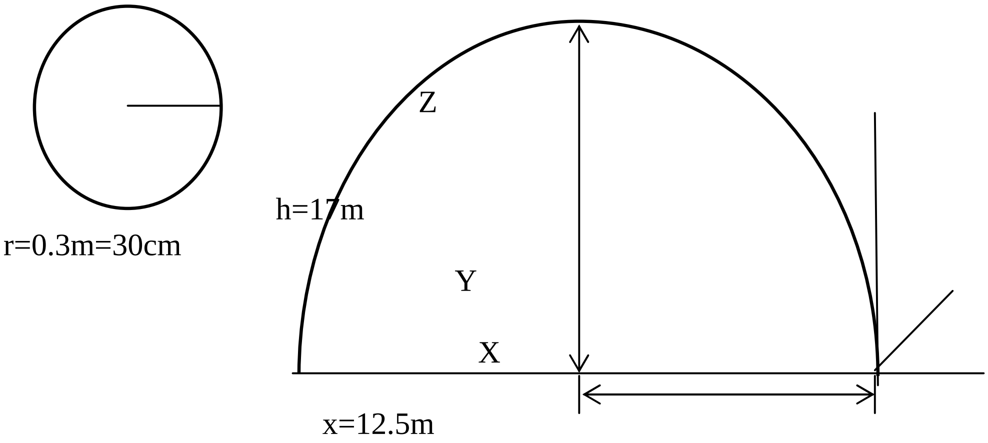


Fig. 4: Geometrical property of the arches

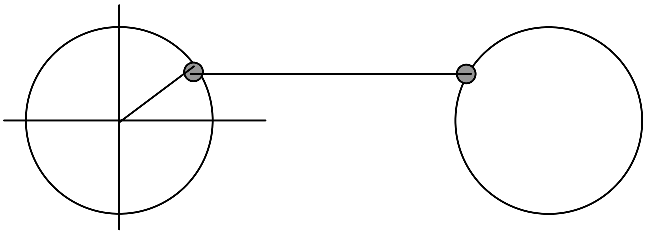
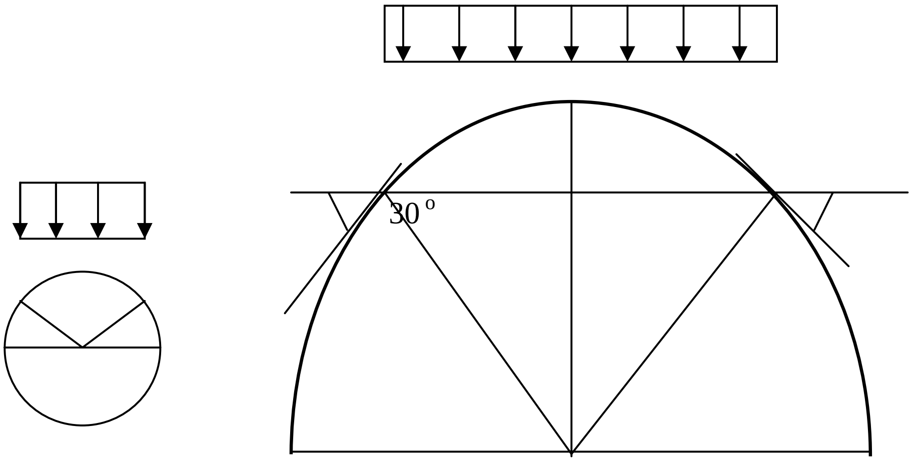


Fig. 5: Connection between arches and fabrics

FULL SNOW LOAD

The first external loading considered is called "full snow load" and is depicted in Fig. 6. The load is uniform over a horizontal projection and is applied over a central region of the structure, since snow will fall off when the slope is high. On the cross section of an arch, the load is applied over the top quarter. In a profile of the structure perpendicular to the longitudinal axis (i.e., in planes parallel to the XZ plane), the load is applied where the slope of the arch or skin is less than 30 degrees with the horizontal. The intensity of the load is increased until it passes 1.92kPa; this value is represented by a "load increment" of unity in the plots.

The displacements of the apex of each arch on one side of the structure are plotted as functions of the load in Figs. 7 and 8. Results for arches on the other side of the center are obtained by symmetry. Figure 7 presents the vertical displacement (z) and Fig. 8 gives the horizontal displacement (y) parallel to the longitudinal axis of the structure. As shown in Fig. 2, arch #5 is closest to the center and arch #1 is at the end. The initial values of z and y are caused by the internal pressure, with z positive if the displacement is upward from the initial configuration of the arch and y positive if the arch displaces toward the end. As expected, the displacements from this initial state tend to increase as one moves away from the center of the structure. Also, most of the curves are almost linear in the range of loading considered in Figs. 7 and 8.



(a) Distribution on the arch (b) Distribution on the tent elevation

Fig. 6: Uniformly distributed snow load on the tent structures

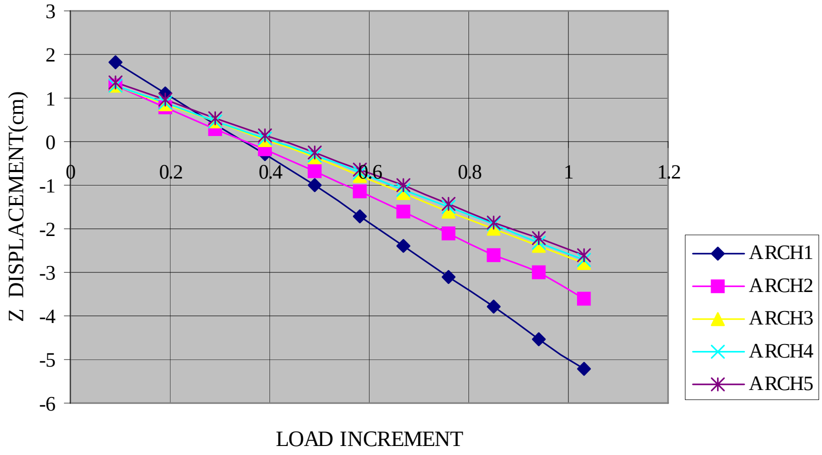


Fig. 7: Displacement curve on apex(Z direction)

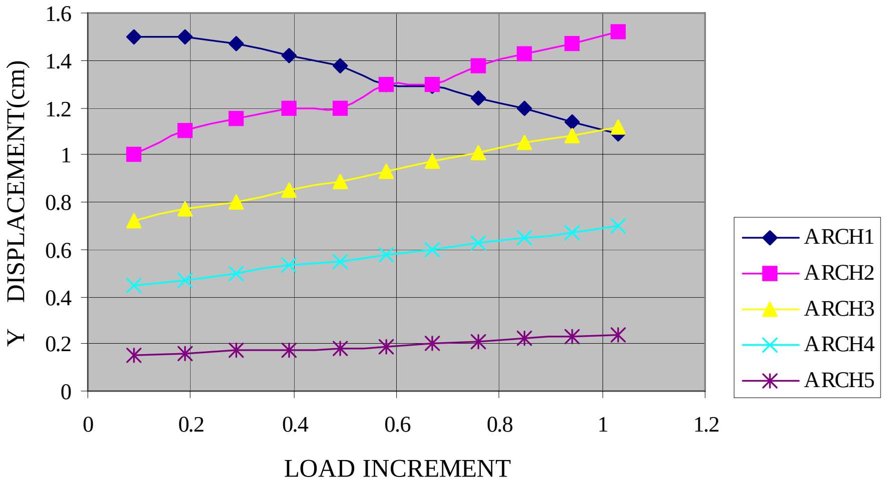


Fig. 8: Displacement curve on apex(Y direction)

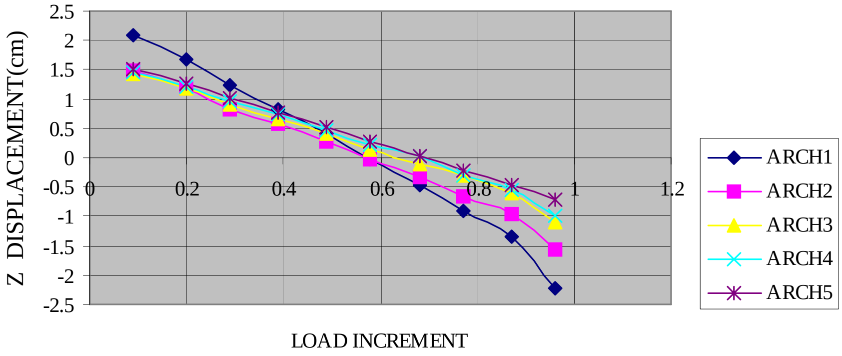


Fig. 9: Displacement curve on apex(Z direction)

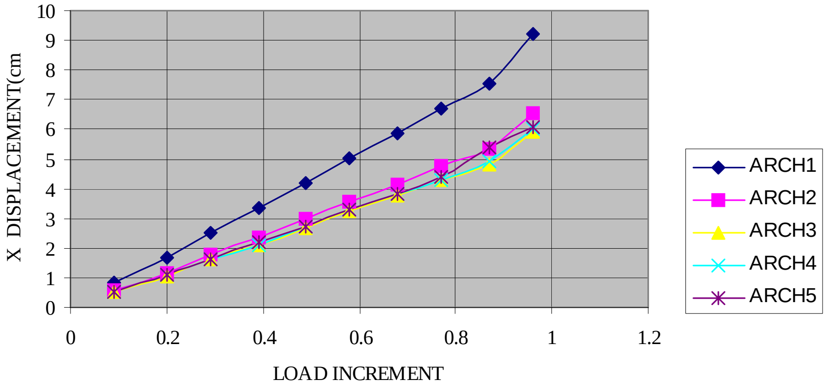


Fig. 10: Displacement curve on apex(X direction)

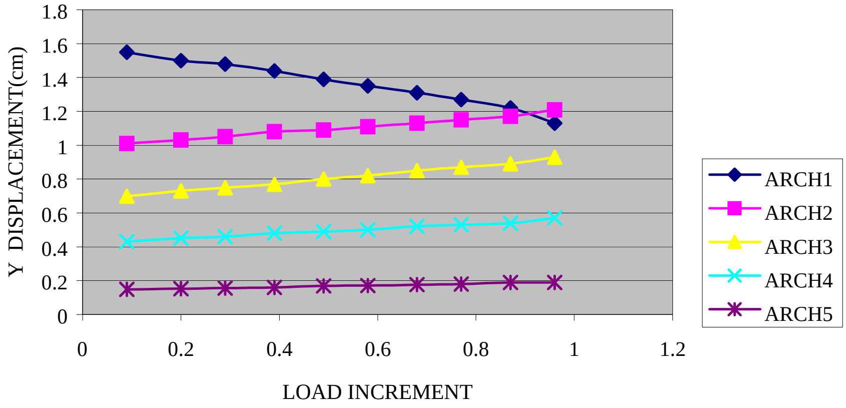


Fig. 11: Displacement curve on apex(Y direction)

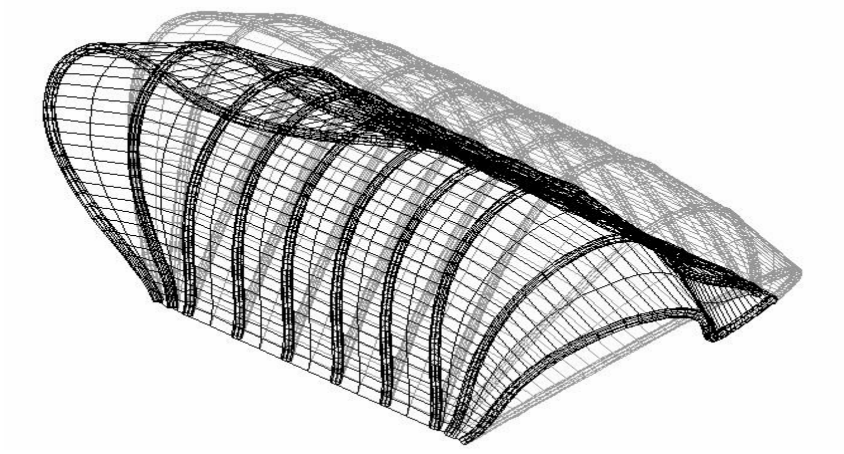


Fig. 12: Natural mode(first)

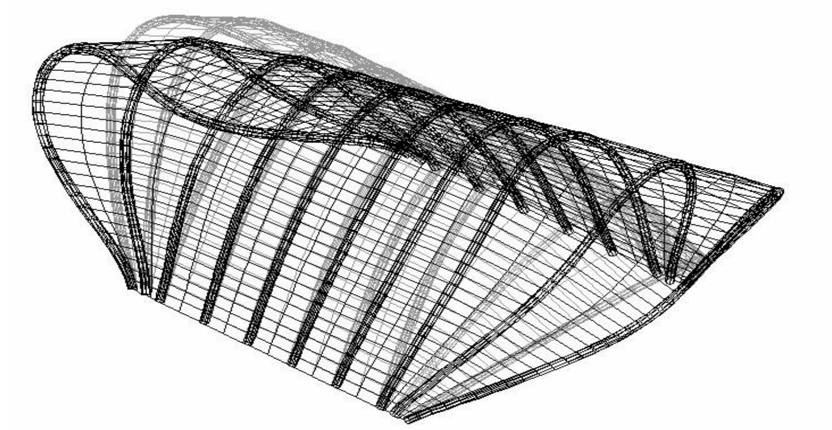


Fig. 13: Natural mode(second)

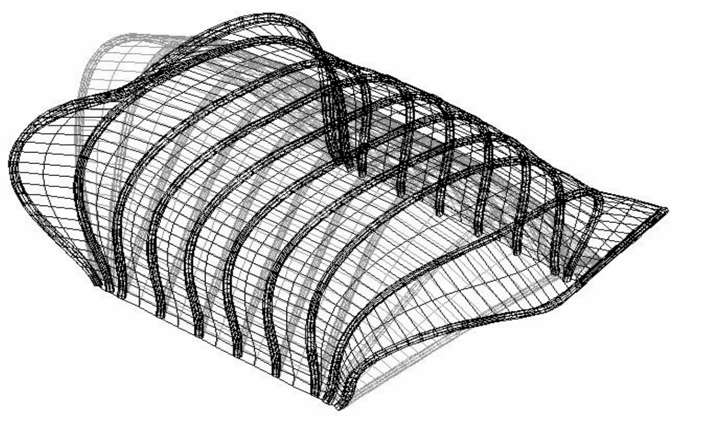


Fig. 14: Natural mode(third)

HALF SNOW LOAD

Next, it is assumed that the snow load only acts on one side of the longitudinal axis. Again there is symmetry with respect to the center of the structure in the Y direction. The z, y, and x displacements of the apex of each arch on one side of the center are plotted in Figs. 9-11, respectively. Vertical (z) displacements are much smaller than before, since the total load is less. The sideways (x) displacements are significant. They are almost the same for all but the end arch in Fig. 11, and become large as the load increases.

VIBRATIONS

Vibration modes can be obtained from ABAQUS (1994). Here the first few modes of the entire structure under no external loading are considered. They are interesting in that they indicate to some extent the manner in which the structure will respond to dynamic loads, such as wind gusts or earthquakes.

The first mode (corresponding to the lowest frequency of vibration) is depicted in Fig. 12. The structure essentially sways back and forth to the side. The second mode, in Fig. 13, involves twisting of the structure about a vertical axis through its center. In the third mode, shown in Fig. 14, the structure exhibits a vertical motion, up and down about the equilibrium configuration. The cross sections bulge out at the sides when the top moves downward, with the greatest bulging occurring in the end arches.

CONCLUDING REMARKS

Pressurized fabric arches have been used to support some lightweight tent-like structures. The design of large structures of this type, such as for shelters for helicopters or airplanes, is under development. Previously the arches were investigated, but here the entire structure was analyzed using the finite element method. The analysis involved ten pressurized arches connected by a flexible material. Displacements under full and half snow loads were determined, and modes of vibration were obtained.

There are various possible applications for these lightweight structures, including use as emergency shelters during natural disasters. They can be transported easily in modules and deployed quickly. The arches are pressurized and sealed, so a continuous supply of air is not needed. The design considered here has the advantage that the end arches can be raised to provide a large opening. Further development and applications of these structures are expected, and they could turn out to be widely used in the future.

ACKNOWLEDGEMENT

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