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Structural behaviour of inflatable PVC fabric cylindrical tubes

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Abstract. Inflatable structures are light weight structures that have often been proposed for aerospace applications. They are light in weight, easily manufacturable and foldable. Thus, they can be easily transported and deployed in space. However, the proper characterization for their properties of these structures is still missing.
The work done in this paper aims at studying the structural properties of inflatable cylindrical tubes, manufactured from PVC fabric. The cylindrical tubes are fixed as cantilever beams and subjected to a load at the beam tip. Samples of different sizes are tested under different inflation pressures and loads. Load-deflection curves are recorded for each test. Results show that the beam stiffness increases with the increase of inflation pressure and beam cross sectional area. The inflatable beams show linear behaviour up to a certain critical load at which wrinkling occurs. Beyond this load the behaviour of the beam becomes nonlinear and can be unstable. Hysteresis phenomenon is also observed during the unloading of the beam. In addition, Free vibration analysis was conducted to study the effect of inflation pressure on the beam natural frequency. This work is a part of project aiming to design and manufacture an inflatable wind turbine blade to overcome the drawbacks of conventional blades.

1. Introduction

Inflatable structures, also called as tensile structures are thin walled structures that rely on the pre-tension of the fabric to gain its stiffness and carry loads. The pressure inside applies tensile forces through the whole structure, while the external loads apply tension and compressive forces. The structure material cannot withstand compressive loads as it leads to a local buckling (wrinkling) in the fabric and that leads to the collapse of the structure. The more pressure applied to the inflatable structure the more rigid it is. However, the fabric material has a tension limit that, if exceeded, will result in a mechanical failure.

1.1. Applications of inflatable structures

Inflatable structures have many advantages; they are light in weight, can be easily folded thus easily transported, easily installed or assembled, fast deployed, easily manufactured, not expensive as other structures and have a reversible behavior. As a result of these advantages, inflatable structures are used in many civil, space, aeronautical and military applications. In civil applications the inflatable structures are used in air supported structures [1] such as stadium roofs, temporary buildings and inflated tents. Also, they can be used in aircraft escape slides and ship life rafts. In space applications, inflatable structures are widely used due to their light weight and ease of transportation. Hence, they are used in the manufacturing of space antennas and reflectors [2, 3], re-entry vehicles and inflatable habitats [4, 5]. A review of inflatable structures applications in space is introduced by H. M. Jenkins [6]. In aeronautical applications inflatable structures are used in the manufacturing of airships, aerodynamic decelerators [7], [8] and inflatable wings [9].

1.2. Inflatable beams

To facilitates effective designs of inflatable structures, the behaviors of their properties have to be thoroughly characterized and understood. During the past years a lot of research was carried on inflatable structures. Most of it focused on structural testing and modeling of these structures.

Many researchers studied the bending behavior of inflatable beams. Clapp et al. [10] studied the bending behavior of braided tubes with integral reinforcing cords, that are made of para-aramid fibers with impermeable urethane gas bladder, Thomas et al. [11] tested the deflections of inflatable tubes made of Ferrari's prestressed fabrics and compared the results to a developed numerical model, Cavallaro et al. [12] investigated experimentally and analytically the bending response of woven pressure-stabilized beams made from Vectran and PEN (polyethylene naphthalate) fabrics. In addition, they studied the micromechanical effects of interacting tows through finite element models. Main et al. [13] developed a model to analyze inflated fabric beams using the shear-moment method. The resulting model showed that the bending behavior of inflatable beams was similar to conventional solid elastic beams prior to beam wrinkling Moreover, experimental data were obtained to verify their bending model. The results of their work show that inflatables can be used in many applications as structural elements if properly designed.

2. Experimental setup

The inflatable beams presented in this paper are tested for static bending, to study their load-deflection behaviour. Three beams are manufactured form polyvinyl chloride (PVC) fabric of 0.6 mm thickness using hot air welding machine, shown in figure 1 the hot air welding machine uses hot air with a temperature that ranges from 300 to 750 ^{0}C to melt the two PVC layers of the fabric together. The three beams with corresponding (l/d >7.5) are manufactured with three diameters of 20, 25 and 30cm, to study the effect of beam diameter on the beam stiffness. The smallest beam is tested at three inflation pressures of 0.5, 1 and 1.5 bar, while the other beams are tested at inflation pressures of 0.5 and 1 bar.

The beams are mounted as a cantilever through a test rig, shown in figure 2, that is designed and fabricated to hold the inflatable beams. In addition, several adapters are manufactured to hold the beams because each beam had a different diameter.

A laser meter is used to measure the beam deflections. The laser meter has an accuracy of 1.5 mm. Several steel rings are manufactured to act as weights that are used to apply the tip loads and a digital weight balance is used to measure the steel rings weight. The digital balance has an accuracy of 1 gram. Also, a pressure gauge is used to measure the internal pressure of the beam. Finally, a fixture is manufactured to hold the steel weights with a hollow body to enable the laser beam to pass by to the point of the applied load. The inflatable beam under load is shown in figure 3.

Figure 1. Hot air welding machine

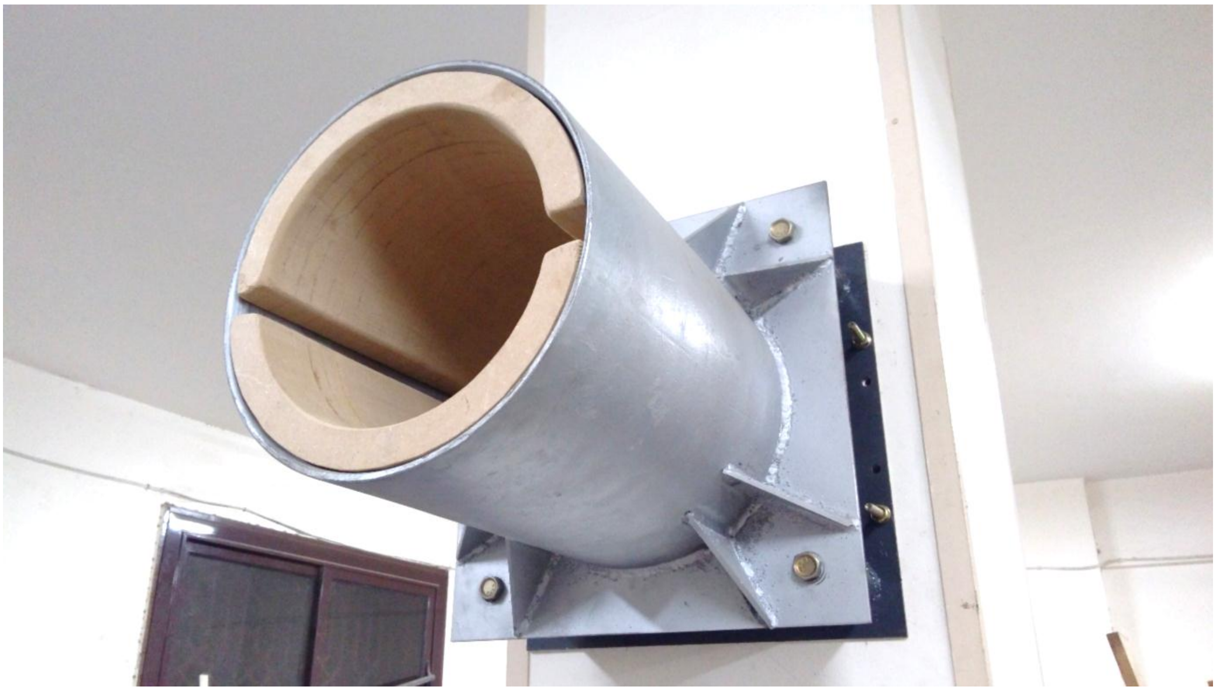

Figure 2. Inflatable beam test rig with beam adaptor.

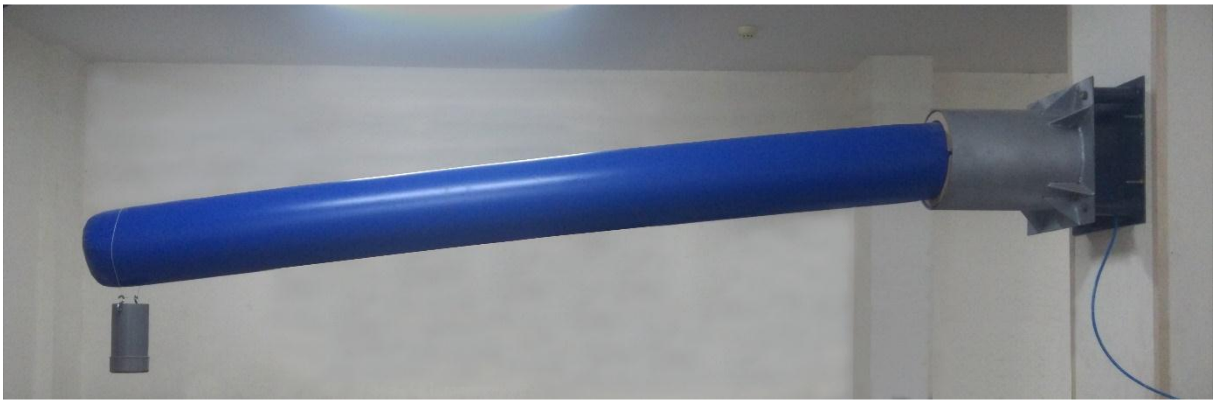

Figure 3. Inflatable beam under loading

3. Results

3.1. Static bending test

Figure 4 shows the load-deflection curve of the 20 cm diameter inflatable beam at three inflation pressures 0.5, 1 and 1.5 bar.

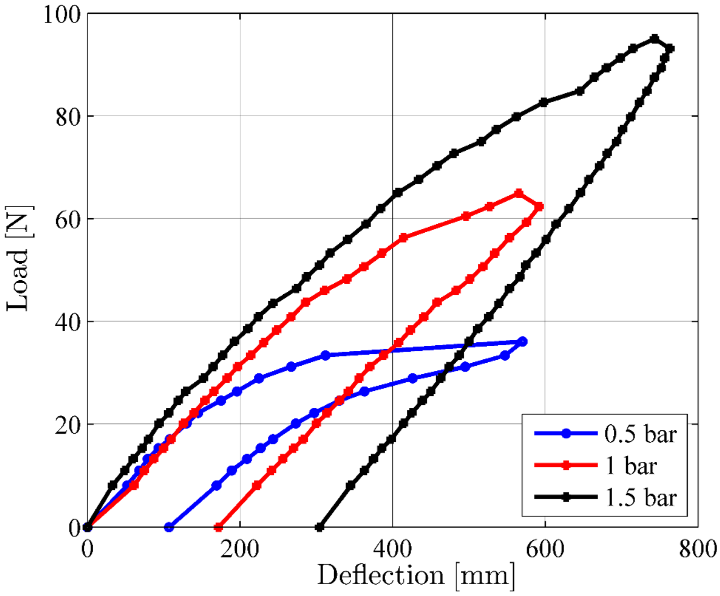

Figure 4. The load deflection curve of 20cm diameter beam

Figure 5 shows the load-deflection curve of the 25 cm diameter inflatable beam at two inflation pressures 0.5 and 1 bar.

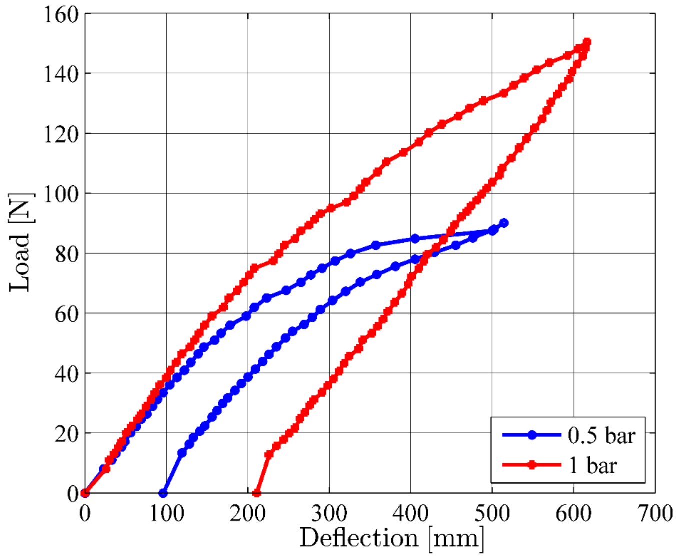

Figure 5. The load deflection curve of 25 cm diameter beam

Figure 6 shows the load-deflection curve of the 30 cm diameter inflatable beam at two inflation pressures 0.5 and 1 bar.

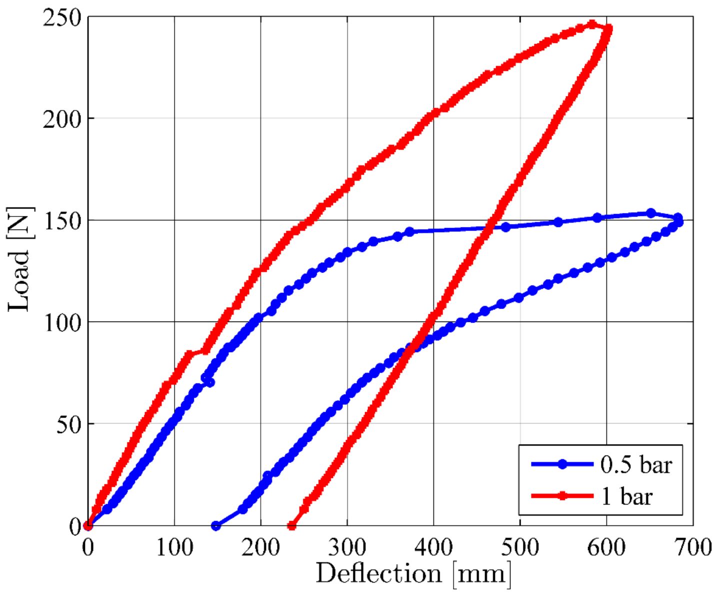

Figure 6. The load deflection curve of 30cm diameter beam

It is shown from figures (4 – 6) that the beam stiffness increases with the increase of Inflation pressure as well as the maximum bearing load of the beams. It is also shown that there is a Hysteresis phenomenon that happens during the unloading of the beams. The stiffness and the maximum bearing load of each beam are recorded in table 1.

Also, during the loading of the beam it was observed at the beginning of the test that by adding constant loads, the deflection of the beam was increasing with a constant rate. Then at larger loads, the deflection rate increased resulting in larger deflections compared to the increase in the load. Simultaneously, wrinkling of the beam was observed as shown in figure 7.

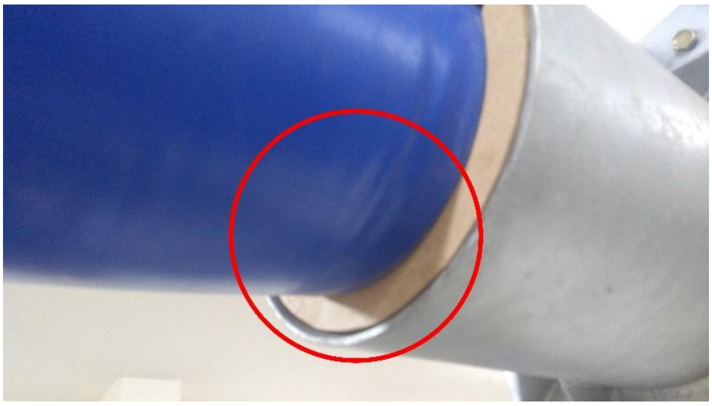

Figure 7. Beam wrinkling phenomenon

Table 1. The stiffness and maximum load values of the three inflatable beams under different inflation pressures

Beam Diameter (mm)	Inflation pressure (bar)	Stiffness (N/m)	Maximum Load (N)
200	0.5	140.57	36
	1	159.74	65
	1.5	206.72	95
250	0.5	347.5	90
	1	382.6	150.5
300	0.5	520	153.5
	1	779.2	246

3.2. Free vibration analysis

Free vibrations of the 250 mm are recorded at different inflation pressures to determine the relationship between the inflation pressure and the beam natural frequency. The vibrations are measured by a vibration analyser device (RH711C). Figure 8 shows the device accelerometer attached to the inflatable beam, while figure 9 shows a sample of the data of the free vibration recording the acceleration vs time at 0.83 bar inflation pressure.

By analysing the measured data, the logarithmic decrement (δ) is calculated from equation 1. Then the damping ratio (ζ) is calculated from equation 2, it is found to be approximately 0.09 and finally the natural frequency is calculated from equations 3 and 4. Figure 10 shows the circular natural frequencies of the inflatable beam at different inflation pressures.

Figure 8. Device accelerometer attached to the inflatable beam

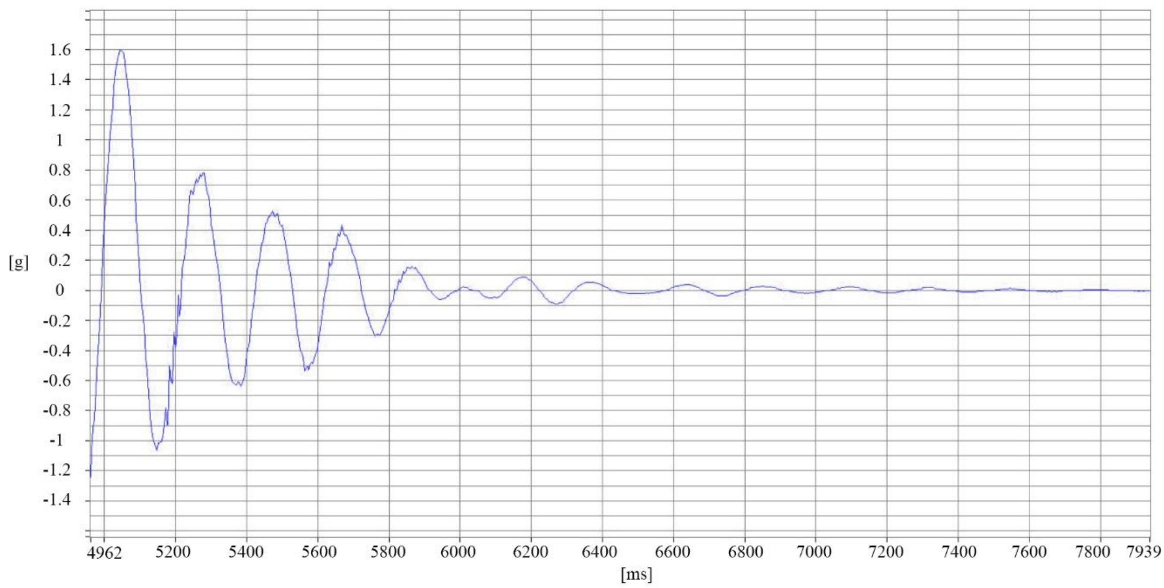

Figure 9. Data sample of acceleration vs. time

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$$\frac{X_1}{X_{n+1}} = e^{n\delta} \tag{1}$$

$$\zeta = \frac{\delta}{\sqrt{4\pi^2+\delta^2}} \tag{2}$$

$$\omega_d = \frac{2\pi}{T_d} \tag{3}$$

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}} \tag{4}$$

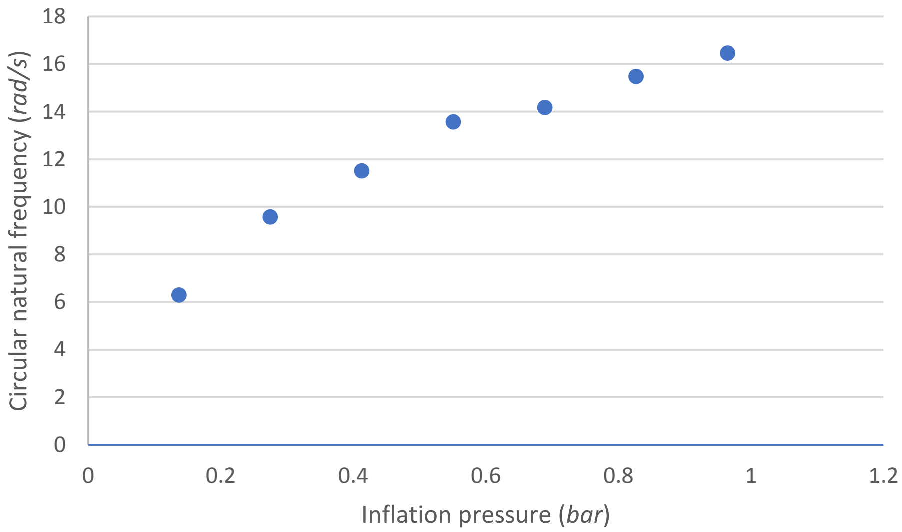

Figure 10. Circular natural frequency vs. inflation pressure

It is shown from figure 10, that the natural frequency of the beams increases with the increase of the inflation pressure.

4. Conclusion

The bending behaviour of three PVC inflatable beams is investigated. The inflatable beams have different sizes and tested at different pressures. Load-deflection curves are plotted for each case. In the beginning, it is observed that the deflection varies linearly with the load. At larger loads, the slope of the curve changes showing larger deflections as compared to the increase in the load. Simultaneously, wrinkling phenomenon is observed. This can be attributed to the beam geometrical and material nonlinearities as the material of the beam is considered as a hyper-elastic material. It is also noted that by increasing the inflation pressure or beam diameter, the stiffness of the inflated beam as well as its maximum bearing load increase. For instance, increasing the pressure of the 300 mm beam from 0.5 bar to 1.0 bar, increases the stiffness by a factor of 1.5. It also increases the maximum bearing load by a factor of 1.6. While by increasing the beam diameter from the 200 mm to 250 mm at 1.0 bar inflation pressure, increases the stiffness by a factor of 2.4 and increases the maximum bearing load by a factor of 2.3. Hysteresis phenomenon is observed during the unloading of the beams, as the beams did not return to their initial position. This can be also attributed to the nature of the hyper-elastic material of the beam. The hysteresis phenomenon of the inflatable beam should be considered during the design of the inflatable structures. Finally, the natural frequency is found to be increasing with the increase of the inflation pressure.

5. References

[1] L. Qingsong, X. Guo, J. Gong, Q. Qing and Z. Li, “Experimental deployment behavior of air-inflated fabric arches and a full-scale fabric arch frame,” Thin-Walled Structures, vol. 103, pp. 90-104, 2016.
[2] C. Cassapakis and M. Thomas, “Inflatable structures technology development overview,” in Space Programs and Technologies Conference, Tustin, CA, 1995.
[3] F. Naderi, W. Weber and G. Knouse, “NASA's mobile satellite communications program; ground and space segment technologies,” in Lausanne International Astronautical Federation Congress, 1984.
[4] S. Veldman and C. A. J. R. Vermeeren, “Inflatable Structures in Aerospace Engineering - An Overview,” Spacecraft Structures, Materials and Mechanical Testing, vol. 468, p. 93, 2001.
[5] M. Di Capua, D. Akin and K. Davis, “Design, development, and testing of an inflatable habitat element for NASA lunar analogue studies,” in 41st International Conference on Environmental Systems, Portland, Oregon, 2011.
[6] C. H. Jenkins, Progress in astronautics and aeronautics: gossamer spacecraft: membrane and inflatable structures technology for space applications, Reston, Virginia: Aiaa, 2001.
[7] B. P. Smith, C. . L. Tanner, M. Mahzari, I. G. Clark, R. D. Braun and F. M. Cheatwood, “A historical review of inflatable aerodynamic decelerator technology development,” in Aerospace Conference, 2010 IEEE, pp. 1-18. IEEE, Atlanta, 2010.
[8] A. C. Young, W. G. Davids, F. M. Cheatwood and M. C. Lindell, “Structural analysis of hypersonic inflatable aerodynamic decelerator pressure tub testing,” Thin-Walled Structures, vol. 131, pp. 869-882, 2018.
[9] G. Brown, R. Haggard and B. Norton, “Inflatable structures for deployable wings,” in 16th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Lake Elsinore, CA, 2001.
[10] J. D. Clapp, A. C. Young, W. G. Davids and A. J. Goupee, “Bending response of reinforced, inflated, tubular braided fabric structural members,” Thin-Walled Structures, vol. 107 , pp. 415-426, 2016.
[11] J. C. Thomas and C. Wielgosz, “Deflections of highly inflated fabric tubes,” Thin-Walled Structures, vol. 42, no. 7, pp. 1049-1066, 2004.
[12] P. V. Cavallaro, M. E. Johnson and M. A. Sadegh, “Mechanics of plain-woven fabrics for inflated structures,” Composite structures, vol. 61, no. 4, pp. 375-393, 2003.
[13] J. A. Main, S. W. Peterson and A. M. Strauss, “Load-deflection behaviour of space-based inflatable fabric beams,” Journal of Aerospace Engineering, vol. 7, no. 2, pp. 225-238, 1994.