INFLATABLE TRIANGULATED CYLINDERS

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Abstract

A study is described into the use of triangulated cylinders as inflatable tubes. Triangulated cylinders are a new way to fold a tube; folding a thin-walled, soft aluminium tube as a triangulated cylinder gives a simple, efficient rigidizable inflatable tube. A major advantage of inflatable triangulated cylinders is that deployment is controlled, while the in-plane deformation for the tube wall remains small. The results of simple tests show the concept to be viable.

1. Introduction

Inflatable components provide a potentially revolutionary approach to the design of deployable structures for space. Their obvious advantages include their simplicity, with no traditional mechanical hinges, their potentially low weight, and the possibility of producing structures with extremely high packing efficiency.

There have been, however, two obvious drawbacks to the use of inflatable structures in space. The first of these is that the inflation of the structure may be uncontrolled; this leads to concern about whether the structure will reliably reach its deployed state, and also concern about the attitude control of the spacecraft during inflation. The second drawback is that inflatable structures may need to remain inflated to retain stiffness in their deployed state, and hence meteorite damage becomes a serious problem.

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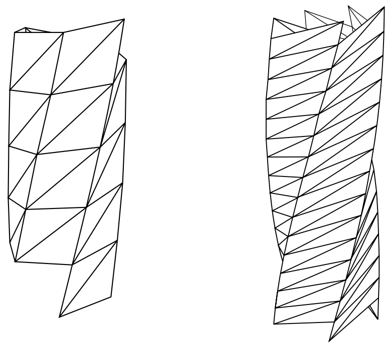


Figure 1. Two examples of the many possible designs of triangulated cylinders.

This paper presents the results of an initial proof-of-concept study into a new design for inflatable columns. The key features of this design are as follows:

(i) The use of a new folding pattern for tubes, christened *triangulated cylinders*, originally studied by Guest and Pellegrino (1994a).

(ii) The use of annealed aluminium as a rigidizable structural material.

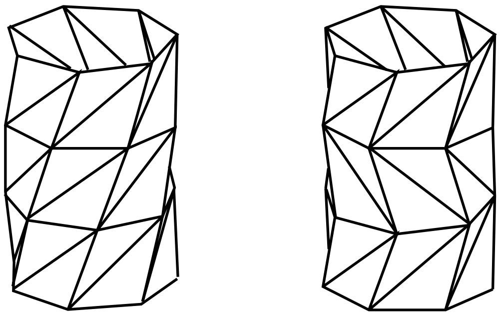
The aim of the study was to prove the concept that combining these features could lead to a reliable component for use as part of an inflatable structure, one that overcomes the drawbacks of inflatable structures mentioned above.

The layout of the paper is as follows. Section 2 of the paper presents the ideas of triangulated cylinders, and rigidizable structures, that lie behind the present study. Section 3 describes the simple experiments that were carried out, and the results obtained. Section 4 considers how the current work could be carried forward, and Section 5 concludes the paper.

2. Background

2.1. TRIANGULATED CYLINDERS

Triangulated cylinders were studied as a potentially effective and simple way of folding a cylinder by Guest and Pellegrino (1994a;1994b;1996). Triangulated cylinders are cylinders that are made up of a number of facets; the edges of these facets approximate to helices. Two examples are shown in



(a) (b)

Figure 2. (a) The fold pattern used in this study; (b) The same fold pattern with alternate rings reversed to prevent relative rotation during deployment.

Figure 1. By satisfying certain geometric rules, it is possible to ensure that these cylinders fold down to an undistorted flat stack of plates.

It can easily be shown that all triangulated cylinders are developable surfaces, and hence, if bending deformation is neglected, they have three unstrained configurations:

(i) as a deployed circular cylinder;

(ii) in a partially folded intermediate state;

(iii) as a fully-folded flat stack of plates.

Between these states, some deformation of the surface is required. However, as was shown in Guest and Pellegrino (1994b), changing the fold pattern allows the deformation between states (ii) and (iii) to be reduced to a suitably small level. Similar calculations could be also be carried out to consider the change from state (i) to state (ii), potentially leading to an optimization that would produce the most suitable design of triangulated cylinder for use as an inflatable tube. In the present early study, however, this has not been attempted.

This paper considers as an example the simplest possible triangulated cylinder, when one of the sets of helices has been reduced to a set of circles (using the notation developed in Guest and Pellegrino (1994a), this could be referred to as the $m = 0$ case). In fact, as an initial proof-of-concept set of experiments, no attempt was made to optimize the geometry used, and triangulated cylinders with the geometry shown in Figure 2(a) were used throughout. These cylinders fold down to a simple stack of plates, in this case forming a hexagonal prism.

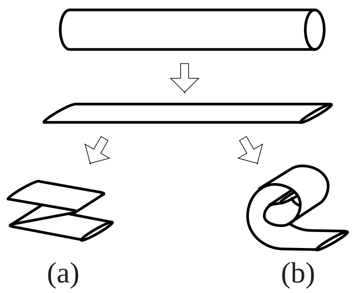


Figure 3. Two alternative ways of folding a cylinder after it has been flattened: (a) a concertina pattern; (b) by rolling.

One apparent disadvantage of triangulated cylinders as a folding concept is that, during deployment, one end of the tube rotates relative to the other. However, this problem can be neatly avoided in the $m = 0$ case by reversing subsequent sets of folds, as shown in Figure 2(b), although again this was not done in the current proof-of-concept set of experiments.

2.1.1. The Use of Triangulated Cylinders for Inflatable Tubes

Two factors combine to make triangulated cylinders a suitable candidate for a folding scheme for inflatable tubes:

(i) the tube retains some structure during its deployment

(ii) there is only a small amount of in-plane deformation during folding.

Because the triangulated cylinder retains some obvious structure during deployment, the deployment process should prove to be repeatable and reliable. This is in contrast to two other forms of folding a cylinder that have been used recently, and are shown in Figure 3. In both of these folding types, the cylinder is initially flattened. In Figure 3(a), the flattened tube has been subsequently folded into a concertina pattern. This was used recently on the Inflatable Antenna Experiment (Freeland and Veal, 1998), which vividly showed the potential danger of incorrectly controlling deployment. An alternative is to roll the flattened tube, as shown in Figure 3(b). This folding has been used recently as part on an inflatable space synthetic aperture radar (SAR) (Lou, Feria and Huang, 1998). Again, this folding method cannot be replied upon to provide controlled deployment, and the SAR tubes use an internal constant torque spring to control deployment.

Triangulated cylinders are not the only way of folding a cylinder axially, but other methods require greater in-plane deformation of the surface of the tube, potentially causing wrinkling and damage to the surface.

2.2. RIGIDIZING INFLATABLE STRUCTURES

A potential drawback to the use of inflatable structures is that loss of pressurization, perhaps due to micrometeorite damage, would lead to the loss of the structure. The solution to this, originally suggested as long ago as the first inflatable structure in space, the Echo I satellite (Elder, 1995), is to have a structure that can be *rigidized* in such a way that the structure does not rely on internal pressure after initial inflation. A number of methods of rigidization have been suggested; examples include epoxy-coated materials that can are cured in sunlight, water-filled gels that become rigid when the gels are allowed to dry, foam-filled structures, and the use of soft aluminium that will retain its final shape once slightly overstressed, the method suggested for the Echo series satellites.

The study described in this paper considers the final method, making the structure from soft aluminium. This has the advantage of simplicity, although of course it has the disadvantage that it will inevitably lead to one-shot devices that cannot be tested before launch.

3. Experimental Procedure and Results

The aims of the experiments were two-fold. The first was to show that forming, folding and deploying inflatable triangulated cylinders made from soft aluminium was feasible. The second aim was to show that the resulting thin-walled tube would still be usable as a structure.

3.1. MANUFACTURE

Aluminium drinks cans were used as a cheap source of thin, seamless aluminium tube. The cans used were first annealed, and the ends were then removed with a grinding wheel to give an aluminium tube with length 100 mm, diameter 67 mm, and wall thickness 0.15 mm. A uniaxial stress-strain curve for the annealed aluminium used is shown in Figure 4. Initial yielding occurred at a uniaxial stress of approximately 40 N/mm^2, with final failure occurring at approximately 110 N/mm^2.

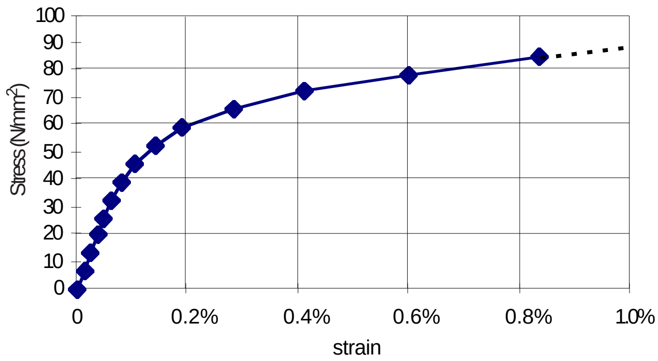


Figure 4. Results of uniaxial stress-strain test on the annealed aluminiun used for the tubes. The ultimate tensile strength was 110 N/mm^2.

The fold patterns for the triangulated cylinders were formed in the annealed aluminium tube. A paper template was placed over the tube, and the inward valley folds were formed by pushing a straight edge into the tube. The outward hill folds formed naturally as a result of this process. Having formed the fold pattern in the cylinder, the tube was sealed using araldite, an epoxy adhesive, to cast in place end fittings to the cylinder. The tube was then fully folded by applying light pressure to these end fittings.

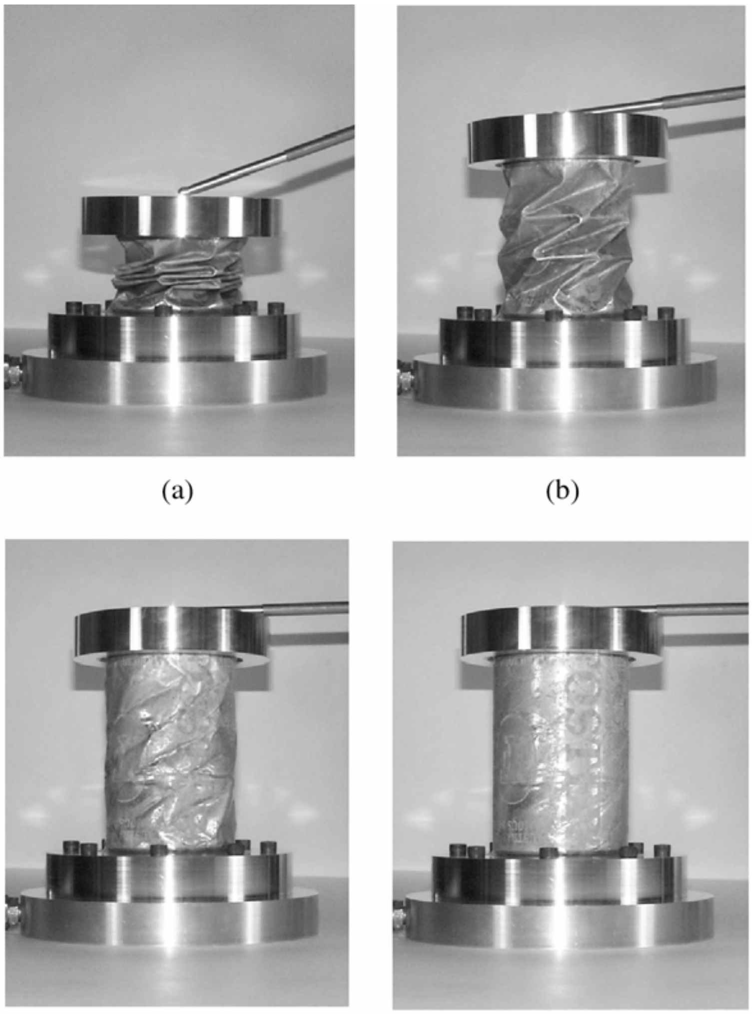
3.2. INFLATION

The tubes were tested by inflating them with water. The results of a successful test are shown in the photographs in Figure 5, and the pressure/extension graph in Figure 6. It can be seen that the tube expanded uniformly under a pressure of approximately 30–40 kPa, and that extension was virtually complete when a pressure of 60 kPa was reached. Beyond this, additional pressure reduced the size of defects left by the folding process, although no additional benefit was visible beyond a pressure of 150 kPa.

3.3. DESTRUCTIVE TESTING

Tests to measure the burst pressure of the tubes, and to test the axial buckling load, were carried out on cylinders that had been folded and inflated, and the results were compared with identical tests on virgin annealed cylinders.

A single test to measure the burst pressure of the tube gave a failure pressure of 510 kPa, compared with failure pressures for the virgin annealed tubes that ranged from 410kPa–650kPa. For the folded-and-inflated tube, failure occurred in one of the panels, and was not initiated at one of the fold patterns. An interesting difference between the folded-and-inflated and the virgin tubes was the amount of barreling that occurred during the test. The virgin tubes had a final plastic circumferential strain of approximately 3%–5%, compared with approximately 1% for the folded and inflated tube. It is conjectured that this difference is due to the mesh of work-hardened material left after folding and inflation.



(a) (b)

(c) (d)

Figure 5. Inflation of a triangulated cylinder: (a) fully folded; (b) partially inflated; (c) fully inflated; (d) fully inflated and pressurized to remove defects.

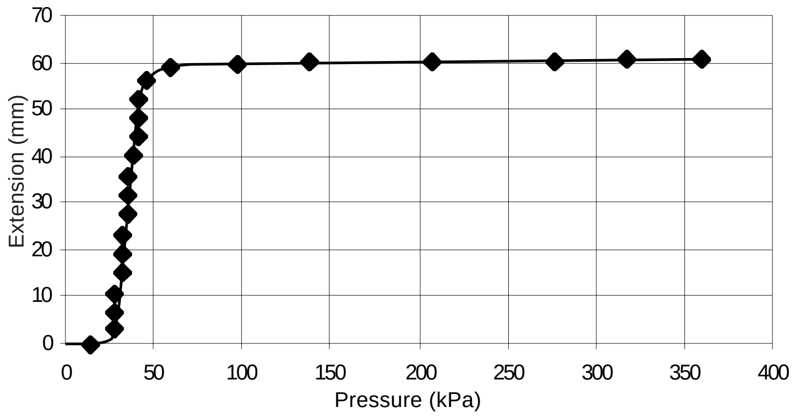
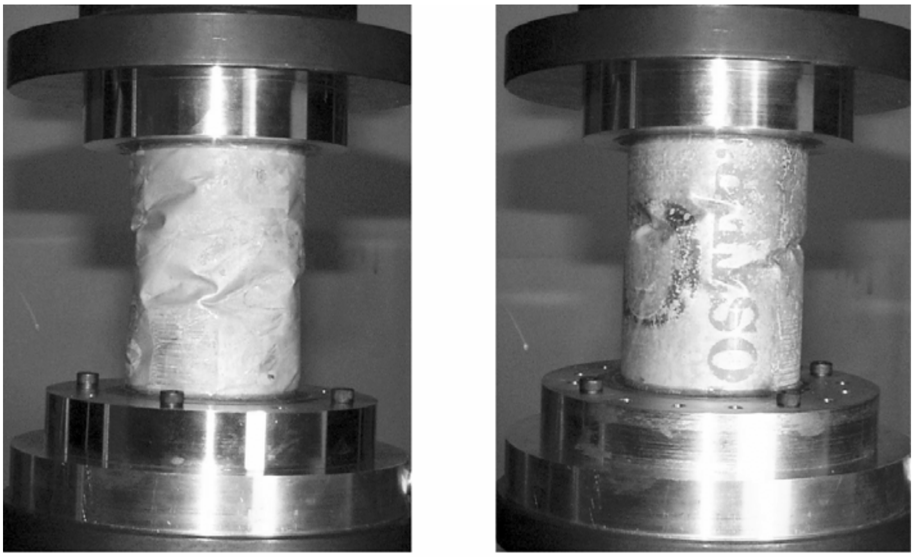


Figure 6. Extension/pressure graph for the inflation of the triangulated cylinder shown in Figure 5.

An axial buckling test was carried out on a folded-and-inflated tube, and the result compared with that obtained for a virgin tube. The aim of the test was to determine if the imperfections left after the folding and inflation process were critical in the response of the final structure. The folded-and-inflated tube failed at an axial load of 490 kN, compared with the virgin tube, which failed at an axial load of 630 kN. For a process as imperfection sensitive as buckling of thin-walled cylinders, it would be a mistake to read too much into a single set of results. However, it is clear that the folded-and-inflated cylinder has not suffered a disastrous loss of strength.

Photographs of the tubes following buckling are shown in Figure 7. It can be seen in Figure 7(a) that buckling has indeed tended to initiate around the valley folds of the original fold pattern, although the fold pattern certainly has not re-formed. The most interesting difference between the folded-and-inflated tube and the virgin tube is the extent of the buckling. For the virgin tube, the buckling is highly localized, while for the folded-and-inflated tube the buckling is much more widespread. Again it may be conjectured that this may be due to the mesh of work-hardened material on the folded-and-inflated tube causing a more elastic buckling response.



(a) (b)

Figure 7. Result of axial buckling tests: (a) a previously folded-and-inflated cylinder; (b) a previously virgin cylinder.

4. Further Work

The project described in this paper is a very basic initial study into inflatable triangulated cylinders. For triangulated cylinders to be considered a viable technology for deployable structures, a number of obvious questions need to be considered, including the following:

(i) How can long sections of triangulated cylinder be folded automatically? If a technology produces a one-shot device, it is essential that the end-user of the product has confidence that the manufacturing process is repeatable, so that tests on other tubes are a reliable guide to the performance of the particular tube being used on a spacecraft

(ii) How repeatable is the inflation process for triangulated cylinders? Neither the results for the very short tubes described in this paper, nor the results for elastically foldable triangulated cylinders described in Guest and Pellegrino (1996) provide enough data to answer this.

(iii) What is the most suitable rigidizable material to use? Annealed aluminium was chosen for simplicity, but would it withstand the rigors of being inflated in a vacuum? An obvious alternative would be aluminized Mylar, but any of the other materials mentioned in Section 2.2 might be suitable.

(iv) What is the most suitable geometry of triangulated cylinder? The complete process of folding a tube from a cylinder to a flat pack of plates has not been studied.

5. Conclusions

This project has shown that rigidizable foldable cylinders are potentially a very useful technology for inflatable tubes. It has shown that short tubes of this design can be folded and inflated, and that the final tube has useful structural properties even when deflated.

6. References

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