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Multistable Textured Shell Structures

A.D. Norman[1,a], M.R. Golabchi[1,b], K.A. Seffen[1,c] and S.D. Guest[1,d]

[1]Department of Engineering, University of Cambridge,
Trumpington Street, Cambridge CB2 1PZ, UK.

[a]adn24@cam.ac.uk, [b]mrg47@cam.ac.uk, [c]kas14@cam.ac.uk, [d]sdg@eng.cam.ac.uk

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Abstract. Multistable structures are a promising basis for reconfigurable systems. A multistable structure will remain in one of its stable configurations until actuation forces it to move to another stable configuration. This paper will describe a promising method of forming structures with useful multiple stable states by using prestressed textured shell surfaces. Textured shell structures have features at a scale intermediate between the global structural scale, and the material scale, and can have some remarkable structural properties. This paper will describe two simple examples: a globally flat, but corrugated shell, and a globally curved, doubly corrugated shell. Both structures show additional stable equilibrium configurations that would not be possible without the textured surface.

Introduction

Multistable structures have tremendous potential as the basis for reconfigurable systems. A multistable structure will remain in one of its stable configurations until actuation forces it to move to another stable configuration. One possible application is to deployable structures, where one stable state is a compact configuration, in which the structure may be stored or transported, and another stable state is an extended configuration in which the structure is used. Another possible application is to reconfigurable aircraft, where different stable states may correspond to alternative aerodynamic configurations.

The paper will give a brief overview of our ongoing work developing multistable structures. It will first describe known ways of forming bistable structures from cylindrical shells. It will then describe some initial work on developing new forms of multistable structure by using *textured* metallic shell structures. Textured shell structures have features at a scale intermediate between the global structural scale, and the material scale. Using these features allows an extra freedom in the design of multistable structures, and we give some examples.

Bistable Cylindrical Shells

Thin cylindrical shells, straight in a longitudinal direction with a curved cross-section, are a common class of engineering structure [1]. The best known examples are simple steel tape measures, an example of which is shown in Fig. 1; but similar structures are also commonly used as deployable structures for space applications, where they are commonly known as STEMs (Stored Tubular Extendable Members). The obvious difference between STEMs and tape measures is that STEMs typically have a cross-section that subtends a greater angle than the cross-section of a tape measure, and indeed may subtend an angle of greater than 360°.

Both STEMs and tape measures are monostable structures – that is, they only have one stable equilibrium configuration, which is when they are extended. This means that, in order for the structure to be stored coiled, it must be contained within a housing, which is likely to be heavy and bulky compared with the lightweight shell structure itself.

Recent work has developed methods to make cylindrical shells that are *bistable*, i.e., the shells are in a stable equilibrium position both when extended and when coiled. Not only does this simplify the way in which long deployable structures might be stored, but may also provide an

Fig. 1: An early (around 1950) example of a tape measure made from a thin cylindrical steel shell. The structure is monostable: it is only in a stable equilibrium state when it is extended. When coiled, the structure must be held within its housing.

underlying structural basis for new types of active structure, where an actuator only has to be used to move a structure between stable configurations, and can be switched off at other times.

Composite Shells. One way to make a cylindrical shell bistable is to make it from a material that is not isotropic [2]. In particular, choosing material properties that enhance the coupling between bending in two directions and increase the material torsional stiffness can make a structure that is bistable. Rolatube Ltd., a small UK company, have patented a method of forming a bistable structure in this way using composite materials. An example of a bistable shell formed from fibre-reinforced plastic is shown in Fig. 2. One important point to note about bistable shells formed in this way is that both stable states show *same-sense bending;* the centre of curvature of the shell in each case is on the same side of the surface.

Prestressed shells. An alternative method of making a shell bistable is to lock in bending stresses in the extended configuration [3]. An example of a structure formed in this way is shown in Fig. 3; in this case the curved shell was formed stress-free, and was then plastically rolled back on itself. When elastically straightened again, residual bending stresses remain, but in the extended configuration these stresses are held in equilibrium with axial stresses in the shell – tension at the edges, and compression along the centre. However, if the shell is flattened, it will now coil elastically to reach a second stable equilibrium. Unlike composite shells, bistable shells formed on this way have two stable states with *opposite-sense* bending; the centre of curvature of the shell in each case is on the opposite side of the surface.

Prestressed Non-Isotropic Shells. It would appear to be promising to combine the prestressing of a shell with a non-isotropic material, in order to give a greater variety of possible bistable behaviour. However, it is not possible to do this directly for the structures described above. To manufacture the composite shells used in the bistable tube shown in Fig. 2 we have used a plastic matrix that is prone to creep, so that any locked-in stresses would disappear over time. Instead, we will describe an alternative approach that combines these ideas. In order to ensure that the structure can be prestressed, we still use a metallic shell, but remove the isotropic behaviour of the shell by forming small surface features in the shell, as described in the following section.

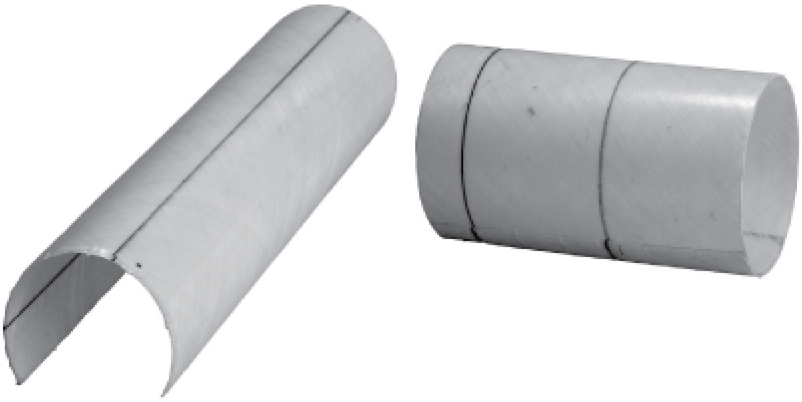


Fig. 2: A bistable shell shown in its initial and coiled configuration. Two lines are marked on the shell; they are straight initially, and form circles in the coiled configuration. The shell is made from fibre-reinforced plastic, and most of the fibres run at ±45° to the lines marked. The two stable states have same-sense bending – the centre of curvature is on the same side of the shell.

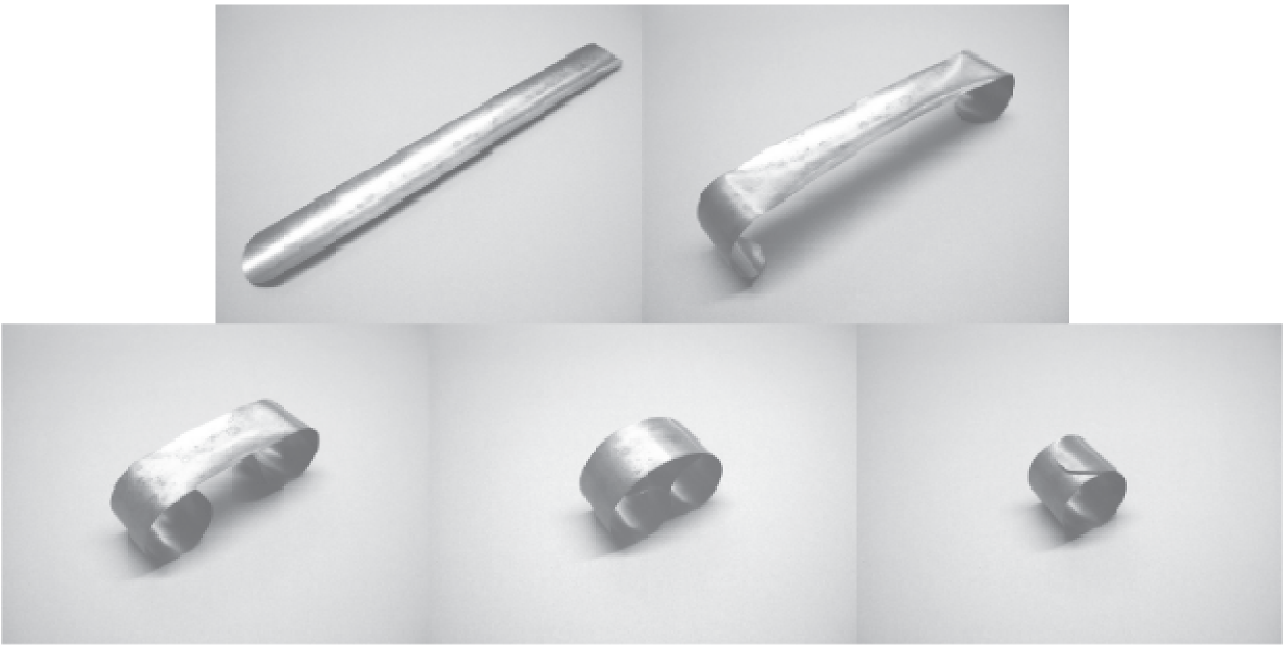


Fig. 3: The coiling of a prestressed bistable metallic shell. The structure shown is in a stable equilibrium position when fully extended (top-left), but contains locked-in stresses. If the structure is flattened, it can be folded to the fully coiled state (bottom-right), which also contains locked-in stresses. The two stable states have opposite-sense bending – the centre of curvature is on opposite sides of the shell.

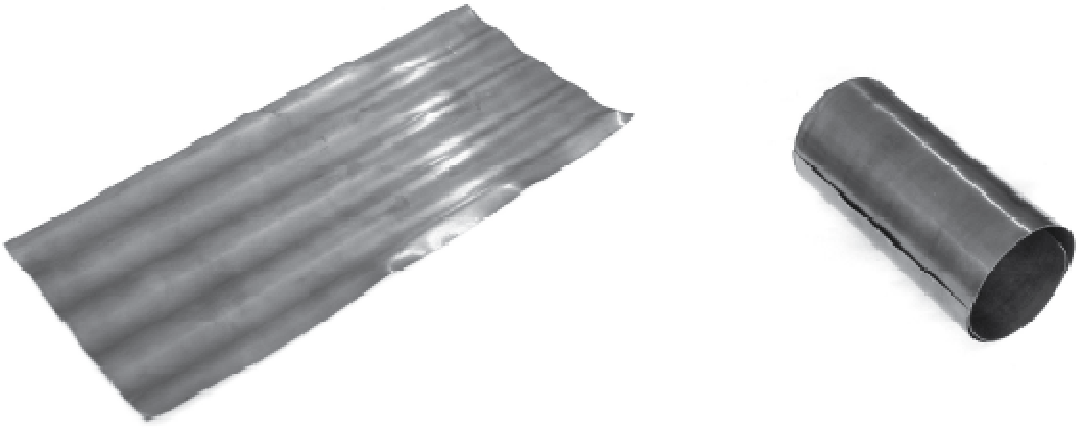


Fig. 4: A singly-corrugated metallic bistable shell. In the extended state, the shell is globally flat, but has a local texture in the form of a corrugation, which gives the shell additional structural depth. The shell has locked-in bending stresses; if the shell is flattened, it can then be coiled to form a second stable state.

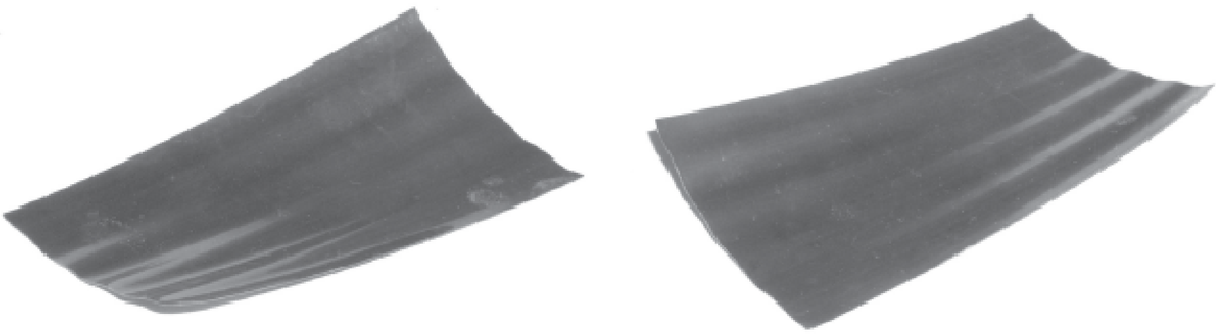
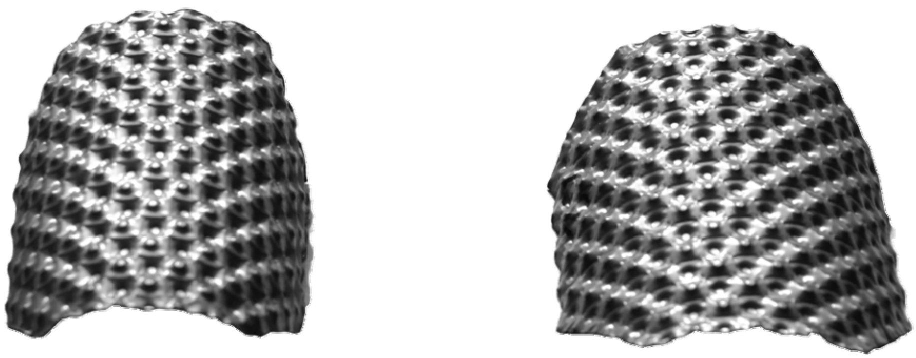


Fig. 5: A corrugated shell, showing a twisting mode that results if the structure is initially curved across the corrugations before it is prestressed. The flat configuration shown in Fig. 4 now becomes an unstable equilibrium, but the coiled state remains a stable equilibrium; the structure is now tristable.

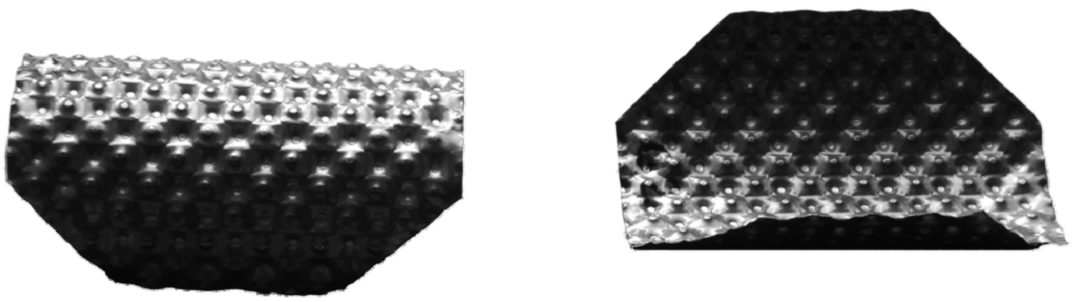
Multistable Textured Shells

This section describes ongoing work to combine the ideas of prestressing of shells, and forming shells that have non-isotropic material properties. To do this, we introduce features in the shell surface that are of an intermediate scale between the overall scale of the structure, and the thickness of the shell itself. We describe this as adding *texture* to the shell surface. We will here describe two simple examples of structures that have been formed in this way, by adding single and double corrugations to the surface, and combining this with prestress.

Singly-Corrugated Shell. The simplest textured surface is a singly-corrugated structure; a metallic example that is globally flat is shown in Fig. 4. This is a monstable structure when not prestressed, but if residual bending stresses are introduced, as described above for prestressed shells, then the structure can be made bistable. In the extended state, the structure has sufficient structural depth that the bending stresses can be equilibrated by axial stresses in the shell, but if the structure is flattened, it will roll up.



(a) First stable state (b)



(a) Second stable state (b)

Fig. 6: Two doubly-corrugated metallic shells, each of which are bistable. Shell (a) is prestressed so that it has two stable states, which are both bending in the same sense; shell (b) has the reverse prestress, and has two stable states in which bending is in the opposite sense. Without prestress, these structures would be monostable.

An interesting feature of the prestressed singly-corrugated shell is that it can be made tristable. If the structure has a global state that is initially curved in a direction perpendicular to the corrugations, then the addition of prestress makes the globally flat state unstable, and a pair of twisted stable configurations appears, as shown in Fig. 5. The coiled state remains stable, and the structure is now tristable.

A more comprehensive and mathematical description of the behaviour of this structure will be found in [4].

Doubly-Corrugated Shell. We have manufactured doubly-corrugated shells using a punching process to give a textured surface that is approximately sinusoidal in two orthogonal directions. Unlike the singly-corrugated shell, these corrugations are made by stretching of the initially flat material; the texture cannot be flattened, and thus the coiling of a globally flat structure, seen in the singly-corrugated shell, is not possible. The surface texture does, however, ensure that the shell is no longer isostatic: there are preferential directions for bending. Thus behaviour can be observed that is not possible for the simple prestressed shell. Two example structures are shown in Fig. 6, each of which has the same initial state, but an opposite state of self-stress. Both have an additional stable state, one in same-sense bending, and one in opposite-sense bending.

Conclusion

Textured shell surfaces offer a promising extra design freedom in the design of multistable structures, particularly when combined with prestressing. We have described two simple example structures where the addition of texture to a shell surface has allowed introduced additional stable states.

The current paper has concentrated on examples where the structural behaviour is essentially uniform across the structure, which means that the states that we have shown all have an underlying cylindrical geometry. Additional design freedom is introduced if this constraint is removed; some initial steps in this direction are described for dimpled shells in [5,6].

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