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Gerngross, T.

Viscoelastic Behaviour in Stratospheric Balloon Structures

by

Tobias Gerngross

Abstract

Large-scale lobed super-pressure balloons are currently considered as future platforms for long duration stratospheric flights. NASA is developing balloon structures capable of carrying several tons for 100 days at altitudes of about 30 km. While the current pumpkin design provides many advantages, the stresses and strains in the thin polymeric film can become a limiting factor. Reliable and accurate numerical models are required that consider both nonlinear time-dependent behaviour and wrinkling of the balloon film. These models need to be verified with experimental results from physical balloon structures.
As experimental observations of time-dependent behaviour on pumpkin balloons are rare and neither nonlinear viscoelasticity nor anisotropic wrinkling have been incorporated in numerical balloon models, computer simulations have remained somewhat disconnected from observations on physical structures. This thesis presents a suitable numerical model for balloon film and thus provides a link between numerical models and experimental observations.

First, user-defined subroutines are developed for the commercial finite element package Abaqus. After deriving a recursive iterative algorithm for viscoelastic behaviour, the nonlinear viscoelastic material model of the balloon film is implemented in Fortran. The code is then verified against analytical models in Matlab and experimental data from cylinder models. The second step towards a complete numerical tool is the formulation and implementation of an algorithm to deal with wrinkling of anisotropic films. Rather than modeling the actual wrinkled shape of the film the aim is to find an "average surface" that is subject to a uniaxial stress state. For this purpose a new effective elasticity matrix has been derived. The implementation of this model in a user-defined subroutine in Abaqus is verified analytically for the geometrically simple case of a rectangular membrane. Then the two models for nonlinear viscoelasticity and anisotropic wrinkling are combined and tested experimentally and numerically on a pressurised cylinder where end displacements are imposed to create a distribution of hoop wrinkles.

Next, experimental methods are developed for the observation of time-dependent deformation, including localized viscoelastic strains and overall shape changes. Because any physical contact with the inflated structure would deform the surface and consequently affect the measurements, a non-contact technique based on photogrammetry is used for these measurements. Inflatable structures of simple geometry are made of the same film as the large-scale balloons and experimental measurements are then made on a 4 meter diameter super-pressure balloon. In parallel, an 8.5 m diameter balloon was tested by NASA.

Finally the results from numerical models and experimental data are compared. The material model fits better for some load cases and the observed differences can be used for adjustments of the material model. In addition the effects of viscoelasticity on lobe design variations are investigated and it is shown how even small changes of the cutting pattern width affect strains and stresses. A comparison is then made between the initial pseudo-elastic design and the eventual viscoelastic situation, where the limitations of the pseudo-elastic model are illustrated. The results need to be considered in the design process. Furthermore, the effects from various modeling details are investigated, including the relevance of gravity and stress history on the strain and stress distributions. Lastly, a detailed numerical model of the physical seam-tendon assembly is used to replicate a swirl in the lobe shape that has been observed on physical balloon structures.

Keywords: super-pressure, balloons, nonlinear viscoelasticity, wrinkling, UMAT, user-defined subroutine, photogrammetry