Large Membrane Structures for Scientific Remote Sensing and Space Exploration

Alexander Tessler, NASA Fellow
NASA Langley Research Center
Hampton, VA 23681-0001, U.S.A.

As part of the NASA Floyd L. Thompson Fellowship, I spent four months in the beginning of 2005 at the International Center for Numerical Methods in Engineering (CIMNE) in Barcelona, Spain. During this visit, I had many opportunities to discuss the new NASA Space Exploration Program with graduate students and faculty at CIMNE, and worked closely with several researchers focusing on the modeling and analysis of thin-film membranes. Here a brief overview of the space exploration technologies that use very large structural membranes is presented, together with some comments related to computational mechanics issues for simulating the response of large membrane structures.

Space Exploration Technologies

In support of the new initiative for space exploration unveiled by President George W. Bush in 2004, NASA centers are facing the challenges to provide the exploration program with the best technologies in the areas of materials, structures, propulsion, radiation shielding, automation, and systems analysis. Some of the most exciting space technologies being explored are large structural membranes designed for scientific remote sensing and space exploration. These include deployable/assembled in-space gossamer structures such as large aperture inflatable antennas, sun shields, telescopes, inflatable habitats, and solar sails (see Figures 1-4) [1,2]. The materials considered are ultra-lightweight polymer films that combine enhanced characteristics of space environmental durability, tear resistance, and self-healing. To enable in-space deployment, inflatable/rigidizable columns are designed for constructing lightweight built-up structures. The synergy of nontraditional testing techniques, advanced analytical and computational methods, and modern super computing is required for designing these novel space structures (see Figures 5-7). In the remainder of this paper the focus is on solar sails and issues related to their successful modeling and simulation.

Solar Sails

Johannes Kepler, the great astronomer and mathematician, envisioned the idea of solar sailing for interstellar space travel in the beginning of the 17th century. Some 300 years later, the Russian engineer-scientist, Fridrikh Arturovich Tsander, wrote in 1924, “For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results. The interplanetary ships to be sent to other planets should be equipped with large mirrors almost one kilometer in area; the interplanetary stations should also have mirrors, but even larger. The light is collected by these mirrors and sent to the mirror of the interplanetary spaceship in flight. The low pressure of light over the tremendous distances of travel will result in tremendous flight speeds, thereby shortening flight duration." (Refer to F. A. Tsander lectures on the website of the Planetary Society [3]).

NASA's solar sail activities date back to the 1970s, when a Halley comet rendezvous opportunity was being planned with the use of a solar-sail propelled spacecraft, but eventually never undertaken. For a fascinating historical review on the subject, see Louis Friedman's chapter in [3]. With the advent of new ultra-light weight, temperature-resistant thin-film materials, the design and construction of practical solar sails are now more feasible than ever before. Over the past several years, NASA's Space Propulsion Technology Project has produced important solar sail technologies that could be ready to launch on a science mission within a couple of years. Independently, the former NASA manager, Louis Friedman, is leading a privately funded, US-Russian non-government organization, the Planetary Society, whose recent project *Cosmos 1* was concerned with launching the first-ever solar sail on June 21, 2005. The mission of *Cosmos 1*, a 100 kg spacecraft, was to circle the Earth at an ever-increasing orbit with the help of its 30-meter petal-shaped solar sail made of 5-micron-thin aluminized Mylar. Regrettably, the Volna booster rocket that carried the spacecraft misfired and crashed less than two minutes after its launch from a Russian nuclear submarine in the Barents Sea.

A solar sail spacecraft, whose sail is made of large thin-film sheets, is propelled through space entirely by sunlight pressure. Alternative sources of beamed energy, such as microwave or laser beams supplied from another spacecraft or a satellite, could provide a secondary power source. The basic notion of solar pressure comes from James Maxwell's description of light as a packet of energy acting as a tiny particle called photon. A solar sail would gain momentum from incidence of sunlight photons that bounce off of its highly reflective surface, producing a constant acceleration of the spacecraft. Since the momentum carried by an individual photon (and transferred to the sail) is very tiny, a solar sail needs a large, highly reflective surface area and a low mass, so that sufficient acceleration can be achieved. Because of their large size–potentially spanning several hundred meters–and operation in a weightless space environment, solar sails cannot be adequately tested in a laboratory, thus necessitating application of reliable, high fidelity computational methods to design such structures using "virtual" testing.

Simulating Structural Wrinkles

Once launched into an earth orbit by a rocket or a space shuttle, the sails are deployed by an inflatable boom system. The deployment results in the small tensile forces that stretch the sail. Thus a several micron-thin membrane would undergo predominately tensile membrane deformations. Although tensile membrane stresses are dominant, there also exist rather low compressive and bending stresses that tend to wrinkle the material, producing geometrically large out-of-plane displacements or what is known as *structural wrinkles*. The presence of structural wrinkles is undesirable. The wrinkles may detrimentally affect the stability, maneuverability, and reflectivity characteristics of a solar sail. Moreover, relatively high thermal stresses can develop near the stress concentration regions from which such wrinkles generally emanate, thus potentially causing the material to tear. Note that the vast majority of the mechanics efforts have been based on purely membrane analyses in which compressive stresses are eliminated by way of modifying the material constitutive relations, and the bending deformations are excluded altogether (e.g., refer to the early tension-field theories in [4-5], and a recent review in [6]). Whereas such analyses are generally capable of determining wrinkled regions and the wrinkle directions, they cannot produce the actual shapes and amplitudes of wrinkles. Recently, there has been an increased effort toward the high-fidelity modeling of structural wrinkles by means of shell-based finite element analysis (e.g., [6-12]).

To predict wrinkling deformations in their complete topological form, both membrane and bending deformations must be considered, as is commonly realized in a shell model. Furthermore, geometrically nonlinear kinematics incorporating large displacements and rotations must be included. When modeling a perfectly flat membrane, the onset of wrinkling can be initiated by slightly perturbing the shell geometry in the thickness (transverse) direction. This will bring about the essential membrane-to-bending coupling in the response even when exclusively membrane loading is applied. A simple and unbiased means of achieving this is by using pseudorandom, small out-of-plane geometric imperfections imposed at the nodes [6-8]. Other perturbed conditions can also be successful, for example, by imposing small transverse forces/pressures, or by starting out with a set of buckling mode shapes. In all of these schemes, the perturbed geometric or load conditions must be small, in relation to the membrane thickness, so as to retain the basic features of the original problem. In Figure 8 are depicted a set of experimentally observed and computationally obtained wrinkled patterns (using ABAQUS [13]) for a thin membrane loaded in shear [6]. In the analysis the membrane is assumed to be linearly elastic and is initially unstressed. The experimentally observed and computationally predicted wrinkling patters compare well qualitatively even though the actual geometric and stress imperfections that occur naturally in the experiment were not included in the finite element model. Similar results have recently been obtained using rotation-free shell elements [14]. These new shell elements, employing only three translation degrees-of-freedom per node, offer the advantage of reducing the number of degrees-of-freedom by a factor of two, as compared to the traditional shell elements that have six degrees-of-freedom per node [15].

For thin membranes exhibiting high stress concentrations, due to the specific geometric features and/or loading conditions, the finite element simulations of structural wrinkles have been less successful, even with the best nonlinear finite element codes and advanced shell element technology. A number of recent efforts have focused on the problem of a square membrane subject to tensile forces at the four corners [6-12] (see Figure 9). The presence of stress concentration tends to suppress the formation of wrinkles in a model. By removing sharp corner regions from the model, and by prescribing distributed tractions instead of concentrated loads, the deleterious effects of stress concentration are alleviated. Consequently, reasonably accurate simulations of wrinkles can be obtained as evidenced by the results in Figure 9. The computational model is able to predict four wrinkles radiating from the truncated corner regions, closely correlating with those in the experiment. The analysis also predicts that curling occurs at the free edges (slack region) as observed in the experiment, although the experiment shows somewhat greater wrinkle amplitudes. Considering the many simplifying assumptions in the computational model, i.e., disregarding the actual imperfections, corner boundary conditions, and inherent asymmetry of the experimental setup, the comparison with the experiment can only be judged as successful from the qualitative point of view. On the other hand, it is noted that the computational results are very sensitive to the kinematic boundary conditions, mesh refinement, and element technology. For example, additional mesh refinement in the regions of applied loading can actually cause the wrinkling pattern to disappear altogether.

Concluding Remarks

Whereas some success in the high-fidelity predictions of the formation and growth of wrinkles has been achieved–particularly when modeling relatively uniform equilibrium states–the problems exhibiting high stress concentrations have been particularly difficult to solve even with the best nonlinear finite element codes and advanced shell element technology. Therefore, this latter class of problems remains to be a major challenge and requires an improved understanding of the phenomenon of structural wrinkling in the presence of stress concentration.

Acknowledgements

The author is indebted to the NASA Floyd L. Thompson Fellowship that made his visit to CIMNE possible. He would also like to thank Professor Eugenio Onate and his research team, Fernando Flores and Gerardo Valdes, for the fruitful technical interactions and discussions. Finally, the author would like to thank the many excellent technical contributions of NASA researchers and contractors whose work on membrane structures was highlighted in this paper.

References

1. Belvin, W. K., “Advances in Structures for Large Space Systems,” 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, AIAA-2004-5898, 2004.
2. Murphy, D, Trautt, T., McEachen, M. , Eskenazi, M., Messner, D., Laue, G., and Gierow, P., “Progress and Plans for System Demonstration of a Scalable Square Solar Sail,” 14th AAS/AIAA Space Flight Mechanics Conference, Maui, Hawaii, 2004.
3. The Planetary Society website: http://www.planetary.org/.
4. Reissner, E., “On Tension Field Theory.” Proceedings of the 5th Int’l Congr. Appl. Mech., 88–92, 1938.
5. Stein, M., and Hedgepeth, J. M., “Analysis of Partly Wrinkled Membranes,” NASA TN D-813, 1961.

6. Tessler, A, Sleight, D. and Wang, J, "Effective Modeling and Nonlinear Shell Analysis of Thin Membranes Exhibiting Structural Wrinkling," Journal of Spacecraft and Rockets, AIAA, vol. 42, no. 2, 287-298, 2005.
7. Tessler, A, Sleight, D., "Toward Effective Shell Modeling of Wrinkled Thin-Film Membranes Exhibiting Stress Concentrations," 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, AIAA-2004-1739, 2004.
8. Wang, J., Chen, T., Sleight, D., and Tessler, A., "Simulating Nonlinear Deformations of Solar Sail Membranes Using Explicit Time Integration," 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, AIAA-2004-1580, 2004.
9. Wong, Y.W. Wong, Pellegrino, S., and Park, K. C., "Prediction of Wrinkle Amplitudes in Square Solar Sails," 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Norfolk, Virginia, AIAA-2003-1982, 2003.
10. Su, X., Abdi, F., and Blandino, J. R., "Wrinkling Analysis of A Kapton Square Membrane under Tensile Loading," 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Norfolk, Virginia, AIAA-2003-1985, 2003.
11. Leifer, J., Black, J. T., Belvin, K. W. and Behun, V., "Evaluation of Shear Compliant Boarders for Wrinkle Reduction in Thin Film Membrane Structures," 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Norfolk, Virginia, April 2003.
12. Blandino J.R., Johnston, J.D., and Dharamsi U.K., "Corner Wrinkling of a Square Membrane due to Symmetric Mechanical Loads," Journal of Spacecraft and Rockets, vol. 35, no. 9, Sept/Oct 2002.
13. ABAQUS/Standard User's Manual, Version 6.3.1, Hibbitt, Karlsson, and Sorensen, Inc., Pawtucket, RI, 2002.
14. Onate, E., Flores, F., and Valdes, G., "Modeling and Analyses of Wrinkled Thin Membranes using Rotation-Free Shell Elements," Private Communications, 2005.
15. Onate, E., and Flores, F., "Advances in the Formulation of the Rotation-Free Basic Shell Triangle," Comput. Methods Appl. Mech. Engrg., vol. 194, 2406-2443, 2005.