Simulation of deployable composite structures based on Mechanics of Structure Genome

Yufei Long*, Orzuri Rique Garaizar† and Wenbin Yu‡
School of Aeronautics and Astronautics, West Lafayette, IN 47907, USA

Juan M. Fernandez§ and Andrew C. Bergan¶
NASA Langley Research Center, Hampton, VA 23666, USA

In this paper, a simulation method for analyzing deployable composite structures is presented. With a proper material model, effective plate/shell properties of the composites is obtained based on Mechanics of Structure Genome (MSG), and then implemented into a user-subroutine UGENS for global structure simulation in ABAQUS. Column bending test (CBT) and composite boom and hub structure are studied for demonstration. A viscoelastic material model with direct integration implementation is adopted in this paper. CBT simulation shows good agreement with experiments during relaxation, while errors are observed when comparing residual deformation. This simulation can be potentially used as a calibration tool for material properties. After CBT simulation, a demonstrative model with a lenticular boom and the hub is created in ABAQUS. Complete process of flattening, coiling, stowage, deploying and recovery is simulated with the viscoelastic material model. Residual deformation of the boom is analyzed.

I. Introduction

Due to the limitation of volume and weight on space application, composite deployable structures are gaining increasing focus from researchers. A deployable structure only occupies a small space during stowage, capable of being packaged to platforms less than 1 m^3, and can be deployed into the size of 5-20 m in mission [1]. Compared with conventional deployable structures, composite deployable structures do not have joints due to the high flexibility of the structures, so that the weight can be greatly reduced. However, high flexibility also means this kind of structures need to undergo large deformation and strain, and time-dependent material behavior is observed because of the long stowage time before deployment. These factors make the analyses of composite deployable structures difficult.

In order to analyze composite deployable structures, both experimental and numerical methods are developed.

*Graduate Research Assistant, School of Aeronautics and Astronautics, 1105 Challenger Ave 100, West Lafayette, IN 47907.
†Graduate Research Assistant, School of Aeronautics and Astronautics, 1105 Challenger Ave 100, West Lafayette, IN 47906, and AIAA Student Member.
‡Professor, School of Aeronautics and Astronautics, 701 W. Stadium Avenue West Lafayette, IN 47907, and AIAA Associate Fellow.
§Research Aerospace Engineering, Structural Dynamics Branch, NASA LaRC, 4 West Taylor Street, Mail Stop 230, and AIAA Member.
¶Research Aerospace Engineering, Durability, Damage Tolerance, and Reliability Branch, NASA LaRC, and AIAA Member.

For studying the constitutive relations of the composites used in deployable structures, experiments are designed for testing composite panels under large bending deformation, including the simple vertical test [2, 3], the platen test [4, 5], the large deformation four-point bending (LD-FPB) test [6], and the latest being the column bending test (CBT) [7]. The CBT is developed at Opterus R&D and improved by NASA Langley Research Center to evaluate the flexure of thin composites. This test method loads the specimen in the vertical direction, generating a stress state close to pure bending. In order to have a better understanding on the distribution of stresses and strains in the specimen during the test, numerical simulations of the CBT also need to be studied. By simulating the CBT, modeling techniques and material constitutive models to be used in further studies can be verified. Rose et al. [8] used a CBT simulation in Abaqus to verify the modeling technique of coincident element method, which combines a layer of orthotropic elastic and isotropic viscoelastic shell together, for implementing orthotropic viscoelastic material properties, so that user-subroutines can be avoided. In addition, with an optimizer, simulation of the CBT has the potential to be used as a tool for calibrating material properties based on experimental data.

Simulation of the CBT provides a way to study and verify the constitutive model, while in order to understand the influence of large bending deformation and long stowage time, a global analysis of composite deployable structures is necessary. However, due to the complexity of a deployable structure with a hub and a boom, many researchers start from simpler models. Bai te al. [9] studied the flattening and bending of a lenticular boom using analytical method. Results were only accurate for small displacement when compared with experiments. Brinkmeyer et al. [10] analyzed the effect of long stowage time to the deployment of a bistable tape spring by comparing an analytical solution with experiments. Failure of deployment caused by long stowage time was not captured by analytical solution. Hu et al. [11] compared two different methods for flattening a lenticular boom by the finite element analysis (FEA) and experiments. Compression was found to generate less stress than tension. Cox and Medina [12] studied strain development and buckling of a triangular boom during rolling, with elastic material properties. Yang et al. [13] did an optimization on section moments and dynamic properties of a triangular boom based on FEA simulation of rolling the boom on the hub for 360°. Scherbarth and Reda Taha [14] simulated the stowage and deployment of a tape spring rolling to a hub, with different time and temperature, using shell elements with Abaqus Explicit. Results were compared with experiments. Leclerc and Pellegrino [15] studied the stress concentration of a triangular boom during coiling using Abaqus. The effect of materials, cross sections and flattening mechanisms are compared and found that both a varying cross section and nip rollers can reduce stress concentration. Gomez-Delrio and Kwok [16] simulated the flattening of a segment of a lenticular boom to analyze the effect of long stowage time on cross section, but no coiling process was involved. No research has been done on simulating the whole process of coiling, stowage and deploying of a composite boom deployable structure with viscoelastic material properties, especially of a lenticular cross section boom.

A simulation framework for composite deployable structures is proposed, and the global simulation is focused in this paper. Staring from the material properties of fiber and resin matrix obtained from experiments, linear viscoelastic effective stiffness matrix of shell elements can be calculated based on mechanics of structure genome (MSG), a general method for constitutive modeling of heterogeneous materials and structures [17, 18]. A finite element model of CBT is constructed in Abaqus, with the effective properties implemented in user-subroutine UGENS, validation of the shell constitutive model is done by comparing simulation to experiments. Then following the same framework, whole process of coiling, stowage and deploying of a lenticular boom is simulated. Residual deformation caused by long stowage time in both the length direction and cross section is investigated right after depolyment. In order to use UGENS, all the simulations in this study use the Abaqus Standard solver.

II. CBT simulation

In CBT, the specimen is vertically clamped by upper and lower arms, which are pinned inside clevises. An initial angle θ exists between the arms and the loading direction, creating an offset between the specimen and the loading axis. Due to this offset, when the clevises move towards each other, a moment is generated and the specimen will be bent. Schematic of a CBT is shown in Fig. 1, with the angle θ, arm length l and gage length s known, clevis displacement δ and applied load P controlled or measured, and angle change ϕ and offset r calculated. In addition to these values shown in Fig. 1, the width of the specimen d is also a known parameter.

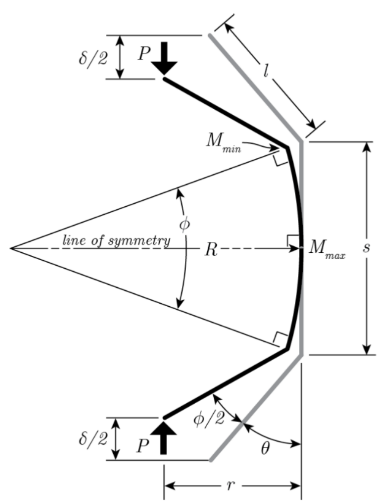

Fig. 1 Schematic of a CBT [7].

Material of the specimen in CBT is M30S/PMT-F7 plain woven composite, and the layup is $[\pm 45]_4$. The M30S fiber is treated as an elastic material and the PMT-F7 resin is viscoelastic. For woven composites, effective properties can be obtained using MSG through a two-step homogenization [19] that firstly calculates the effective yarn properties based on fiber and matrix properties, then effective shell properties obtained using yarn and matrix properties. The effective shell properties are fitted into Prony series and then implemented in UGENS with the direct integration method, in which increment of the shell sectional forces ΔN and moments ΔM are calculated using

$$\begin{aligned} \Delta N\left(t_{n+1}\right) &= A_{eq}\Delta\epsilon\left(t_{n+1}\right) + B_{eq}\Delta\kappa\left(t_{n+1}\right) + \Omega_N \\ \Delta M\left(t_{n+1}\right) &= B_{eq}\Delta\epsilon\left(t_{n+1}\right) + D_{eq}\Delta\kappa\left(t_{n+1}\right) + \Omega_M \end{aligned} \tag{1}$$

where A_{eq}, B_{eq}, and D_{eq} are equivalent tangential stiffness matrices calculated from the Prony series of the shell properties, $\Delta\epsilon$ is the membrane strain increment, $\Delta\kappa$ is the curvature increment, Ω_N and Ω_M are matrices determined from the loading history. Sectional forces and moments at the end of the current increment are obtained by adding the increments ΔN and ΔM to the sectional forces and moments from previous increment.

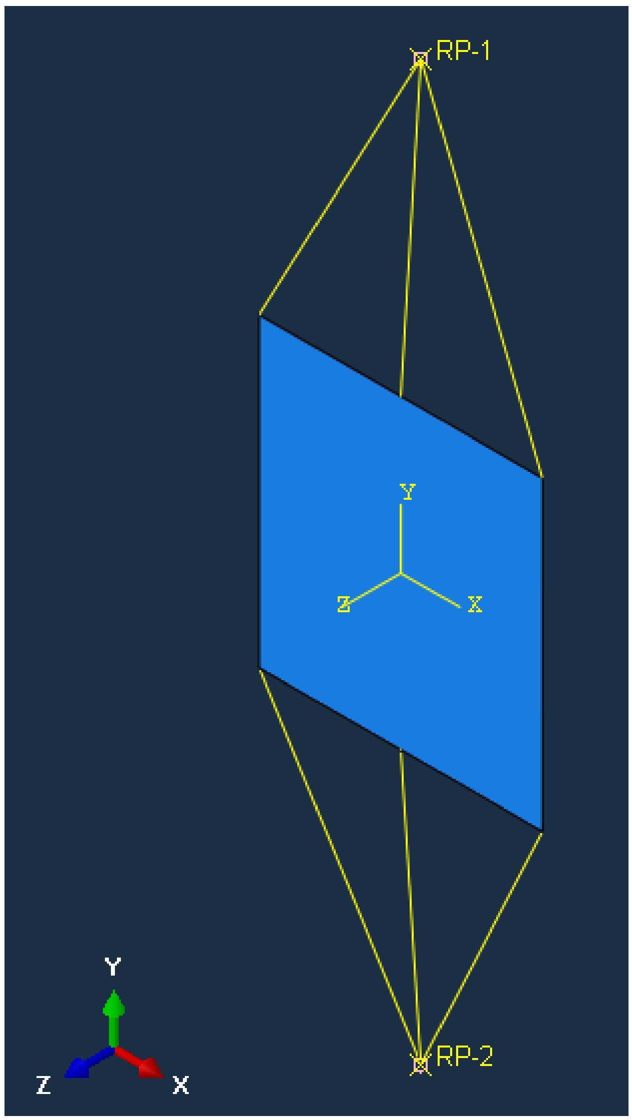

Fig. 2 CBT model in Abaqus CAE.

A CBT model is built in Abaqus. By reproducing experimental results through simulation, effectiveness of the modeling technique and user subroutines can be demonstrated, so that a realistic model of the hub and composite boom can be studied. The CBT model in Abaqus CAE is shown in Fig. 2, the specimen between the clamps is modeled with the general-purpose shell element S4, and clamped regions are neglected. The pins are represented by two reference points, with all degrees of freedoms (DOFs) except for the rotation around x axis of the lower reference point RP-2, and rotation around x axis and displacement in y direction of the upper reference point RP-1, are constrained. Kinematic couplings are applied between the upper and lower clamped edge of the specimen and the corresponding reference points RP-1 and RP-2, as the yellow lines shown in Fig. 2. These couplings connect the displacement of the edges with those of the reference points by rigid bodies, and ensure that the edges have the same rotation as the corresponding reference points, which mimic the arms in real experiments. The analysis consists of four steps. In the first step, a displacement in y direction is applied on RP-1 that bends the specimen. Then, this configuration is kept for a time span to allow relaxation caused by viscoelasticity. After relaxation, the displacement boundary condition in y direction at RP-1 is removed, so that the reaction force at the reference points becomes zero and the specimen is unfolded by its internal stress. The unfolded configuration is also kept for some time, during which the specimen gradually recovers its original shape. These four steps can be referred as folding, relaxation, unfolding, and recovery, respectively. Geometric nonlinearity is enabled in all the steps.

III. Global Boom and Hub Simulation

To study the effect of coiling, stowage, and deploying of composite deployable structures, a model containing the hub and the boom is required. In a deployable structure, the boom is assembled to the hub, usually a cylinder, and coiled to the hub by rotation. This coiled configuration is kept during stowage, which can be as long as several years, and finally the hub is rotated in the inverse direction and the boom can be deployed. Geometry of the boom can still change after deployment because of viscoelasticity. For simulating this process, a boom using shell model and a hub represented by a cylindrical surface is created in Abaqus. Comparing to the high flexibility of the boom, the hub, usually made with metals, has a much larger stiffness, so it can be modeled as a rigid body.

In this study, the boom has a lenticular cross section, which consist of two Ω-shaped shells and glued together along the web. Geometry parameters of the cross section are listed in Table 1, with the definition of the segments based on [20]. Radius of the hub is 90 mm. Layup in segment 1 consist of a layer of uniaxial composite between two layers of

Table 1 Geometry of the lenticular boom.

Segment 1 Radius (mm)	Segment 2 Radius (mm)	Subtended Angle (°)	Flattened Height (mm)	Web Width (mm)
26.5	12	90	130	4.5

plain weave composite, with the orientation of [45/0/45]. In segment 2 and the web, the layer of plain weave composite on the inner side of the boom is removed, while in the web, a layer of film epoxy is add for joining the two pieces of shell together. Both the epoxy and plain weave composites are viscoelastic. In the finite element model, these three sections have different effective properties due to different layups.

Due to the complexity of the problem, some simplifications have to be adopted to avoid convergence issue. Finite element model of the deployable structure is shown in Fig. 3. In addition to the boom and the hub, two rigid flattening

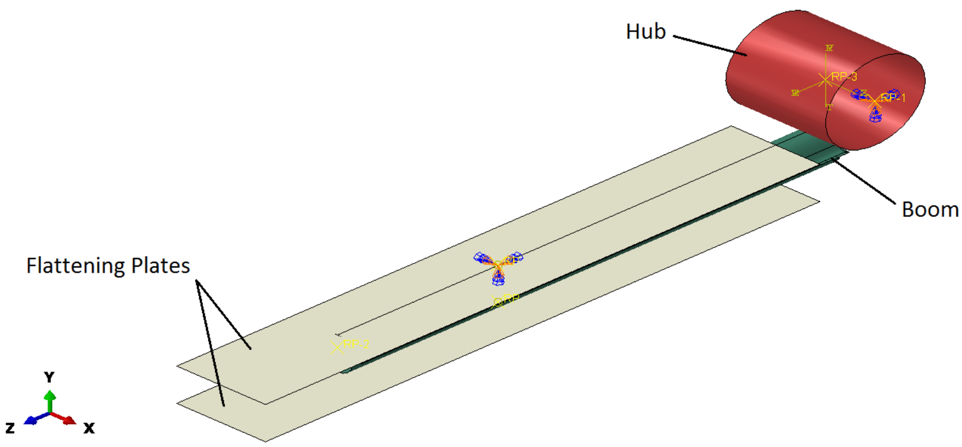

Fig. 3 Model of the deployable structure in Abaqus CAE.

plates are also included in the model. Different from a real structure, the whole boom is flattened all together by moving the plates towards each other, so that convergence issue caused by local buckling during the transition from the lenticular cross section to the flattened cross section in the boom segment near the hub can be avoided. This technique can be justified as comparing to the stowage time, coiling and deployment are finished in a short time, so the way of flattening has little impact on the total energy dissipation, which is main source of residual deformation. For the same reason, implicit dynamic quasi-static step is used for flattening, coiling and deploying steps to ensure convergence while general static step is used for stowage step for better accuracy. A kinematic coupling between the center of the hub and the nodes the hub end of the boom is applied as the driver of coiling. After the boom is flattened, rotation is only applied to the center of the hub, while the cylinder surface remains fixed, only acting as a support of the boom. This technique avoids applying multiple contact behavior to fix the boom on the hub, reducing complexity of the model. A preliminary result of the residual curvature in the hoop direction SK2 is shown in Fig. 4.

IV. Contents of the Full Paper

In the full paper to be presented on the conference, more details of the CBT and global boom and hub model will be provided, including material properties, step time, applied boundary conditions and loads. Comparison between the CBT simulation and experiments will be presented, emphasizing the moment during relaxation and residual strain and curvature during recovery. A thorough investigation of the residua deformation will be performed. The simulation

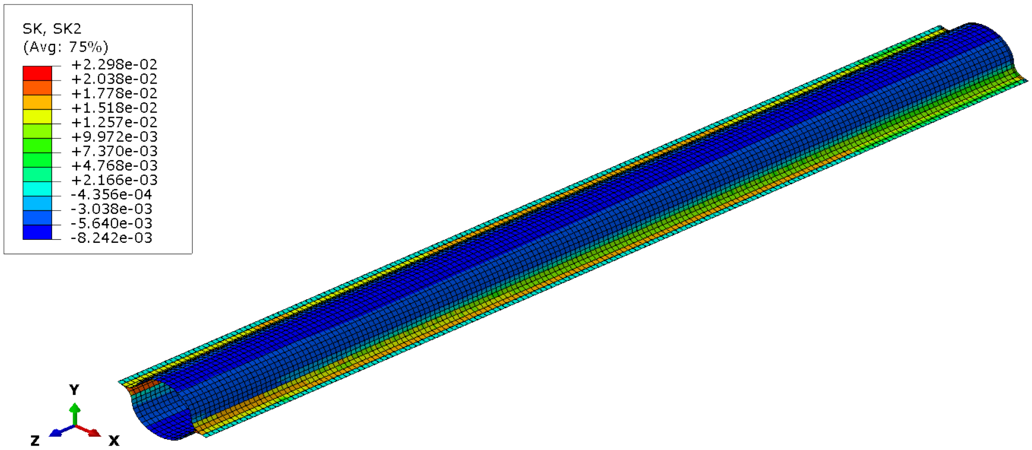

Fig. 4 Preliminary result of the residual curvature in the hoop direction.

results of the composite boom will be compared with test data.

Funding Sources and Acknowledgments

This research was supported, in part, as part of the Small Business Technology Transfer (STTR) grant from NASA. The authors would like to acknowledge the support of the NASA STTR Phase I: T12.01-3920 (contract number: 80NSSC19C0530). Prof. Wenbin Yu is the co-founder and CTO of AnalySwift, a company that might license a version of a Purdue software code based on the work presented in this article. The views and conclusions obtained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsement, either expressed or implied of the funding agency.

References

[1] Fernandez, J. M., "Advanced Deployable Shell-Based Composite Booms For Small Satellite Structural Applications Including Solar Sails," 2017.

[2] Wisnom, M., and Atkinson, J., "Constrained buckling tests show increasing compressive strain to failure with increasing strain gradient," *Composites Part A: Applied Science and Manufacturing*, Vol. 28, No. 11, 1997, pp. 959–964.

[3] Yee, J., and Pellegrino, S., "Folding of woven composite structures," *Composites Part A: Applied Science and Manufacturing*, Vol. 36, No. 2, 2005, pp. 273–278.

[4] Yee, J., and Pellegrino, S., "Biaxial bending failure locus for woven-thin-ply carbon fibre reinforced plastic structures," *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 2005, p. 1811.

[5] Yee, J., and Pellegrino, S., "Composite tube hinges," *Journal of Aerospace Engineering*, Vol. 18, No. 4, 2005, pp. 224–231.

[6] Sanford, G. E., Ardelean, E. V., Murphey, T. W., and Grigoriev, M. M., "High strain test method for thin composite laminates," *16th International Conference on Composite Structures. Porto, Portugal*, 2011.

[7] Fernandez, J. M., and Murphey, T. W., "A simple test method for large deformation bending of thin high strain composite flexures," *2018 AIAA Spacecraft Structures Conference*, 2018, p. 0942.

[8] Rose, T., Calish, J., and Lopez Jimenez, F., "Modeling of Viscoelasticity in Thin Flexible Composites using Coincident Element Method," *AIAA Scitech 2020 Forum*, 2020, p. 0693.

[9] Bai, J., Xiong, J., Gao, J., and Yi, X., "Analytical solutions for predicting in-plane strain and interlaminar shear stress of ultra-thin-walled lenticular collapsible composite tube in fold deformation," *Composite Structures*, Vol. 97, 2013, pp. 64–75.

[10] Brinkmeyer, A., Pellegrino, S., and Weaver, P. M., "Effects of long-term stowage on the deployment of bistable tape springs," *Journal of Applied Mechanics*, Vol. 83, No. 1, 2016, p. 011008.

[11] Hu, Y., Chen, W., Gao, J., Hu, J., Fang, G., and Peng, F., "A study of flattening process of deployable composite thin-walled lenticular tubes under compression and tension," *Composite Structures*, Vol. 168, 2017, pp. 164–177.

[12] Cox, K., and Medina, K. A., "Scalability of Triangular Rollable and Collapsible Booms," *AIAA Scitech 2019 Forum*, 2019, p. 2026.

[13] Yang, H., Liu, L., Guo, H., Lu, F., and Liu, Y., "Wrapping dynamic analysis and optimization of deployable composite triangular rollable and collapsible booms," *Structural and Multidisciplinary Optimization*, Vol. 59, No. 4, 2019, pp. 1371–1383.

[14] Scherbarth, M., and Taha, M. R., "Stowage Testing and Modeling of Viscoelastic Composite Tape Springs," *AIAA Scitech 2019 Forum*, 2019, p. 1748.

[15] Leclerc, C., and Pellegrino, S., "Reducing Stress Concentration in the Transition Region of Coilable Ultra-Thin-Shell Booms," *AIAA Scitech 2019 Forum*, 2019, p. 1522.

[16] Gomez-Delrio, A., and Kwok, K., "Stowage and Recovery of Thin-ply Composite Deployable Structures," *AIAA Scitech 2020 Forum*, 2020, p. 0205.

[17] Yu, W., "A unified theory for constitutive modeling of composites," *Journal of Mechanics of Materials and Structures*, Vol. 11, No. 4, 2016, pp. 379–411.

[18] Yu, W., "Simplified Formulation of Mechanics of Structure Genome," *AIAA Journal*, 2019, pp. 1–9.

[19] Liu, X., Tang, T., Yu, W., and Pipes, R. B., "Multiscale modeling of viscoelastic behaviors of textile composites," *International Journal of Engineering Science*, Vol. 130, 2018, pp. 175–186.

[20] Lee, A. J., and Fernandez, J. M., "Inducing Bistability in Collapsible Tubular Mast Booms with Thin-Ply Composite Shells," *Composite Structures*, 2019, p. 111166.