Simulation of the Deployment of a Flexible Roll-Up Solar Array Using Multi-Body Dynamics Software

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Future missions to the outer planets will require significant power that may be provided by large, 300 kW class, flexible roll-up solar arrays. To support the development of these arrays there is high value in simulating the nonlinear dynamics of stowing, deploying, and performance of large deployable solar array structures, especially with the profound limitations of physical testing. Physical testing of prototypes on earth with gravity can be difficult or impossible. Multi-body dynamics software is an ideal platform for developing simulations modeling deployment of flexible, spacecraft structures. This paper presents a dynamic simulation of the deployment of a roll-up solar array using multi-body dynamics modeling software. Additionally, the paper presents the development of a set of software tools that automate tedious tasks associated with developing models of these structures. The tools will aid in the development of future simulation of structures using roll-up boom technology.

I. Introduction

Future missions to the outer planets will require significant power that may be provided by 300 kW class, flexible roll-up solar arrays. To support the development of these arrays there is high value in simulating the nonlinear dynamics of stowing, deploying, and performance of large deployable solar array structures, especially with the profound limitations of physical testing. Physical testing of prototypes on earth with gravity can be difficult or impossible. This is especially true for large structures, such as 300 kW class solar arrays. Some physical testing can be accomplished using gravity offloading. Such testing can be used to measure quasi-static loads where it is sufficient to have zero gravity in two dimensions. However, it is not possible to evaluate the true 3D dynamics of the solar array with physical testing, and high fidelity simulation capabilities are needed. This paper will present a dynamic simulation of the deployment of a roll-up solar array using multi-body dynamics modeling software. Additionally, the paper presents the development of a set of software tools to aid in the development of future simulation of rolled-out boom structures. The software tools were developed to reduce time spent on tedious tasks during the model development.

II. Background

Multi-Body Dynamics (MBD) software is used to develop computationally efficient models of non-linear flexible bodies undergoing large displacements. The software allows a combination of rigid and flexible bodies to be employed in the development of a system model. MBD software has been available commercially since the mid 1980's[1-4]. The early software platforms could evaluate both rigid and flexible bodies but had limitations. They were useful for evaluating large rigid body motions provided the motions of the flexible members were small. Starting in the 1990's theory was presented that formed the basis for the development of algorithms used to evaluate flexible bodies undergoing large deformations[5-10]. Since the mid 2000's MBD software has evolved such that it is useful for evaluating systems with both rigid and flexible bodies, with both types of structures undergoing large deformations.

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Historical overviews through the mid 2000's of the influence of MBD on the development of space systems, MBD formulations for flexible spacecraft structures, and the evolution of MBD software for modeling spacecraft is presented in Refs [11 & 12].

Modern MBD software is a necessary tool for evaluating deployable solar array structures. As early as 1996 Tadikonda et. al.[13] recognized the need for developing tools to evaluate the transient elastic behavior of the Solar Array Structures. The Solar Array Flight Experiment (SAFE) extension mast consisted of a coilable lattice structure that was designed to be deployed from and retracted into a canister[14]. The authors modeled the equations of motion for mast deployment in a format that could be implemented using MBD software. Other more recent studies using MBD that are relevant to the development of future deployable solar arrays are presented in Refs [15-17].

Simulating the large motions in spacecraft solar arrays during roll-up and deployment can cause nonlinear Finite Element Analysis (FEA) software to have convergence problems, and the run time can be long. Existing nonlinear structural analysis simulation software cannot effectively simulate structural assemblies with significant motion. Even if it could do the simulation, developers of this simulation software are unable to justify the development costs to produce a vertical application for deployable spacecraft structures. Multi-body dynamics software is an ideal platform for modeling structures undergoing large deformations and for developing vertical applications to simplify the modeling of flexible, deployable, spacecraft structures.

The purpose of the work presented here is to present the development of a suite of software tools using modern MBD software[18] that are used to model the deployment of a roll-up solar array. The primary structure is a slit-tube rollable boom. The tools automate many of the tedious and redundant tasks associated with the development of MBD models.

III. Model Development

A. Overview

The proper simulation of flexible spacecraft structures such as deployable booms requires the combination of nonlinear structural analysis and the consideration of large motions. For example, the tubes of a roll-up solar array undergo very large deformations during the assembly and the deployment processes. A promising technology is Multi-body Dynamics (MBD) software that includes solution techniques that efficiently handle large motions in a mechanical assembly. The roll-up solar array application consists of a set of functions that are layered on commercial Multi-Body Dynamics (MBD) simulation software that also has the capability of nonlinear simulation of flexible (Finite-Element [FE] or mesh-based) bodies. The benefit of the application is to provide advanced simulation capabilities to spacecraft design engineers that are more efficient to use and require less specialized knowledge to use. Also, the development of this initial solar array application can lead to the development of additional vertical applications for the simulation of other types of deployable space structures.

A typical slit tube, roll-up boom is shown in Fig. 1 below. These booms may be manufactured from metallic or composite materials. For spacecraft applications, in the pre-launch stowed configuration the boom material is rolled onto a cylindrical mandrel. For deployment the material is unrolled and strain energy causes the tubular shape to form. Figure 1 shows the sequence of shapes the boom material forms during deployment.

Figure 1. Slit-tube, rollable boom used for spacecraft applications. As tube unrolls, strain energy causes boom to form the tube structure. Image courtesy of ROCCOR, Inc.

The functions that must be carried out to model the deployment of a rolled-out slit tube boom are 1) the forming of the slit tube around a mandrel located at the end of a solar array boom, 2) the tube must be rolled onto the mandrel to simulate the stowed configuration, and 3) the tube must be deployed into the proper shape. Figure 2 shows an overview of the forming of the tube onto the mandrel.

Initially the tube is in its deployed shape and the mandrel is in contact with the tube at a single point along the top of the tube, but no pressure is applied to the tube to form it to the mandrel. This is shown in Fig. 2a. In Fig. 2b the mandrel is in contact with the tube but this time a pressure applied from inside the end of the tube begins to push the tube walls outwards. The result is that the tube begins to flatten. As the pressure is continued to be applied, shown in Figs. 2c and 2d., the tube continues to flatten until it is formed to the mandrel, shown in Fig 2e. The pressure magnitude and location is chosen to allow the tube to form smoothly around the mandrel. Once the tube is formed to the mandrel it is constrained to the mandrel to simulate an attachment point.

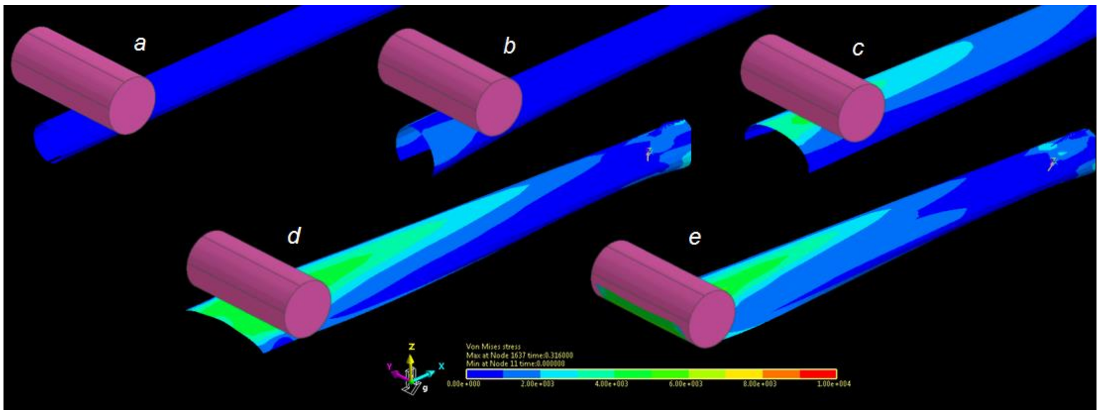


Figure 2. Sequence for forming the slit tube onto the mandrel.

Once the boom is formed to the mandrel, the roll-up simulation starts in which the boom is rolled-up smoothly around the mandrel until the stowed configuration is achieved. Constraints and applied loads are used to control the windup motion and maintain the desired tension on the boom. When the boom is fully wound onto the mandrel the simulation is modeling accurately the stowed configuration of the roll-up slit tube boom, including the pre-stress caused by flattening the tube. Once this configuration is achieved, it becomes the initial configuration and conditions for the deployment simulation. During the deployment simulation the proper definition of the restraining forces provided by the damping mechanism is important for properly controlling the deployment.

B. Solar array implementation using Multi-Body Dynamics software.

The overview presented above describes the procedure for a single tube. The full solar array model developed using multi-body dynamics software contains the entities shown in Fig. 3. These include the mandrel, the slit tube roll-up boom, the photovoltaic blanket, and the frame body. The mandrel and frame body are treated as rigid bodies, while the tube and blanket are treated as flexible bodies and are meshed.

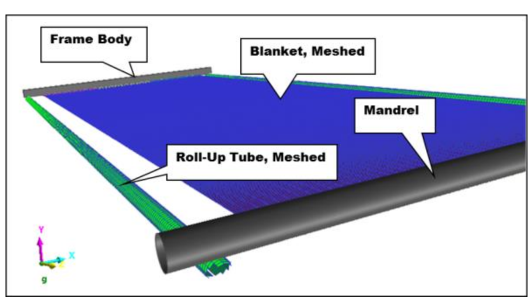


Figure 3. Multi-body dynamics of complete solar array.

A vertical application was developed within the multi-body dynamics software to simplify the model development and automate tedious and repetitive tasks. Application functions were developed for forming the tube to the mandrel, rolling the tube onto the mandrel, and deploying the tube. The functions are accessed from within the software graphical user interface from a tab in the main menu bar. The menu bar is shown in Fig. 4. Each application has a set-up function and a run function. The run function is identified by the arrow in the lower right corner of the icon.

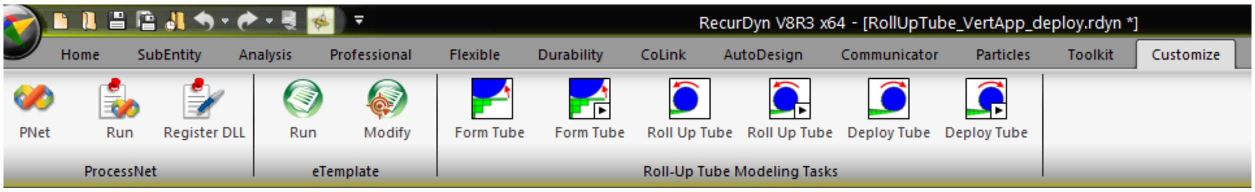


Figure 4. Graphical User Interface (GUI) menu bar showing application functions for forming tube to the mandrel, rolling tube onto the mandrel and deploying the tube from the mandrel.

To increase the efficiency of the tube-forming and rolling-up simulations, the blanket and one tube are initially removed from the solar array model shown in Fig. 3. This configuration is shown in Fig. 5. The bodies are positioned such that the mandrel is in contact with the slit tube, but no pressure is being applied to form the tube to the mandrel and none of the bodies are connected at the start.

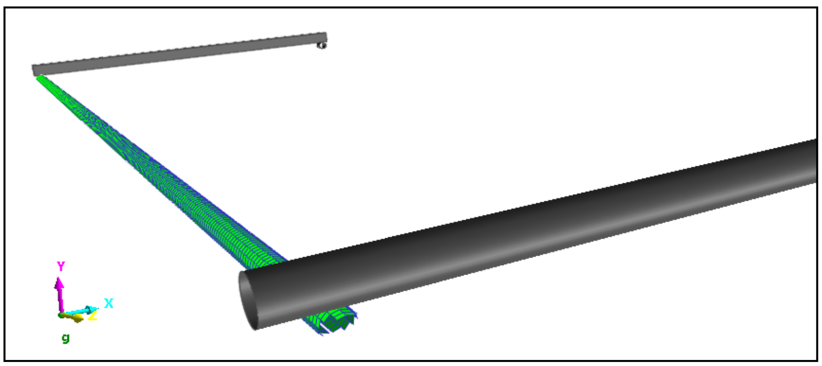


Figure 5. Frame body, slit tube, and mandrel used to illustrate the functionality of the application functions.

The application functions, shown in Fig. 4 are organized on the menu bar from left to right in the order that they are used. Opening the Form Tube application opens the set-up window shown in Fig. 6. The user clicks on the various “Select” buttons in order to choose from the screen the frame body, slit tube and mandrel, and also the desired endpoints, arc centers, or nodes in order to define contact and connection points between bodies. There is also a measuring function available to determine the radii of cylinders used to model contact between the tube and the other bodies. The explain buttons provide help to the user to aide in selecting proper connection and contact points and nodes, and for measuring contact radii.

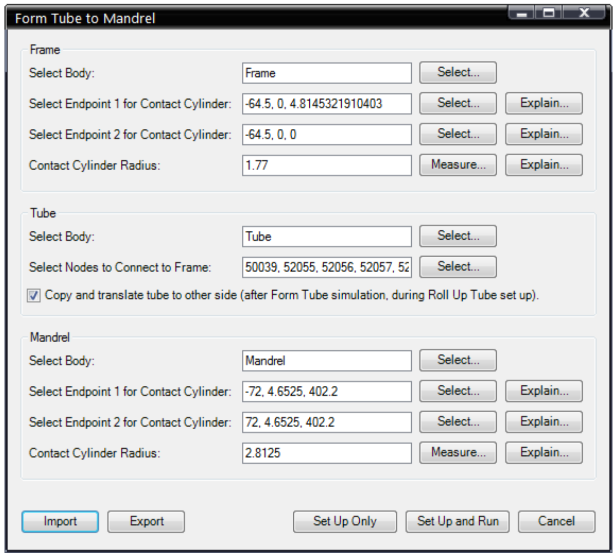
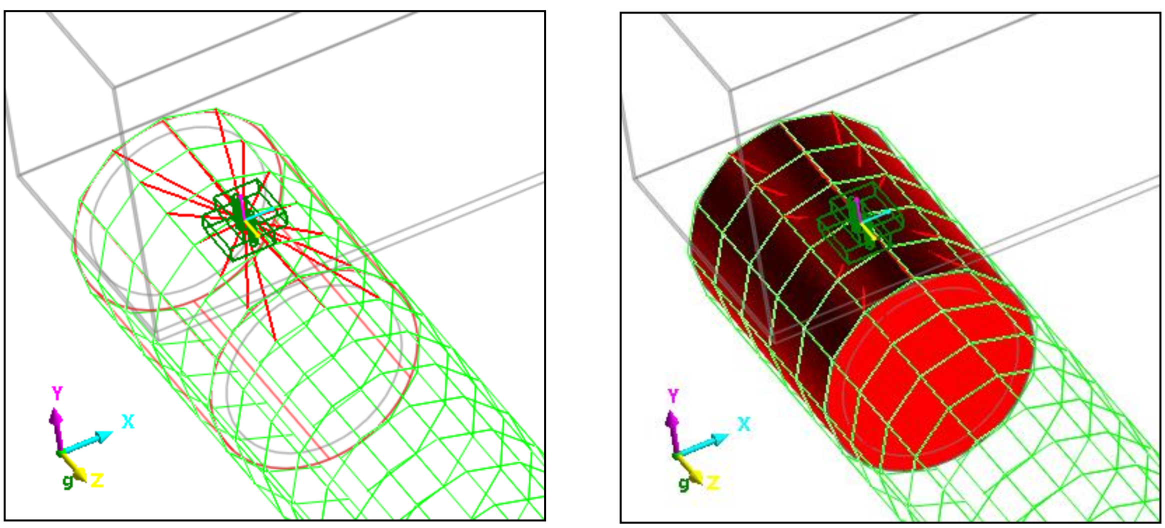


Figure 6. The Form Tube application set-up window.

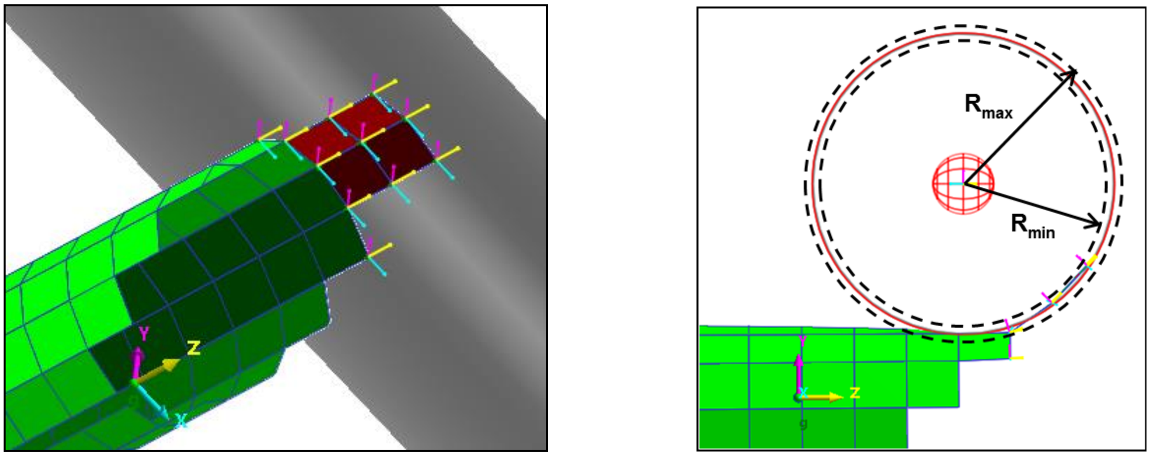
The Form Tube application creates joints and contact cylinders as shown in Fig. 7. Joints are created between bodies as needed. In this case a fixed joint is created between the tube and the frame body to constrain motion in the three coordinate directions. A Force Distributing Rigid (FDR) element (Fig. 7a) is created to distribute the constraining force over multiple nodes. A cylinder (Fig. 7b) is also created to provide a contact surface that approximates the geometry of the actual bracket on the frame. Interactions between surfaces, in this case the tube end and the frame bracket and also the mandrel can be defined to prevent the tube passing through the frame or mandrel.



a. b.

Figure 7. Illustration of fixed joint, Force Distributing Rigid (FDR) Element and cylinder used to define contact interactions between frame and tube as created by the Form Tube application are shown.

As the Form Tube application is run pressure is applied to elements extending past the mandrel centerline in the +Z direction. These nodes are shown in Fig. 8. The positions of the nodes are tracked during the simulation. The minimum and maximum radii are used to determine when the simulation will stop. When all the nodes fall within the range prescribed by the two radii, the simulation will stop. The user may also stop the simulation when they think the tube is sufficiently formed to the mandrel.



a. Bottom View b. Side View

Figure 8. Nodes where pressure is applied during Form Tube application (shown in brown) and minimum and maximum radial distances used to control tube rolling.

During the simulation, a monitoring window, shown in Fig. 9, displays the status of the Form Tube simulation. The "Zoom In to Tube End" option configures the view for the best evaluation by the user. The "Stop Simulations" option will halt all simulations. Figure 10 shows graphically the application of pressure to the nodes shown previously in Fig. 8a, and the change in radial distance from the center of the tube as the nodes and associated elements are formed to the mandrel. As indicated on the graph the simulation will stop when the maximum radial distance of all nodes where pressure is applied fall within the radial tolerance specified by the maximum and minimum radii, R_{max} and R_{min}, shown in Fig. 8b.

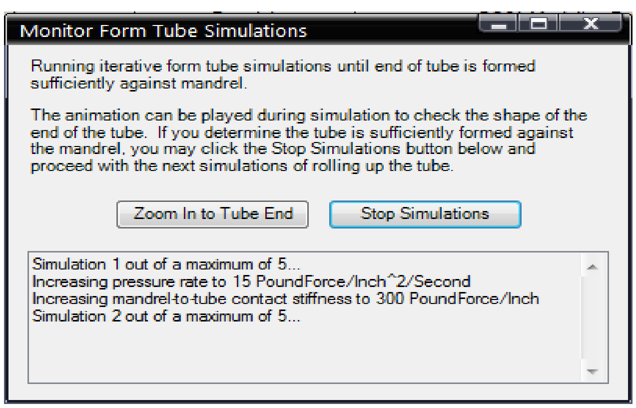


Figure 9. Monitor window that is displayed when Form Tube application is run.

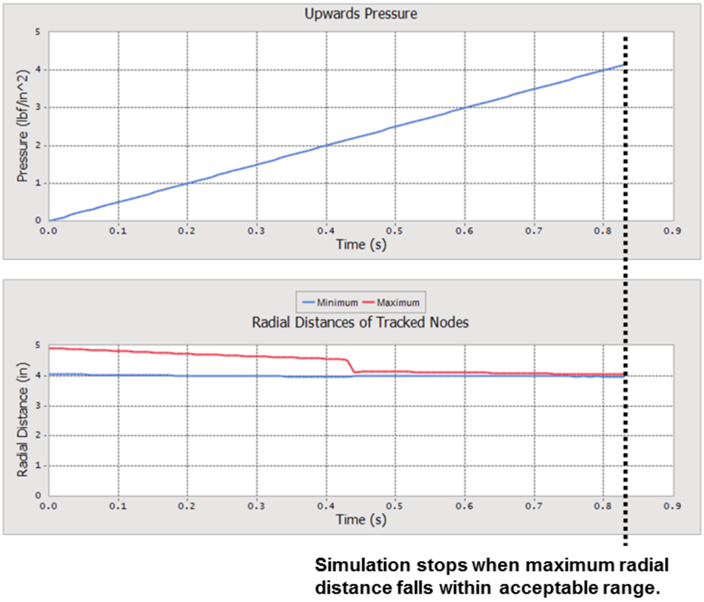


Figure 10. Graphical representation of applied pressure history and radial distance from tube center as a function of time for nodes that are formed to the mandrel.

Note that in the Form Tube application set up window, shown in Fig. 6, there is an option to "copy and translate the tube to other side". As noted on the application window, if this option is chosen this task is accomplished after the Form Tube simulation is run. After the completion of the Form Tube simulation the next application task that is used is the Roll Up Tube (Set Up) application. Figure 11 shows the copied tube at the opposite side of the mandrel. In the Roll Up Tube (Set Up) application window, shown in Fig. 12, the user has the option of defining the percent of tube that is rolled onto the mandrel or the number of times the tube is wrapped around the mandrel. The software will calculate the simulation end time automatically.

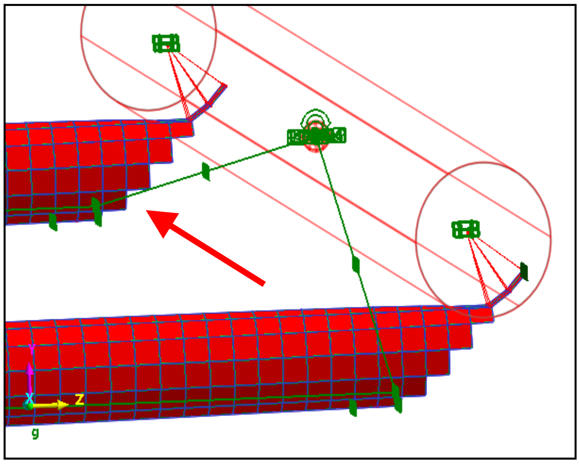


Figure 11. If the option to copy tube to other side of the mandrel is chosen during the Form Tube (Set Up) application, the tube will be replicated and formed to the opposite side of the mandrel as shown.

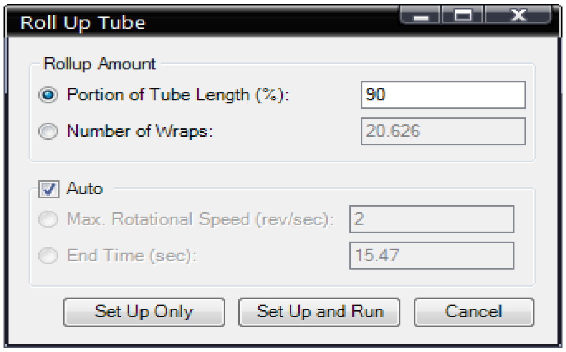


Figure 12. Roll-up Tube application set-up window.

When the Roll-up Tube simulation is executed the tube will be rolled onto the mandrel. While this task is accomplished data is acquired from the system on the roll-up torque and the predicted shear force required to stabilize the system during the subsequent deployment simulation. These values are required for the later deployment simulation. The driving torque on the revolute joint at the center of the mandrel is equal to the roll-up torque exerted by the slit tube on the mandrel. The driving torque is acquired and is used to estimate the stabilizing shear force between the tube and the mandrel. This shear force is necessary to prevent the tube from unravelling. The shear force applied in the simulation replicates a layer of sticky silicone-like tread applied to the top of the tube in the actual system. The configuration of the system during the running of the Roll-up Tube application is shown in Fig. 13.

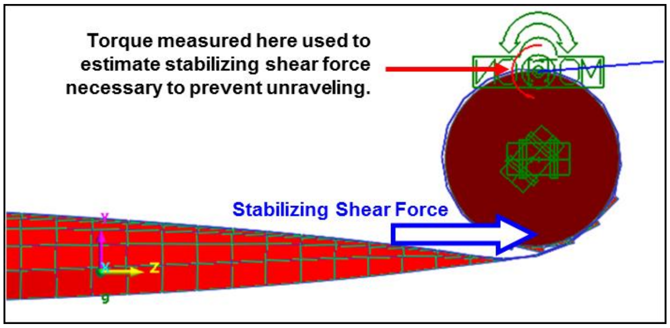


Figure 13. Configuration of system during running of Roll-up Tube application.

During execution, pressure is applied to mesh elements close to the mandrel, shown in red in Fig. 14. This presses the tube against the mandrel to facilitate a smooth roll up. The nodes of these elements are tracked during the simulation. If any of the nodes penetrates the mandrel surface beyond a user determined tolerance, the application stops the simulation, increases the contact resistance between the tube and the mandrel, and starts a new simulation run. As the tube is rolled onto the mandrel, another measure taken to assure a smooth roll up is the application of separating forces, also shown in Fig. 14, on the nodes of the selected elements that are located on either side of the tube slit. The material damping coefficient, which is set by the user, may be changed in order to reduce the simulation run time.

Once the tube is rolled onto the boom, this configuration becomes the starting point for the deployment simulation. The user opens the Deploy Tube application and configures the simulation using the set-up window, shown in Fig. 15. The user has the option to choose how the mandrel is constrained. The options are to constrain the mandrel in translation, the X and Y directions within a plane or allow the mandrel to be unconstrained in all degrees of freedom. The data collected on the shear force during the execution of the Roll Up Tube simulation is used during deployment simulation execution, to simulate the shear force provided by the silicone tread that prevents the system from unraveling. The silicone tread also adheres to the layers of tube, and as the mandrel unrolls the force required to separate the tread controls the deployment speed. A rotational damping coefficient is applied to the mandrel to simulate this separation force. The End Time estimate is based on the rotational damping coefficient, the tube roll-up torque and the material damping coefficient for the tube. The user must specify an end time that is much greater than the estimated end time and select the Auto-Stop Simulation When Deployed option. This will minimize the risk of the simulation ending before the array is fully deployed.

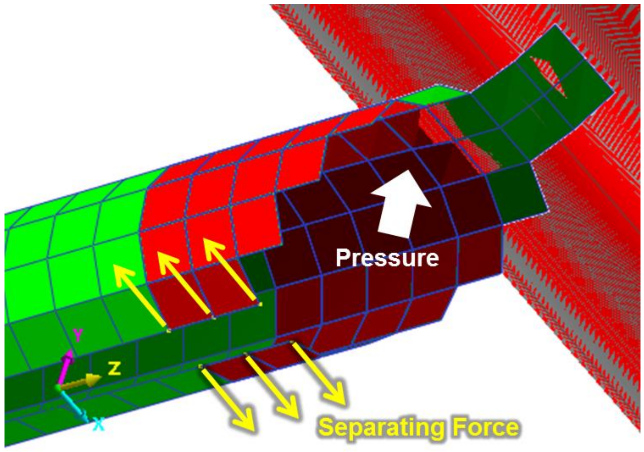


Figure 14. Rolling tube onto mandrel showing mesh elements where pressure and separating forces are applied.

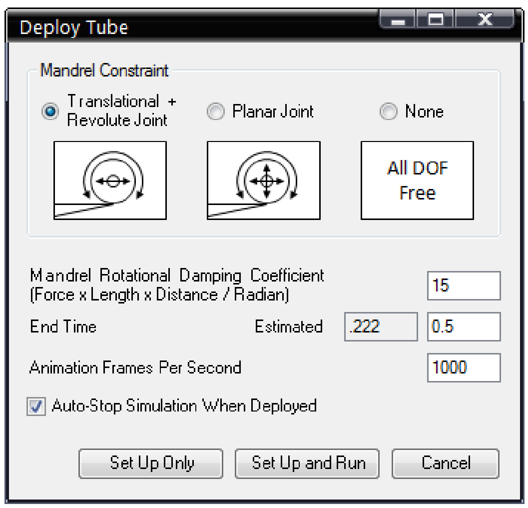


Figure 15. Deploy Tube Application set-up window.

During execution of the Deploy Tube simulation a constant force and balancing torque, shown in Fig. 16, are applied at the bottom of the mandrel. This simulates the shearing force discussed previously that is applied through the use of a silicone tread in the actual system. As discussed previously, this force prevents the tube from experiencing an uncontrolled unravelling from the mandrel. The rotational damper simulates the silicone separation force.

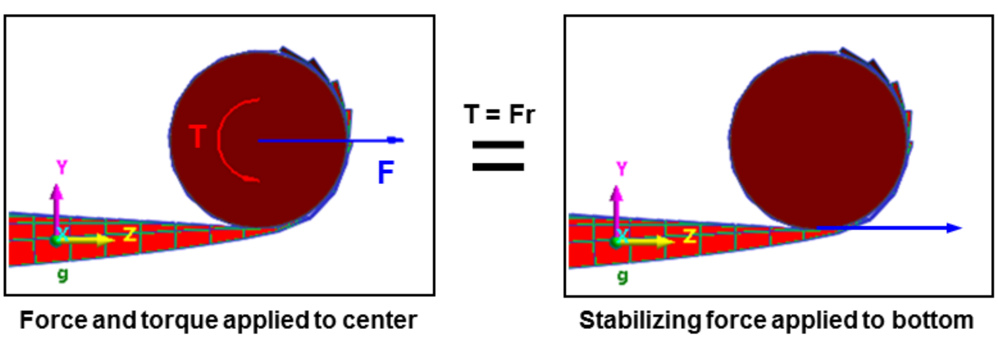


Figure 16. Execution of Deploy Tube simulation showing constant force and balancing torque.

IV. Deployment Performance

The deployment simulation shows the unrolling of the tube and the release of stress in the slit tubes as the material unwinds from the mandrel and recovers into its semi-circular, slit tube cross section. The release of stress can be seen in Fig. 17 which shows two images of the boom during and after deployment. The first image shows the stress distribution during deployment while the second image shows the distribution at the end of the tube deployment. For this example a deployment distance of 20” was used. This is long enough to demonstrate the deployment, but short enough in length so that the simulation time was reasonably short.

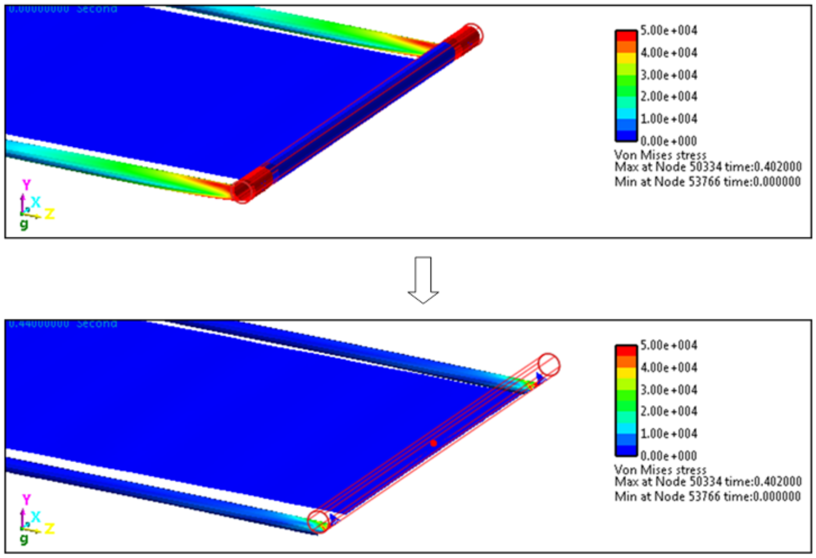


Figure 17. Stress in slit tubes during and at the end of deployment.

A plot of the time history of the mandrel position during deployment as well as the torque applied by the rotational spring located at the center of the mandrel, shown in Fig. 18. The spring acts as a rotational damper and the damping varies linearly with the rotational velocity of the mandrel.

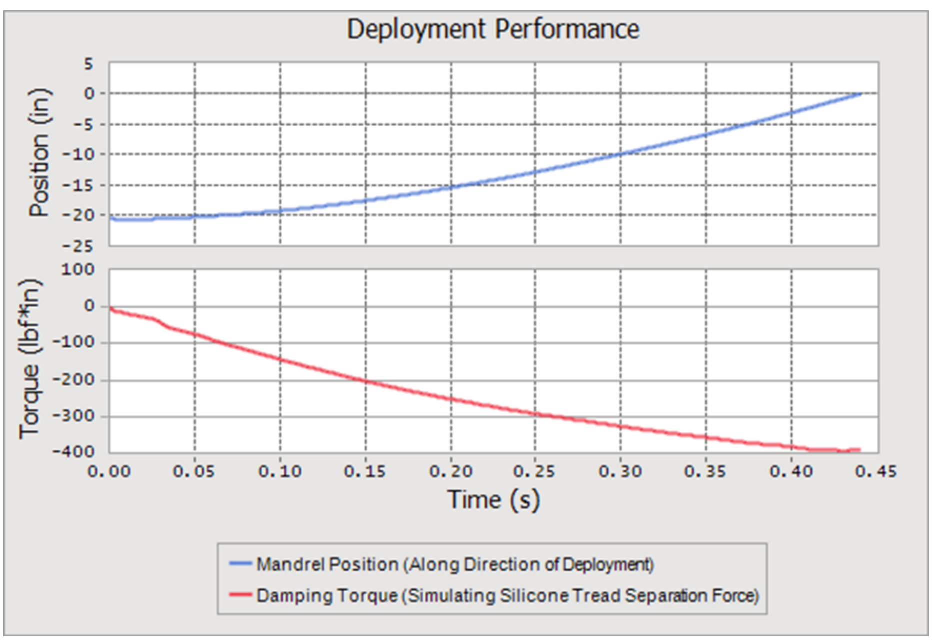


Figure 18. Time histories of the mandrel position during deployment and the damping torque.

V. Summary

Multi-body dynamics software is an ideal software platform for developing simulations of deployable spacecraft structures such as large solar arrays that employ roll-up slit tubes in their design. This paper presents a methodology for using MBD software to develop deployment simulations for this class of structure. Additionally, a vertical application comprised of routines to automate the task of forming the tube to the mandrel, rolling the tube onto the mandrel and finally deploying the tube was presented. This vertical application will speed development time by reducing the need to perform tedious tasks during simulation development and reduces the need for specialized knowledge of the MBD software package.

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