Structural Analysis Methodology for Space Deployable Structures using Multi-Body Dynamic Solver

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The purpose of this paper is to provide detailed structural analysis implementation for space deployable structures using a multi-body dynamic solver. The selected commercial code is MSC/ADAMS. Four benchmark problems are used to evaluate mechanism motion, frictional contacts, and geometrically non-linear large deformation. This paper examines the software functionality, performance, accuracy and ability to solve the benchmark problems. The discussions covered are related to solver convergence, tracking internal force, velocity and acceleration of different parts in each model and comparing results to closed form solutions if available.

Nomenclature

E = Young's Modulus
G = Shear Modulus
ρ = Density
ν = Poisson's Ratio
v = Velocity
g = Gravitation constant
F = *Force*
t = Time
μ = Coefficient of friction

I. Introduction

COMPUTATIONAL models are a common way to predict structure behavior and internal loads in different components of deployable structures for space application. In many cases a ground test is performed with support equipment for correlation purposes but the ultimate goal of predicting loads during on-orbit deployment can currently be achieved through modeling [1]. Deployable structures are traditionally analyzed using almost exclusively multi-body dynamic solvers [1,2]. In this study a multi-body dynamic solver is considered to predict structural performance that has large rigid body motion and highly non-linear events i.e. large structural deformation and contact. The large motion and non-linear events can be in both low and high frequency domains. These highly nonlinear deployable structures usually have multiple joints, contacts within the structure between dissimilar materials, including soft-goods, composites, and metallic parts. The aim of this paper is to further assess the current capabilities of the multi-body dynamic solver and to recommend practices for the construction and simulation of large-scale deployable structures by analyzing selected benchmark problems presented in [3].

A similar benchmark modeling approach was also used with two other software packages for accuracy and performance comparison purpose, those results are presented in two separate papers. The first paper that has been published uses Sierra Solid Mechanics which is developed by Sandia National Laboratories [4] and the second accompanying paper is set to be published and uses the commercial non-linear finite element (FE) code LS-Dyna [3].

II. Numerical Methods

A. Multi-body Dynamic Solver (MSC/ADAMS)

ADAMS multi-body dynamic solver (MBD solver) has been widely used for large motion deployable structures and, with development of more robust solvers that include limited finite element capabilities, more details/fidelity can be added to the models. Since most of the mechanical systems used for space structures are numerically stiff (meaning the ordinary differential equations that govern the equations of motions have close and widely separated eigenvalues, both low and high frequencies), a stiff integrator called "GSTIFF" is selected to handle the solution efficiently. The

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GSTIFF integrator has multiple options for the equation formulation techniques. The formulation chosen to carry most of the current study is SI2 (Stabilized-Index Two). The benefits of the SI2 formulation are: (1) accurate result prediction, especially for velocities and accelerations (compared to Index-3 formulation, which is the default solver, that can have error in velocities and accelerations), (2) numerically very robust and stable at small step sizes (compared to Index-3 formulation that can encounter corrector failures at small step sizes), and (3) tracks high frequency oscillations accurately [5]. Note that SI2 is an implicit numerical solver.

B. Time Step Control

Time step is controlled by a parameter in solver settings called Hmax, which defines the maximum time step that the integrator is allowed to take. It is common to run a convergence study where the Hmax is reduced while monitoring critical results. When results are stable and don't change as a result of changing Hmax, the proper value has been achieved.

III. Element Types

Unlike finite element solvers MBD solver does not have specific element types available, but in order to model flexible bodies, there are a few options that are discussed here:

1. Discrete Links

In this method, the beam-like structures are discretized into many parts that are connected through forces. This method has relatively low run time, but setting up the model is not very efficient and requires more work compared to other methods. A contact force has to be defined between each and every links that comes in contact during simulation. Such contact force can be programmed in a large-scale project. Another hurdle in using discrete links is the post processing since the contact force won't be a straight output and it is up to a user to sum up all forces defined between parts.

2. Flexible Bodies:

In this method, the FE mesh is generated in an FE package and solved outside MBD solver and then imported as a Modal Neutral File (MNF). The MNF includes node locations and connectivity, nodal mass and inertia, mode shapes, and generalized mass and stiffness for mode shapes. The modes in this method are a slightly modified version of the Craig-Bampton modes, which are better suited for modeling large rigid body motion [5]. Recently the option to automate most of this process has been released in MBD solver. The model setup and parameterization is also challenging when using this method.

3. FE_Part

Introduced in MBD solver in 2014, the FE_Part is MBD solver's native modeling object for beam-like structures. The formulation of this method includes stretching, shearing, bending and torsion of beam-like structures with proper representation of mass and inertia. The major advantages of using this method compared to the other two methods mentioned above are: model preparation and parameterization are much easier and geometric nonlinearity is also supported [5].

IV. Contact Algorithm

The contact algorithm is based on the IMPACT function which is a nonlinear contact formulation. The contacting bodies are faceted and the volume of intersection is calculated. The centroid of that volume is where MBD solver looks for the closest points on both bodies. The distance between those points on the solid bodies is the penetration depth that is used for calculating the contact force [5].

V. Benchmark Problems

Modeling of very complex deployable structures in any software requires confirmation that small subsystems from within the large assembly can be modeled properly. These subsystem models should accurately capture the physics of different parts and their interactions. Such building blocks approach should highlight the strengths and shortcomings of each software on very specific problems.

In following benchmark problems, a simple subsystem of deployable structures has been separated and studied. In some cases, there are multiple ways of modeling the same physical problem with different methods even within one software package. The focus of comparison between different modeling methods has been mainly on feasibility of using it in large-scale models considering accuracy, setup time and run time.

i. Benchmark Problem 1 - Pendulum

The rigid body movement of a flexible member is one of the building blocks in complex deployable structures. Such motion is similar to a simple pendulum that may hit other beam-like structures [1]. In this problem the pendulum, released from an initial position, makes contact with an inclined barrier in its path and its flexibility allows it to bend away from the barrier so it can climb up and continue its movement [3]. This load-case setup is illustrated in Figure 1.

The purpose of this study is to assess a solver's capability and accuracy against a closed form solution [3]. The following solver capabilities are assessed: large rigid body motion, elastic deformation, contact, and contact friction.

1. Physical Data

The inclined barrier is aluminum: ρ=2800 kg/m^3, ν=0.33, E= 71 GPa. The pendulum is M55J: ρ=1633 kg/m^3, ν=0.45, E= 231 GPa. Barrier out of plane angle is 5 degrees and the coefficient of friction between pendulum and barrier is μ=0.2. Also the tip mass is 0.43 kg. Total simulation time is t=1.24 seconds.

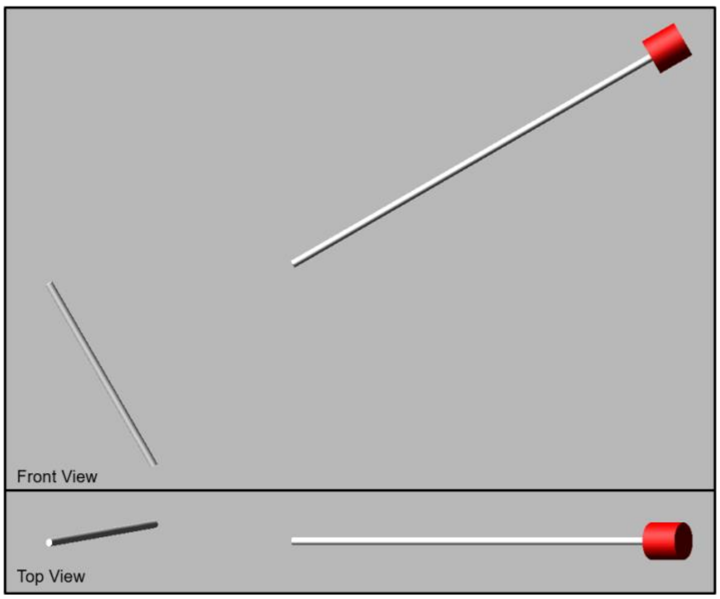

Figure 1. Pendulum Model

2. Results and Discussion

The pendulum is modeled using all three different methods discussed earlier. In order to have a side-by-side comparison for run time between different methods, all solver settings were set to be identical. The solver settings used for the simulation during the pendulum free falling without any contact is different from the moment the pendulum comes in contact with the barrier. This has been implemented to speed up the run time process and, in a more complex model, the solver setting change can be done through sensors.

Case 1: As described in the element type section, the most time-consuming model setup was related to the discrete link method. Also, defining contact between beam segments that come in contact with one another is not straightforward. Contact forces were defined between every element in the pendulum and all elements in the barrier. Aside from these drawbacks, rigid body to rigid body contact is handled very efficiently in the MBD solver and even with all described complexities this model runs faster than the other two methods.

Case 2: The flexible bodies method had the longest run time among these models, and requires some effort for preparation of flexible bodies, but after the MNF files are ready, the model setup in MBD solver is more straightforward compared to the discrete link method. Also, post processing of results is more user friendly. One of the benefits of using flexible bodies is the fact that they can be used as preloaded parts at the start of simulation if needed. In this example, both pendulum and barrier were modeled using solid elements. With current MBD solver limitations shell elements can't be used for contact.

Case 3: In comparison to the other two methods, FE_Part model setup and modification is much easier and does not require any programming skills. However this method currently does not support initial preload in the parts.

The results for all three studied cases are shown in Figure 2 and key data are summarized and compared with the closed form solution in Table 1.

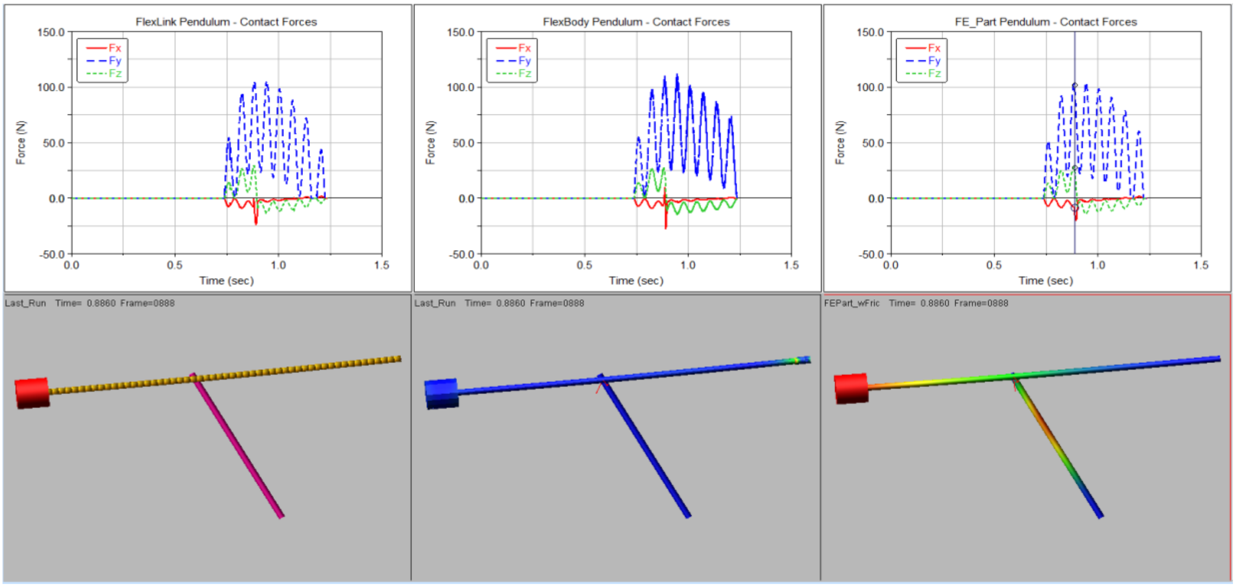

Figure 2. Pendulum Friction Contact Results.

Table 1. Pendulum Friction Contact Results Summary

	MBD Solver			Closed-Form Solution [3]
Element Type	Flexlink	Flexbody	FE_Part	Beam Theory
Max rotation after contact (deg)	23.89	24.16	24.66	24.55
First Contact Force Peak [N]	57.1	57.6	54.1	62.4
Max Contact Force [N]	109.4	114.6	107.2	
CPU Time	5 min	1 hour 36 min	15 min	
Number of CPU cores	8	8	1 CPU	
Solver Type	GSTIFF, SI2	GSTIFF, SI2	GSTIFF, SI2	
Number of elements	83 Parts	9508 solid elements	83 beams	
Notes	Rigid parts are connected through forces	Reduced FE model, 78 modes for each part	1 CPU core limitation	

ii. Benchmark Problem 2 - Flexure Bump

A common one-way irreversible sliding and locking mechanism used in deployable structures is a ratchet/detent setup. In this model, the ratchet is a cantilevered beam represented as a flexure, and detent is a bump that moves toward the flexure tip as shown in **Error! Reference source not found.**.

The purpose of this benchmark problem is to assess reaction forces and contact convergence. The following solver capabilities are assessed: contact friction, solid elements in contact, and run time for small elements. The following two cases are considered:

a. The bump is moving toward the flexure tip with a constant velocity of v=4 mm/sec causing the flexure to deflect upward.
b. In order to study the effects of higher velocity on detent force, the speed of the moving bump at the time of contact is increased from 4 mm/sec to 40 mm/sec.

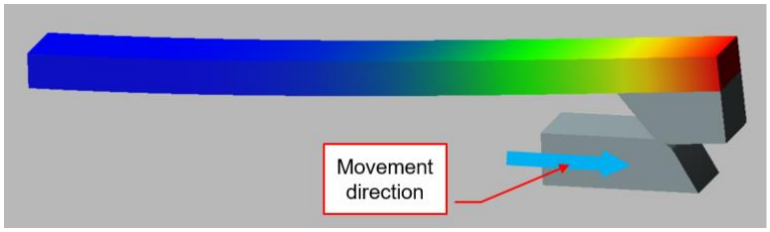

Figure 3. Flexure bump deformed shape

1. Physical Data

Both flexure and bump are Titanium: ρ=4428 kg/m^3, ν=0.31, E=110 GPa and coefficient of friction between them is μ=0.2. Total simulation time is t=1.25 sec.

2. Results and Discussion

Four different models with the following setups were built in MBD solver.

Case 1: Flex On Flex Contact With Flexible Body as Flexure: In this method both flexure including its tip and bump are modeled as Flexible Bodies. The flexure end is fixed to ground with a fixed joint, and the bump is connected to ground with a translational joint. A linear motion on the translational joint moves the bump at a constant speed. The setup for the FE of both flexure arm and bump is to extract adequate mode shapes to capture the behavior of the structure properly (in this example, 72 modes for flexure and 36 modes for bump). The flexure and bump are constructed of 2305 and 937 elements respectively. The run time for this model is about 4 hours.

Case 2: Flex On Rigid Contact With Flexible Body as Flexure: Since the majority of the displacement at the contact between the flexure and bump is coming from the flexure arm and not local deformation of the contact points, this study and the following two are investigated. The main reason for pursuing methods other than flex on flex contact is solver run time inefficiency. As can be seen in Table 2, there are different methods of modeling the same problem with significantly reduced run time. This becomes even more important once the subsystem is integrated into a much larger complex model for the entire deployable structure. In order to study the flex on rigid contact scenario, the flexible bump that slides on a translational joint was replaced with a rigid part and CAD geometry. Contact properties such as stiffness and coefficient of friction were not changed from the flex on flex model.

Case 3: Rigid On Rigid Contact With Flexible Body as Flexure Arm: To further simplify the flexure bump model for the MBD solver, both flexure tip and bump are converted to be rigid parts with CAD geometries. The flexure tip is attached to the cantilevered beam with a fixed joint with similar contact properties as before. Since the contact geometry for this model is CAD based, the contact force is smooth and less bumpy compared to the two previous methods, as can be seen in Figure 4. The flexure arm in this case has 1345 elements.

Case 4: Rigid On Rigid Contact With FE_Part as Flexure Arm: A different method to model the flexure arm is using the FE_Part. As described earlier, the FE_Part has its own pros and cons. Depending on the modeling needs, it might be the proper solution for some users. In this method, similar to the previous method, both flexure tip and bump are rigid parts with CAD geometries while 5 elements build the flexure arm.

Time history results for cases 1, 3 and 4 are shown in Figure 4. As can be seen in Table 2, the MBD solver is more efficient dealing with rigid on rigid contact compared to other methods.

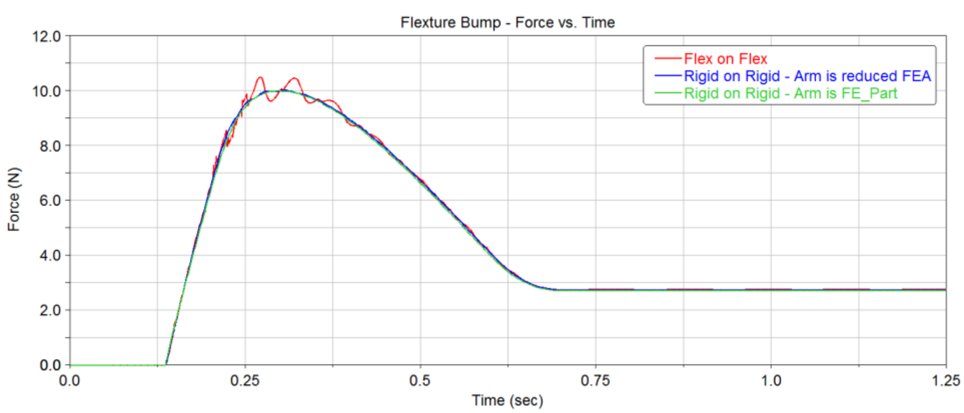

Figure 4. Flexure bump moving force results

Table 2. Flexure and Bump Results Summary for v=4 mm/sec and v=40 mm/sec

Bump v=4 mm/sec	MBD Solver		
Case Description	Element Type	Bump Fx [N]	Run Time
Both flexure and bump are flexible	Solids (reduced FEA)	10.5	3 hours 50 mins
Flexure is flexible bump is rigid	Solids (reduced FEA)	10.1	2 hours 4 mins
Flexure arm is flexible, flexure tip and bump are rigid	Solids (reduced FEA)	10.0	Under 2 mins
Flexure arm is flexible, flexure tip and bump are rigid	Beams (FE_Part)	10.0	Under 2 mins
Bump v=40 mm/sec			
Flexure arm is flexible, flexure tip and bump are rigid	Beams (FE_Part)	10.5	Under 2 mins

iii. Benchmark Problem 3 - Two Straps Setup

There are many types of deployable structures made of thin wall flexible joints [1] or a network of flexible straps making the structural surfaces of reflector mesh type antenna [2]. Also, structures with membrane components such as sunshield or the reflective surface of a deployable mesh antenna are often made of soft fabric attached to a network of structural straps. Usually each strap is a long flat flexible beam that deflects and stores bending energy similar to compressing a spring during the stowing process. Note these types of material could have a wide range of axial and bending stiffness. When there is minimal stiffness in absence of a tension field, they are treated as soft-goods such as cable or fabrics. In general, these types of soft-goods are modeled accurately when there is a tension filed and have been omitted when there is no tension. This was mainly due to software limitations and their secondary contributions. However, in some recent applications their representation in the deployment model became necessary, mainly for their stored strain energy contributing to bloom force [2] and also studying snag issues. The following case is developed to study the behavior of strap type structures.

Three masses are connected with highly flexible tapes, as shown in Figure 5. The outer masses are pushed towards the fixed center mass using prescribed displacement to simulate the stowing procedure. When two end masses touch the mass in the middle, the stowing process is complete. Those three masses are held together until stored strain energy reaches steady state, then the end masses are released to deploy. The purpose of this study is to assess stored strain energy in the system and its release. Additionally, forces, contacts and joints between straps and end-masses are assessed.

The displacement is applied for stowing in 8 seconds, held for 2 seconds, followed by either return to the original position in 8 seconds or instantaneous release for dynamic deployment.

Quasi-Static Stowing/Deployment With Gravity: All deployable structures are stowed very slowly with gravity present. The stowing process is monitored carefully to protect the sensitive soft-goods and to prevent them from snagging to other parts. The quasi-static analysis, see Case 1, is run for both stowing and deployment to ensure the results are repeatable and that similar loads are generated in both directions.

<u>Case 1:</u> Quasi-static stowing and quasi-static deployment are all under gravity effects for this small subsystem study. The displacement is applied for stowing in 8 seconds, held for 2 seconds, and moved back in 8 seconds.

<u>Case 2:</u> Quasi-static stowing and quasi-static deployment with gravity but without strap to strap contact. In order to understand the importance of introducing contact between soft-goods, in this specific case the strap to strap contact was removed from Case 1. As can be seen in Table 3 the max force does not change significantly (reduced by 5%) when the contact is not included. But one has to keep in mind that in this example the straps are not constrained from both sides (they only contact on one side and are free to move on the other side), therefore, the effect is minimal, if there are more straps in a more confined space, the contact will affect the stowing force more significantly.

Dynamic Deployment With and Without Gravity: Actual deployment of the structure is performed by sudden release of restraints that hold the stowed structure together. The energy stored in bending and compressing straps together during the stowing process gets released and pushes the other components of the structure. This phenomenon is called “bloom” and is a highly dynamic event. This highly dynamic event can be with gravity simulating ground operations, see Case 3 below, and it can be without gravity representing on-orbit deployment, see Case 4 below. Understanding of these two deployment events is crucial in predicting the internal component loads and also overall satellite attitude.

Case 3: Quasi-static stowing and dynamic deployment are all under gravity effects for the same subsystem. The displacement is applied for stowing in 8 seconds, held for 2 seconds, followed by sudden release for dynamic deployment.

Case 4: Quasi-static stowing is under gravity and dynamic deployment is without gravity effects for the same subsystem. The displacement is applied for stowing in 8 seconds, held for 2 seconds, followed by sudden release for dynamic deployment.

1. Physical Data:

Strap dimensions are 0.432 m long and 9.525 mm wide and 0.18 mm thick. The strap material properties are: E=41.8 GPa, G=16.1 GPa, ν=0.3, ρ= 2657.271 kg/m3. The mass for a single end mass is 0.227 kg and mass simulator length is 50.8 mm long. The attachment between end mass and strap is a pin joint which is 12.7 mm away from each mass edge. When in stowed position, strap attachment points shall be 25.4 mm apart. End masses are moving with constant speed of 50.8 mm/sec during the stowing process. [3]

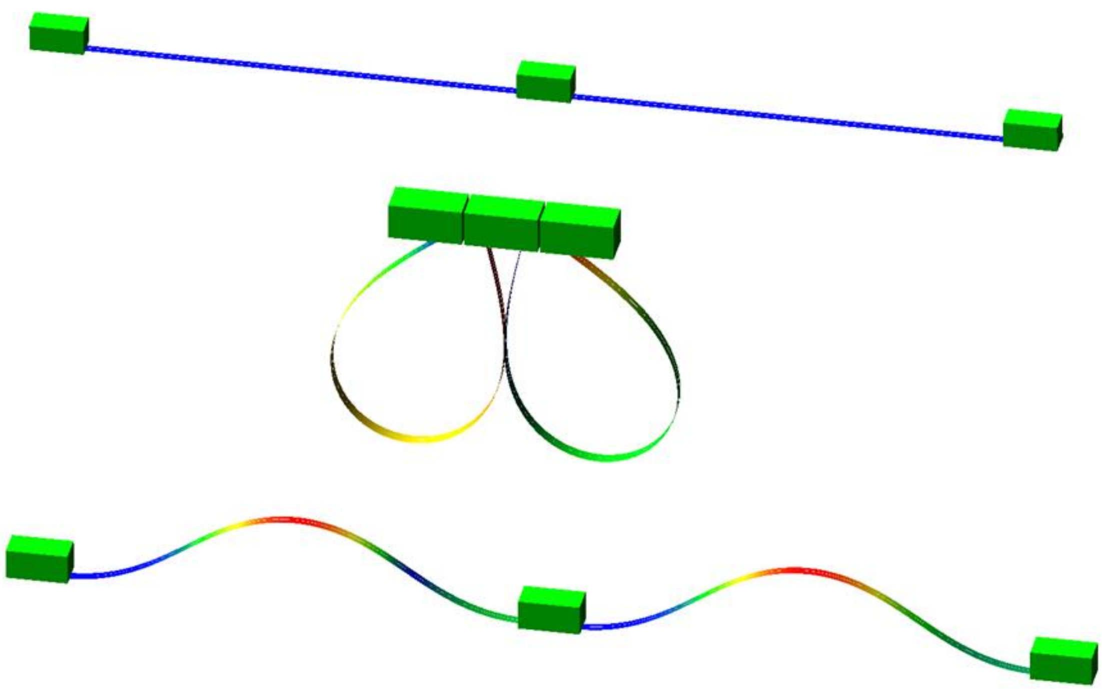

Figure 5. Two Strap Setup in Deployed, Stowed, and During Dynamic Deployment

2. Results and Discussion:

Simulation of straps will require large deformation of beam-like elements which fits the description of the FE_Part. Each strap is modeled with 20 elements and strap ends are connected to the box above it with a pivot joint. A contact force is also defined between the two straps. Snapshots of different stages of the simulation (quasi-static stowing and dynamic deployment) are shown in Figure 5.

The force vs. time results for three cases are shown in Figure 6**Error! Reference source not found.** and key data are summarized and compared in Table 3**Error! Reference source not found.**.

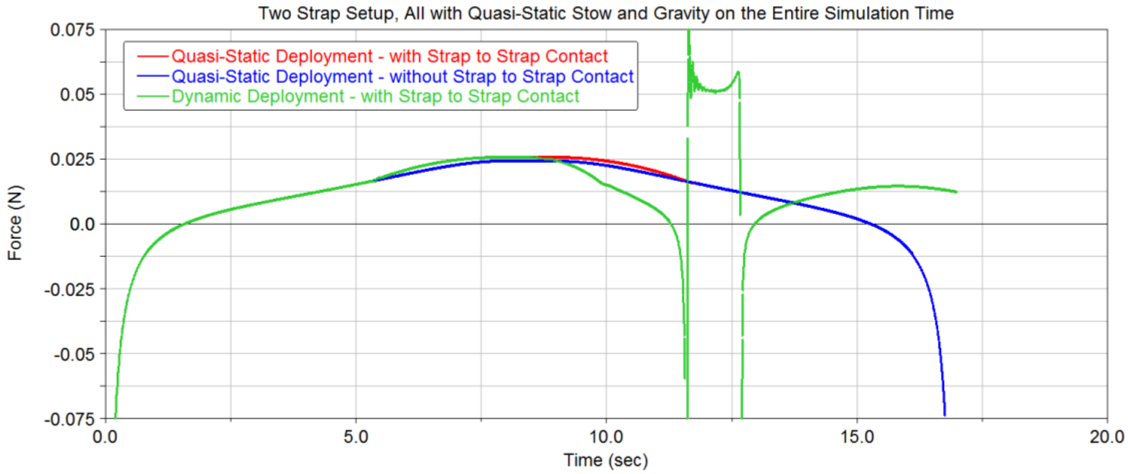

Figure 6. Two Strap Force Results

Table 3. Two Straps - Results Summary

	MBD Solver		
Case Description	Gravity	Stowed Force[1] [N]	Run Time (t= 18 sec)
Quasi-Static both Stow and Deployment (with contact)	Yes	0.0257	9 min 24 sec
Quasi-Static both Stow and Deployment (without contact)	Yes	0.0243	1 min 18 sec
Quasi-Static Stow, Dynamic Deployment (with contact)	Yes	0.0257	7 min 25 sec
Quasi-Static Stow, Dynamic Deployment (with contact)	Only for Stowing	0.0257	8 min 4 sec
[1] Maximum force along the cart motion			

iv. Benchmark Problem 4 – Straps and Fabric

As mentioned in Benchmark Problem 3, the deployable antenna reflector surface is often a soft fabric attached to a network of straps. In this benchmark study a small section of straps and fabric has been simulated as described in Figure 7.

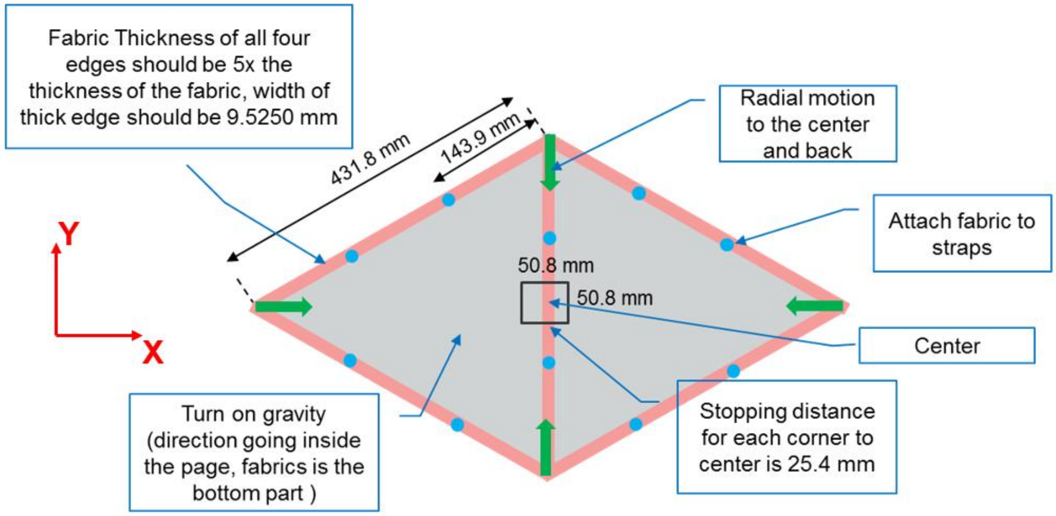

Figure 7. Fabric Attached to Five Straps Setup

1. Physical Data:

Each strap length is l = 0.432 m, other strap dimensions and material properties are similar to the straps in Benchmark Problem 3. Fabric material properties are E = 344.7 MPa, ν = 0.3, ρ= 553.6 kg/m^3, all four outer edges should be five times thicker than the rest of the fabric. Since the MBD solver does not have shell elements the FE_Part with joints has been used to build the fabric. Therefore, the fabric is constructed by beam elements that are 21 mm wide and 0.025 mm thick (except on four outer edges they are 0.127 mm thick). These beams are fixed in all DOFs to each other when they cross. Each strap can pivot about the Z axis w.r.t. other straps crossing it at both ends. The fabric is connected to each strap with 4 fixed joints (at blue dots and strap ends). All four corners are constrained to only allow radial movement towards the center, therefore two corners can only travel in X and two can travel in Y directions. Displacement is applied in X and Y directions to the four corners, and gravity is applied in -Z direction for stowing.

Applied displacement is for stowing in 5 seconds, hold is for 0.5 second to reach steady state, and then corner ends are released in radial directions for dynamic deployment.

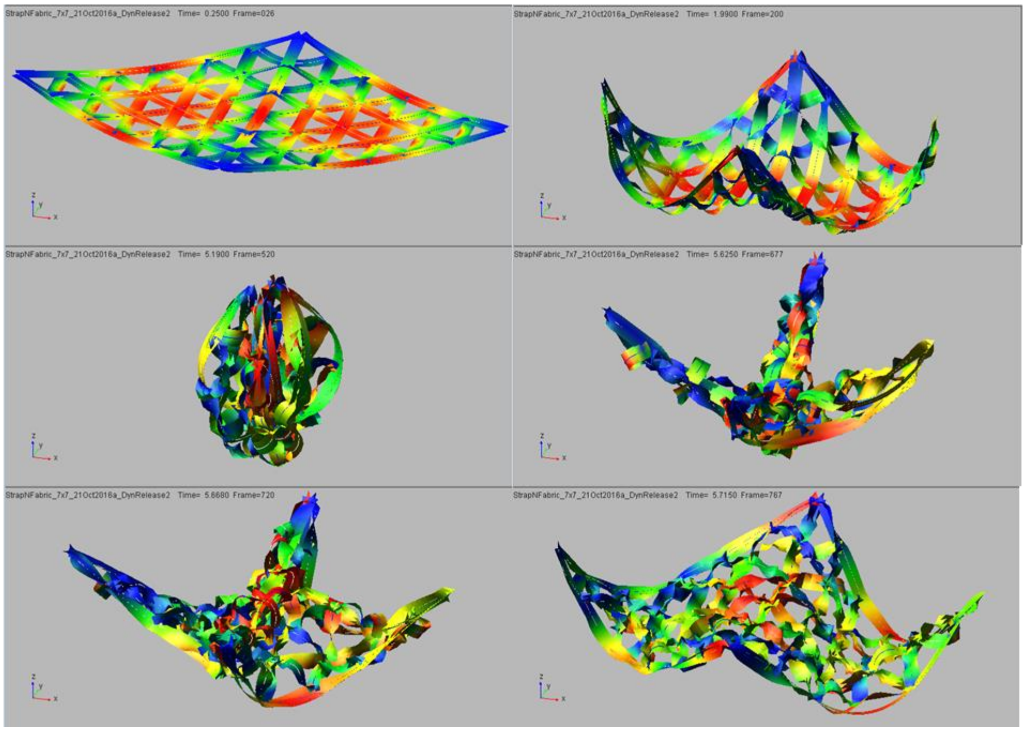

Figure 8. Straps and Fabric Stowing and Deployment Snapshots

2. Results and Discussion:

With current MBD software capabilities, simulating a small portion of straps plus fabric proved to be a big challenge, model setup required many lines of programming to create the beams separately and lay them next to each other properly, furthermore another macro was developed to tie everything together with fixed and revolute joints where necessary.

The model as developed, was very unstable and took many solver setting iterations to run, even after finding the proper solver setup, the model only ran for 5.7 sec of simulation time which took over 10 hours of run time. Since the developed model was challenging for the software to run, contacts were not introduced to further complicate the problem.

Considering setup and run-time challenges, this approach is not currently recommended for simulating fabric in this MBD software.

Figure 8 shows snapshots of the quasi-static stowing and dynamic deployment, Figure 9 shows the force required to stow the assembly in both X and Y directions.

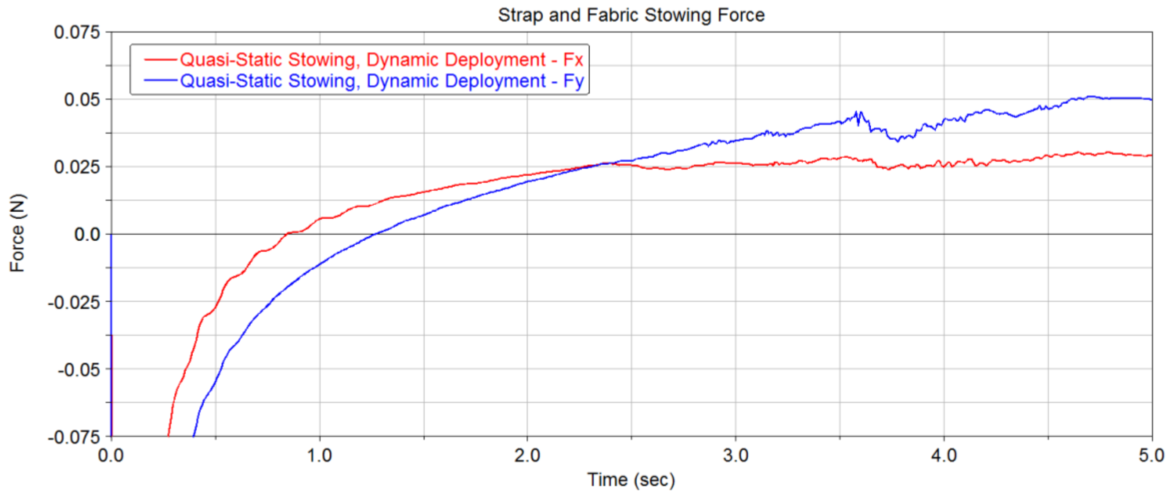

Figure 9. Strap and Fabric Results

VI. Lessons Learned

In the examined benchmark problems using MBD solver, optimizing solver settings for each model is key to keeping the run time low and manageable. For example, in models where contact has been defined, turning off contact and taking larger time steps before contact happens could significantly lower the computation time. The contact force can then become activated with a distance or time sensor. Also, rigid to rigid contact solves much faster than other options, therefore, wherever possible, this contact algorithm is preferred. Constructing fabric with FE_Part and tying them together is not recommended since both model setup and run time showed to be not feasible even for a scaled down problem..

Modeling complex deployable structures requires confirmation that all small subsystems from within the large system can be modeled properly. These subsystem models should accurately capture the physics of different parts and their interactions with each other. If these subsystems are complicated and CPU-intensive, then it is recommended to build a detailed model and extract force/displacement functions based on subsystem results and then implement them as functions in the system level model.

Acknowledgments

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