Jet Propulsion Laboratory
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An Evaluation of Structural Analysis Methodologies for Space Deployable Structures

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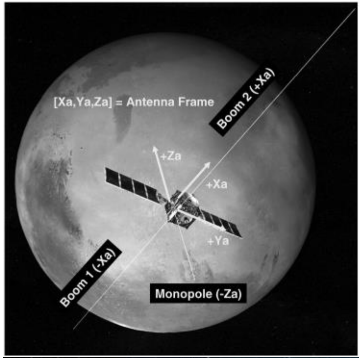
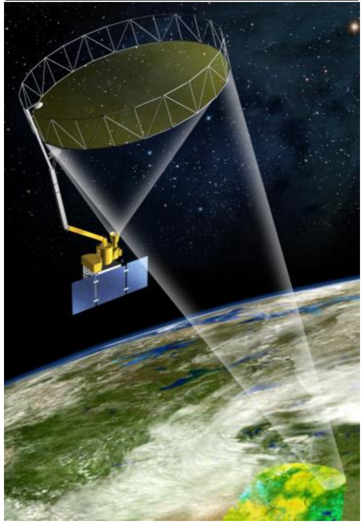
Introduction & Background

- Develop and improve techniques required to analyze the deployment of large deployable space structures
  - Aiding design, predicting deployment behavior, and provides insight into anomalies
  - Verification prior to flight, as an augmentation to test, gravity effect mask the true dynamic behavior
- Traditionally, multi-body dynamics solvers (large angle motion and large displacements) have been used
  - Hybrid method - component nonlinear FE results within a multi-body dynamics solver as a simplified part
  - Cannot model slack soft-goods materials nor effects of local mechanism imperfections, essential for investigating possible snags and anomalies
- Evaluate capabilities of nonlinear finite element solvers



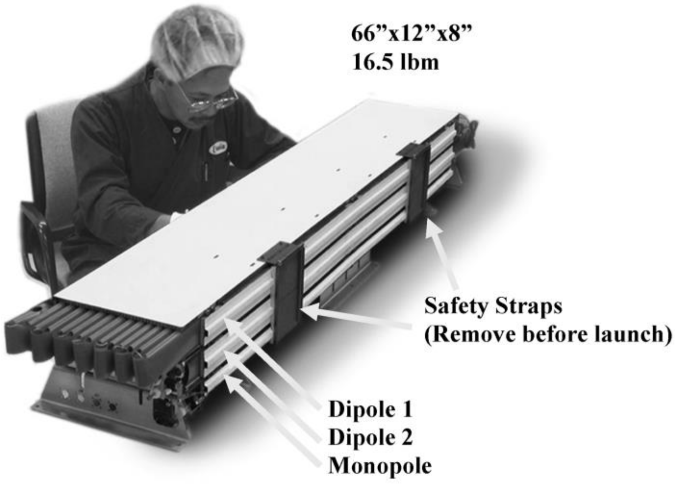
MARSIS booms



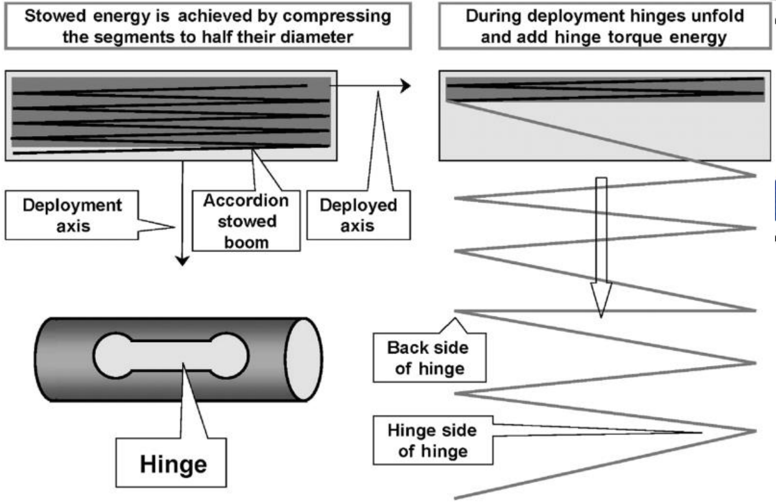
Soil Moisture Active Passive (SMAP)

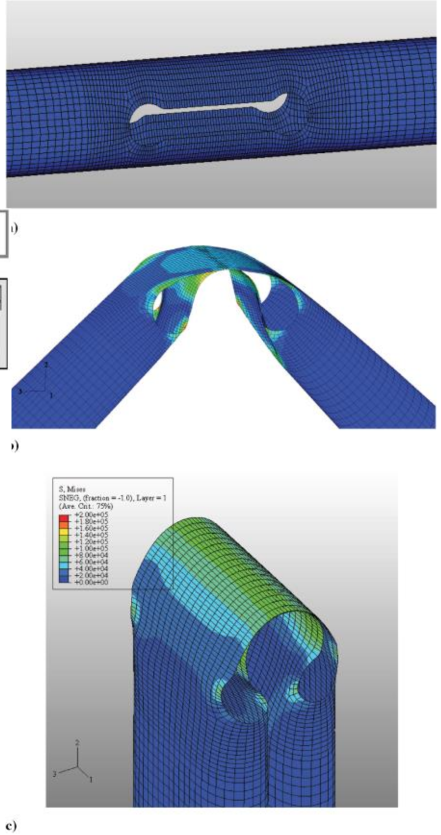
MARSIS Antenna Booms Deployed on May 2005

- MARSIS antenna employs a total of three FFT booms made of composite tubes with lenticular joints: two that form a 40 m dipole and the third acting as a 7-m monopole antenna



Stowed MARSIS antenna FFT booms and cradle before launch

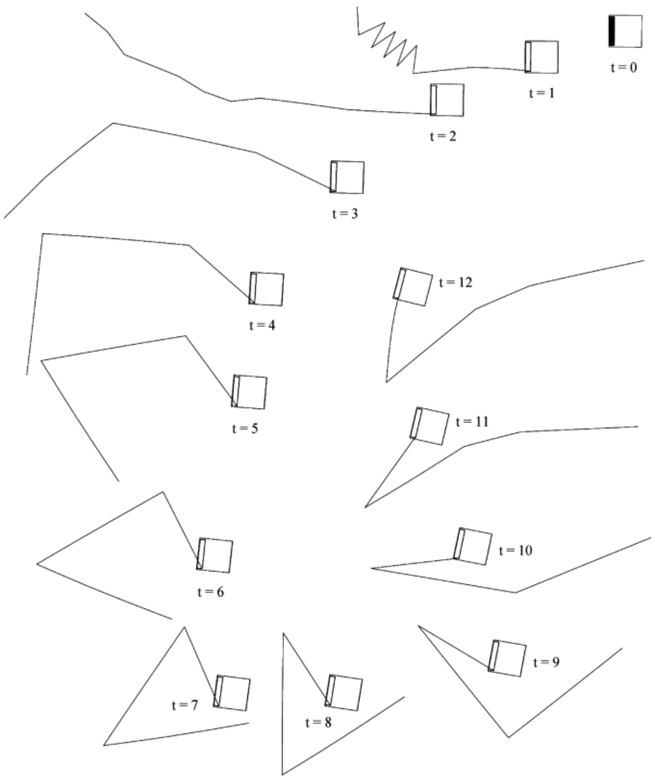




Lenticular joint was characterized with ABAQUS and testing

MARSIS Antenna Booms Deployed on May 2005

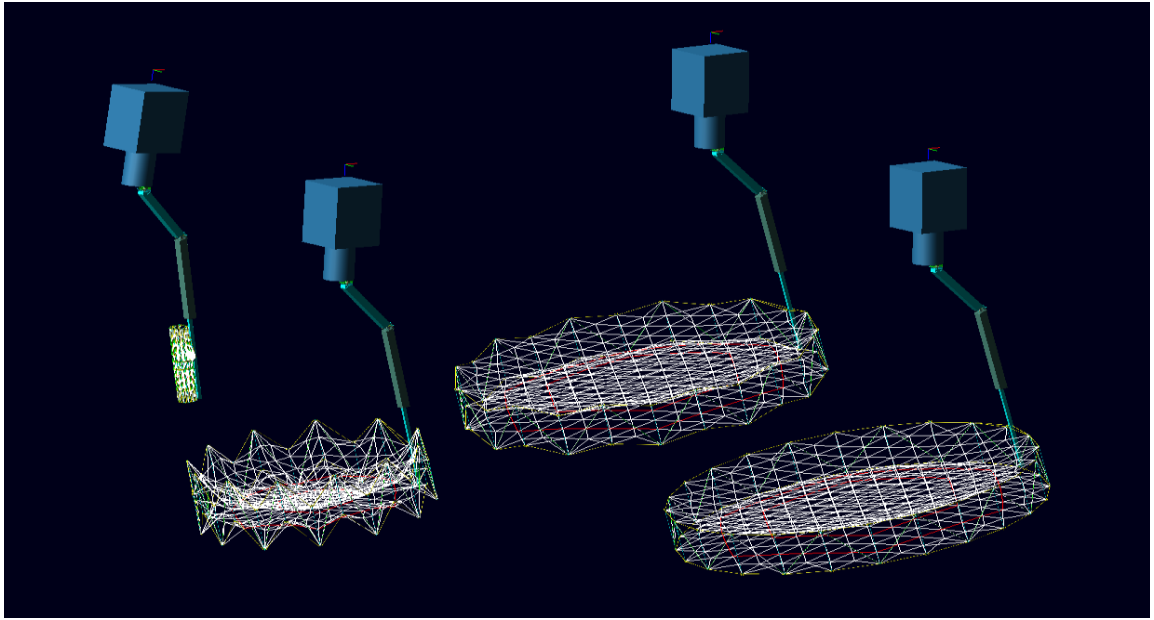
- The deployment was achieved by release of stored strain energy in an uncontrolled and dynamic event:
  - Extremely high stored energy resulted in a chaotic deployment
- A hybrid technique was used
- Adams multi-body dynamics was used for on-orbit deployment predictions
- Lenticular joints were characterized using ABAQUS and testing
- Contact between segments and within individual hinges
- Large rigid body motion plus large elastic/plastic displacement



ADAMS Simulation at Different Deployment Stages

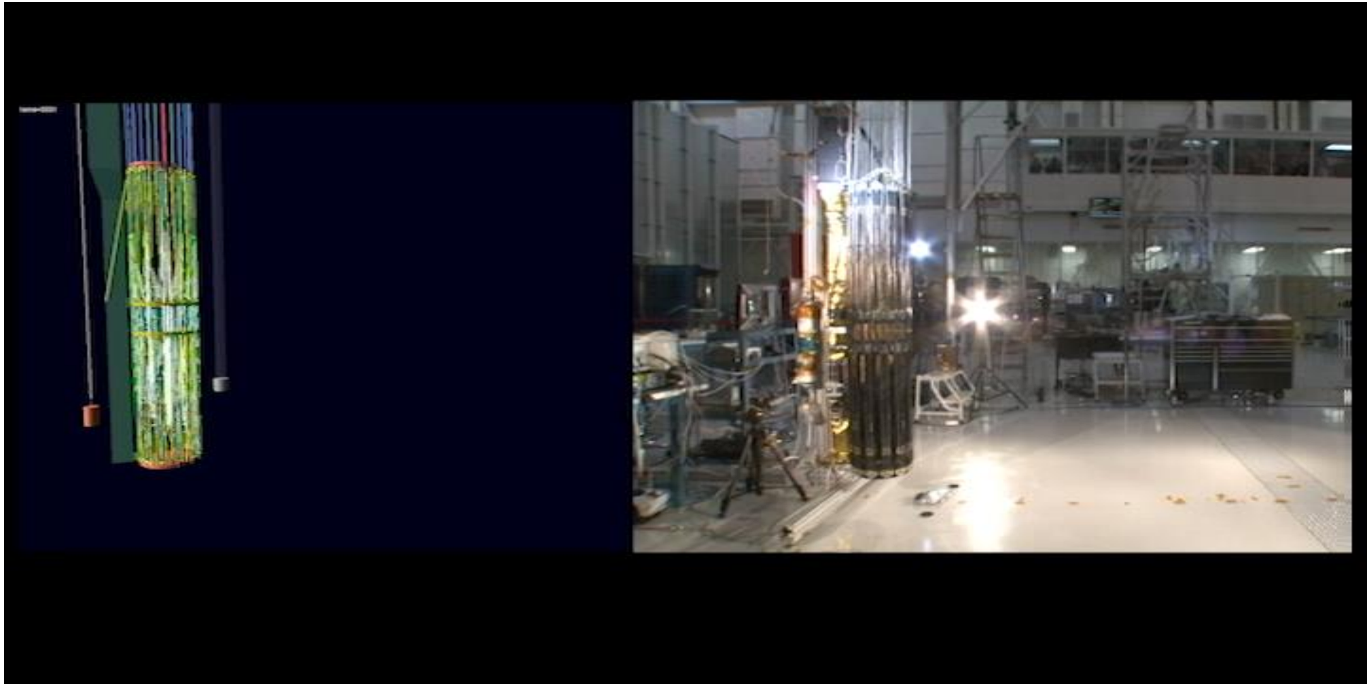
SMAP Reflector was Deployed on March 2015

- Structure is made of: Flexible members, mechanical joints, with or without free play (spherical, cylindrical, sliding), and soft goods (tapes, cable, mesh)
- Deployment was achieved by a combination of uncontrolled stored strain energy release (bloom) and motor actuation through cables, gears, linkages
- Contact between:
    - Different parts
    - Within individual parts
- Large rigid body motion plus large elastic displacement



ADAMS Simulation: Stowed, Bloom, Crenellation, Full

SMAP AstroMesh Reflector Bloom
System Level GSE Model Correlation to GSE Tests

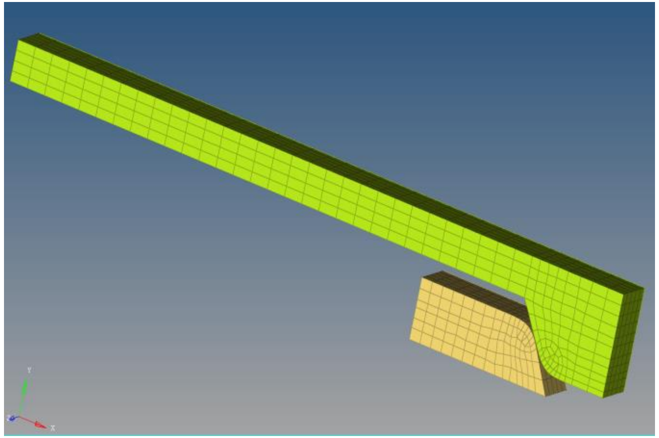


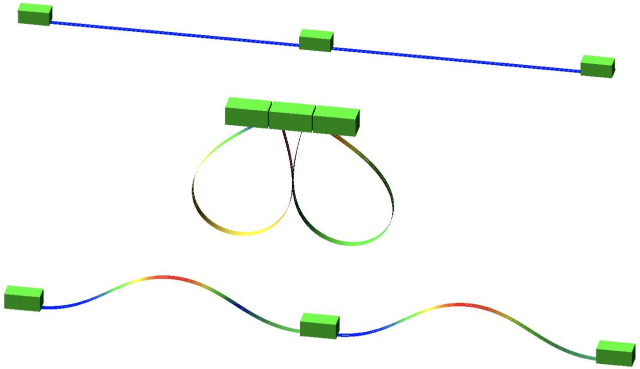
ADAMS Bloom simulation **JPL Bloom test on 09-09-2014**

This study was done as a part of JPL's risk review

Approach

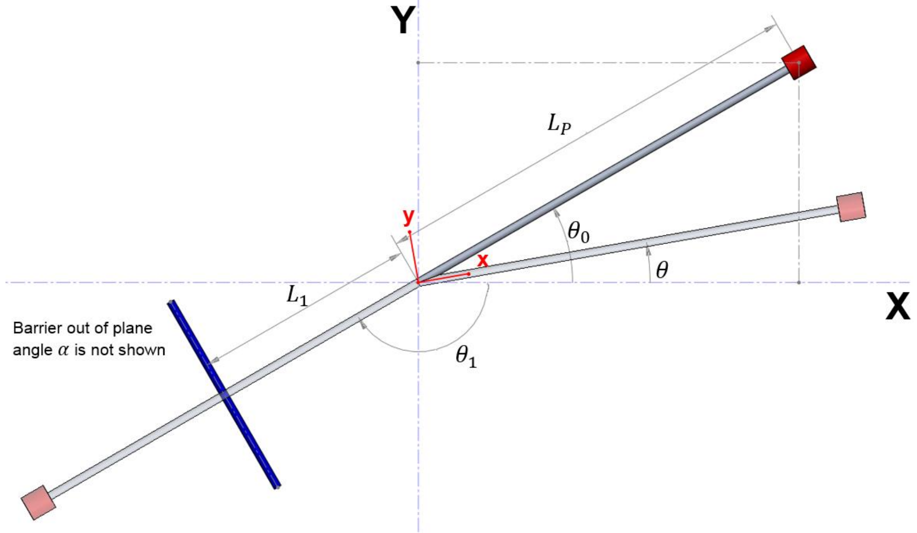
- Evaluate the capability of existing software and technology
  - Multi-body dynamics
  - Nonlinear FEM
  - Hybrid of two methods
- Develop a series of benchmark problems that are applicable to large deployable structures
- Analyze these benchmark problems using:
  - ADAMS multi-body dynamics – Implicit method
  - LS-Dyna nonlinear finite element (FE) code – Explicit method
  - Sierra large scale parallel nonlinear FE code- Implicit and Explicit methods
- Recommend new approach and technology:
  - Near future
  - Long term
- Validate the selected analytical methods for a large assembly applicable to current projects at JPL [2017]





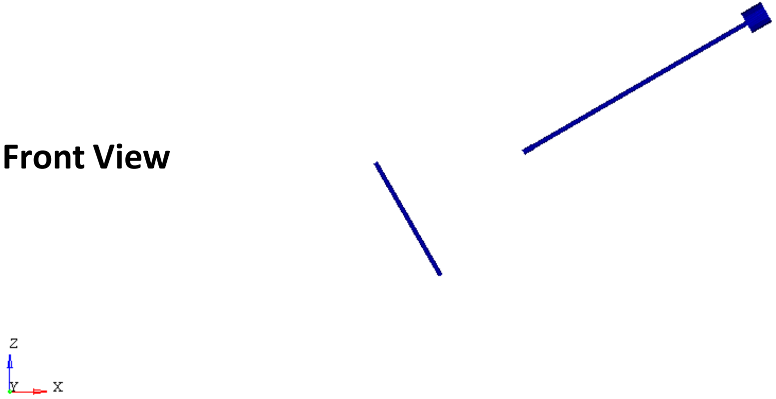
Benchmark Problem 1: Flexible Pendulum

- Motivation for this problem:
  - Evaluate the nonlinear FE capabilities for large rigid body motion in addition to elastic deformation
  - Evaluate behavior during contact between different parts
- ADAMS: Flexlink, Flexbody, and FE_Part
- LS-Dyna: Beam, shell, and solid
- Sierra: Beam, shell, and solid
- Maximum rotational angle after impact and initial peak force are compared

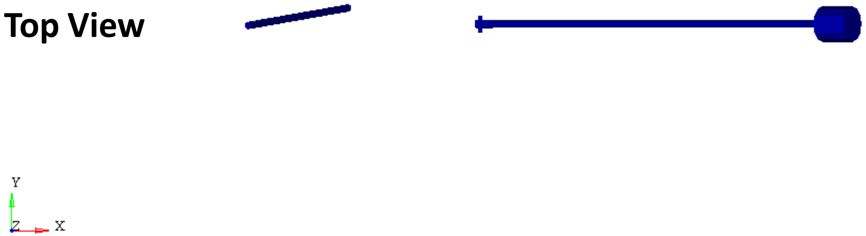


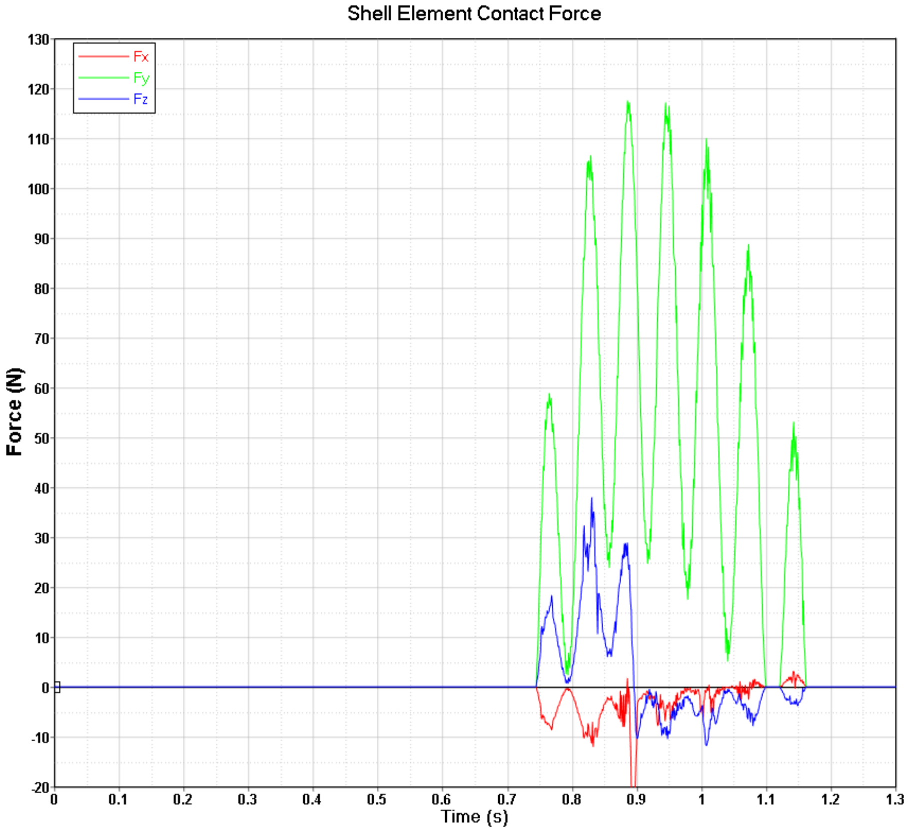
Flexible Pendulum: LS-Dyna - Shell Elements

Front View

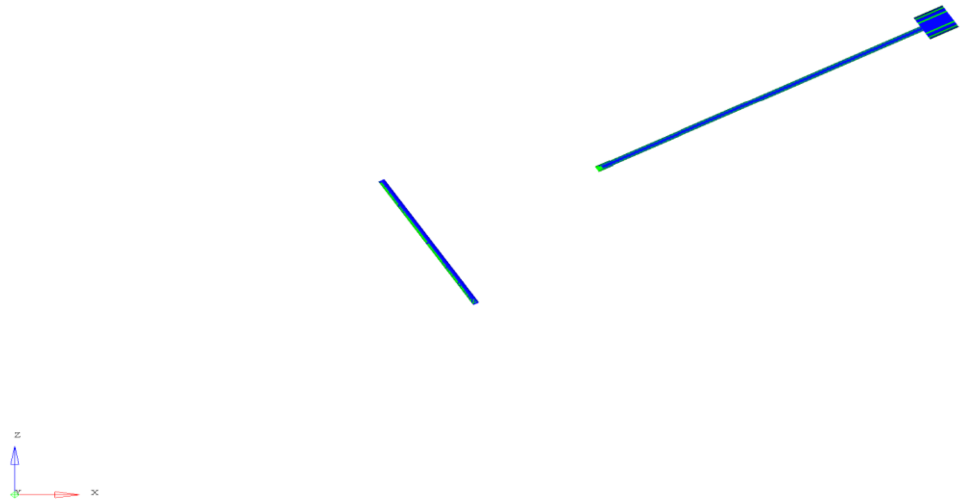


Top View

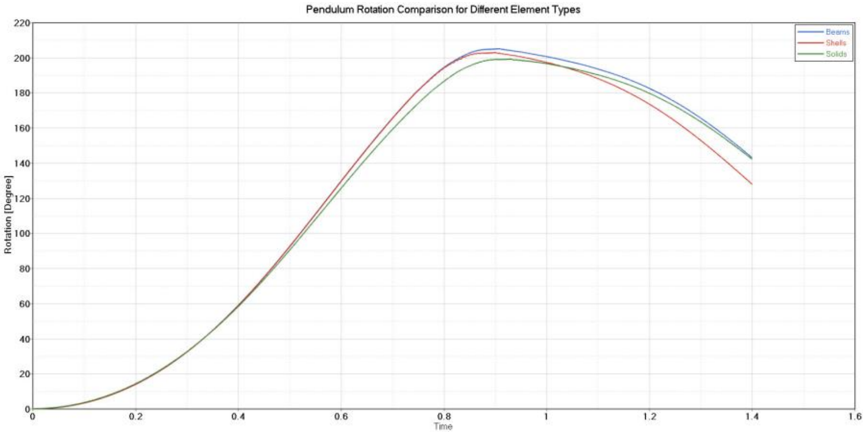




Flexible Pendulum: LS-Dyna - Beam, Shell, and Solid Elements



- **Model with solid elements moves slower resulting in a lower impact force and travel, possible numerical error**



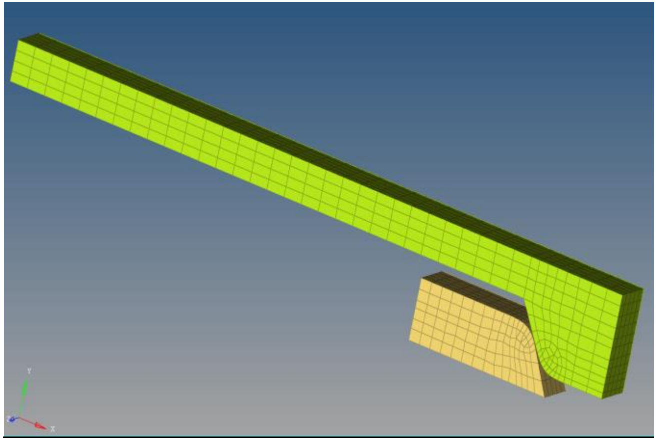
Model with shell elements should provide the best results

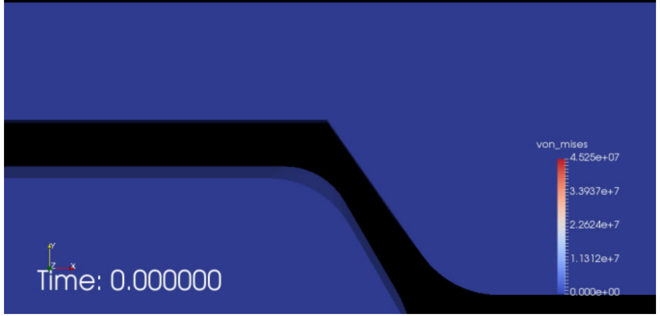
Flexible Pendulum: Summary

	MBD Solver			FE Solver (model decomposition not tuned)			Closed-Form Solution
Element Type	Flexlink	Flexbody	FE_Part	Beam	Shells	Solids	Beam Theory
Max rotation after contact (deg)	23.89	24.16	24.66	24.87	22.94	18.3	24.55
First Contact Force Peak Fm [N]	57.1	57.6	54.1	55.1	61.4	50.6	62.4
Max.Contact Force Fm [N]	109.4	114.6	107.2	108.3	121.1	96.3	
CPU Time	5 min	1 hour 36 min	15 min	5 min 30 sec	2 hours 30 min	17 hours	
Number of CPU cores	8	8	1 CPU	4	16	16	
Solver Type	GSTIFF, SI2	GSTIFF, SI2	GSTIFF, SI2	SMP	MPP/ MPI	MPP/MPI	
Number of elements	83 Parts	9508 solid elements	83 beams	192	2876	8380	
Notes	Rigid parts are connected through forces	Reduced FE model, 78 modes for each part	1 CPU core limitation	Adjusted Contact settings	Adjusted Contact settings	Element type not adequate for geometry	

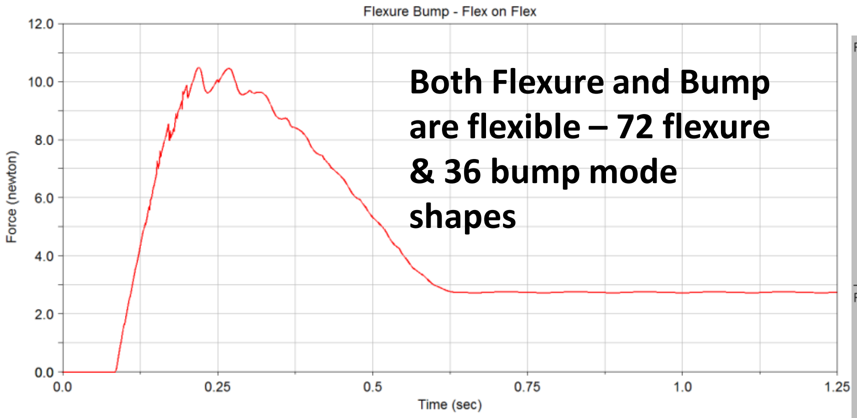
Benchmark Problem 2: Contact between a Flexure and a Bump

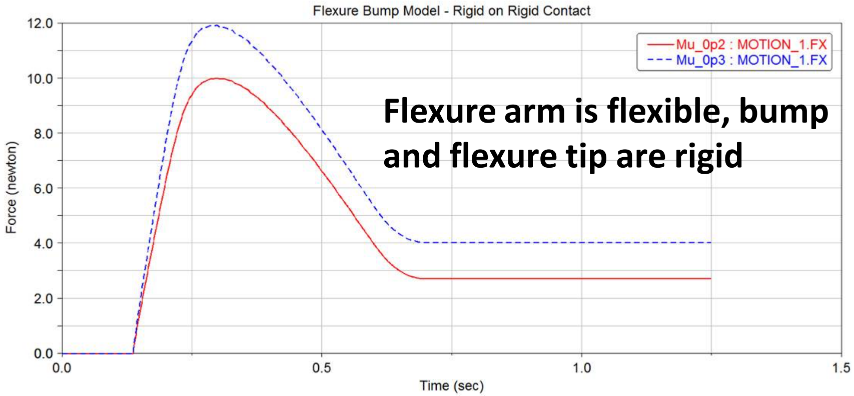
- Motivation for this problem:
  - Evaluate large displacement between two parts
  - Characterize semi stiff contact
- Bump angle is 60 degree and Flexure angle is 55 degrees, line contact
- ADAMS: Flexlink, Flexbody, and FE_Part
- LS-Dyna: Beam, shell, and solid
- Sierra: Beam, shell, and solid
- Peak forces are compared

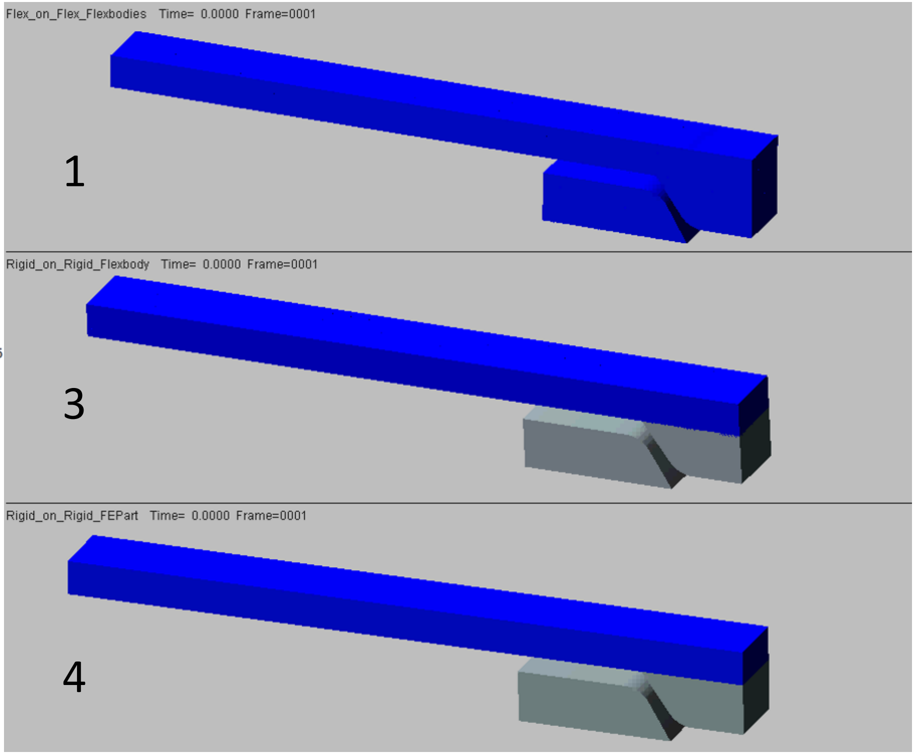




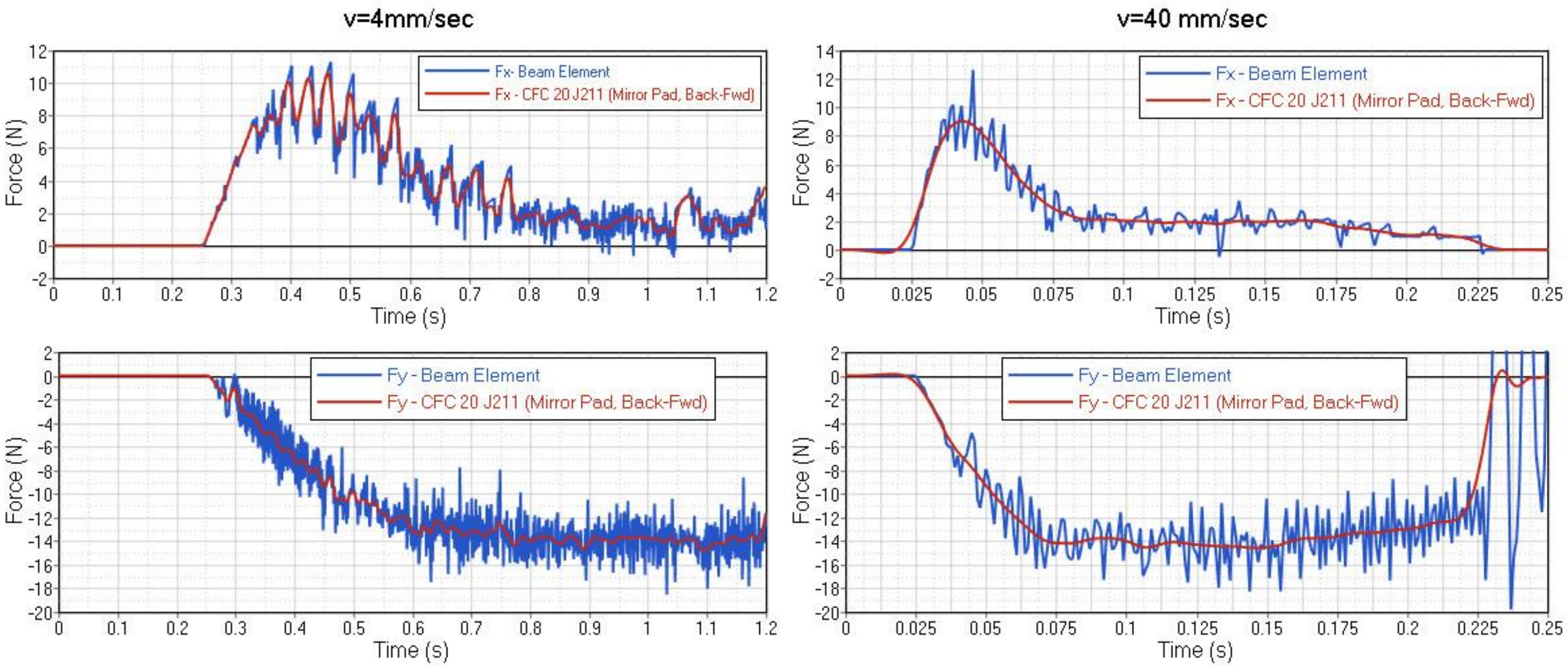
Flexure-Bump : ADAMS







Benchmark Problem 2: LS-Dyna – Beam Element/Rigid Contact



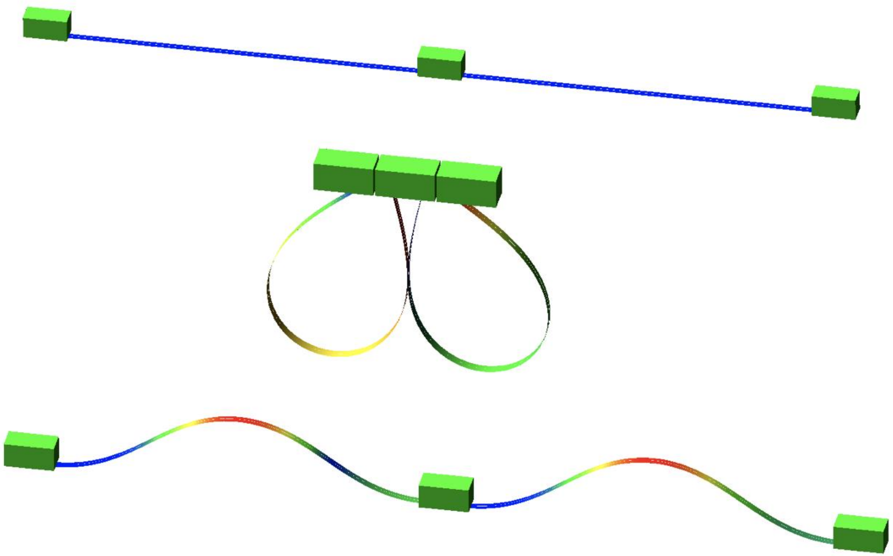
Flexure-Bump: Summary

Flexure and Bump Results for v=0.004 m/sec – Results Summary

Bump v=0.004 m/sec	MBD Solver			FE Solver (no reduced FE or mass scaling)		
Case Description	Element Type	Bump X-Force [N]	Runtime	Element Type	Bump X-Force	Runtime
Both flexure and bump are flexible	Solids (reduced FEA)	10.5	3 hours 50 mins	Solids	12.6 (10.2 N filtered)	8 hours 55 mins
Flexure is flexible bump is rigid	Solids (reduced FEA)	10.1	2 hours 4 mins	Solids	11.9 (10.2 N filtered)	8 hours 42 mins
Flexure arm is flexible, bump and flexure tip are rigid	Solids (reduced FEA)	10.0	Under 2 mins	Solids	13.0 (9.6 N filtered)	3 hours 8 mins
Flexure arm is flexible, bump and flexure tip are rigid	Beams (FE_Part)	10.0	Under 2 mins	Beams	11.9 (10.4 N filtered)	16 mins

Benchmark Problem 3: Double Straps

- Motivation for this problem:
  - Evaluate highly flexible parts with large displacements and contact
  - Establish stored strain energy
- Straps and moving cart are modeled in a deployed configuration
- Simulations:
  - Quasi-static stowing with gravity (ground)
  - Quasi-static deployment to determine deploying force
  - Dynamic deployment with gravity (ground)
  - Dynamic deployment without gravity (on-orbit)
- ADAMS: FE_Part, beam elements
- LS-Dyna: Shell elements
- Sierra: Shell elements
- Force profiles are compared

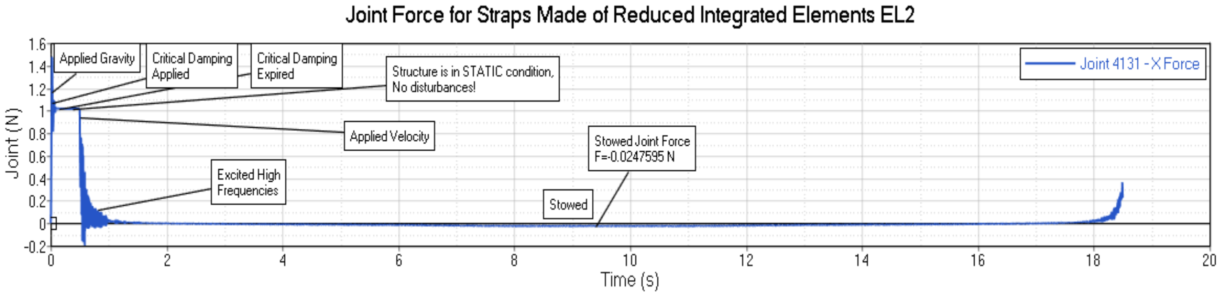


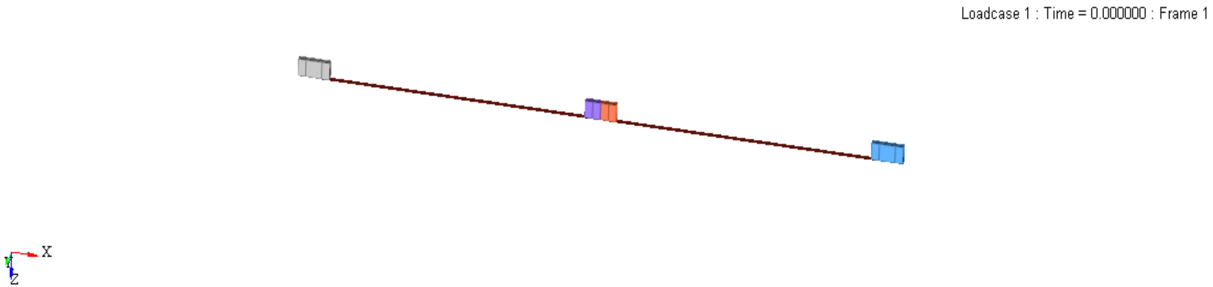
ADAMS: Deployed, stowed, during deployment

Double Straps: Summary

LS-Dyna simulation is shown

- Shell Elements
- Gravity was applied initially
- Velocity control was used for cart motion, applied at 0.5 sec after steady-state condition due to the gravity was achieved



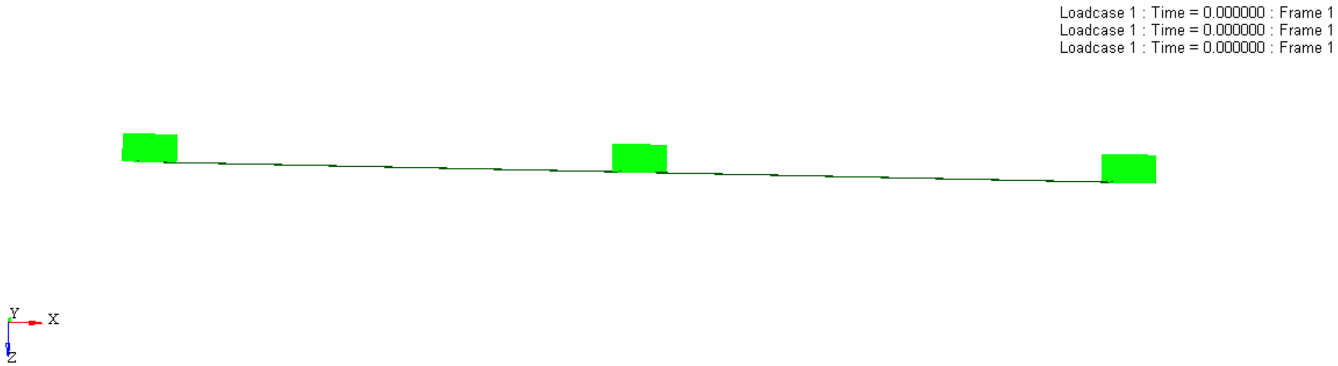


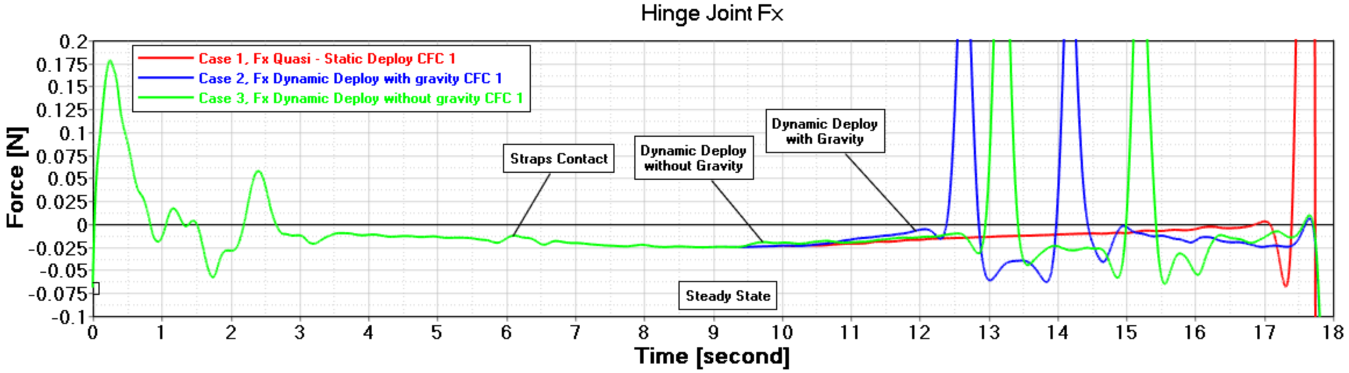
Runtime is about 1.5 hours

	ADAMS	LS-Dyna	Sierra
Element	Beam (FE_Part)	Shell	Shell
Maximum Stowing Force [N]	0.026	0.025	0.025

Double Straps: LS-Dyna – Shell Elements

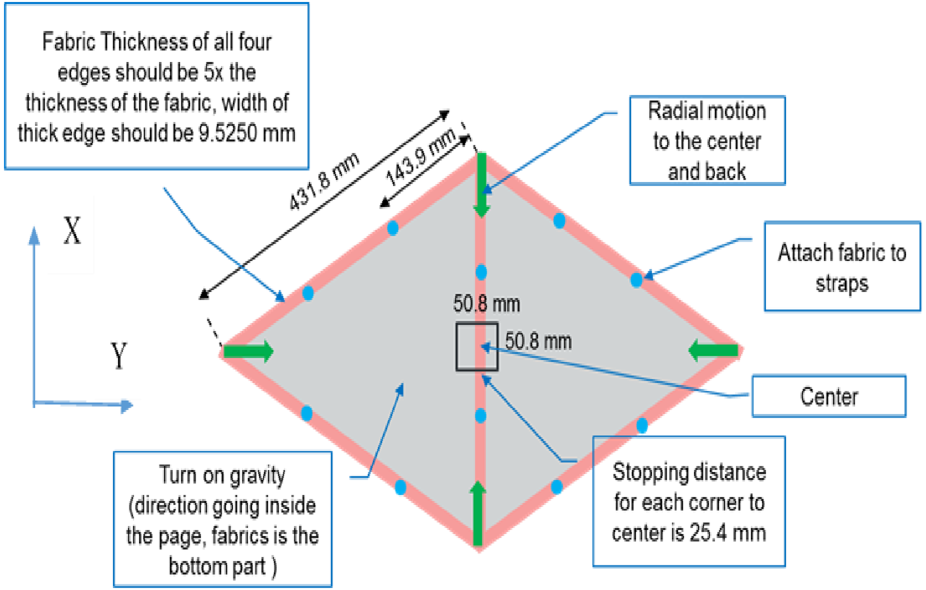
- Gravity was applied initially
- Displacement control was used for cart motion (step velocity), applied at 0.5 sec after steady-state condition due to the gravity was achieved





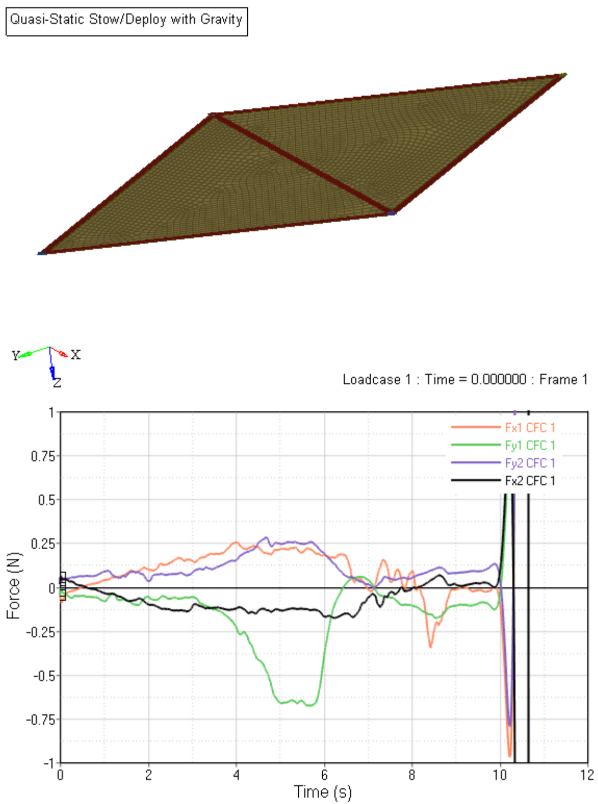
Benchmark Problem 4: Fabric & Straps

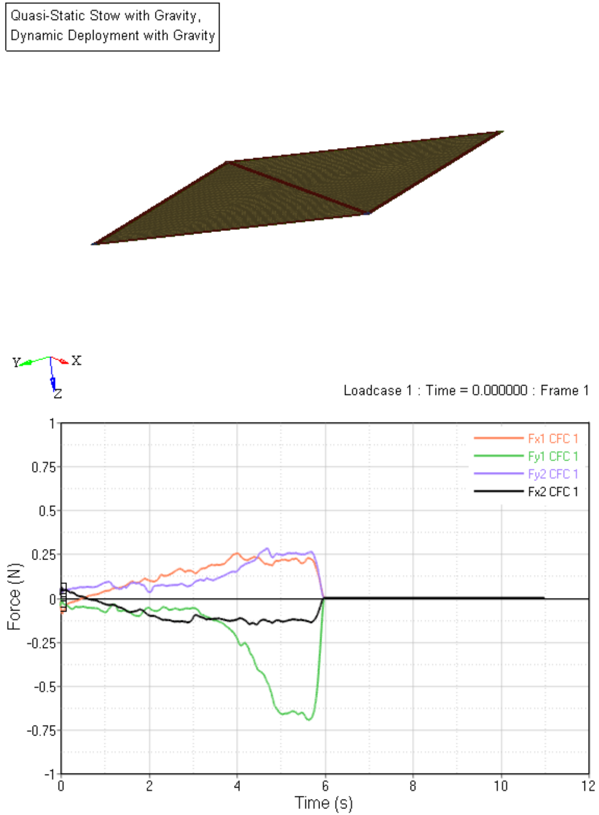
- Motivation for this problem:
  - Evaluate highly flexible parts with large displacements and contact
  - Establish stored strain energy
- Straps and moving cart are modeled in a deployed configuration
- Simulations:
  - Quasi-static stowing with gravity (ground)
  - Quasi-static deployment to determine deploying force
  - Dynamic deployment with gravity (ground)
  - Dynamic deployment without gravity (on-orbit)
- LS-Dyna: Shell elements simulating membrane only
  - Displacement control was used for applied motion
  - Both gravity and forced displacement started at time zero

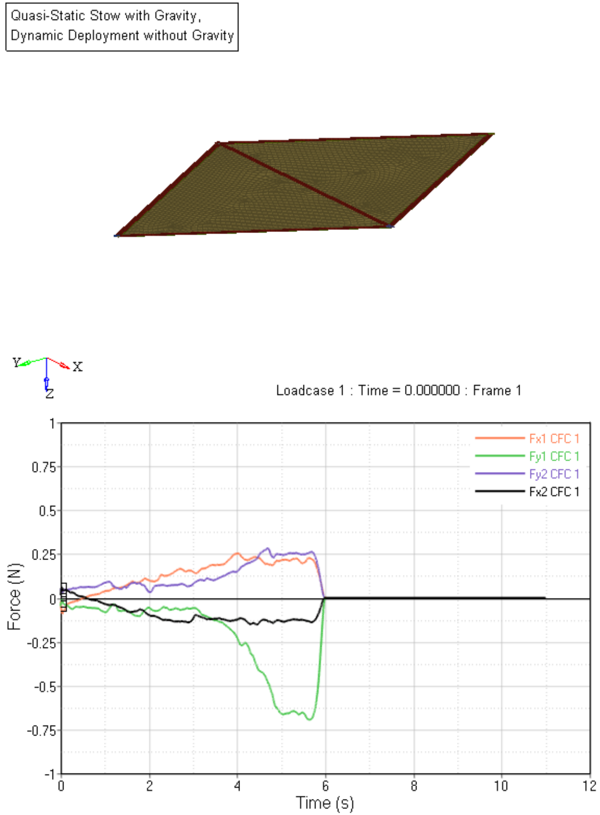


Fabric and Straps Model

Straps and Fabric



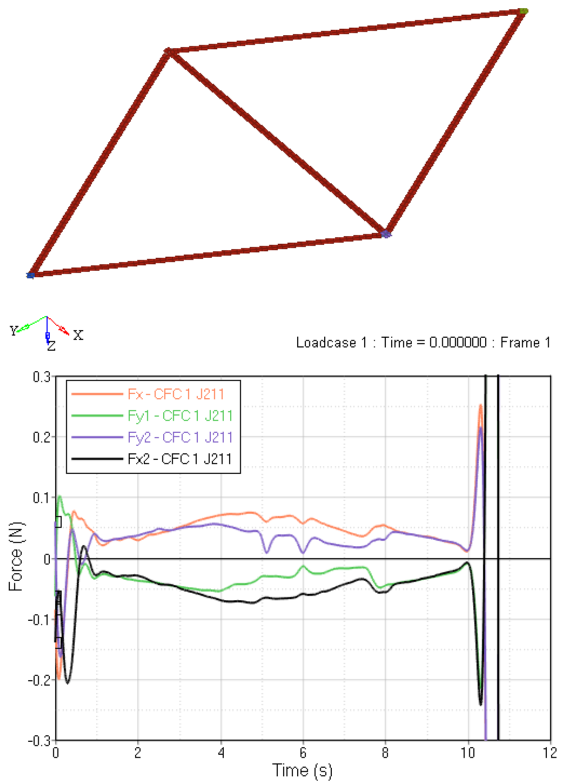




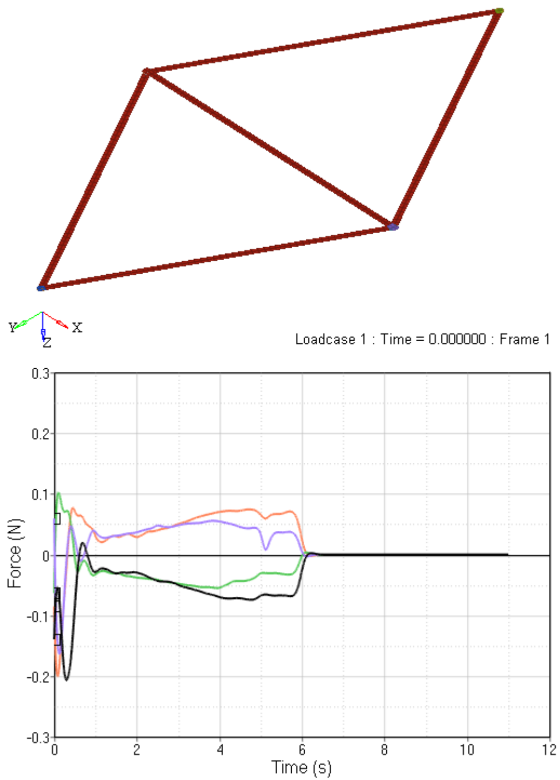
Runtime: 3.5 hours

Five Straps

Quasi-Static Stow/Deploy with Gravity

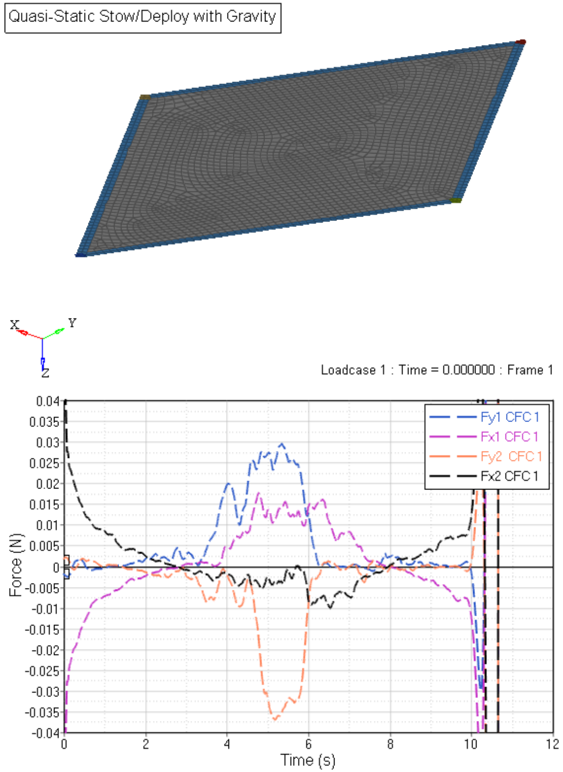


Quasi-Static Stow with Gravity, Dynamic Deployment with Gravity

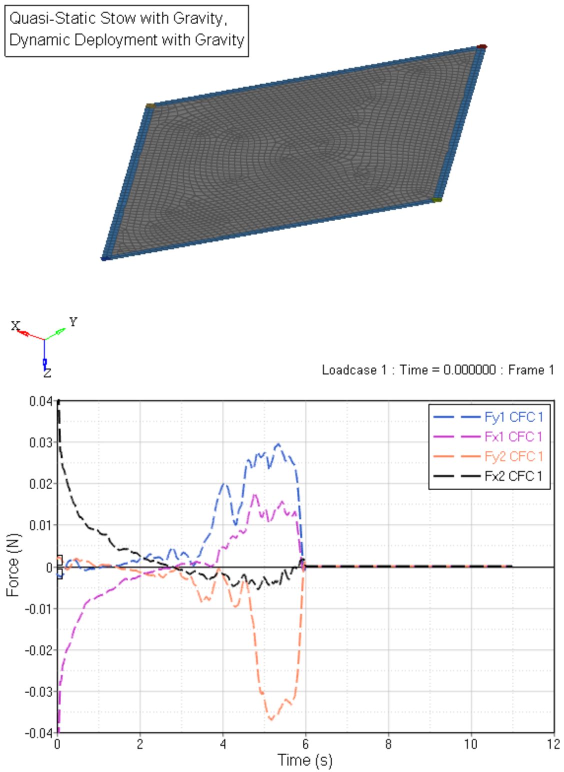


Quasi-Static Stow with Gravity, Dynamic Deployment without Gravity

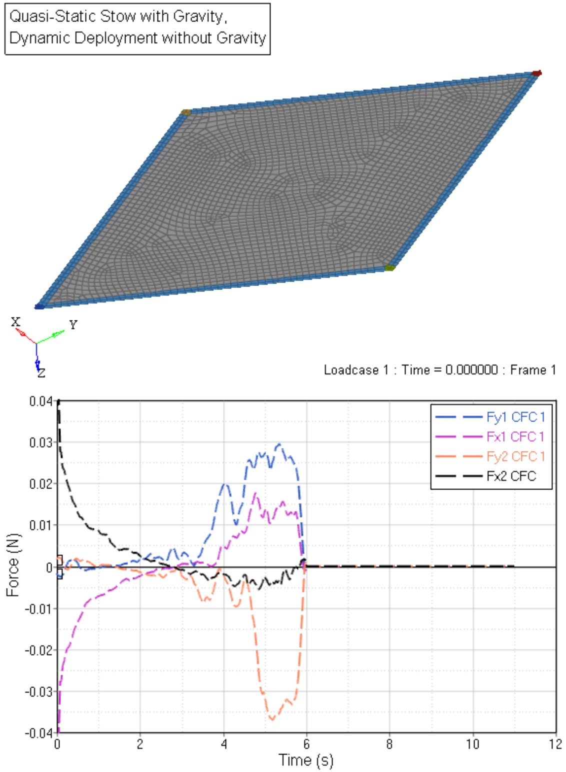
Fabric



Quasi-Static Stow/Deploy with Gravity
Loadcase 1 : Time = 0.000000 : Frame 1
Fy1 CFC 1
Fx1 CFC 1
Fy2 CFC 1
Fx2 CFC 1
Force (N)
Time (s)

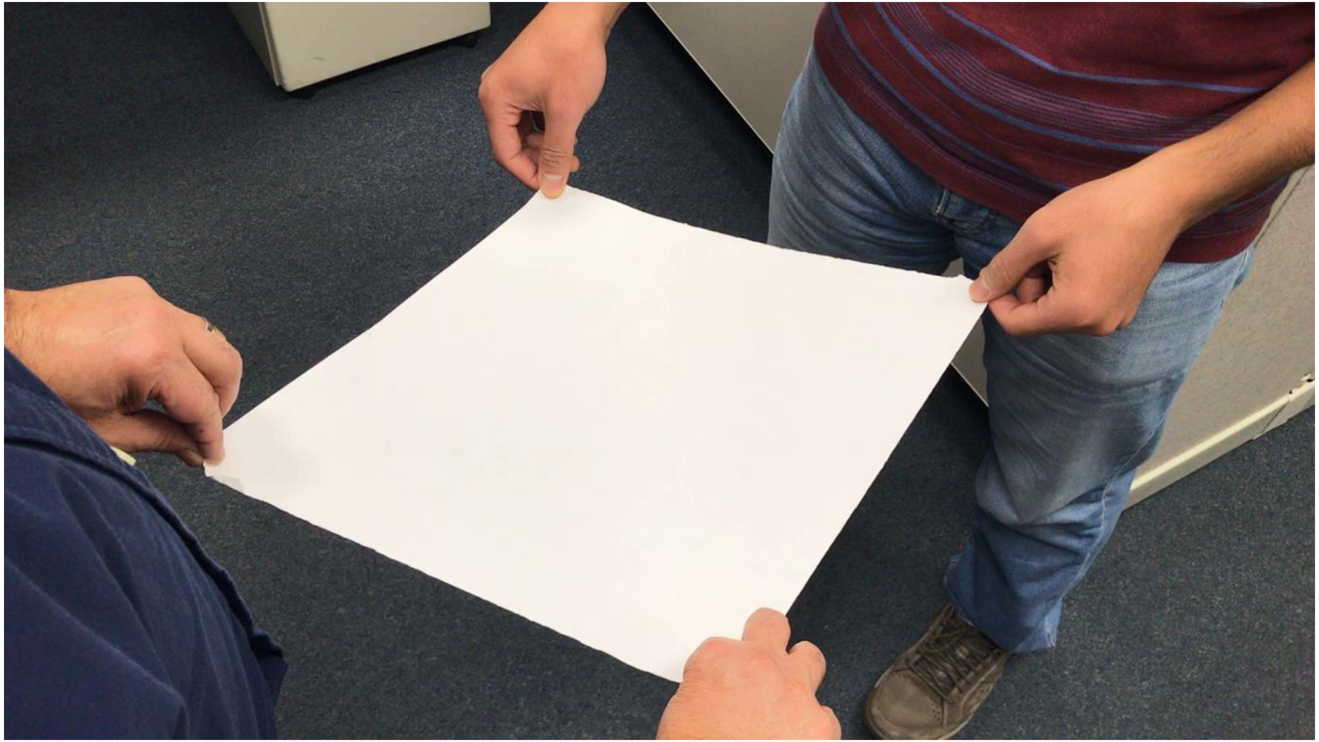


Quasi-Static Stow with Gravity,
Dynamic Deployment with Gravity
Loadcase 1 : Time = 0.000000 : Frame 1
Fy1 CFC 1
Fx1 CFC 1
Fy2 CFC 1
Fx2 CFC 1
Force (N)
Time (s)

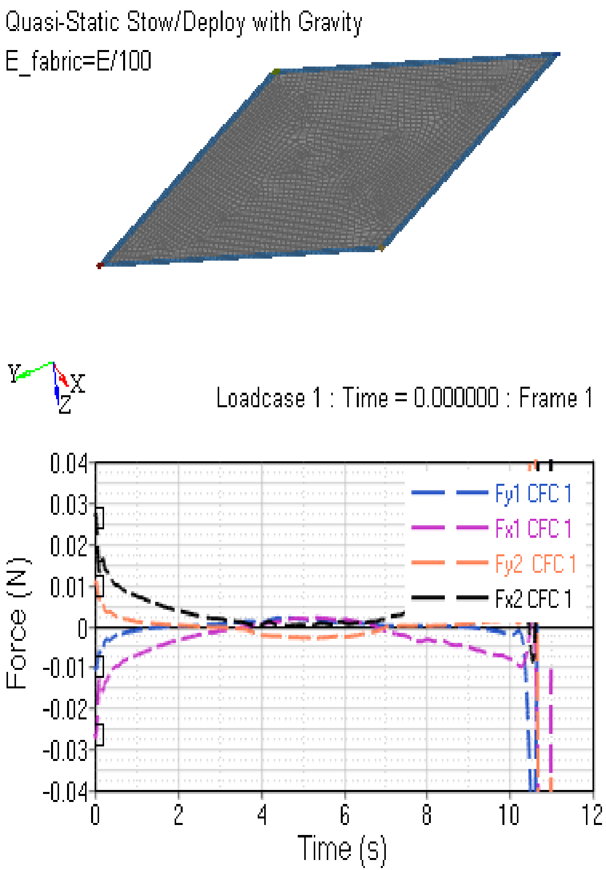


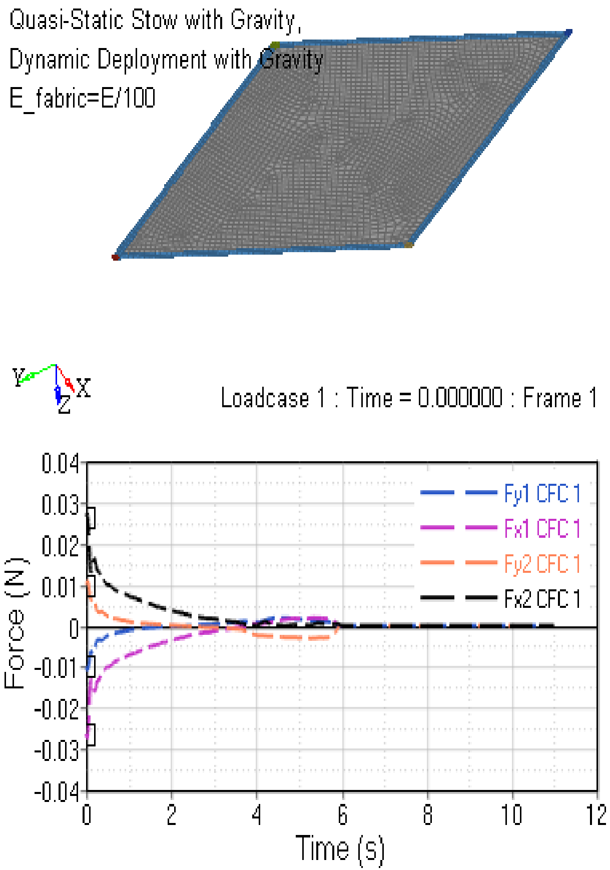
Quasi-Static Stow with Gravity,
Dynamic Deployment without Gravity
Loadcase 1 : Time = 0.000000 : Frame 1
Fy1 CFC 1
Fx1 CFC 1
Fy2 CFC 1
Fx2 CFC
Force (N)
Time (s)

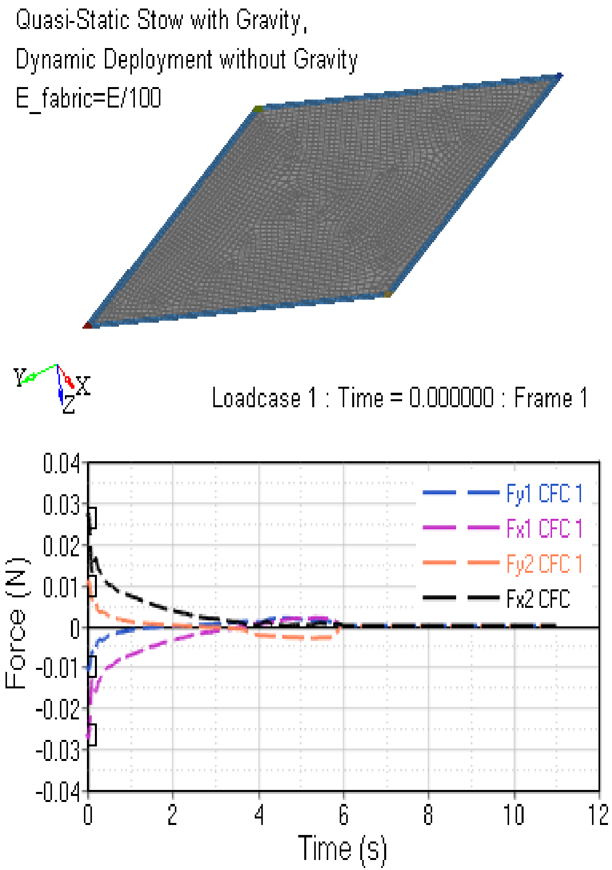
Fabric



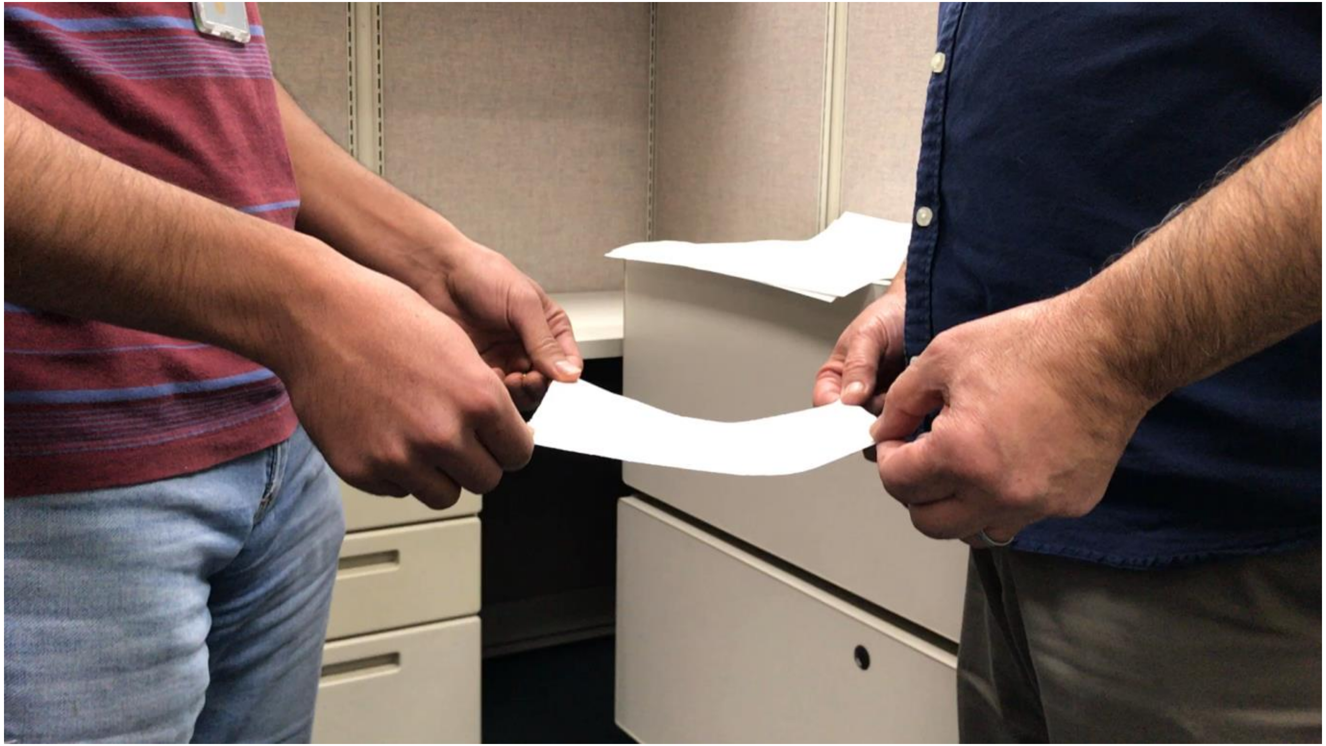
Fabric – More Flexible by a factor of 100



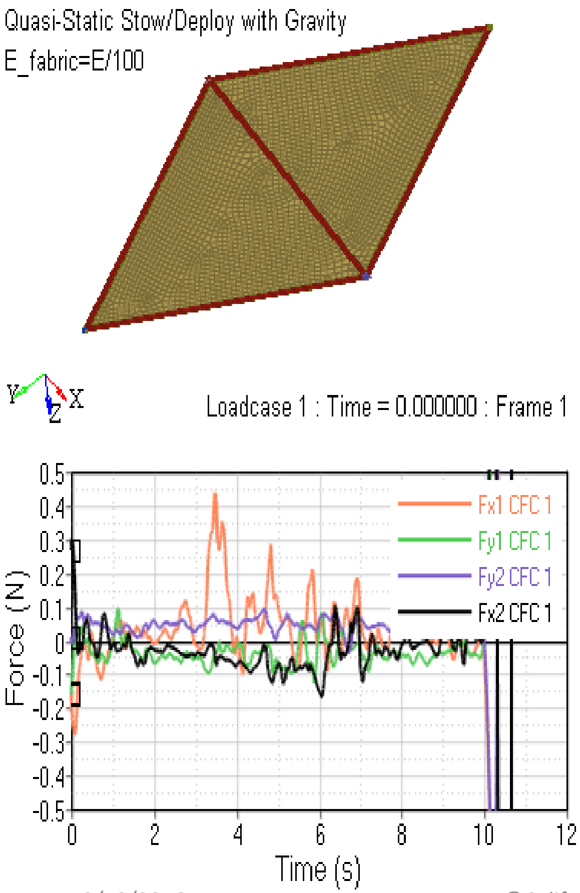


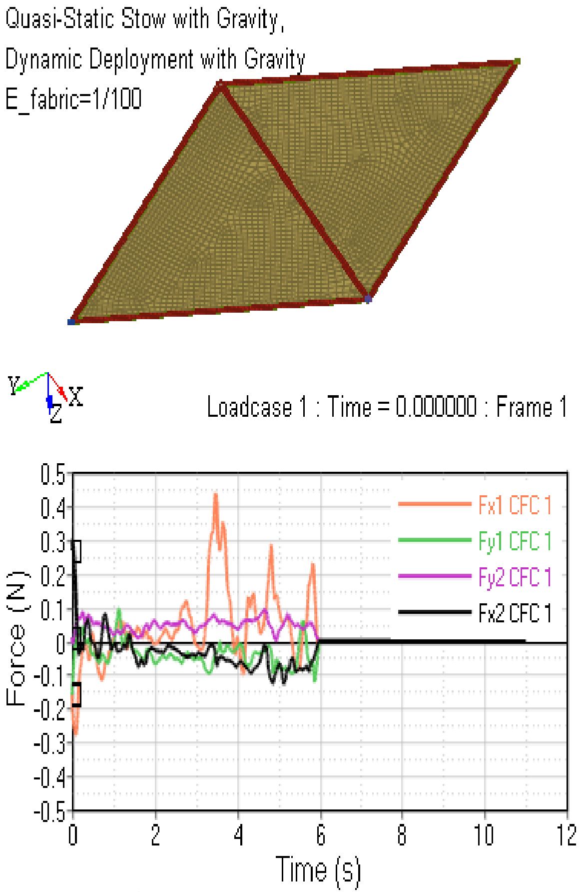


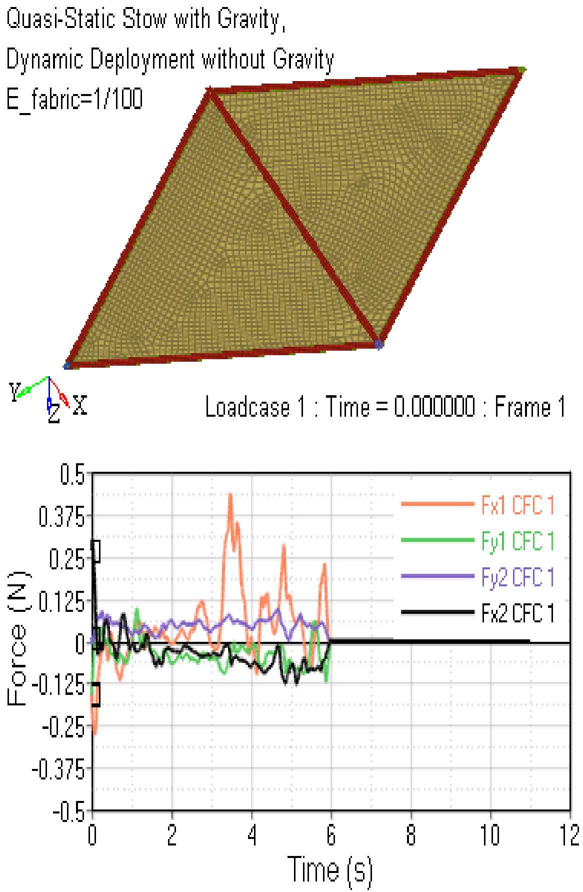
Fabric – More Flexible by a factor of 100



Fabric and Straps – Fabric, More Flexible by a factor of 100







Conclusion

- Benchmarks are introduced for evaluating the performance of numerical simulations of space deployable structures with:
  - Large angle motion, contact between flexible bodies, and the presence of both soft and stiff mechanical components
- The benchmarks were used in companion studies to evaluate the ADAMS multi-body dynamics code[1], the LS-Dyna nonlinear FE code[2], and the Sierra large scale parallel nonlinear FE code
- All three codes could be used for these benchmarks
  - May lead to larger scale, higher fidelity simulations in the future
- Task continuation by modeling and analyzing a much larger sub-assembly problem applicable to current projects at JPL

[1] To be published in near future
[2] To be published in near future