Jet Propulsion Laboratory
California Institute of Technology

Modeling and Simulation Challenges for Softgoods in Space Deployable Structures

Authors: Velibor Cormarkovic, presenter
Lee D. Peterson Ph.D.,
Mehran Mobrem Ph.D.

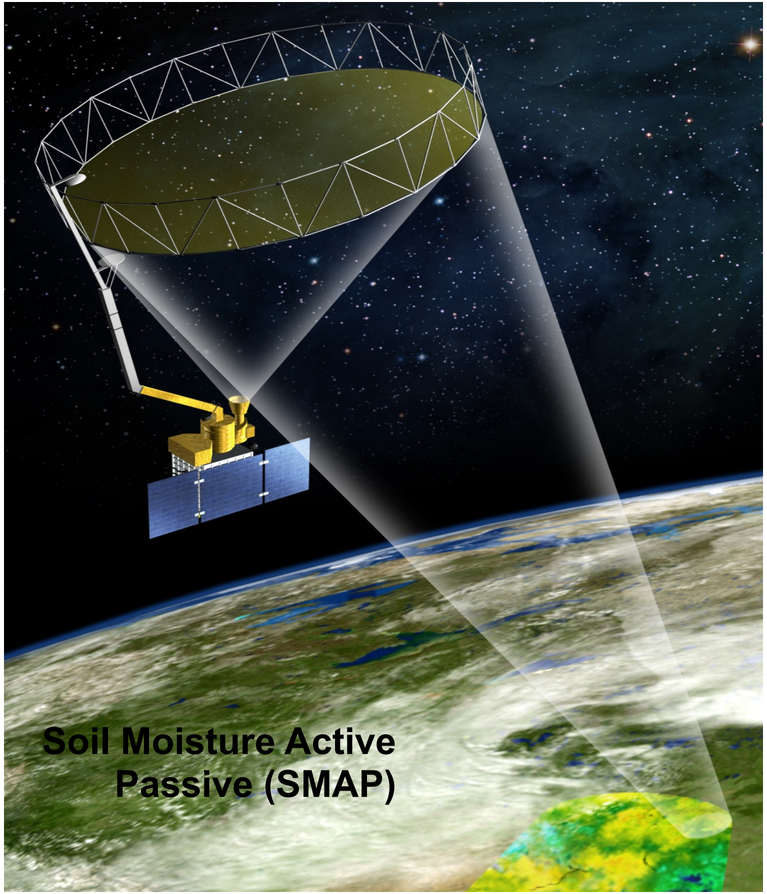
01/07/2019

AGENDA

- Introduction
- Simulation Scenarios and Benchmark Problems
  - Structure of Interest
- Results for Benchmark Problems
- Results Summary
- Conclusions and Recommendations

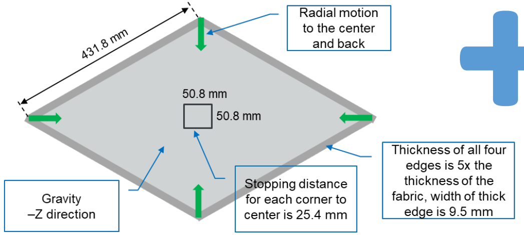
Introduction

- Advance techniques for large deployable space structures with softgoods components, work continuation by Mehran Mobrem et al. "*An Evaluation of Structural Analysis Methodologies for Space Deployable Structures*", AIAA SciTech 2017
  - Design, deployment behavior, anomalies insight
  - Verification prior to flight
- "Softgoods" are high compliance components with large angle unfolding during deployment
- Traditionally, multi-body dynamics solvers have been used, with limitations in:
  - Modeling slack in soft-goods material or local mechanism details and imperfections, which prevents investigating possible snags and anomalies
- LS-DYNA explicit and implicit solvers can be viable solution

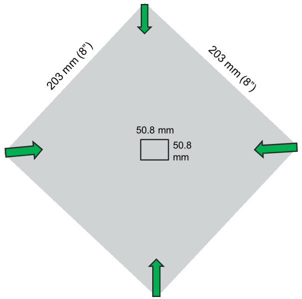


Structure of Interest

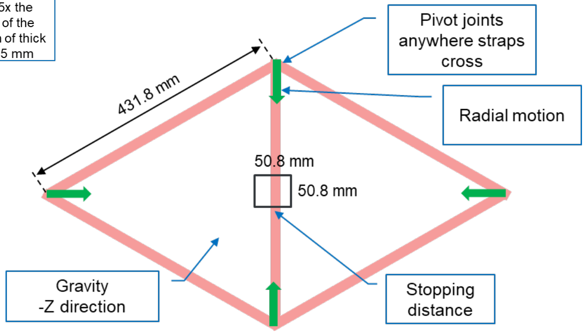
Benchmark Problem 1 (Printer Paper)



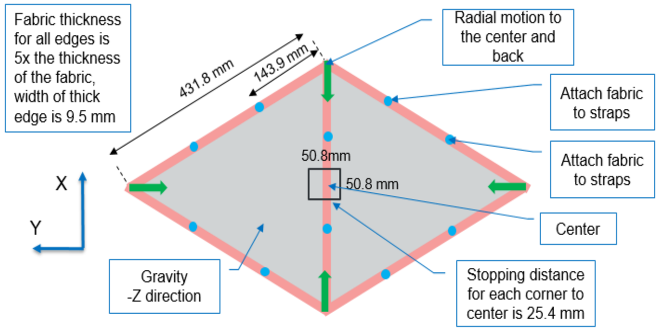
Benchmark Problem 2 (Tissue Paper)



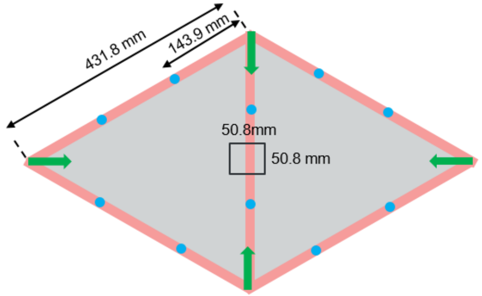
Benchmark Problem 3 (Five Straps)



Benchmark Problem 4 (Five Straps with Printer Paper)



Benchmark Problem 5 (Five Straps with Tissue Paper)



Benchmark Problems

			Used for Testing			
	Description	Compared to test	Folding	Stow Forces	Stored strain energy	Contacts
1	Fabric Only, Printer Paper Fabric stiffness equivalent to printer paper	√	√	√	√	√
2	Fabric Only, Tissue Paper Tissue paper stiffness ≈ (Printer Paper stiffness)/100	√	√	√	√	√
3	Five Straps, No Fabric		√	√	√	√
4	Five Straps with Printer Paper Combined BP 1 and BP 3		√	√	√	√
5	Five Straps with Tissue Paper Combined BP 2 and BP 3		√	√	√	√

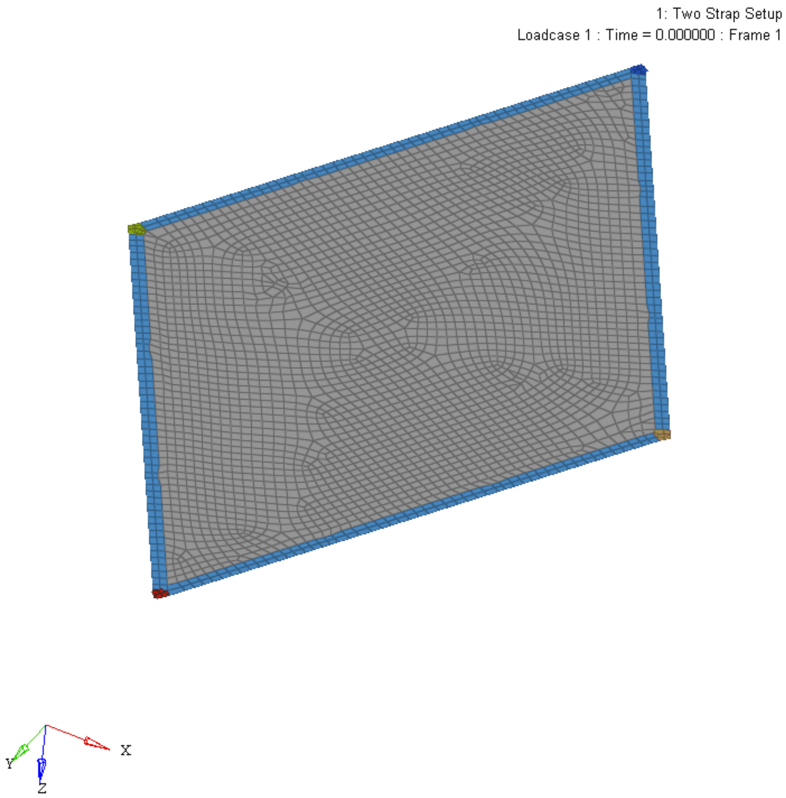
Simulation Scenarios

- Three simulation scenarios representing aspects of ground stow, deployment mechanics and on-orbit deployment mechanics are applied to five benchmark problems

Simulation Scenario	Quasi-Static Stow	Quasi-Static Deployment	Dynamic Deployment	Used to Test
1	1 g gravity	1 g gravity	-	• Repeatable results • Similar loads are generated in both directions
2	1 g gravity	-	1 g gravity	• Sudden release of restraints holding stowed structure together • Analytical model validation against on-ground test
3	1 g gravity	-	No gravity	• On-orbit bloom effects on spacecraft attitude in the orbit environment

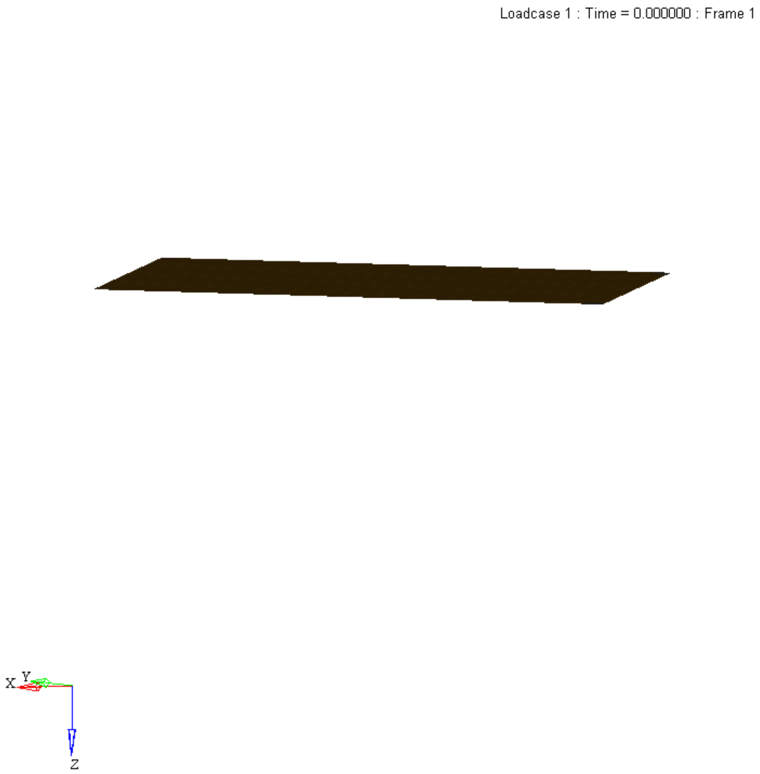
RESULTS

Folding Fabric (Printer Paper) Simulation v. Test



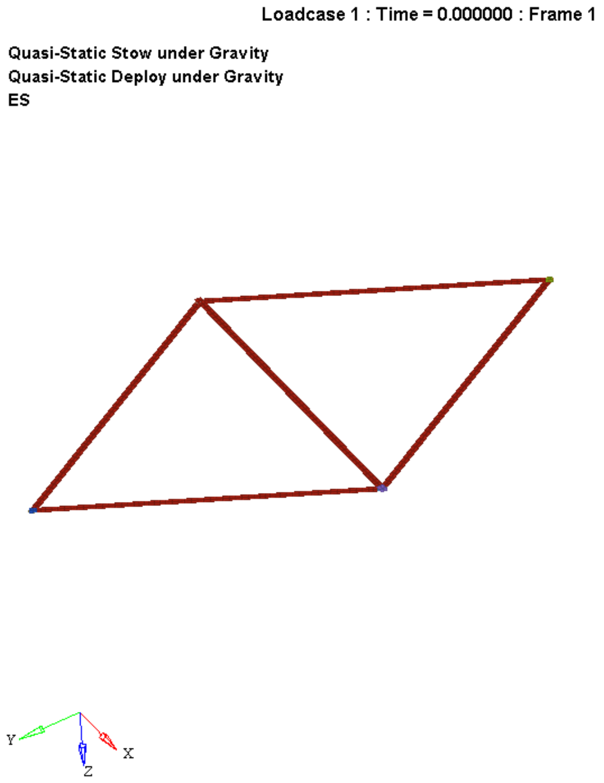
Good qualitative deformation agreement for folding fabric (Printer Paper)

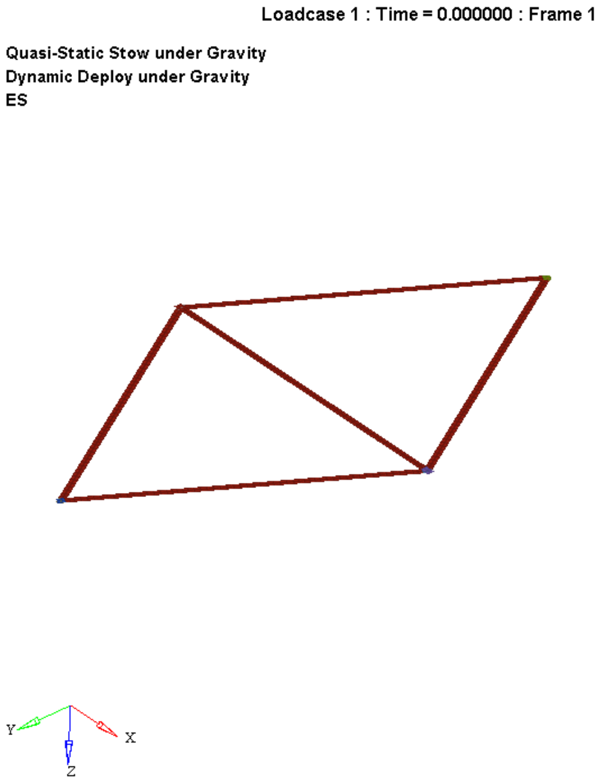
Folding Fabric (Tissue Paper) v. Test

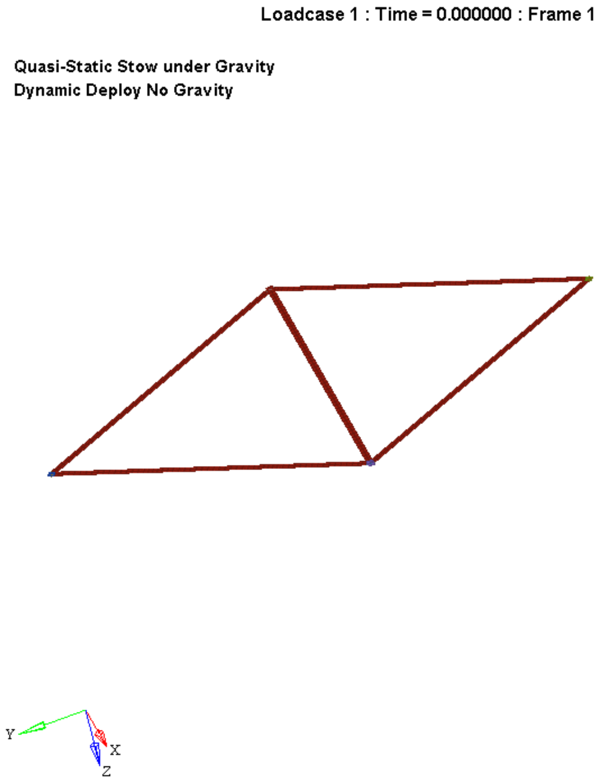


Tissue Paper has good qualitative deformation agreement with test

Deformation for Five Straps

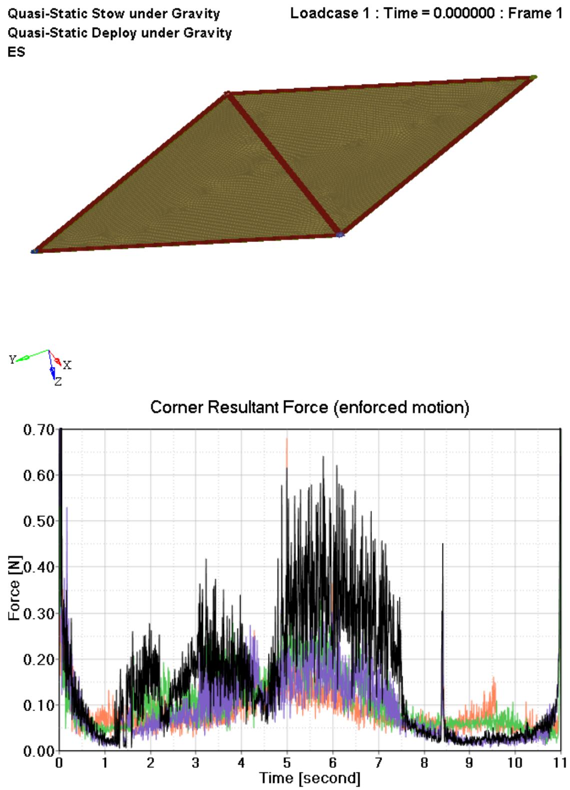


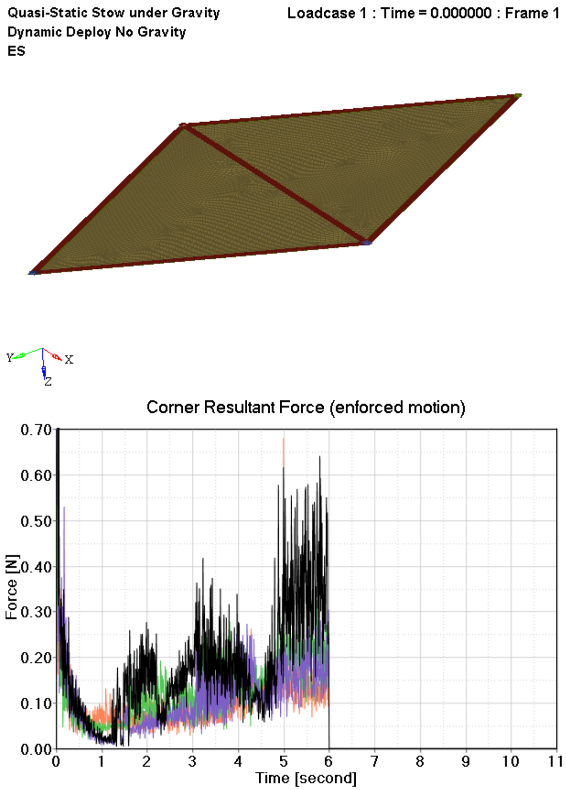


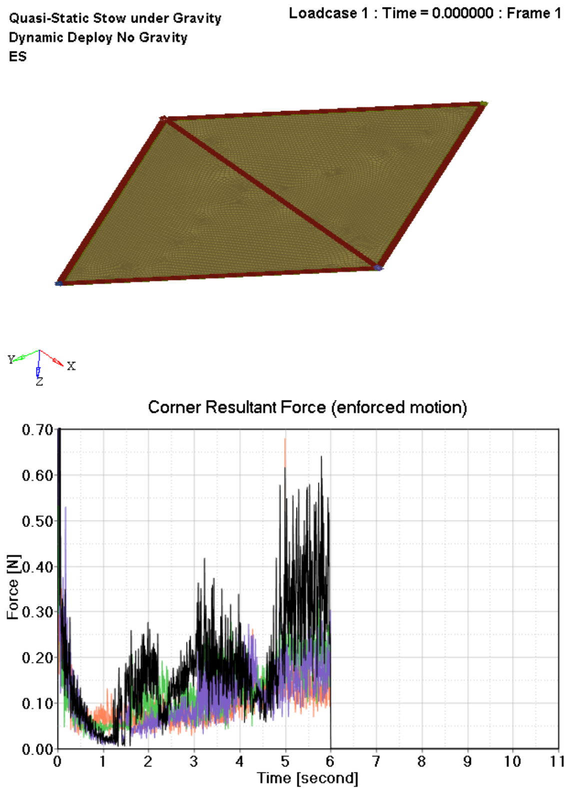


Five Straps benchmark problem has expected deformation shapes

Fabric (Printer Paper) Attached to Five Straps

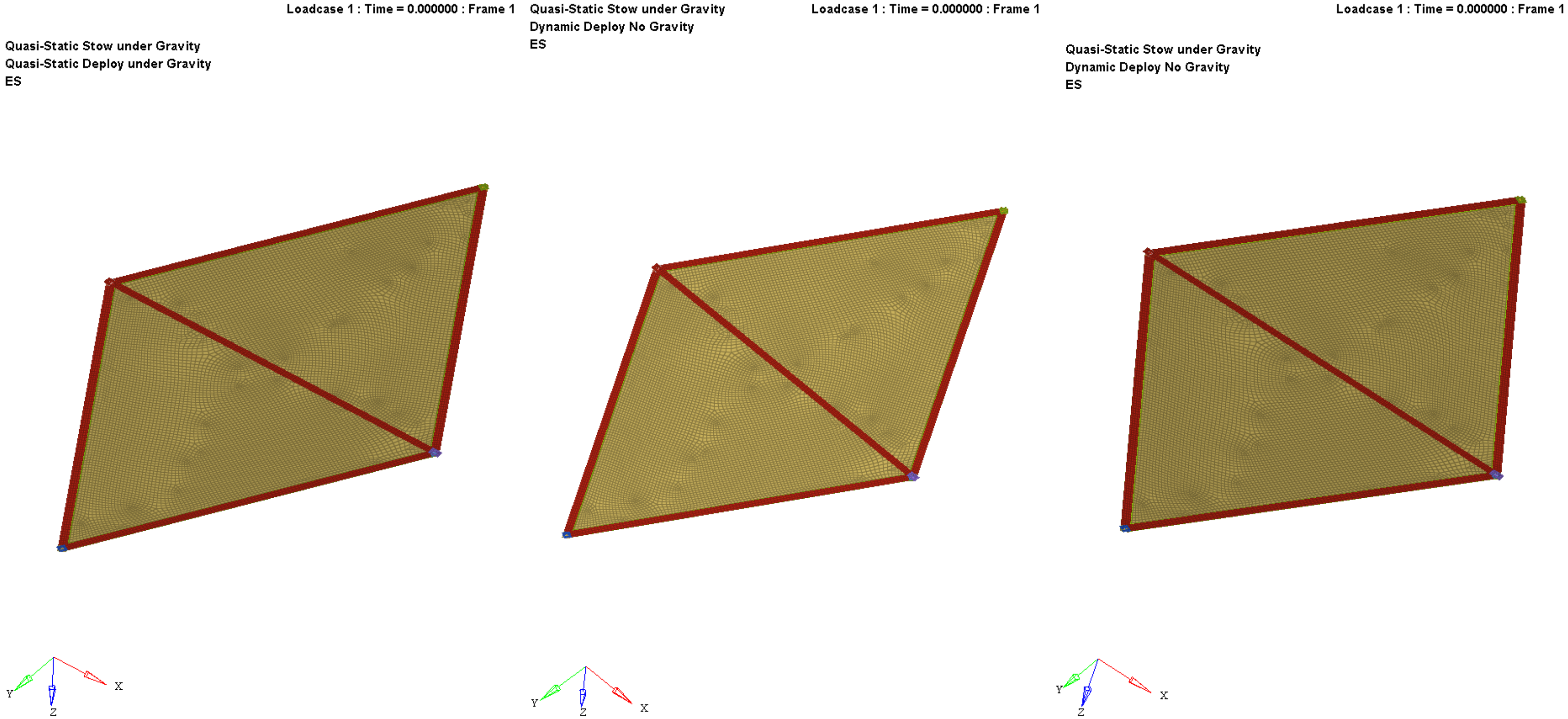






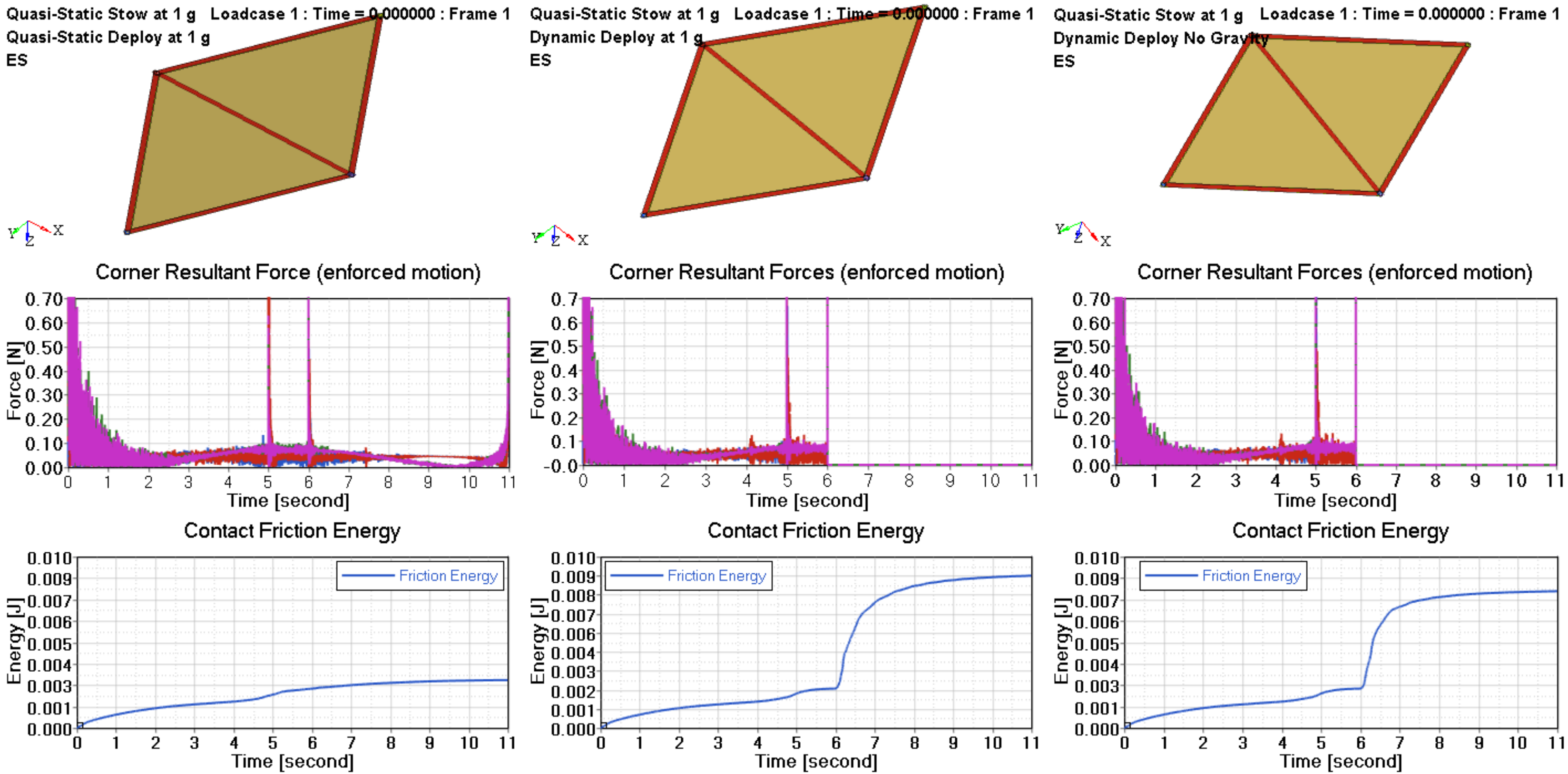
Explicit solver force time history results have expected and consistent time history

Fabric (Tissue Paper) Attached to Five Straps



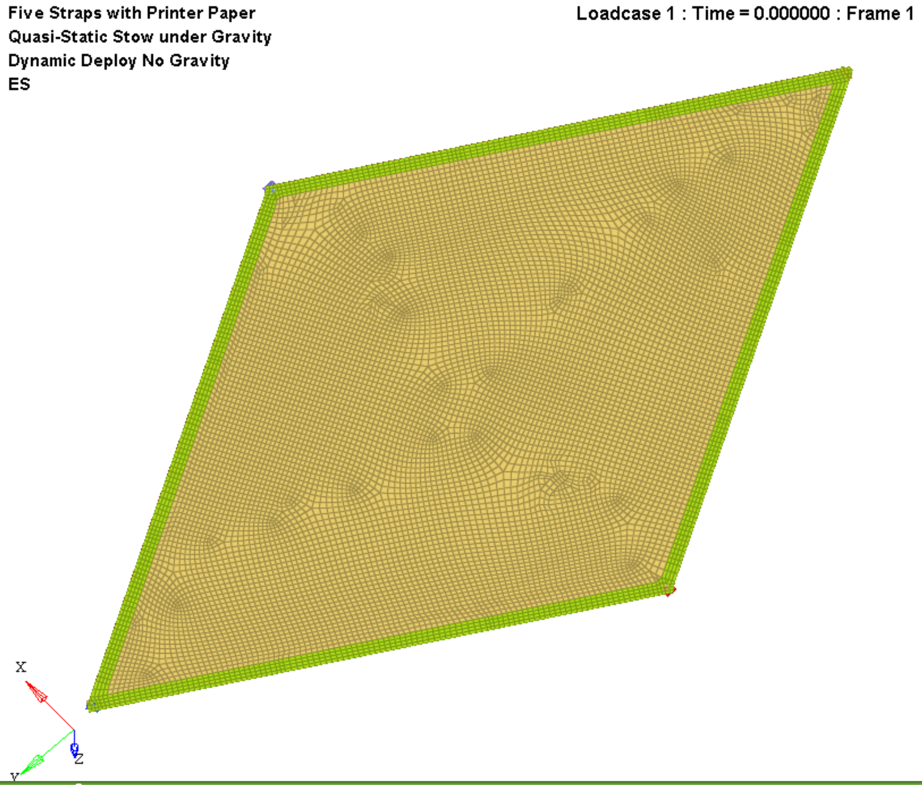
Five Straps with Tissue Paper benchmark problem has expected deformation shapes

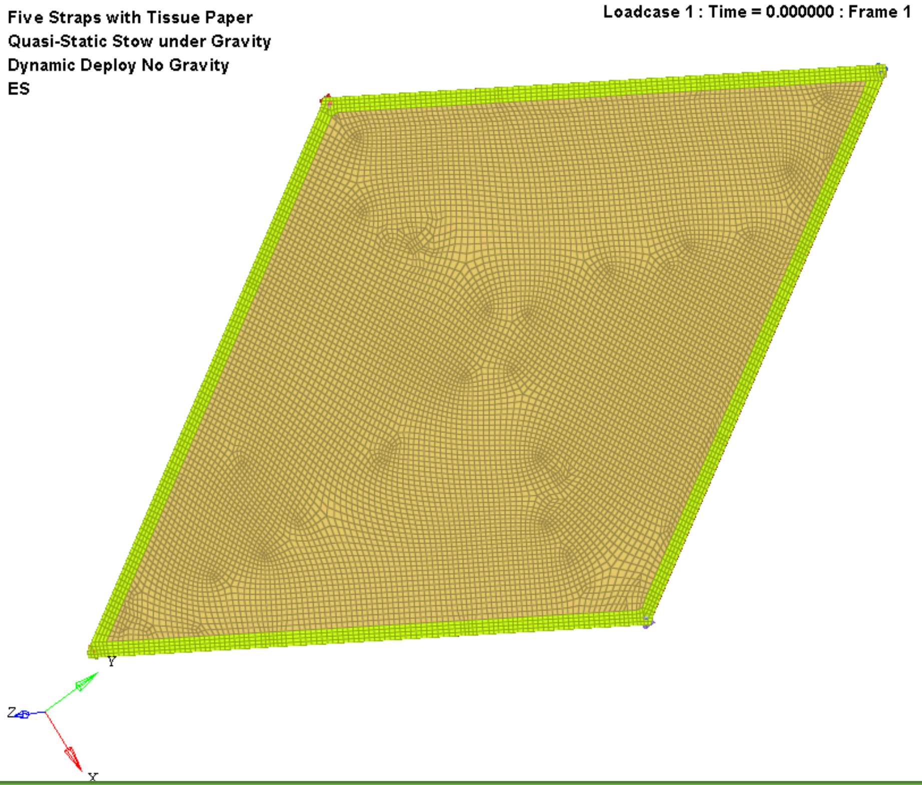
Fabric (Tissue Paper) Attached to Five Straps



Low stow forces and low contact sliding energy

Comparison: Benchmark 4 v. Benchmark 5





FE/mesh for fabrics are shown, comparison of Benchmark 4 and Benchmark 5 have expected deformation shapes

Results Summary for Stow Forces

Result Summary for Stow Force		Simulation Scenario Description		
		Quasi-Static Stow		
- = IS not converging on a solution		Quasi-Static Deploy with Gravity	Dynamic Deploy with Gravity	Dynamic Deploy No Gravity (On-orbit)
Benchmark Problem	Stow Force	IS (ES)	IS (ES)	IS (ES)
#1 Printer Paper	F_R-Stowed [N]	0.09* (0.1)	0.03* (0.1)	0.08 (0.1)
#2 Tissue Paper		- (0.001)	- (0.001)	- (0.001)
#3 Five Straps		0.07 (0.1)	0.07 (0.1)	0.06 (0.1)
#4 Printer Paper and Five Straps		- (0.6)	- (0.6)	- (0.6)
#5 Tissue Paper and Five Straps		- (0.1)	- (0.1)	- (0.1)

* The difference is due to different releases of software used to obtain the results

Stow forces have expected trend

Results Summary for Run Time, CPUs and Solver Type

Results Summary for Run Time		Quasi-Static Stow		
- =IS not converging on a solution		Quasi-Static Deploy with Gravity	Dynamic Deploy with Gravity	Dynamic Deploy No Gravity (On-orbit)
Benchmark Problem		IS (ES)	IS (ES)	IS (ES)
#1 Printer Paper	Number of CPU cores / Solver	16 (8)/MPP	16 (8)/MPP	16 (8)/MPP
	Run time	1.75 h (2.5 h)	1.5 h (2.5 h)	1.4 h (2.5 h)
#2 Tissue Paper	Number of CPU cores / Solver	- (1/SMP)	- (1/SMP)	- (1/SMP)
	Run time	- (40 min)	- (40 min)	- (40 min)
#3 Five Strap	Number of CPU cores / Solver	1/SMP (8/MPP)	1/SMP (8/MPP)	1/SMP (8/MPP)
	Run time	1 h (3.25 h)	1 h (3.25 h)	6.8 h (3.25 h)
#4 Printer Paper and Five Straps	Number of CPU cores / Solver	- (40/MPP)	- (40/MPP)	- (40/MPP)
	Run time	- (15.1 h)	- (15.1 h)	- (15.1 h)
#5 Tissue Paper and Five Straps	Number of CPU cores / Solver	- (40/MPP)	- (40/MPP)	- (40/MPP)
	Run time	- (15 h)	- (15.15 h)	- (15.1 h)

The run times are reasonably low

Benchmark Problems Results Summary

Fabric Only, Printer Paper, both solvers completed the simulation

- Good qualitative deformation agreement between simulation and test at stow
- Small discrepancy in implicit solver stow force due to different software releases use

Fabric Only, Tissue Paper, explicit solver completed the simulation

- Good qualitative deformation agreement between simulation and test at stow

Five Straps, No Fabric, both solvers completed the simulations

- Good agreement in stow forces

Five Straps with Printer Paper, explicit solver completed the simulation

- The stow force increase due to addition of Printer Paper to the structure

Five Straps with Tissue Paper, explicit solver completed the simulation

- Stow force is closer to Five Straps due to factor of a hundred drop in fabric stiffness

About Implicit and Explicit Solvers, Based on Own Experience

	Implicit	Explicit
Used for	Static, low frequency dynamic	Dynamic loading, transient, oscillatory, high frequencies
Deformation and motion	Linear and moderate nonlinear	Highly nonlinear
Material models	Limited	Robust
Contact Algorithms	Limited	Robust
Stability	Unconditionally stable	Conditionally stable
Time step	Large	Small (Upper limit per Courant–Friedrichs–Lewy condition)
Convergence	Require global convergence per time step Inverts global matrix	Doesn’t assemble global matrix, only element matrix
Matrix Inversion	Non-diagonal global matrix, not easy to invert	Diagonal element only matrix, easy to invert
CPU requirement	High	High
Memory Requirement	High (large RAM memory and hard disk space to invert the global matrix)	Low
Software robustness	Not as robust (Null Pivots, Divergence) Doesn’t require high quality mesh	Robust for complex problems and large assemblies Require high quality mesh

Conclusions and Recommendations

- Both explicit and implicit solvers can be viable solutions to simulate softgoods in deployable structures

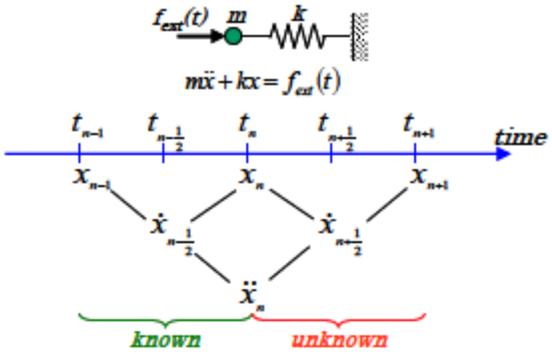
- The explicit solver was able to compute all benchmark problems, having reasonable run time and acceptable results.
    - The run time for large deployable structures made of many components (order of 1000) is not practical if deployment time is long (~ 1 hour), may limit solver use for uncertainty quantification

- The implicit solver solved two out of five benchmark problems, Printer Paper and Five Straps.
    - The results are similar and with shorter run time compared to those of explicit solver
    - Convergence parameter tuning required to solve more problems accurately
    - Solver improvements required to analyze complex deployable structures with long duration deployment time

- Task continuation by analyzing larger sub-assembly problem applicable to current JPL projects

BACKUP SLIDE

European Cooperation for Space Standardization



Explicit integration scheme (Central Difference Calculation)	Implicit integration scheme (Newmark-beta method β=1/4, γ=1/2)
$\ddot{x}_n = \frac{f_{Ext}(t_n)-kx_n}{m} = \frac{f_{Ext}(t_n)-f_{Int}(t_n)}{m}$	$x_{n+1} = \left(\frac{4m}{\Delta t^2}+k\right)^{-1}\left[f_{Ext}(t_{n+1})+m\left(\frac{4}{\Delta t^2}x_n+\frac{4}{\Delta t}\dot{x}_n+\ddot{x}_n\right)\right]$
$\dot{x}_{n+\frac{1}{2}} = \dot{x}_{n-\frac{1}{2}}+\ddot{x}_n\Delta t_n$	$\ddot{x}_{n+1} = \frac{4}{\Delta t^2}(x_{n+1}-x_n)-\frac{4}{\Delta t}\dot{x}_n-\ddot{x}_n$
$x_{n+1} = x_n+\dot{x}_{n+\frac{1}{2}}\Delta t_{n+\frac{1}{2}}$	$\dot{x}_{n+1} = \dot{x}_n+\frac{1}{2}\Delta t(\ddot{x}_n+\ddot{x}_{n+1})$

Figure 9-3: Principle of implicit and explicit integration scheme on a SDOF system

Space engineering Mechanical shock design and verification handbook, European Cooperation for Space Standardization, **ECSS Secretariat ESA-ESTEC, Requirements & Standards Division Noordwijk, The Netherlands, ECSS-E-HB-32-25A** 14 July 2015