Modeling and Simulation Challenges for Softgoods in Space Deployable Structures

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This paper examines modeling and simulation challenges for deployable spacecraft structures with softgood components. Previous studies highlighted the numerical challenges due to the mixture of high stiffness and low stiffness contact in this class of structures. This paper examines the use of the commercial LS-DYNA nonlinear finite element code on a set of relevant benchmark problems. These benchmarks combine frictional contact and geometrically nonlinear large motion in simplified models that include a wide range of relative stiffnesses. This study compares the effectiveness of the LS-DYNA implicit and explicit solvers for these problems. Explicit solvers were previously shown to be robust for this class of problem, but at the cost of long duration simulations that may limit the ability to use the simulation in uncertainty quantification. Implicit solvers have been shown to be faster, but can be sensitive to the selection of contact enforcement parameters and not very robust. This study shows that the LS-DYNA explicit and implicit solvers are both viable options with acceptable performance on these benchmarks.

Nomenclature

E = Young's Modulus
G = Shear Modulus
ρ = density
ν = Poisson's Ratio
v = velocity
NIP = number of through-thickness integration points
g = gravitation constant
F = Force
SMP = shared memory processing solver
MPP = massive parallel processing solver
F_R = Force magnitude
l = length
thk = thickness
t = time
μ = coefficient of friction
IS = Implicit Solver
ES = Explicit Solver
FE = Finite Element

I. Introduction

LARGE deployable space structures often include "softgoods" for major components. The term "softgoods" refers to components with intentionally high compliance that undergo large angle unfolding during deployment. Examples of softgoods include the mesh fabric in a deployable microwave reflector, the canopy of a supersonic parachute, or the body of an inflatable truss. Generally, although their motion is geometrically nonlinear, their deployment is usually within a purely elastic domain. These highly nonlinear deployable structures may have multiple joints, contacts within the structure with dissimilar materials, including softgoods, foam, composites, and metallic parts. A robust structural analysis software/tool should be able to analyze these deployable structures during their deployment. The aim of this paper is to further assess the capabilities of non-linear finite element solvers and to recommend practices for the construction and simulation of large-scale deployable structures by analyzing selected benchmark problems [1]. LS-DYNA's [2] nonlinear FE implicit and explicit solvers are selected for this study.

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Simulating the deployment of a large space structure with softgoods is challenging due to the presence of several key physical phenomena. Contact both within the softgood, between the softgood and other components is a primary consideration. Simulating contact is not challenging with modern finite element solvers. However, as shown in [1], simulating contact over the timescales and load magnitudes seen during deployment remains a challenge. Deployment of large space structures usually involves a time period of minutes or hours, while contact, elastic release and expansion may locally involve vibrations on the order of tenths or hundredths of a second. Preloads can be on the order of tens of Newtons, while contact forces might be a three orders of magnitude smaller. Nonlinear large angle motion including contact over such a wide frequency range and range of forces can challenge existing finite element solvers.

To further our understanding of these issues, this paper focuses on the use of LS-DYNA non-linear finite element (FE) solver for softgood deployment. LS-DYNA is well known as a platform for simulating automotive airbags, a technology driven primarily by the automotive industry's crashworthiness and occupant protection requirements. But automotive airbags are mechanically different from softgoods in large deployable structures. Compared with softgoods on large deployable structures, airbags are a thicker material that deploy under comparatively higher frequency and higher magnitude loads than space structures. Whether LS-DYNA would be effective for softgoods in large deployable structures is an open question. Prior work by the authors in Reference [3] provided a similar comparison on some of the benchmarks studied here, but analyzed using Sandia Sierra Solid Mechanics finite element code.

LS-DYNA offers both implicit and explicit solvers, which might be considered for this challenge. The explicit solver (ES) is ordinarily used for simulating airbag deployment. It can accommodate large angle nonlinear dynamic motion over, in principle, a wide range of frequencies and forces. The limitation of the ES is that it requires smaller time steps compared to implicit solver. This makes ES best suited for short duration, high frequency problems, such as airbag deployment. The implicit solver (IS) can, in principle, accommodate similar mechanics as the ES, but is suitable for lower frequency, longer duration simulations. This makes the IS attractive for space deployable structure problems including fabric. However, the IS time integration involves an iterative solution of the nonlinear equilibrium equations. The convergence of this iteration is degraded both by contact and by a wide dynamic range of loads due to stiffness differences. Simulating softgoods in large deployable structures has features that can confound both the ES and the IS, and it is not clear which, if either, would be more appropriate.

This paper focuses on the relative performance of the IS and ES on a set of selected benchmark problems. These problems were previously defined in Reference [1], and they contain simplified combination of the relevant mechanics in the problem of interest. The results of this study show that both IS and ES are viable options.

The paper is organized as follows. The first section is an introduction, followed by second section that provides the rationale for benchmark problems and simulation scenarios. The third section provides simulation scenario definitions followed by benchmark problems definition in the fourth section. Conclusions and recommendation are provided in the fifth section. All tables and figures appear at the end of the paper.

II. Simulation Scenarios and Benchmark Problems

There are deployable structures, e.g., sunshield structures or the reflective surface of a deployable mesh antenna, that are made of soft fabric membranes and attached to a network of structural straps. Each strap can be a long flat flexible beam that deflects and stores bending energy similar to compressing a spring during the stowing process.

These structures could have different types of material using a wide range of axial and bending stiffness. Common practice is, for example, to model softgoods such as cable or fabric when there is tension and omit them when there is no tension [1].

Modeling of very complex deployable structures in any software requires confirmation that small subsystems from within the large assembly can be modeled properly. The example sub-system shown in Figure 1 embodies the relevant pathologies of interest to this study. It captures the physics of different parts and their interactions in a more complex model, but is simple enough to help define benchmarks for evaluating code suitability for the more complex system model. The structure of interest in Figure 1 is comprised of fabrics attached with fourteen rivets to five straps setup. Four rivets out of those fourteen are placed on the corners of connecting straps and fabric allowing straps to rotate with respect to each other. The remaining ten rivets are placed about 143.9 mm away from the corners on each strap connecting the fabric and straps.

The most important challenge in this subsystem is the simulation of the response due to the release of stored strain energy when folded softgoods (stowed configuration) are released. This example subsystem was used to define five benchmark problems that are described below.

A. Simulation Scenarios

Three simulation scenarios were applied to each of the five benchmarks. These scenarios represent different aspects of mechanics that are important to capture in simulations of ground stow and deployment mechanics and on-orbit deployment mechanics.

1. Simulation Scenario 1– Quasi-Static Stow and Quasi-Static Deployment under Gravity Loading

Scenario 1 is quasi-static stowing and quasi-static deployment under gravity to ensure the results are repeatable and that similar loads are generated in both directions. The displacement is applied in X and Y directions shown in Figure 1 over a 5.0 second period. The package is held for 1.0 second, and then allowed to expand slowly over the next 5.0 seconds. Both stowing and deployment are under gravity acceleration g=9.81 m/s^2 applied in –Z direction.

2. Simulation Scenario 2 – Quasi-Static Stow and Dynamic Deployment under Gravity Loading

Scenario 2 is the same as Scenario 1, but the release is dynamic instead of quasi-static. This simulates sudden release of restraints that hold the stowed structure together. The energy stored in bending and compressing straps and fabric together during the stowing process is released and the system is allowed to expand. This phenomenon is sometimes called "bloom" and can be highly dynamic, high frequency event. This simulation is used for validating the analytical model while predicting the internal component loads and overall behavior under 1-g testing.

3. Simulation Scenario 3 - Quasi-Static Stow under 1-g and Dynamic Deployment without Gravity Loading

Scenario 3 simulates on-orbit bloom. This is used to evaluate the effect of the bloom on spacecraft attitude in the orbit environment.

B. Benchmark Problems

The above 3 simulation scenarios were implemented for each of five benchmarks. The benchmark problems consist of subassemblies of the system shown in Figure 1. Fabrics within the structure of interest can have a range of stiffness. To capture this range two extremes fabric stiffness's are selected. Printer Paper stiffness is selected for upper range fabric stiffness, and tissue paper is selected for lower range fabric stiffness.

From Figure 1, the fabric sides are l = 431.8 mm long, the fabric's thickness is 0.0254 mm, all four edges are five times thicker (5 x 0.0254 mm) having width of w=9.525 mm. The assumed material properties for fabrics are: Young's modulus E = 344.7 MPa (Printer Paper), Poisson's ratio ν = 0.3, and density is ρ= 553.6 kg/m^3. Fabric made of tissue paper has thickness of 0.0254 mm and material properties E = 3.447 MPa (Printer Paper stiffness /100), ν = 0.3, and ρ= 553.6 kg/m^3.

Five straps are made of equal length l=432 mm straps, width w=9.525 mm and thickness of 0.18 mm that are connected at their ends using rivets. The strap material properties are: E=41.8 GPa, ν=0.3, ρ= 2657 kg/m^3. Details of the small sub-assembly model are shown in Figure 3. The fabric is attached below straps with respect to gravity Z direction.

Benchmark Problem #1 – Fabric Only, Printer Paper is a part of the structure of interest. The fabric with stiffness equivalent to printer paper, see Figure 2, is separated and analyzed on its own for three simulation scenarios.

For Scenario 1, the Printer Paper deformation is used for qualitative comparison against fabrics, followed by Scenario 2 and Scenario 3 analyses.

The fabric finite element model has 12373 membrane elements; four elements at each corner are made of rigid material to avoid analysis singularities. Enforced displacement defined in simulation scenarios is applied to the four rigid corners. The four corners are moved in five seconds to end position of 25.4 mm away from the fabric center. The corners are held at the end position for one second, during hold period the stow force is recorded. Simple linear elastic material is used. The self-contact interaction is established within the fabric.

Finite element model implementation for fabric material uses membrane elements. This is accomplished by use of fully integrated shells setting through-thickness integration points to 1 and default setting warping hourglass control. The number of through-thickness integration point is reduced to 1 to eliminate bending stiffness computation on the shell elements, which is an effective way to convert shell elements into membrane elements. IS requires mortar type contact to prevent parts in contact to stick to each other.

The problem tests feasibility of fabrics folding simulation, ability of fabrics to store strain energy, forces during stow and contact interactions.

Benchmark Problem #2 – Fabric Only, Tissue Paper: This benchmark consists of a square piece of tissue paper 202.3 mm (8") on a side. The tissue paper stiffness was 100 times smaller than the stiffness of the paper in Benchmark Problem #1. Both the FE model and the tissue paper are identical in size. The stowing behavior of the FE model is compared to actual stowing of a tissue paper for qualitative comparison, see results section.

Finite element model implementation, model setup and simulation scenarios are identical to Printer Paper benchmark problem. Similarly, tissue paper problem tests feasibility of lower range stiffness fabric folding simulation, ability of fabrics to store strain energy, forces during stow and contact interactions.

Benchmark Problem #3 – Five Straps, No Fabric: This benchmark consists of the five straps without the fabric, as shown in Figure 3, and analyzed on its own for three predefined simulation scenarios. The Five Straps have 2248 shell elements, elements at straps ends are made of rigid material. Those rigid elements from different straps are connected via revolute joints. Enforced displacement was applied to the four corner rigid elements. The four corners are moved in five seconds to end position at 25.4 mm away from the center. The corners are held for one second in the end position. At the end of the hold, the corners are either quasi-statically moved back to its original initial position or released for dynamic deployment with and without gravity, as called for by the specific Scenario.

Finite element model implementation for straps uses fully integrated shell elements with 5 through-thickness integration points along with default settings warping hourglass control. Each strap end, i.e. corners, are connected to other straps using revolute joint that allow relative rotation of the straps with respect to each other. The model includes both self-contact for each strap and contact between the straps. Implicit solver requires mortar contact type to prevent parts in contact to stick to each other. The material model is linear elastic material for both fabric and straps. This problem tests the feasibility of simulating strap folding and compression during stowing.

Benchmark Problem #4 – Five Straps with Printer Paper: This benchmark combines benchmark problem #1 and benchmark problem #3. The Printer Paper fabric is attached to Five Straps using fourteen rivets, four rivets at the corner and ten rivets at the 143.9 mm distance from the corners. The same setup and the same simulation scenarios described in benchmark problem #1 are used to evaluate this benchmark problem. The Printer Paper stiffness may indicate greater stow forces compared to lower range of fabric stiffness. This is a numerically difficult problem to solve due to contact between parts with dissimilar stiffness.
This problem tests the ability to simulate folding and compression of the straps and the fabric together.

Benchmark Problem #5 – Five Straps with Tissue Paper: This benchmark is the same as benchmark problem #4, but with tissue paper instead of Printer Paper.

III. Results

The results summary is in the Table 1 and Table 2, followed by figures at the end of the paper. The tables compares the Quasi-Static/Gravity Scenario with the Dynamic-Deploy/Gravity Scenario and the Dynamic-Deploy/No-Gravity Scenario. Table 1 summarize stow forces and Table 2 summarize run times, number of CPUs and solvers used to solve the benchmark problems. Both implicit solver (IS) and explicit solver (ES) are used to compute the results.
For problem 1, the run times are comparable accounting for the number of processors. For problem 2, only explicit solver solved the problem having low run time on a single CPU core. The problem 3, Five Straps, is an example where Scenario 1 and Scenario 2 implicit solver is faster due to either slow quasi-static loading or dynamic motion with gravity. For Scenario 3, which is without gravity, implicit solver is still faster accounting for number of processors. The difference in speed between implicit and explicit solver reduced by factor of two due to explicit solver converging faster using smaller time step. Smaller time step is required to capture on-orbit highly dynamics deployment without gravity. For problems 4 and 5, all runs are executed using MPP explicit solver on 40 CPU cores having reasonable run times for the problem complexity.

C. Benchmark Problem #1 Results – Fabric Only, Printer Paper

The results of qualitative deformation comparison between simulation and Printer Paper indicate good deformation agreement during stowing hold period, see Figure 4. The qualitative agreement assessment is based on stowed shape of the Printer Paper being very close to stowed shape of FE model.
The results for the Printer Paper benchmark for three simulation scenarios are summarized in Table 1.Resultant stow force is at expected low magnitude of approximately F_R= 0.09 (0.1) N with reasonably low run time. The number within parenthesis denotes explicit solver results. There is a small discrepancy in implicit solver result for Scenario 2, see Figure 5, between the peak stowed force due to different releases of software used to obtain the solution.

Both the implicit and explicit solvers successfully completed the simulations in all three scenarios. Explicit solver results in Figure 6 show expected shapes and stow forces for both on ground operation and on-orbit deployment.
At stowed position from 5 to 6 seconds, deployment at 8 seconds and at final state at 11 seconds both solvers have expected fabric shapes. For Scenario 1 the fabric shape is almost identical to its starting shape. For Scenario 2, the final shape indicates gravity sag, which is likely shape for ground operations. For Scenario 3 the final fabric shape is almost flat, which is likely on-orbit shape.

D. Benchmark Problem #2 Results – Fabric Only, Tissue Paper

The results of qualitative deformation comparison experiment between simulation and Tissue Paper indicate good deformation agreement during stow hold period, see Figure 7. The qualitative agreement assessment is based on tissue paper stowed shape being close to FE model stowed shape.

Stow resultant force F_R=0.001 N has expected low magnitude, see Table 1.

Only explicit solver successfully completed the simulations. Implicit solver may require solver parameter tuning to obtain convergence and subsequent solution for all three simulation scenarios.

Stowed shape, deployment shape at 8 seconds deployed shape at the end of the run are as expected for all three scenarios, see Figure 8. The same fabric shapes are already observed in Benchmark problem #1.

E. Benchmark Problem #3 Results – Five Straps, No Fabric

Table 1 shows stow forces for both implicit solver and explicit solver to have expected low magnitude of approximately F_R=0.07 (0.1) N. There is a small discrepancy between the peak stowed forces due to a different convergence to a solution. Both the implicit and explicit solvers successfully completed the simulations in all three scenarios.

The stowed shape, deployment shape at 8 seconds into the run, and deployed shape for all three scenarios have expected straps deformation both on the ground and on-orbit, see Figure 9.

Both solvers demonstrated very robust contacts having reasonable run times indicate the very nature of the solvers'.

F. Benchmark Problem #4 Results – Five Straps with Printer Paper

Table 1 shows stow forces of F_R= (0.6) N. The forces are reasonable and consistent for all three scenarios. The force increase is expected with respect to previously solved benchmark problems due to adding Printer Paper to the structure and additional contact interaction between straps and Printer Paper, see Figure 10.

Only explicit solver successfully completed the simulations in all three scenarios. Contact algorithms worked without issues. This problem challenged contacts using parts with dissimilar stiffness, which affects contact penalty stiffness computation and may negatively influence contact algorithm performance. The solver demonstrated robust surface to surface, edge to edge and edge to surface contacts. Expected on ground and on-orbit shapes are recorded, see Figure 11.

G. Benchmark Problem #5 Results – Five Straps with Tissue Paper

Table 1 shows the stowed force from benchmark problem five F_R= (0.1) N for tissue paper attached to Five Straps benchmark, see Figure 12. The stowed force from benchmark problems two F_R= (0.0008) N, three F_R= (0.1) N and benchmark problem four F_R= (0.6) N are used as a comparison for this benchmark problem. This benchmark problem stow force is closer to five strap problem, which is both expected and reasonable trend due to drop in fabric stiffness from Printer Paper to tissue paper by a factor of a hundred.

Only the explicit solver successfully completed the simulations in all three scenarios. The explicit solver's contact algorithms worked without issues after contact penalty stiffness was scaled using 0.001 scale factor. Contact search frequency in explicit solver was changed from default of every 200 time steps down to 50 time steps.

IV. Conclusions and Recommendations

This paper showed that 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 without difficulties, having reasonable run time and acceptable results. Note, the explicit solver run time for large deployable structures made of many components (order of 1000) similar to these benchmark problems would not be practical when the deployment time is long (~ 1 hour). The implicit solver was able to solve only two out of five benchmark problems, Printer Paper and Five Straps. The results from implicit solver for these two problems are similar to those of explicit solver. Perhaps, with more convergence parameter tuning implicit solver would be able to solve more problems accurately. Advantage of implicit solver is its shorter run time, compared to explicit solver, which is critical for long deployment durations. Improvements on implicit solver is required in order to analyze complex deployable structures with long duration deployment time.

Acknowledgments

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Table 1. 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 attached to Five Straps		- (0.6)	- (0.6)	- (0.6)
#5 Tissue Paper attached to Five Straps		- (0.1)	- (0.1)	- (0.1)

Table 2. Results Summary for Run Time, CPUs and Solver Type

Results Summary for Run Time		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		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 h 43 min (2 h 30 min)	1 h 24 min (2 h 30 min)	1 h 22 min (2 h 30 min)
#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	59 min (3 hour 14 min)	1 h 3 min (3 hour 14 min)	6 h 51 min (3 hour 14 min)
#4 Printer Paper attached to Five Straps	Number of CPU cores / Solver	- (40 /MPP)	- (40 /MPP)	- (40 /MPP)
	Run time	- (15 h 10 min)	- (15 h 5 min)	- (15 h 7 min)
#5 Tissue Paper attached to Five Straps	Number of CPU cores / Solver	- (40 /MPP)	- (40 /MPP)	- (40 /MPP)
	Run time	- (15 h 0 min)	- (15 h 10 min)	- (15 h 7 min)

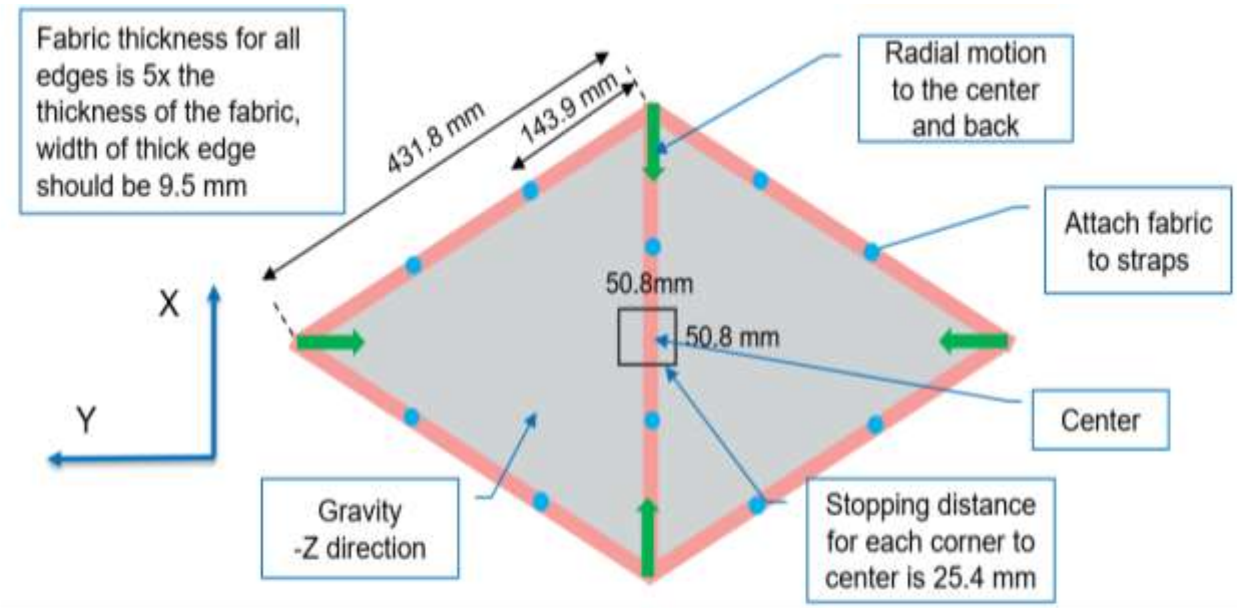

Figure 1. Structure of Interest - Fabric Attached to Five Straps Model Setup

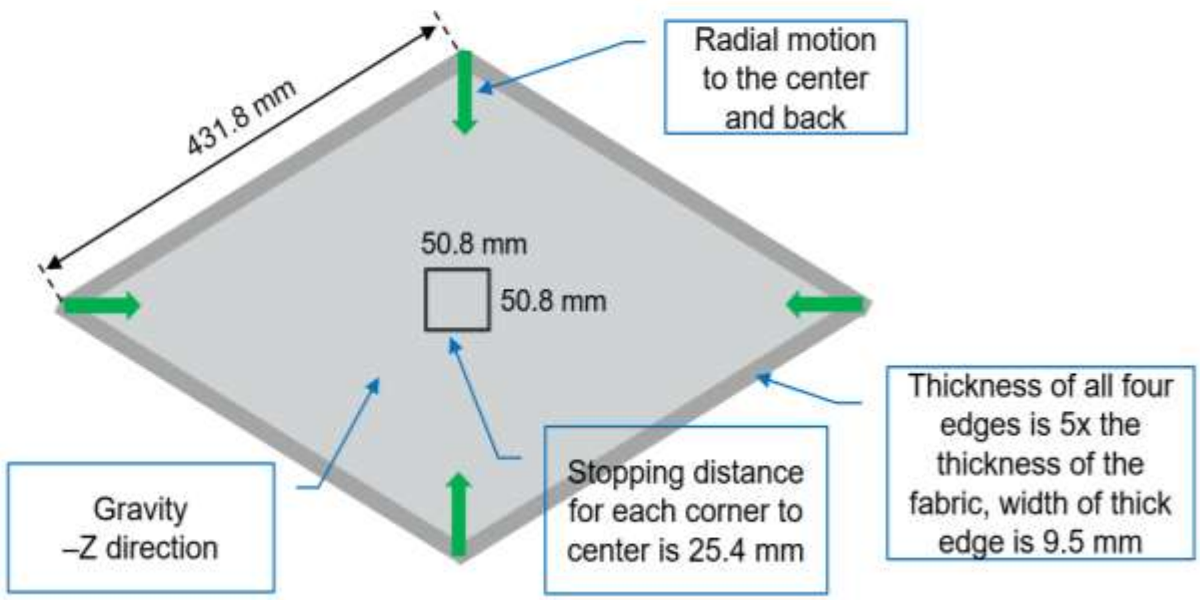

Figure 2. Fabric Only Model Setup

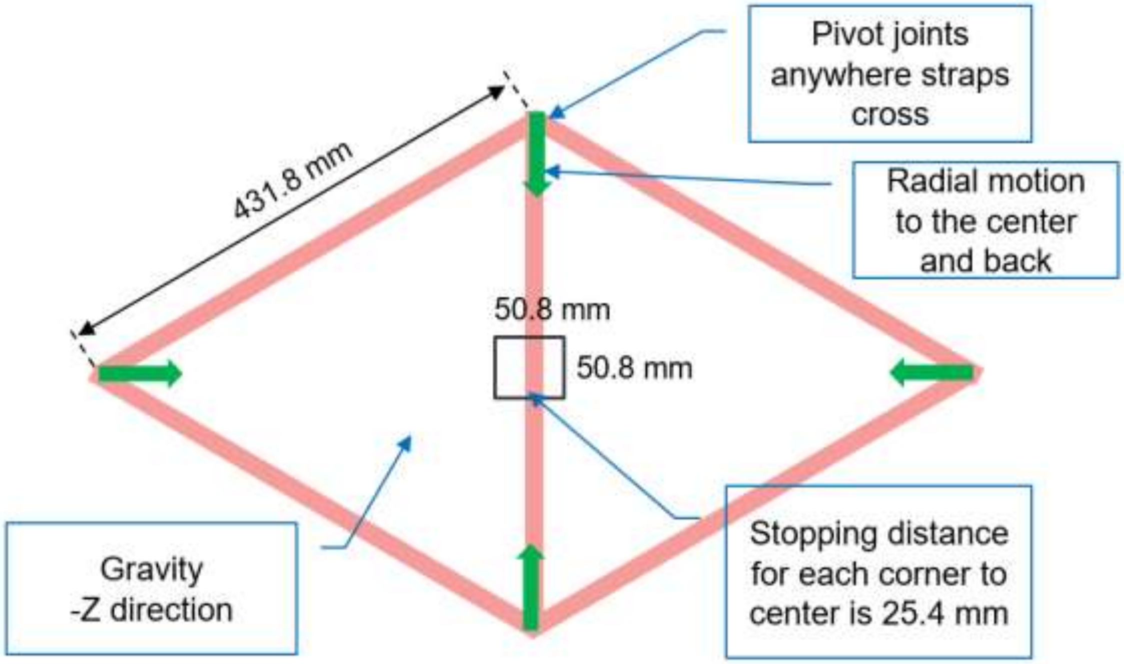

Figure 3. Five Straps Model Setup

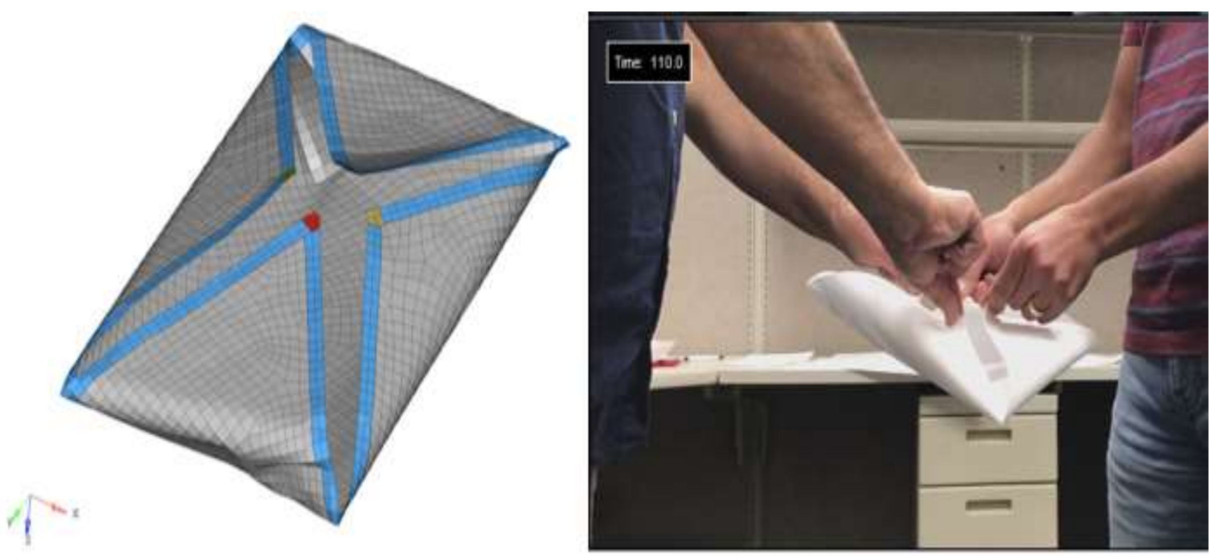

Figure 4. ES Has Good Qualitative Deformation Agreement for Folding Fabric (Printer Paper)

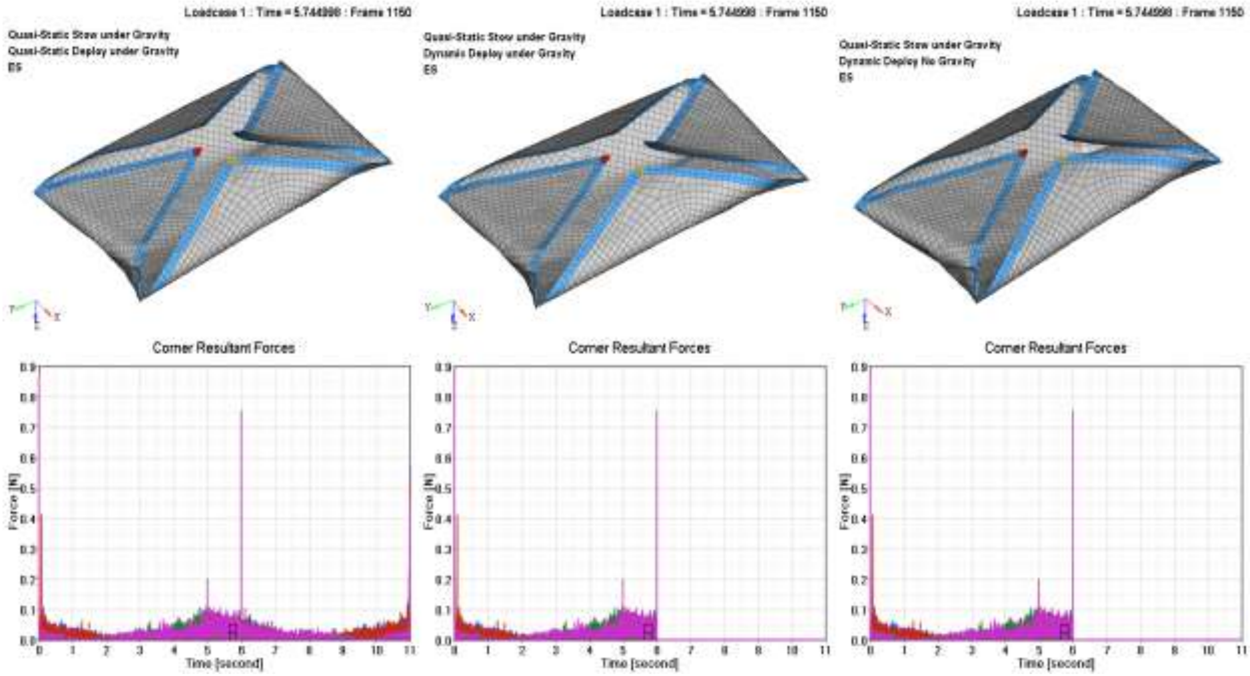

Figure 5. ES Stowing Force Time History for Folding Fabric (Printer Paper). *The Scenario 2 shows slightly lower resultant forces and slightly different deformation pattern.*

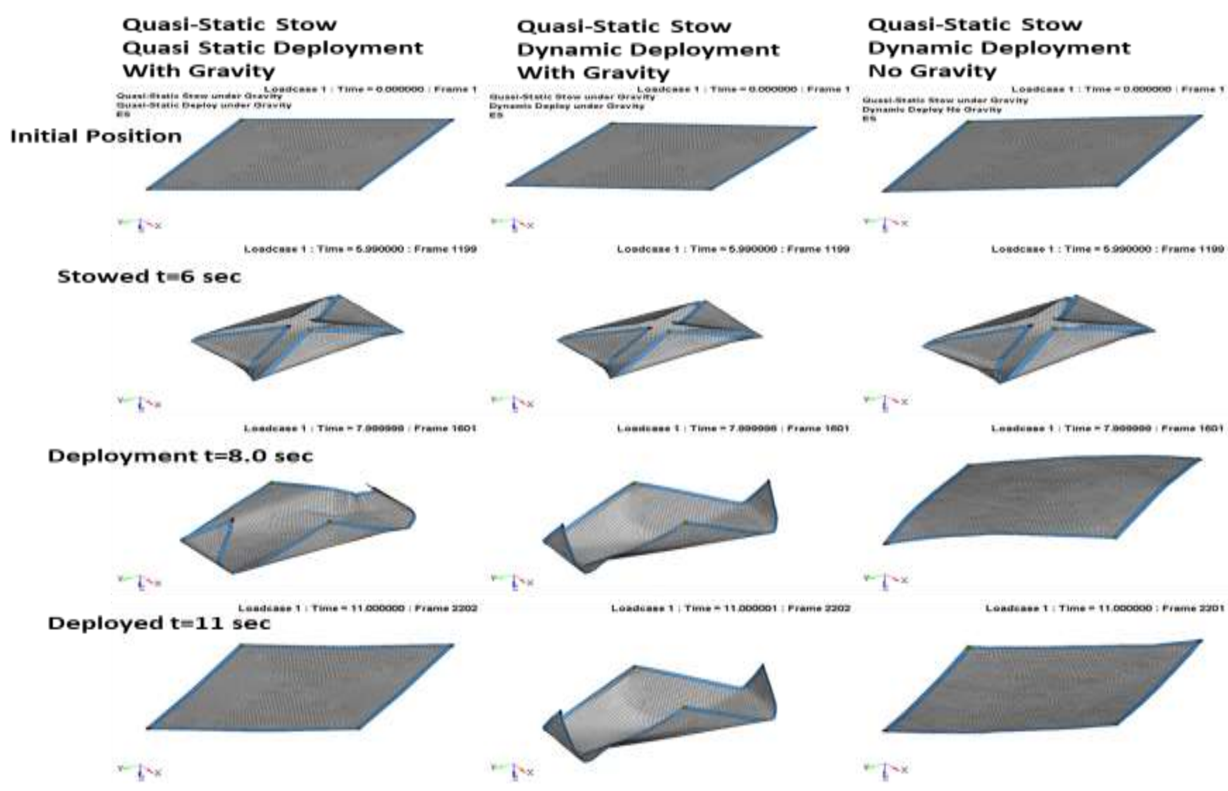

Figure 6. ES Deformation Snapshot for Fabric (Printer Paper)

Figure 7. ES Has Good Qualitative Deformation Agreement for Folding Fabric (Tissue Paper)

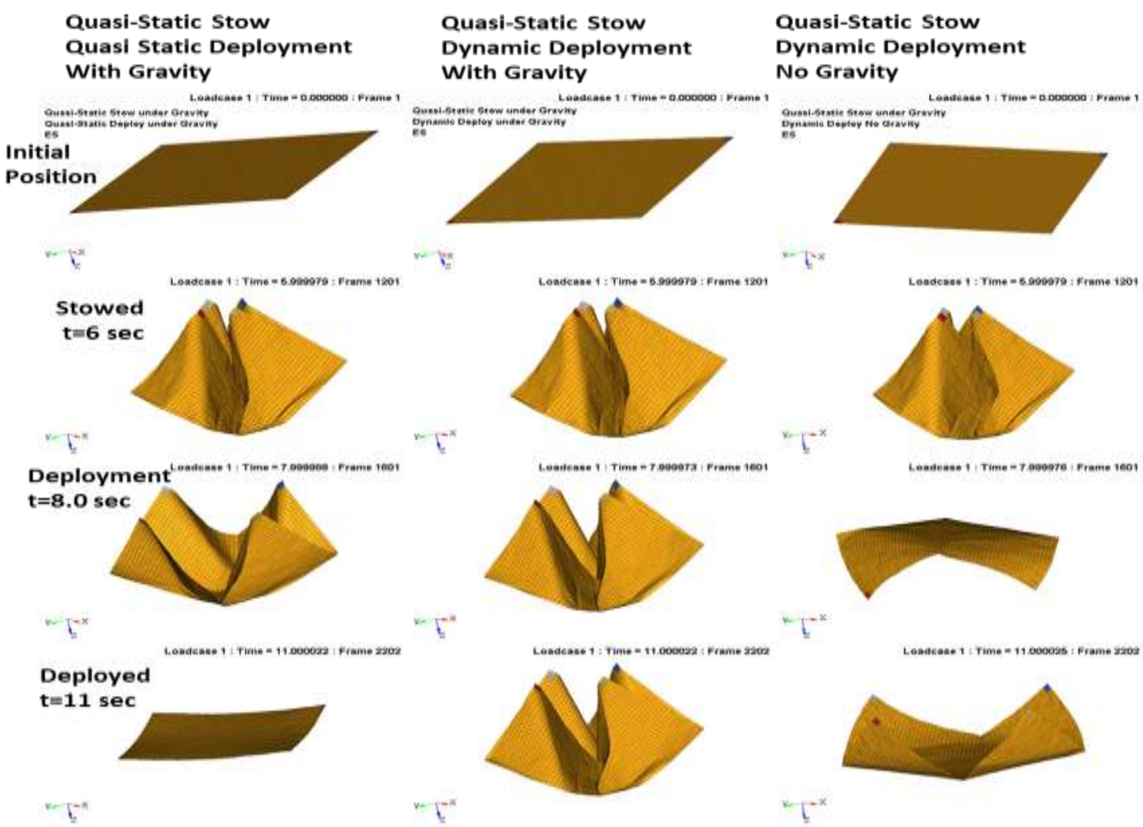

Figure 8. ES Deformation Snapshot for Fabrics (Tissue Paper)

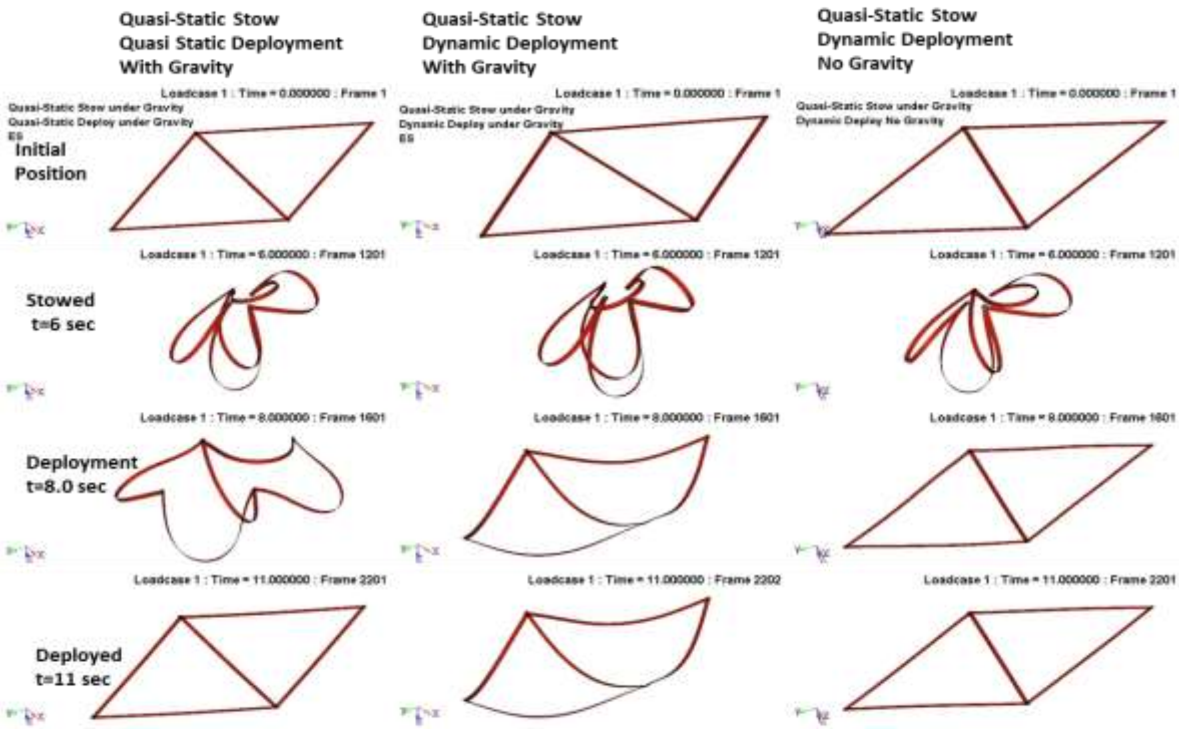

Figure 9. ES Deformation Snapshot for Five Straps

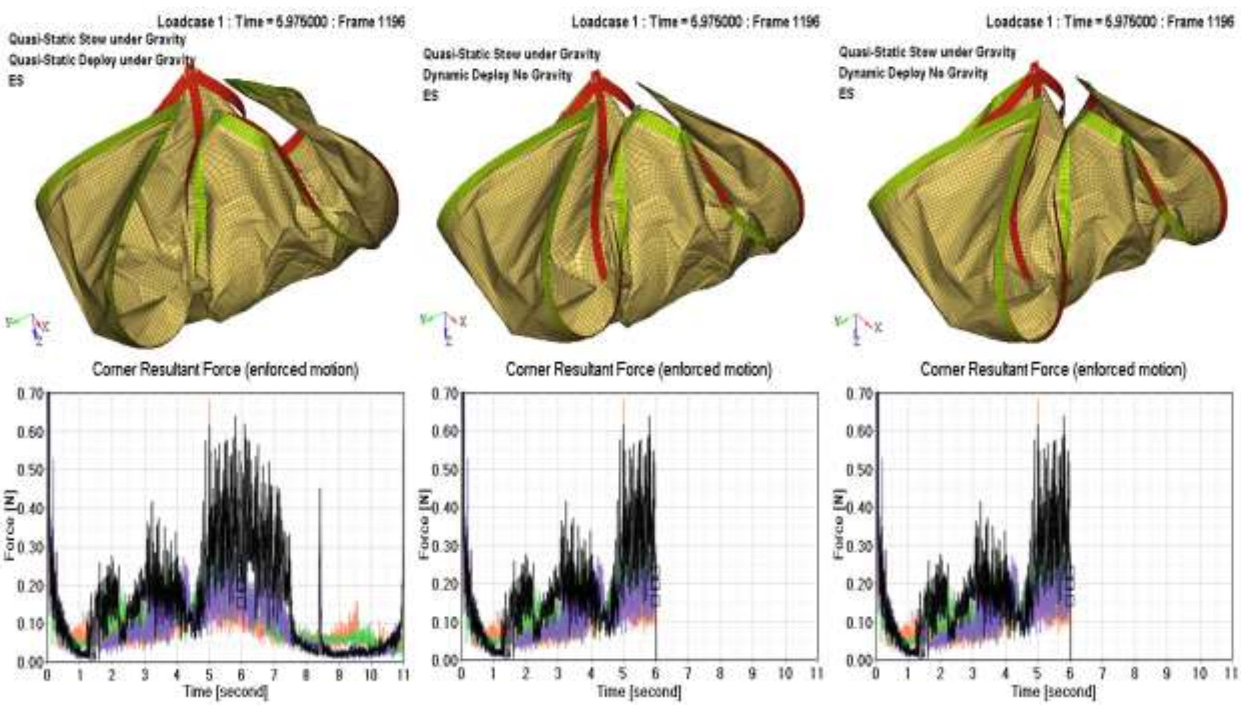

Figure 10. ES Force Time History for Fabric (Printer Paper) Attached to Five Straps

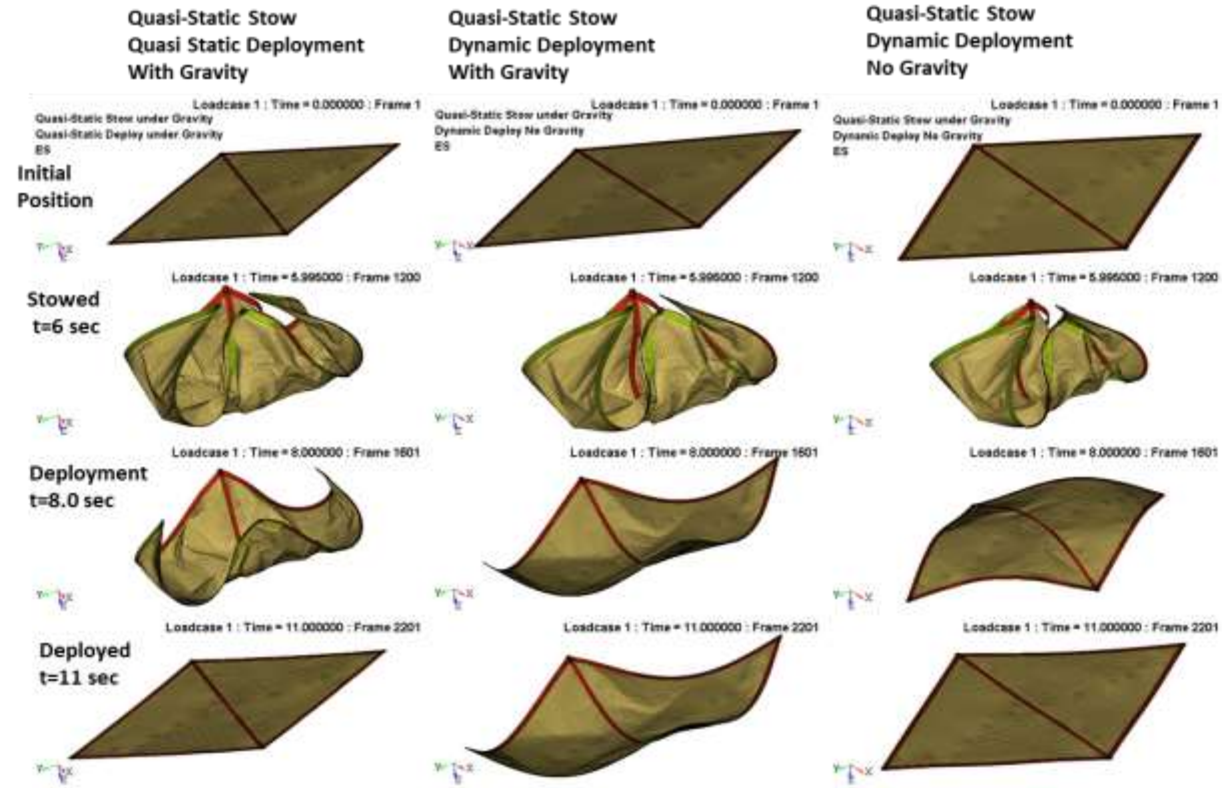

Figure 11. ES Deformation Snapshot for Fabric (Printer Paper) Attached to Five Straps

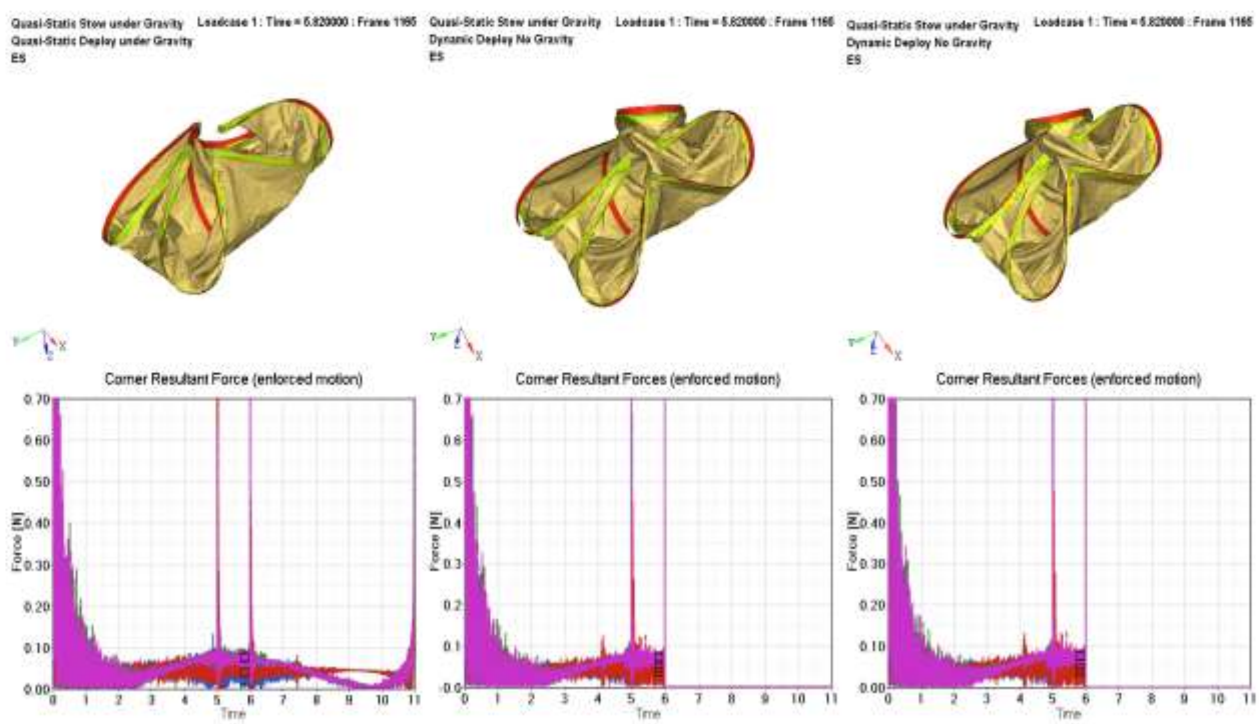

Figure 12. ES Force Time History for Fabric (Tissue Paper) Attached to Five Straps