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Deployment Simulation Methods for Ultra-Lightweight Inflatable Structures

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DEPLOYMENT SIMULATION METHODS FOR ULTRA-LIGHTWEIGHT INFLATABLE STRUCTURES

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Abstract

Two dynamic inflation simulation methods are employed for modeling the deployment of folded thin-membrane tubes. The simulations are necessary because ground tests include gravity effects and may poorly represent deployment in space. The two simulation methods are referred to as the Control Volume (CV) method and the Arbitrary Lagrangian Eulerian (ALE) method. They are available in the LS-DYNA nonlinear dynamic finite element code. Both methods are suitable for modeling the interactions between the inflation gas and the thin-membrane tube structures. The CV method only considers the pressure induced by the inflation gas in the simulation, while the ALE method models the actual flow of the inflation gas. Thus, the transient fluid properties at any location within the tube can be predicted by the ALE method. Deployment simulations of three packaged tube models; namely coiled, Z-folded, and telescopically-folded configurations, are performed. Results predicted by both methods for the telescopically-folded configuration are correlated and computational efficiency issues are discussed.

Introduction

Ultra-Lightweight Inflatable (ULI) space structures have become attractive because they can meet structural requirements for space applications at a low cost. These thin membrane structures can be fabricated and deployed for millions of dollars less than conventional structures. Recently NASA's In-Space Propulsion (ISP) technology program has supported the development of solar sails for deep space science exploration missions as shown in Figure 1. In order to achieve the cost reduction, the four supporting booms of this square solar sail need to be folded to fit the shroud of a launching vehicle and use only a small amount of inflation gas to deploy them in space. Solar sails capture the momentum of sunlight photons [1,2]. The area density of the available momentum is small. As a result, solar sails must be large. The thrust provided by these large sails is so small that the sails must also be thinner than paper to produce useful thrust vectors on the spacecraft. Billowing solar sails are less effective than flat solar sails due to the reduced momentum exchange provided by oblique incidence photons. To keep billowing within allowable limits, membrane tension is provided. The tension can be introduced by employing inflatable booms to stretch the membranes as shown in Figure 1.

Testing prototypes in space is prohibitively expensive. Deployment tests of solar sails in a laboratory do not accurately simulate their deployment in space. Even if a ground test is conducted in a vacuum chamber, the gravity effect cannot be avoided. Gravity will affect the deployment dynamics, the structure's shape, and the regions experiencing self-contact during the inflation deployment. Thus, laboratory testing of ULI structures should be supplemented with computational simulations.

Many researchers have conducted computational simulations of the inflation deployment process for membrane structures. A closed form approximate analysis of the inflation deployment of a rolled (coiled) tube was derived by Steele and Fay [3]. The model gives insight into understanding the unrolling process. However, an infinite plane supports the unrolling tube. The constraint of the plane limits the application of this model for simulating deployment in-space. Haug et al. [4] and Salama et al. [5] employed the control volume (CV) method with the finite element method to investigate folded space rigidizable antenna structures and folded inflatable cylindrical tubes, respectively. The CV method, implemented in the PAM-CRASH [6] and LS-DYNA [7] codes, is based on an airbag inflation model developed by Wang and Nefske [8]. As this approach neglects the inertia of the inflation gas, it may not be adequate for simulating deployment with a high velocity gas. To include the inflation gas inertia effect in the deployment simulation, the Arbitrary Lagrangian and Eulerian finite element method (ALE) [9-13] needs to be used. The ALE method models the actual flow of the inflation gas. Thus, the transient fluid properties at any location within the tube can be predicted by the ALE method. However, the ALE method is computationally expensive since it requires the use of many ALE solid elements for modeling the inflation gas flow.

The purpose of this study is to employ both the CV and the ALE methods, available in LS-DYNA Version 960, to simulate the dynamic deployment of various inflatable thin-membrane tubes in folded configurations. The CV method is used to simulate the deployment of three folded tube models including coiled, Z-folded and telescopically-folded configurations, while the ALE method is used to simulate the telescopically-folded configuration. Deployment characteristics predicted by both methods are compared, and the computational issues related to both methods are discussed. During a previous in-space flight experiment, the existence of residual air caused a premature initial deployment of an inflatable antenna [14]. The issue of residual air effects on the Z-folded tube deployment is also investigated in this study with the CV method.

Finite Element Models for Three Folded Tubes

Finite element models of the three folded tube configurations used for deployment simulations with the CV method are shown in Figures 2 through 4. In the first model, the tube is packaged in a coiled configuration, in the second model it is in a Z-folded configuration, and in the third model it is in a telescopically-folded configuration. In each model, the inflatable membrane structure is modeled by discretizing it into a set of CVs. A longitudinal section of an inflatable tube and the inflation gas inside it form a CV. The boundary of the CV, called the control surface, changes its shape as the internal pressure is increased. Very thin and soft membrane elements are placed between adjacent CVs. These membrane elements stretch as the CVs deform. The total area of the membrane elements is referred to as the orifice area, which controls the flow of inflation gas between adjacent CVs. All models employ fully integrated Belytschko-Tsay 4-node membrane elements [15]. A number of simulations were performed to observe the effects of the tube's finite element discretization on the opening dynamics. These simulation studies indicate that the meshes of all folded tube models are refined enough for modeling the self-contacts properly during the deployment.

The finite element model for the coiled tube configuration is displayed in Figure 2. It consists of seven CVs and is created by employing a simple Archimedean spiral equation, $r = a\theta + r_0$. The symbol a represents a constant, θ is the sweep angle, and r_0 is the initial radius as shown in Figure 2. The nodes are created starting at $\theta = 0$ and $r_0 = 1.5$ inches and continue up to a user defined length of 24 inches. MATLAB [16] is used to generate this model. The nodes at $\theta = 0$ and $r = r_0$ are fixed during the deployment.

The finite element model for the Z-folded tube configuration is displayed in Figure 3. It consists of four CVs with three orifices that are placed at the three fold lines. Boundary conditions are given to ensure that the tube will be deployed vertically. The dimensions of the folded tube are given in the figure. The finite element model of the telescopically-folded tube configuration is displayed in Figure 4. Note that this is a tapered tube, the narrower upper section is tucked in the wider bottom section, and the whole tube is modeled as one control volume. Both the Z-folded and the telescopically-folded model are generated by MSC/PATRAN [17].

The finite element model of the telescopically-folded tube used for the ALE simulation is shown in Figure 5. Note, the telescopically-folded tube model is encompassed by the solid Eulerian mesh which is used to model the flow of the inflation gas. The gas injector is also modeled with a solid Eulerian mesh. The inflator is modeled as a large gas reservoir with a pressure of 10 psi and with a temperature of 75° F. The inlet area to the injector is 2.25 in^2, and the inlet velocity is 12417.56 in/sec. In this analysis, the effect of back pressure (the pressure within the tube near the inlet) change during inflation is neglected. Thus, the mass flow rate into the tube is a constant of 0.52 lbs/sec.

All three folded tubes are made of polyethylene and have a wall thickness of 0.006 inches. The values of the tube's Young’s modulus, Poisson's ratio, and density used are 25,000 psi, 0.25, and 0.033 lbm/in^3, respectively. The inflation is air at 70^{o} F with a molecular weight of 28.97 lbm/lbmole. The gas flows into one end of the tube with an inflation mass flow rate of $0.1 \times t$ lbm/sec, where t is the inflation time, for the coiled tube model and the Z-folded tube model.

Two Inflation Deployment Simulation Methods

Two dynamic inflation deployment simulation methods are presented in the following sections. Equations pertinent to both methods are given.

1. The CV method

A more detailed description of the inflation modeling including the contact algorithm is available in the literature, [7,8]. The incremental volume change for a CV depends on the net inflow-mass rate, the equation of state for the gas, and the dynamics of the membrane structure bounding the CV. Assuming all variables are known at time $t-\Delta t$, an approximation of the internal energy, $E(t)$, in the CV at time t is given by

$$E(t) = E(t - \Delta t) + c_p \dot{m}(t) \Delta t T_{in} \tag{1}$$

where c_p is the specific heat at constant pressure, Δt is the time step, T_{in} is the inflation gas temperature, and $\dot{m}(t)$ is the mass flow rate of the inflation gas.

The gas mass density, $\rho(t)$, within the CV is approximated from the mass flow rate as follows,

$$\rho(t) = [m(t - \Delta t) + \dot{m}(t)\Delta t] / V(t - \Delta t) \tag{2}$$

where $V(t-\Delta t)$ is the CVs volume at time $t-\Delta t$. According to the equation of state for an ideal gas, the pressure, $p(t)$, is calculated as,

$$p(t) = (k - 1)\rho(t)\frac{E(t)}{m(t)} \tag{3}$$

where k is the ratio of the specific heat at constant pressure to the specific heat at constant volume. The pressure is used as input to the finite element analysis to determine the structural configuration at time t. The equation of motion of the inflatable structure has the form

$$[M]\{\ddot{D}\} + [C]\{\dot{D}\} + [K]\{D\} = \{R^{ext}\} \tag{4}$$

where $[M]$, $[C]$, and $[K]$ are the global mass, damping, and stiffness matrices computed with respect to the current configuration, $\{R^{ext}\}$ is the external load vector which includes the pressure load; and $\{D\}$, $\{\dot{D}\}$, and $\{\ddot{D}\}$ are displacement, velocity, and acceleration vectors with respect to the current configuration at time t. Employing an explicit approach, the finite difference form of Equation (4) is expressed as

$$\begin{aligned}\left[\frac{1}{\Delta t^2}[M] + \frac{1}{2\Delta t}[C]\right]\{D\}_t &= \{R^{ext}\}_{t-\Delta t} - [K]\{D\}_{t-\Delta t} \\ &+ \frac{1}{\Delta t^2}[M](2\{D\}_{t-\Delta t} - \{D\}_{t-2\Delta t}) + \frac{1}{2\Delta t}[C]\{D\}_{t-2\Delta t}\end{aligned} \tag{5}$$

where Δt is the time step. Equation (5) is solved for $\{D\}_t$ and the structure's shape at time t is then available. This method is very efficient when the damping matrix and the mass matrix are made to be diagonal by employing lumping procedures. Time steps on the order of 10^{-6} seconds are typically required for the deployment models. As a result, the "wall clock" time, for a desktop workstation, can be on the order of weeks to simulate the deployment of a structure, which in real time inflates in a few minutes.

The work performed by the volume expansion reduces the internal energy. Therefore, a modified internal energy, $E(t)^*$, can be obtained according to the internal energy evolution equation,

$$E(t)^* = E(t)\left[\frac{V(t)}{V(t-\Delta t)}\right]^{1-k} \tag{6}$$

where $V(t)$ is the volume at time t computed using the divergence theorem.

2. The ALE Method

The Arbitrary Lagrangian Eulerian [ALE] finite element method is suitable for solving transient, nonlinear fluid-structure interaction problems [9-13]. The ALE method possesses both Eulerian and Lagrangian features to generalize the kinematical descriptions of the fluid domain. Hence, ALE methods address the shortcomings of purely Lagrangian and purely Eulerian descriptions. These shortcomings include mesh distortions problems if the Lagrangian description is used to model the fluid, and complexity in handling fluid-structure coupling for the Eulerian description.

In the ALE method, both the motion of the mesh and the material must be described. The motion of the material in the spatial domain, x, is described as

$$x = \phi(X, t) \tag{7}$$

where X are the material coordinates. The function $\phi(X, t)$ maps the body from the initial configuration to the current or spatial configuration.

Another reference domain is the ALE domain. Here, χ is used to define the ALE coordinates. In most cases, the initial spatial, ALE, and material domains are collocated, $\phi(X,0) = \chi(X,0) = X$. The ALE domain is used to describe the motion of the mesh and is independent of the motion of the material. The ALE domain is also used to construct the initial mesh. It remains coincident with the mesh throughout the computation, so it is also considered as the computational domain.

The motion of the mesh is described by

$$x = \hat{\phi}(\chi, t) \tag{8}$$

where $\hat{\phi}$ maps the point at χ in the ALE domain to the location x in the spatial domain.

In the ALE method, the inflation gas is considered as an inviscid compressible fluid. Three conservation equations and an equation of state are solved. The three conservation equations are expressed in the ALE frame as

$$\frac{\partial \rho}{\partial t}\Big|_{\chi} = -\rho \frac{\partial v_i}{\partial x_i} - c_i \frac{\partial \rho}{\partial x_i} ,$$

$$\rho \frac{\partial v_i}{\partial t}\Big|_{\chi} = (\frac{\partial p}{\partial x_i} + \rho b_i) - \rho c_j \frac{\partial v_i}{\partial x_j} ,$$

$$\rho \frac{\partial e}{\partial t}\Big|_{\chi} = (p \frac{\partial v_i}{\partial x_i} + \rho b_i v_i) - \rho c_j \frac{\partial e}{\partial x_j} \tag{9}$$

where $c_i = v_i - w_i$. In this expression, ρ is the fluid density, p the pressure; and v_i is the fluid velocity, w_i is the mesh velocity, and b_i is the body force in the i-direction. The total specific energy is defined as

$$e = \frac{1}{2} v^2 + E \tag{10}$$

where $E = E(t)/m(t)$ is the specific internal energy, and $E(t)$ is defined in Equation 1. For compressible fluids, the pressure is defined by an equation of state

$$p = f(\rho, E) \tag{11}$$

These partial differential equations given above, as well as the equation of motion of the inflatable tube, are then discretized using finite element modeling methods. The resulting system of ordinary differential equations are solved by explicit time integration. The fluid and structure interactions were achieved by coupling the Lagrangian shell elements (Slave) to Eulerian or ALE fluid elements (Master) using penalty parameters.

Inflation Deployment Simulation Results

The aforementioned two methods are used to simulate the inflation deployment of various folded tube configurations. The CV method is used to simulate the deployment process of a coiled, a Z-folded, and a telescopically-folded model. The ALE model is only used to simulate the inflation deployment of the telescopically-folded model. Tube internal pressure and volume changes during the inflation are plotted. For the telescopically-folded tube model, internal pressure and time predicted by both methods are correlated to illustrate that both models can generate comparable results. In addition, the computational efficiency of both methods and the use of multiprocessors to speed-up the simulations are discussed.

1. CV Method Simulation Results

a. Coiled Tube Model

The unwinding of the coiled tube is shown in Figure 6. The tube is fully deployed at time 0.35 sec. We define the tube as deployed when it appears to be fully extended and is free of kinks. The volume and pressure as a function of time for each CV are shown in Figures 7 and 8, respectively. Figure 7 shows that the tube sections (CVs) open one by one. Figure 8 shows that the pressure is about 8 psi when it is fully deployed (t=0.35 sec) and the pressure of all CVs are quite uniform during the deployment.

b. Z-Folded Tube Model

Inflated shapes of the Z-folded tube in various stages of deployment are shown in Figure 9. The time required to fully deploy the tube is 0.19 sec. The volume and pressure as a function of time for each CV are shown in Figures 10 and 11, respectively. The nominal volume of a fully opened central CV is 91 in^3. The pressure at the moment of full deployment (t=0.19 sec) is 2.4 psi. The pressure in CV-1, which is the inlet of the inflation gas, builds up faster than in other CVs initially.

The orifices located at the connections between the control volumes control the amount of inflation gas going into each control volume per unit time. An additional Z-fold deployment model is created to investigate the effects of increasing the number of orifices. In this second model, eight CVs are created by installing orifices at the three fold lines and at the midsection of each of the four segments. The computed dynamic deployment characteristics are similar to the four CV Z-folded models discussed above, and small increases of deployment pressure, time and amount of inflation gas are predicted as shown in Table 1.

Table 1. Inflation time, internal pressure, and total mass of the inflation gas for Z-fold deployment simulations.

Inflation rate dm/dt (lbm/sec)		Inflation time*, ** τ (sec)	Pressure**, $p(\tau)$ (psi)			Total Inflation Mass** $m(\tau)$ (lbm) x10^{-3}
			First CV	Last CV	Ave. of all CVs	
$0.1 \times t$	4-CVs	0.19	2.30	2.13	2.24	1.81
	8-CVs	0.20	2.57	2.20	2.33	2.00

* Time step, $\Delta t = 8.35\text{x}10^{-6}$ seconds
** τ = time at full deployment

The effect of the presence of residual air on the deployment of the Z-folded tube is also investigated. Each CV, after the first one, is assumed to have a residual air mass of 2.703x10^{-5} lbm, which induces a pressure of 0.1 psi for a fully opened CV. The first CV is inflated by the inlet gas only and does not have any residual air present. At the start of the deployment simulation, the residual air expands each subsequent CV causing them to push each other apart. These initial motions allow the inflation gas to flow between CVs easier, and allow for a low pressure deployment.

The results of the residual air deployment simulation at an inflation rate, $0.01\times t$ lbm/sec, are shown in Figures 12-14. Again, the residual air causes the control volumes to expand simultaneously at the beginning of the deployment and push each other upward, see Figures 12 and 13.

c. <u>Telescopically-folded Model</u>

Inflated shapes of the telescopically-folded tube in various stages of deployment are shown in Figure 15. The telescopically-folded model contains one CV. The mass flow rate into the tube is a constant of 0.518 lbs/sec. The time required to fully deploy the tube is 0.012 sec. The volume and pressure as a function of time the CV are shown in Figures 16. At the moment of the tube being fully deployed, its internal volume is about 210 in^3 and internal pressure is 10.0 psi.

2. <u>Inflation Deployment Simulation of Telescopically-folded Model Using ALE Method</u>

a. <u>ALE Results</u>

The deployment process of the telescopically-folded tube predicted by the ALE method is shown in Figure 17. It takes about 0.013 sec to achieve the full development. The pressure changes inside the tube at various locations are plotted in Figure 18. These locations are shown on the insert figure. An inflation gas density plot is shown on the bottom half of the ALE model on the insert figure. Small leakages of inflation gas outside the tube are observed. However, the leakages may not be significant since the internal pressure at the moment of full deployment correlates well with the pressure predicted by the CV method as discussed in the following sections.

b. <u>Comparisons of CV results with ALE results</u>

Results from the Control Volume (CV) method and the ALE method are compared for evaluating the deployment characteristics predicted by both methods. The deployment processes predicted by both methods are shown in Figures 15 and 17. At t=0.002 seconds, the CV method predicts that the inner section of the tube is collapsed while the ALE method predicts that the inner tube is compressed inward by the incoming gas flow. At t=0.006 seconds, with the CV method, most of the inner tube is still not extruded while with the ALE method, most of the inner section is packed together at the exit. The times required for full deployment predicted by the CV and ALE methods are very close. They are 0.012 and 0.013 seconds, respectively.

The pressure histories predicted by both methods are shown in Figure 18. The solid line with solid square marks is the pressure history predicted by the control volume method. Because this model only contains one control volume, the pressure predicted is uniform everywhere within the tube. The ALE method models the inlet gas as compressible flow and the actual fluid movements of the inflation gas are computed, so it can predict the pressure history of each element. Note, Elements A to E are uniformly located within the tube. Since the mass flow rates used by CV simulation and the ALE simulation are the same, the pressure at any moment predicted by the CV method could be considered as the average pressure predicted by the ALE method. The CV pressure curve shown in Figure 18 seems to support this statement.

c. Computational Efficiency

This study finds that a deployment simulation using the CV method is more computationally efficient than using the ALE method. A lengthy computational time is needed to simulate an inflation deployment with the ALE method. The computational times using one processor and four processors to simulate the deployment of a telescopically-folded tube on a SGI Onyx 2 machine are listed in Table 2. To complete the deployment simulation of the telescopically-folded tube using a single processor, the control volume method needs elapsed (clock) time of 0.30 hours and the ALE method needs elapsed time about 1.89 hours. Using four processors, the computational time for the CV method is reduced by about 27% while the computational time for the ALE method is reduced by about 29%. Thus, using more processors for a deployment simulation may not significantly reduce the computational time.

Table 2. Computational Times (in clock time)

Methods	Deployment Time, sec	Single Processor, hr	Four Processors, hr
CV method	0.012	0.30	0.22
ALE method	0.013	1.89	1.34

Concluding Remarks

The control volume (CV) method and the ALE method, as implemented in the LS-DYNA nonlinear dynamic finite element code, were employed to simulate the inflation deployment of three folded tube models including a coiled tube configuration, a Z-folded configuration and a telescopically-folded tube configuration. The CV approach is attractive because it uses a simple ideal gas law to compute the pressure change in each CV, and then uses the pressure to drive an incremental finite element analysis of the opening structure.

Additional simulations to evaluate the effects of the number of CVs used and the effects of the presence of residual air in the Z-folded configuration are also conducted. It was found that the number of CVs used to model the tube structure does not significantly affect the deployment simulation results. However, a very small amount of residual air can dynamically open the control volumes, pushing them apart from each other. Not including the residual air in the simulation may render an invalid or inaccurate deployment process.

The ALE method can model better the fluid (inflation gas) and structure (tube) interactions, since the three fluid conservative equations of mass, momentum, and energy are solved to predict the transient fluid properties at every location within the tube. However, this study found that the ALE method is much more computationally intensive than the CV method. The computational CV method generates inflation deployment simulation results that correlate well with the simulation results of the ALE method.

The CV and ALE methods are suitable for generating simulations of the dynamic inflation deployment process. This study found the computational challenges that could limit the wide applications of these two methods are: (1) the lengthy computational simulation time required due to the small time step used in the explicit code, and (2) the lack of robustness of the software that may terminate the simulation process prematurely. More computationally efficient and robust methods need to be developed in the future.

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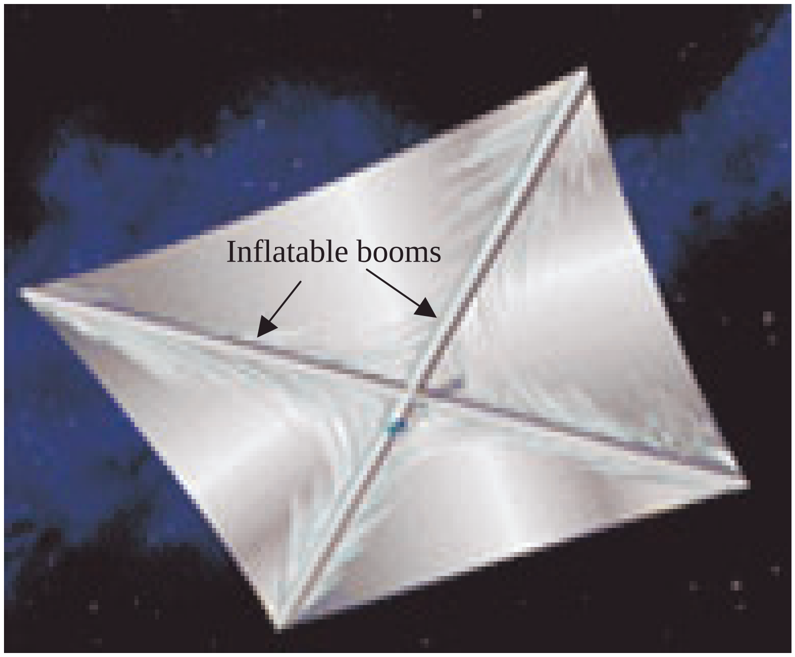


Figure 1. Solar Sail.

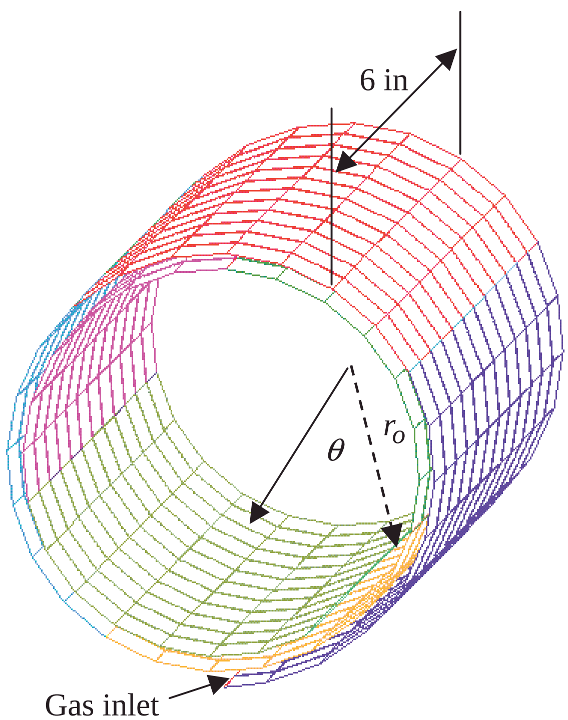


Figure 2. Finite element model of a coiled tube.

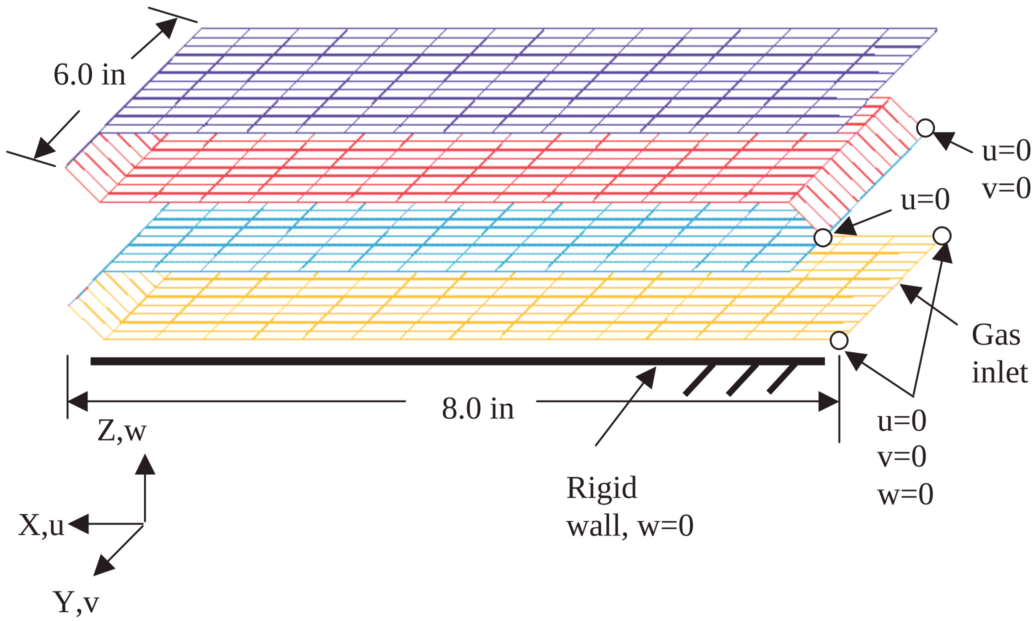


Figure 3. Finite element model of a Z-folded tube.

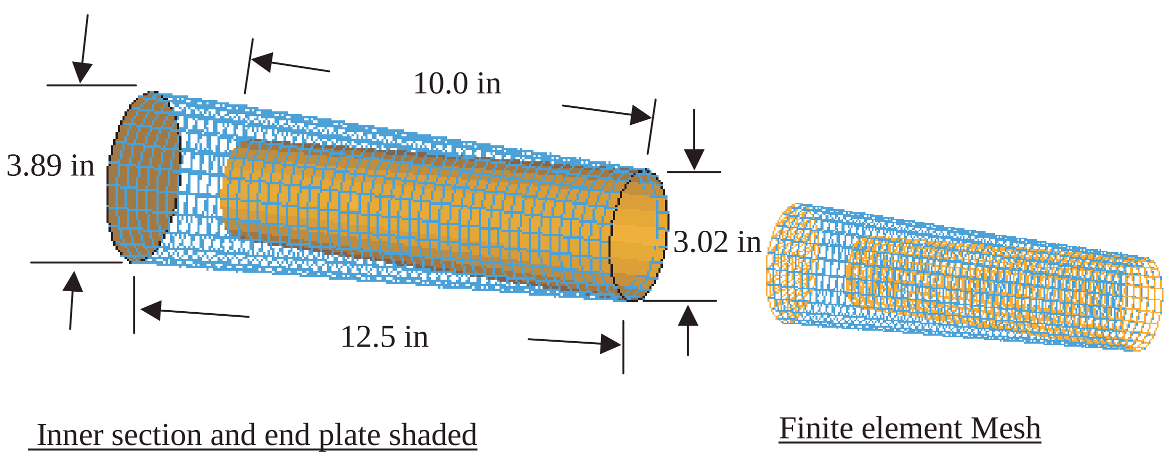


Figure 4. Telescopically-folded tube model.

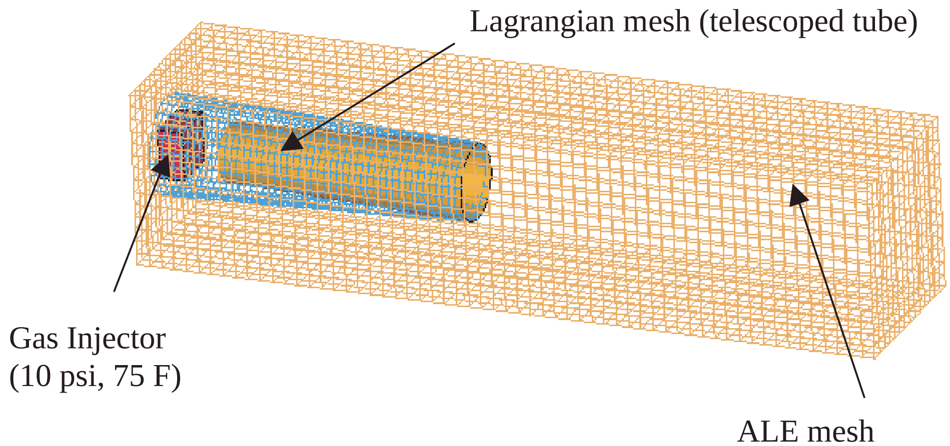


Figure 5. Telescopically-folded model.

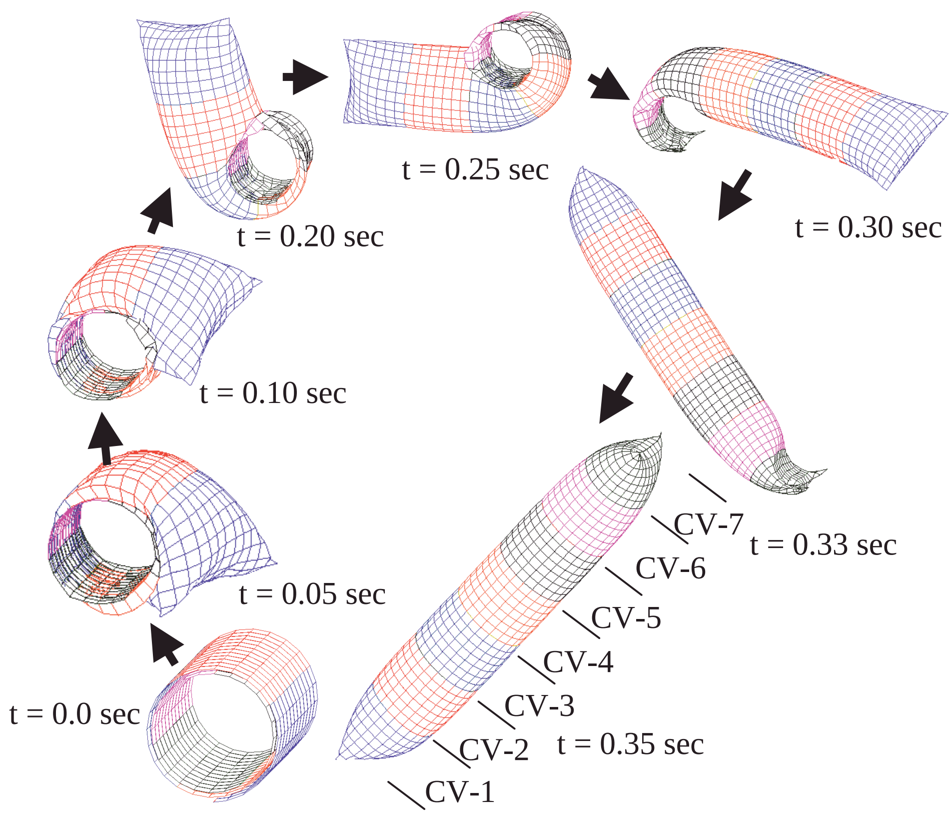


Figure 6. Coiled tube at different deployment stages.

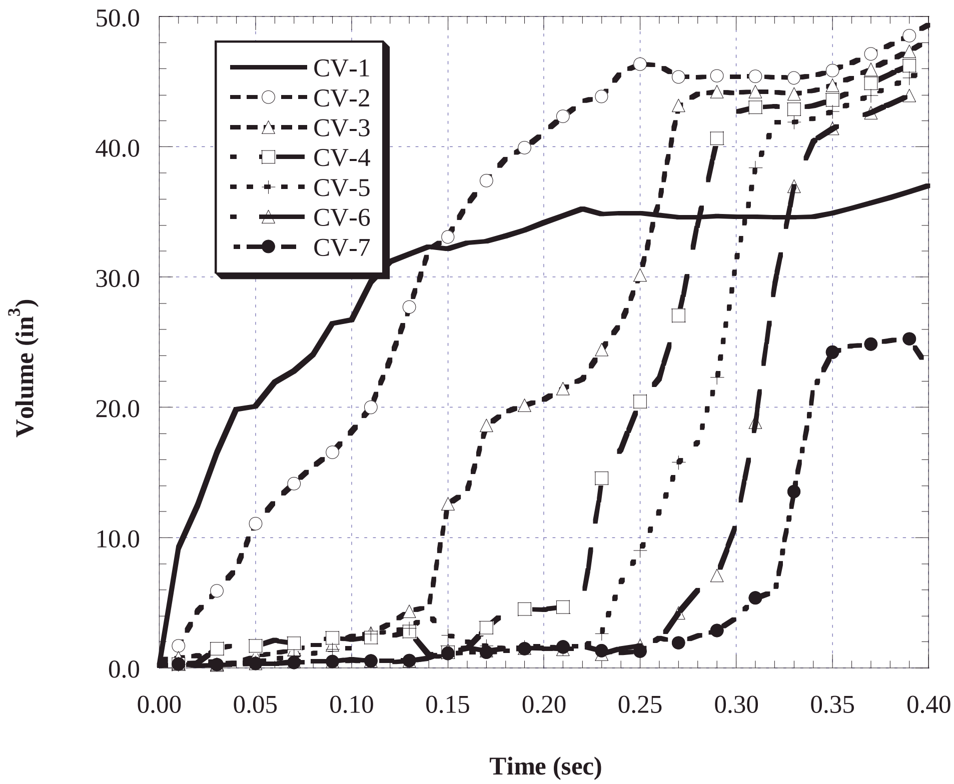


Figure 7. Volume of each control volume (CV) as a function of time.

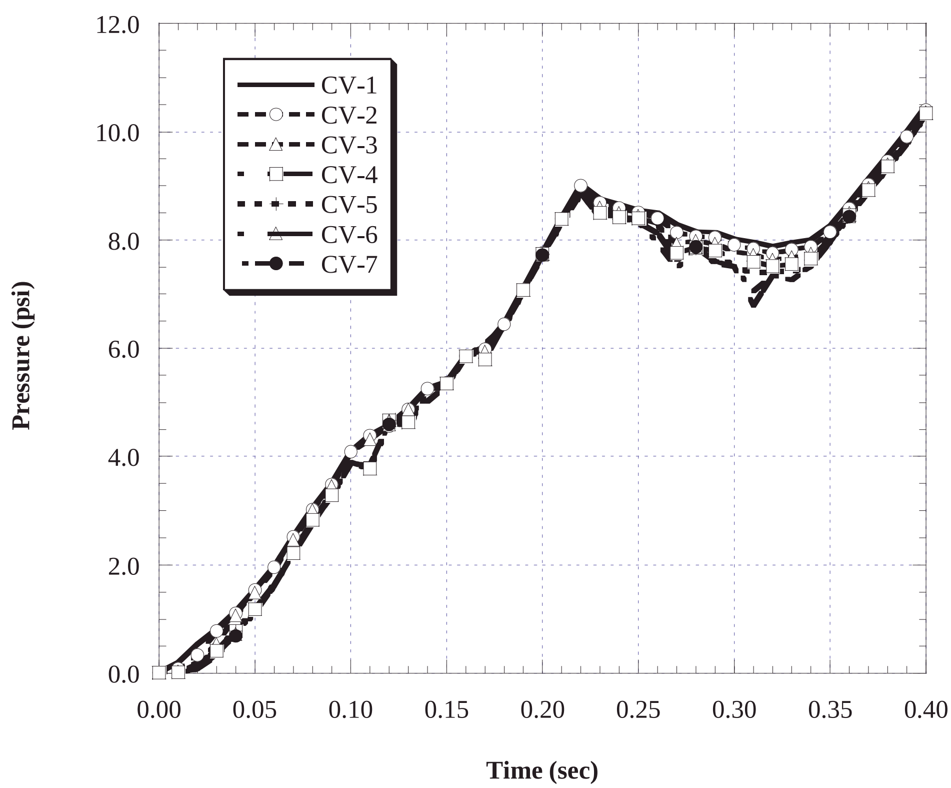


Figure 8. Pressure of each control volume (CV) as a function of time.

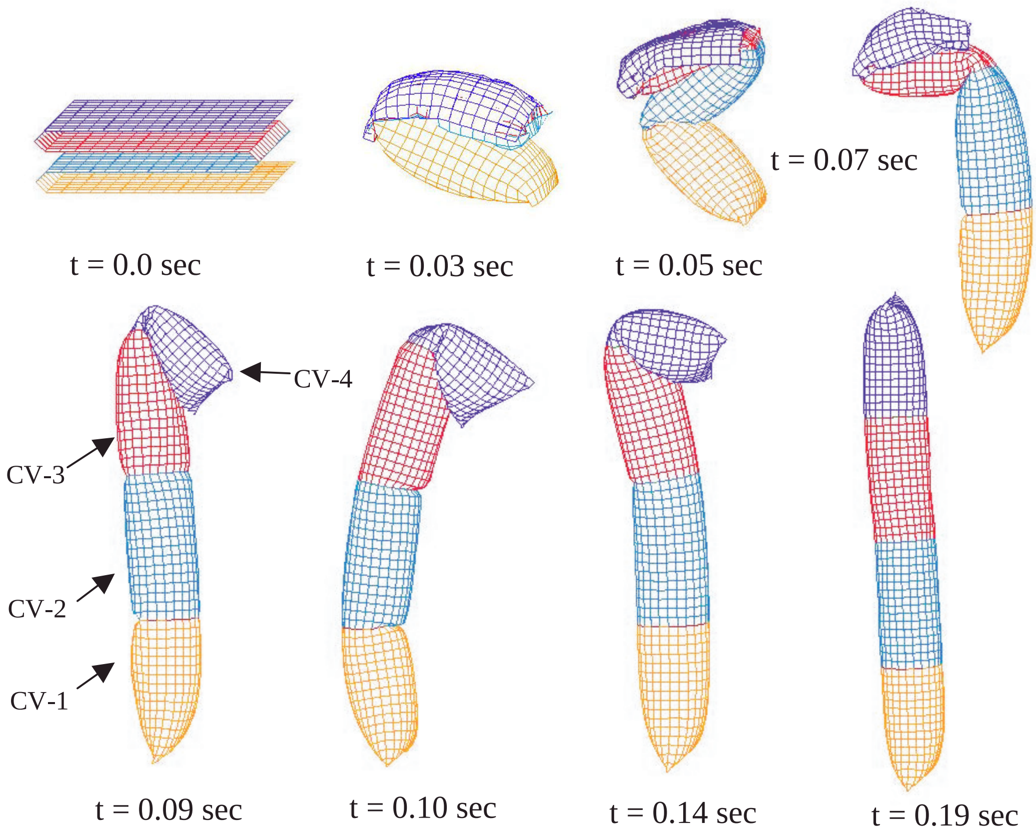


Figure 9. Z-folded tube at different deployment stages.

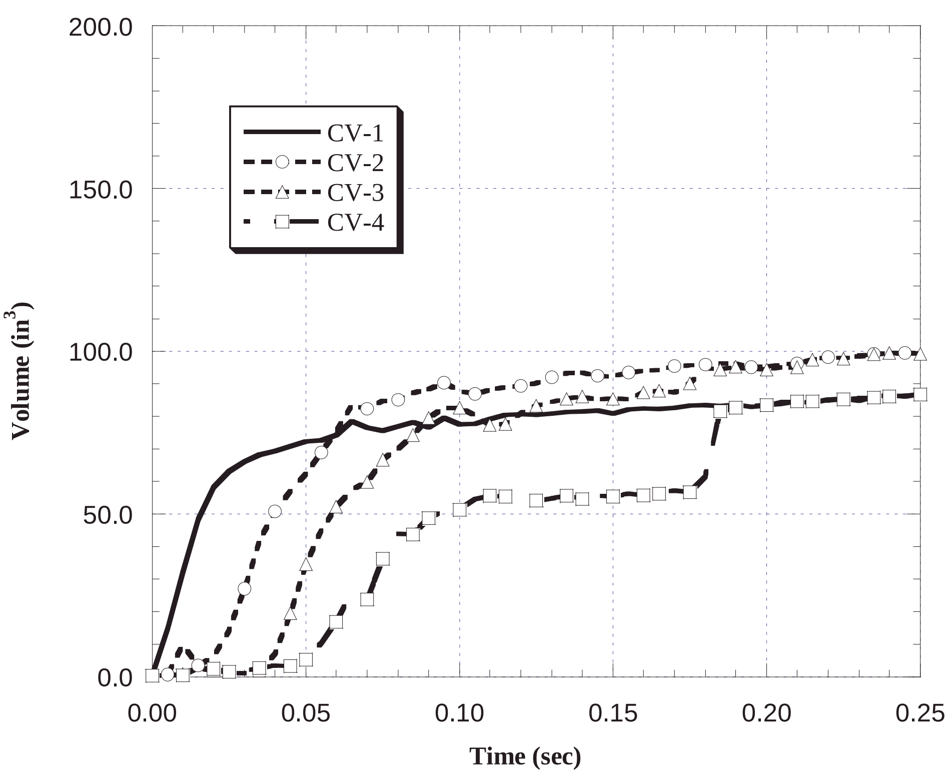


Figure 10. Volume of each control volume (CV) as a function of time.

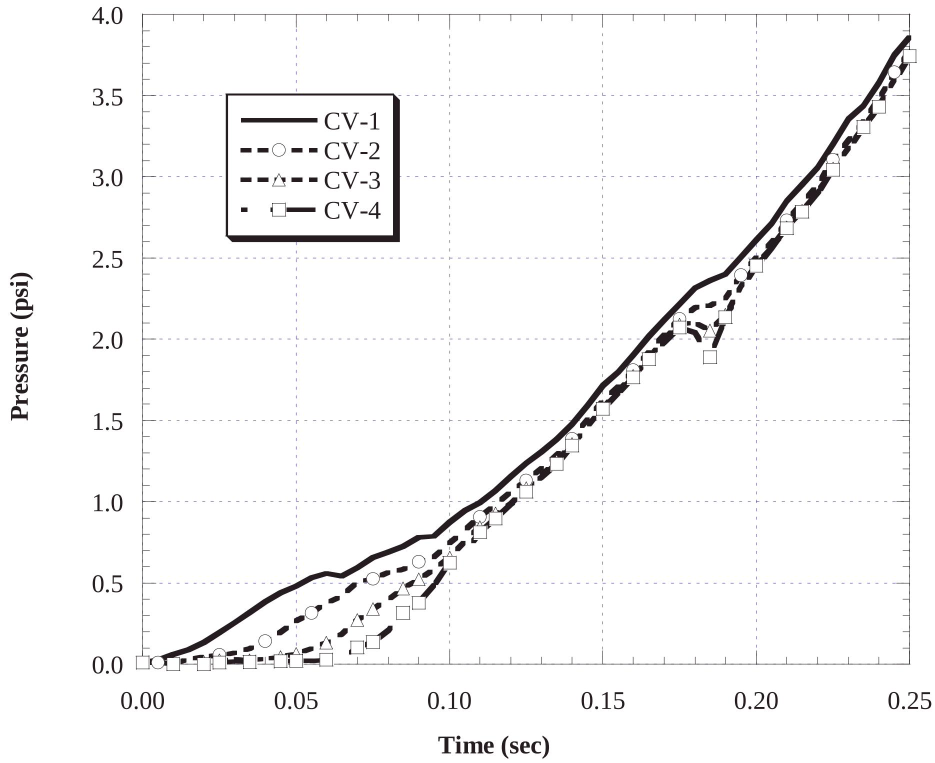


Figure 11. Pressure of each control volume (CV) as a function of time.

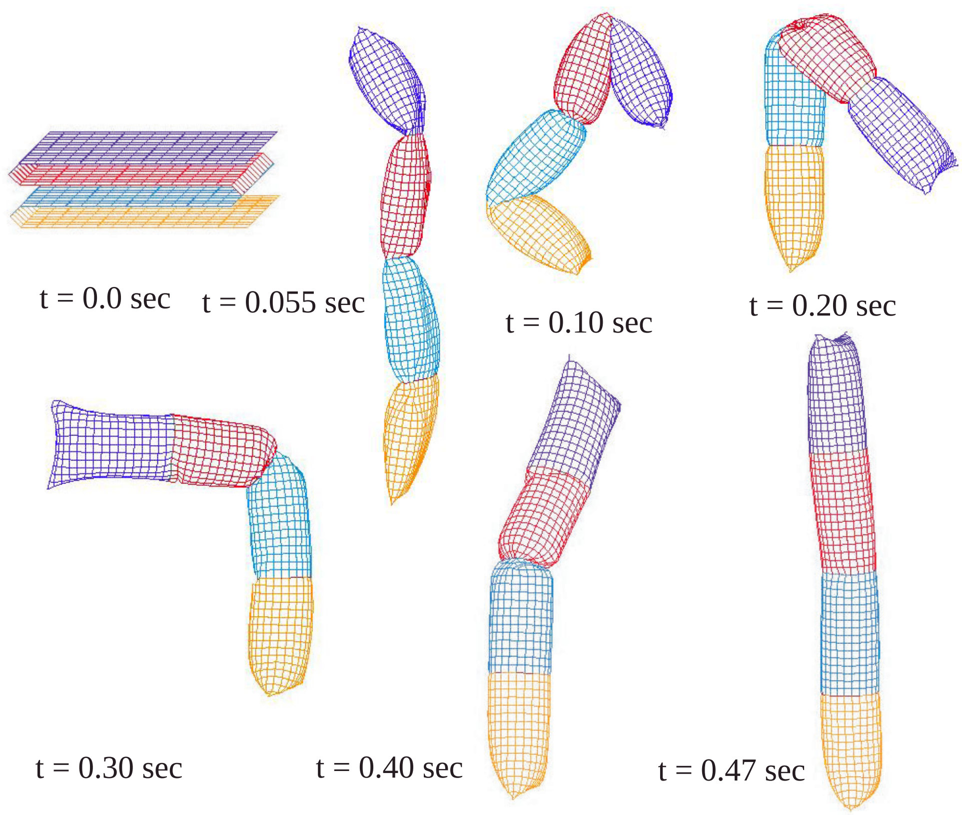


Figure 12. Different deployment stages of the Z-folded tube with residual air.

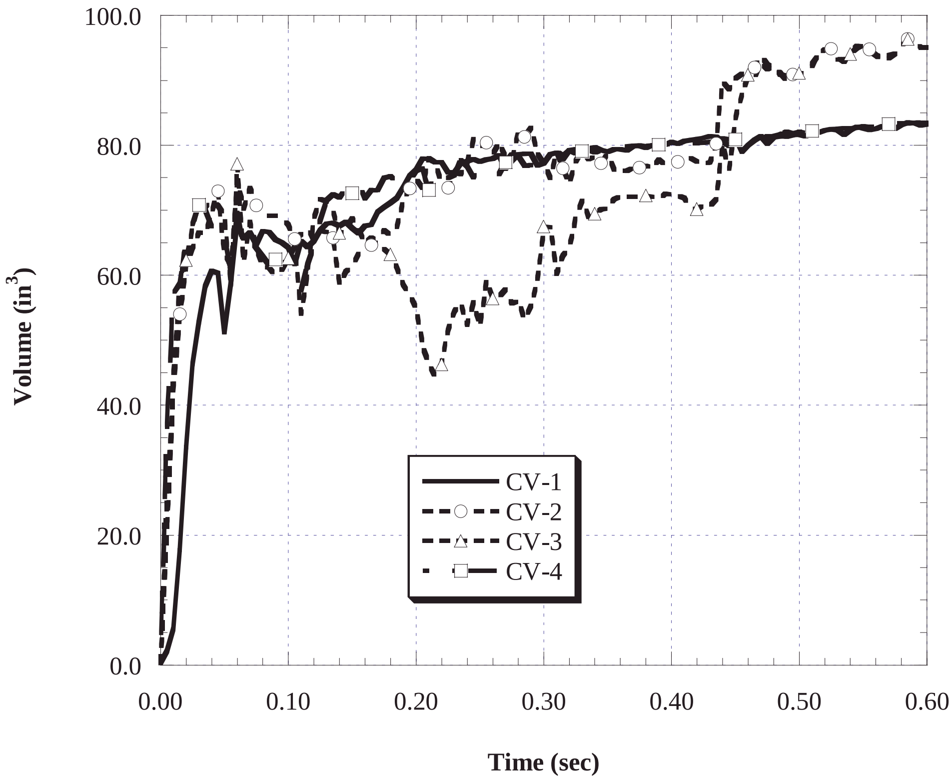


Figure 13. Volume of each control volume (CV) as a function of time for the residual air case.

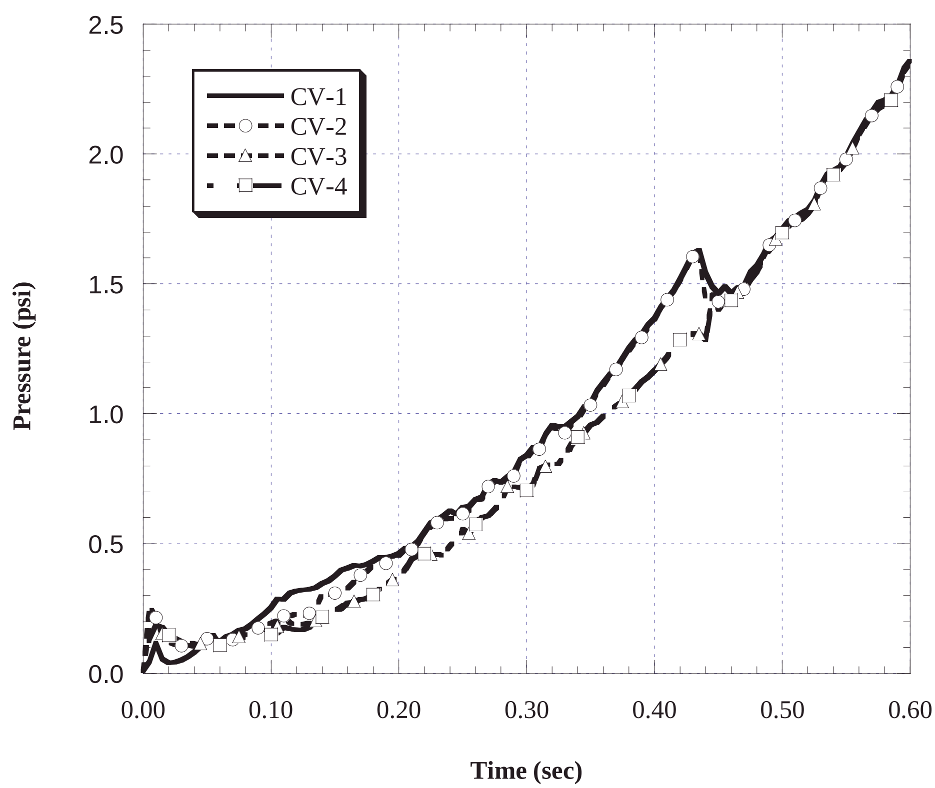


Figure 14. Pressure of each control volume (CV) as a function of time for the residual air case.

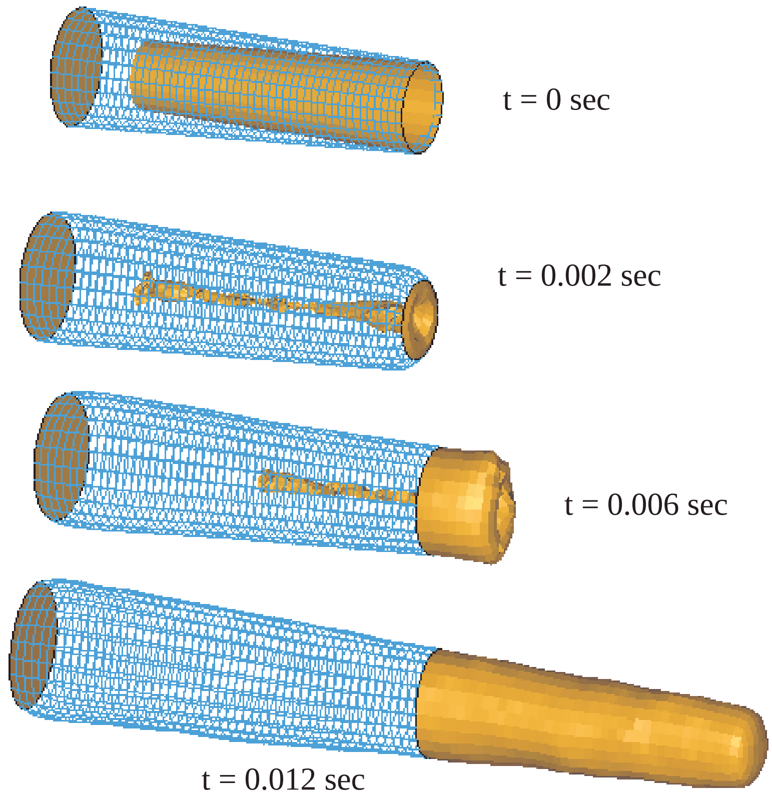


Figure 15. Telescopically-folded tube at different deployment stages.

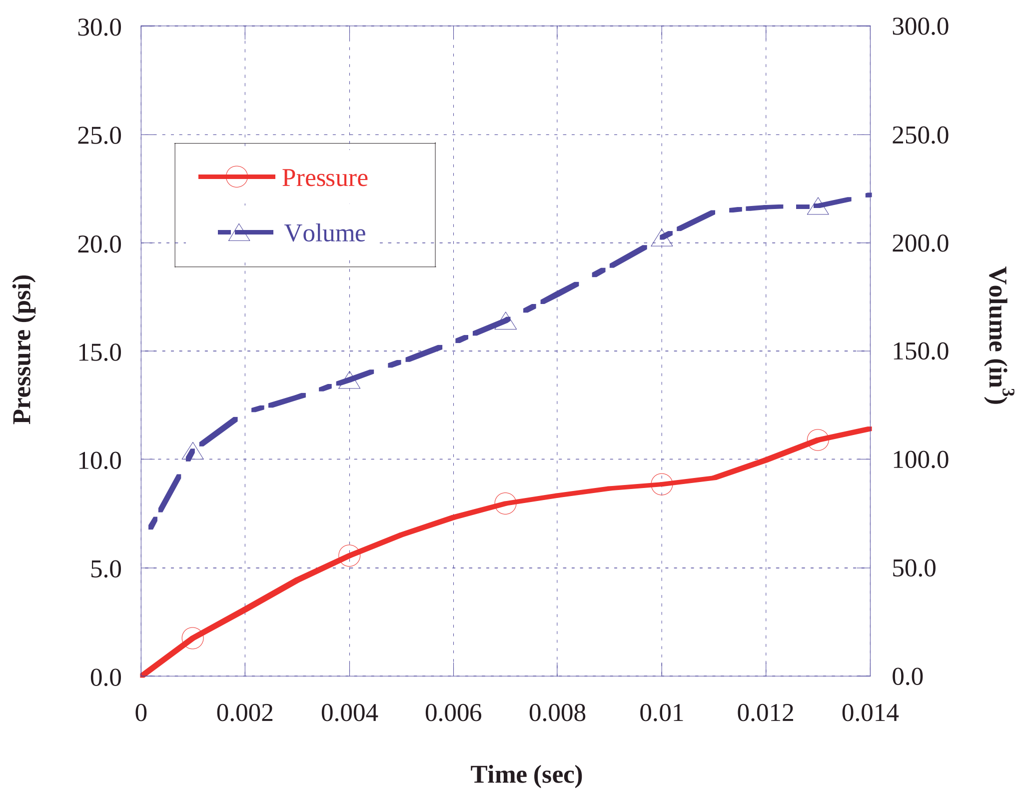


Figure 16. Pressure and volume history of the telescopically-folded tube deployment.

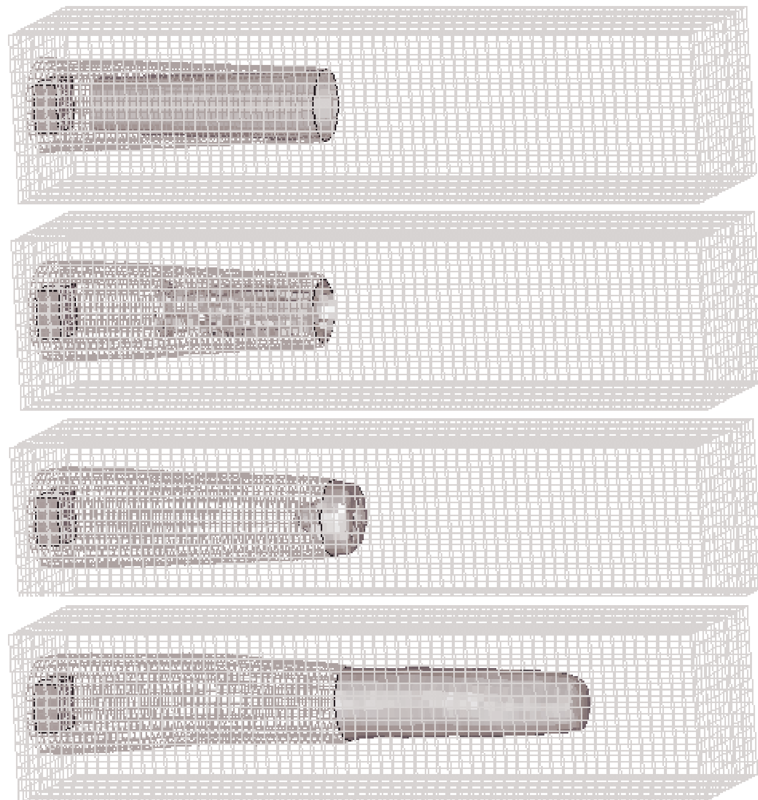
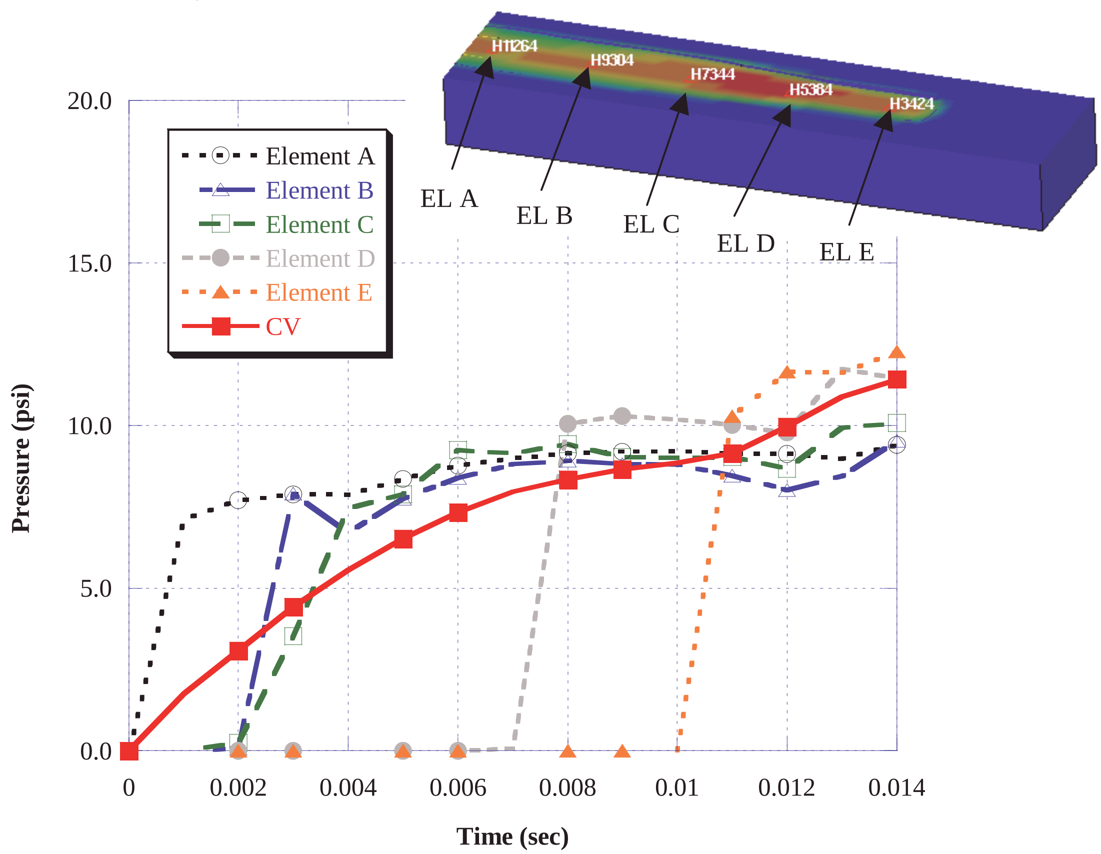


Figure 17. Telescopically-folded tube deployment.



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13. ABSTRACT *(Maximum 200 words)*
Two dynamic inflation simulation methods are employed for modeling the deployment of folded thin-membrane tubes. The simulations are necessary because ground tests include gravity effects and may poorly represent deployment in space. The two simulation methods are referred to as the Control Volume (CV) method and the Arbitrary Lagrangian Eulerian (ALE) method. They are available in the LS-DYNA nonlinear dynamic finite element code. Both methods are suitable for modeling the interactions between the inflation gas and the thin-membrane tube structures. The CV method only considers the pressure induced by the inflation gas in the simulation, while the ALE method models the actual flow of the inflation gas. Thus, the transient fluid properties at any location within the tube can be predicted by the ALE method. Deployment simulations of three packaged tube models; namely coiled, Z-folded, and telescopically-folded configurations, are performed. Results predicted by both methods for the telescopically-folded configuration are correlated and computational efficiency issues are discussed.

14. SUBJECT TERMS
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