Deformation of a Ram-Air Canopy due to Control Line Retraction

A thesis submitted in partial fulfillment of the requirements
For the degree of Master of Science in
Mechanical Engineering

By
Wilson Tang

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The thesis of Wilson Tang is approved:

_________________________  _______________________
Vidya Nandikolla, Ph. D.      Date

_________________________  _______________________
Christoph Schaal, Ph. D.      Date

_________________________  _______________________
Vibhav Durgesh, Ph. D., Chair Date

California State University, Northridge
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Abstract

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By

Wilson Tang

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This work addresses the application of finite element techniques to simulate and obtain the quasi-steady state geometry and stress field of a fully inflated MC-4 ram-air canopy in steady flight under a prescribed pressure distribution and several control line pull scenarios. Until recently, parachute systems have been designed using prototype testing. Although these design methods have produced many successful iterations of parachute designs that are used for military and civilian applications, these methods can become rather costly and time consuming. As a result, the need for more cost and time efficient parachute designs have driven the need for computational based methods as an alternative to past design techniques.

An innovative approach was developed to model the ram-air canopy. This was done by starting with the cut-pattern of the MC-4 canopy to create an “un-inflated” geometry that was then “inflated” using LS-DYNA finite element simulations. Shell elements were used to model the canopy and both 1D and 2D seatbelt elements were used for the control and suspension lines. The canopy loading used both a uniform pressure loading and a
pressure distribution based on an earlier rigid model flow simulation. Control line retractions up to 53 inches, corresponding to 100% line pull, were examined. Results indicate that even though the trailing edge of canopy deforms substantially as a result of control line retraction, global measurements for the canopy span and arc-anhedral, as measured by nodes on the leading edge, were minimally affected. The trailing edge deflection increased with the extent of line retraction and was more pronounced toward the canopy edge. The average trailing edge displacement was approximately equal to the control line retraction. In addition, local nodal displacements at the leading edge of the canopy indicated that the leading edge deformed somewhat with substantial control line retraction.

In addition, the in-plane stresses on the canopy fabric were investigated. The stress analysis was performed using spatial averaging techniques within a specified area. Results indicate that the average stresses on the canopy fabric increase in an approximately linear fashion as the control lines are progressively retracted. Furthermore, the peak stresses near the 25% chord region from the leading edge were found to not vary systematically with control line retraction since this region is farther away from the additional loading due to control line retraction at the trailing edge of the canopy. As a result, canopy stresses in regions near the trailing edge will vary with control line retraction while canopy stresses in regions near the leading edge will not undergo significant changes.
1. Introduction

Currently, parachute systems are used to in a wide variety of applications such as the transportation of air-dropped humanitarian aid packages, deployment of soldiers into combat zones, and even recreational sport activities. Based on the application, there are two main choices on the type of parachute geometries. The first type is a classical round canopy that is a drag-based parachute used to slow down payloads or personnel that are vertically dropped. This type of parachute is typically inaccurate due to being susceptible to variations in the wind and drop point of the system due to the lack of maneuverability. The second type is a parafoil or ram-air canopy as shown in Fig. 1.1 that incorporates lift and drag similar to traditional flight surfaces in order to glide to a designated target. This type of parachute alleviates the problems that affect round based parachutes by being steerable. In this work, a ram-air parachute such as the MC-4 system used in military applications was investigated.

Figure 1.1. Ram-air parachute system in flight [11].
Ram-air parachutes are typically made of a light and flexible fabric that, when inflated, resembles a low-aspect ratio wing with an arc-anhedral shape as shown in Fig. 1.2. The geometry of a ram-air canopy is made of ribs that are sewn to the top and bottom surfaces of the canopy to form multiple cells across the span of the canopy. The leading edge of the canopy is left open in order for air to be forced into the deployed canopy for inflation purposes and to create the airfoil shape of the canopy. Each of the internal ribs also have holes called cross-ports that aid the inflation process by allowing air to move across each canopy semi-cell or half-cell. To form the arc-anhedral shape of the canopy, sets of cascading suspension lines are attached to the bottom seam of every other rib. These suspension lines meet and go through a slider that allows the suspension lines to slowly spread out to alleviate structural issues that are experienced during the rapid deployment of the inflating canopy.

Figure 1.2. Component breakdown of a typical ram-air parachute [1].
To deliver accurate payloads for military purposes using conventional methods, the aircraft transporting the parachute system must fly at low altitudes and close to the designed target. Although this method increases the accuracy of the payload drop, the trade-off is increased exposure and risk to enemy attacks. To alleviate the risks, the aircraft must travel at higher altitudes with trade-offs such as decreased accuracy due to the variations in wind [1]. These issues have led to the development of computer guided parachute systems.

In the late 1960s, gliding parachute systems were introduced and have enabled the more recent development of Precision Aerial Delivery Systems (PADS). These systems usually consist of a ram-air parafoil along with a control system to steer the parachute system. The steering operation of a ram-air parafoil is somewhat similar to conventional aircraft control surfaces. In the case of ram-air parafoils, control lines that are attached to the trailing edge of the canopy can be retracted to mimic the movement of aircraft control surfaces. The complexity of PADS control systems has driven the need for computational modeling to observe the deformation of a ram-air canopy because of control line retraction.

Computational simulations of ram-air canopies require the use of Fluid-Structure Interaction (FSI) methods that couple computational fluid dynamics (CFD) and structural dynamics (SD) solvers. However, past findings also suggested that to the first order, the decoupling of the fluid and structure dynamic solutions may be acceptable in the case of the MC-4 parachute system under steady flight conditions [2]. In this work, the deformation of the MC-4 ram-air canopy due to control line retraction with prescribed pressure distributions along with the stress field on the canopy fabric were investigated using some of the techniques incorporated from a previous effort [2]. Even though general knowledge exists regarding the way control lines affect the canopy, a quantitative means of assessing
the variation of the canopy geometry with the line length would provide a deeper understanding and a useful tool for parachute system trajectory control schemes.

1.1. Literature Review

Ever since its development, numerical simulations based on the finite element method has been used as an alternative tool over empirical testing to solve complicated problems by reducing the problem into more simpler calculations. In the field of parafoils, the modelling of trajectory control schemes using numerical simulations for autonomous parachute systems to transport payloads has become increasingly popular [16, 17]. Further research into incorporating the aerodynamic effects of varying flight geometries of the canopy in flight will provide insight on how to create less complex control algorithms.

To obtain more accurate canopy geometries, FSI simulation methods have been investigated by incorporating canopy geometries determined using structural simulation results into computational fluid dynamic solvers. Recent investigations of FSI methods for parachute systems have demonstrated that the full scale canopy model can be simplified as a single half cell with periodic symmetry across the canopy ribs [5]. Although this method reduces computational cost when performing FSI simulations, the aerodynamic effects of asymmetric canopy geometries due to control line retraction are not readily available by using a single half cell. Future developments to observe the aerodynamics of a full scale canopy along with line retraction scenarios will first require the structural geometry of the complete canopy. In this work, the groundwork for computationally determining the unknown flight geometries of the canopy due to control line retraction from the known cut-pattern of the canopy was developed.
Despite numerical simulations becoming a more popular method for analysis of complex parachute systems, empirical testing is still necessary for verifying computational results and has led to specific guidelines in parachute design based on empirical data [1]. No amount of numerical results will serve as a replacement for physical testing. This is especially important in parachute design where the lives of paratroopers are at risk. However, the use of computational results to serve as a design tool for developing new computational methods while refining available techniques will provide insight on the expected behavior of a parachute system in flight.

1.2. Goals

The goals of this project were to:

- Develop a full-scale parachute canopy model in steady flight with control lines attached using existing software suites that include HyperWorks and LS-DYNA due to the compatibility and ease of use between them.
- Observe, validate, and quantify the deformation of the canopy under different control line scenarios.
- Explore in-plane stresses throughout the canopy fabric.

The simulation approach and control line implementation are presented in Sections 2 and 3 while verification cases, results, and conclusions are presented in Sections 4, 5, and 6. Section 2 discusses the software that was used to develop the canopy, the material properties of the parachute system, and the boundary conditions used to inflate the canopy. Section 3 describes how the control lines were implemented in the parachute system and some of the difficulties that arose. Section 4 describes various classical cases that were used to verify the implementation of some of the simulation features available for the LS-
DYNA structural solver. Section 5 discusses the results found by comparing simulation results to flight image data along with the deformation of the canopy due to control line retraction.
2. **Simulation Approach**

In general, finite element based simulations require a model and the material properties of the various components of the model along with the boundary conditions such as applied loads and constraints. The majority of the effort was spent during this phase of the project in order to create a model that can be readily refined or iterated for different line pull scenarios.

2.1. **Software**

As noted previously, the software of choice for this project included the HyperWorks 14.0 suite along with LS-DYNA R8.1.0. Simulations were carried out using LS-DYNA finite element code, which is a non-linear structural solver that can be used for thin walled structures. The simulated inflation of the ram-air canopy was facilitated through the use of separating the simulation pre-processing into two separate files as an input for the LS-DYNA structural solver. The first file was generated using HyperMesh as a pre-processor that included the model geometry and types of elements used along with the surfaces on which the prescribed pressure distributions were applied. The second file was a text document that contained all the necessary simulation information such as the simulation time step, material properties, contact behavior, and loading on the canopy. A sample input text file may be provided upon request. The benefit of separating the inputs of the simulation into separate files is that the simulation information can be easily adapted to accommodate multiple canopy inflation scenarios.

2.1.1 **LS-DYNA Control Cards**

In addition, LS-DYNA provides user control over the solver through the use of cards such as *MAT_FABRIC and *SECTION_SHELL. Since this study involves
inflatable fabric structures, the use of the *MAT_FABRIC card was appropriate since this material card is intended for airbag inflation simulations using fabric materials. This card also has several material formulations that can be invoked by specifying a FORM input based on the requirements of the simulation. The default and least computationally expensive fabric formulation for this material card is FORM=0 while the latest and most advanced fabric formulation is FORM=14. To determine the need for more accurate fabric behavior [14] using FORM=14, various case studies were performed and compared using the different material formulations in section 4. Since this study also involves the use of shell elements, the use of different shell formulations was also investigated for the *SECTION_SHELL card. This card has several shell formulations that can be invoked by specifying a ELFORM input. The default and least computationally expensive formulation for this card is ELFORM=2. For membrane structures such as fabrics, the ELFORM=5 may be invoked. In addition to the shell formulations, the user can specify the amount of integration points through the thickness of the shell elements. To determine the need for more accurate fabric behavior [12] through the using ELFORM=5, the use of these card inputs was examined for various classical solutions to validate their use in the canopy simulation in section 4.

2.2. Model Development

The overall dimensions of the MC-4 canopy consists of a 370 ft\(^2\) planform area, 28.5 ft span, and 13 ft chord. This canopy is made up of 14 half cells separated by ribs with cross ports for inflation purposes as shown in Fig. 2.1. Four groups of suspension lines per side with different lengths are attached to every other loaded rib. For steering purposes, control lines are attached to the trailing edge of the five ribs that form the four half cells on
the two ends of the canopy. Since the goal of the project is to obtain the quasi-steady state model of the canopy in flight, components that aid in the inflation process such as the pilot chute along with components below the slider were ignored in this study. The components to be modelled include the parachute canopy itself along with the suspension and control lines. The rectangular slider with a size of 27-by-28 inches was also incorporated into this study and was simulated by designating four fixed nodes in the model where the suspension and control lines are attached.

![Diagram of parachute system](image)

Figure 2.1. Component layout of the MC-4 parachute system [3].

After understanding the geometrical features of the MC-4 parachute system, the canopy model was developed using HyperMesh as a pre-processor. In order to obtain simulation results that reasonably match the physical behavior of the thin canopy fabric, the canopy was treated as a thin walled structure using shell surfaces. This modelling method involved translating the canopy geometrical specifications from the cut-pattern of
the MC-4 [4] into nodal coordinates and allowed the ease of modifications to the canopy geometry when required. To demonstrate this process, the drawing of the MC-4 for one of the ribs on the side of the canopy also called the side panel is shown in Fig. 2.2. Using the known dimensions and locations of each feature of the side panel, the features were designated as nodal coordinates and connected using lines as shown in Fig. 2.3. The lines were then joined together to form a surface that can be discretized. In a similar fashion, the rib for the canopy was created and shown in Fig. 2.4. This process was repeated several times until the required ribs and side panels were created.

![Figure 2.2. Engineering drawing of a side panel for the MC-4 canopy [4].](image)

After creating the side panels and ribs that span the canopy geometry, the top and bottom surfaces of the canopy were created using the known parafoil shape established by the ribs and the canopy dimensions. Since each component of the canopy was created individually, the surfaces of the canopy were joined together to allow HyperMesh’s meshing algorithm to create a uniform and continuous mesh. The result of this combined structure is shown in Fig. 2.5 for the topology of the canopy model. The color of the lines on the topology have different meanings in HyperMesh. Red lines indicate free edges where no surfaces are joined together while green and yellow edges represent shared edges between two and three surfaces, respectively. After joining the surfaces, the canopy was then meshed.
The choice of finite element types was based on the geometry and expected behavior of the parachute system. The initial “uninflated” geometry of the canopy was comprised of mainly rectangular surfaces. As a result, the canopy was discretized into 35,962 2D quadrilateral and triangular shell elements with a maximum element size of 2.88 inches. In addition, the compressive stress elimination feature was enabled for these elements using the LS-DYNA package since fabrics do not undergo compression [5]. After
discretizing the shell model into finite elements, the trailing edge was observed to be free of imperfections along with a maximum element aspect ratio of 4.26. The next set of components to be modelled was the suspension and control lines.

Using a similar method for creating the canopy surfaces, nodal points were extracted from the drawing of the MC-4 system for the suspension lines as shown in Fig. 2.6. To reduce complexity in the modelling of the suspension and control lines, the deformation of the suspension and control lines due to aerodynamic loads was assumed to be negligible during steady flight. These nodal points were then connected using 1D seatbelt elements. These 1D seatbelt elements are single degree of freedom elements that connects to two nodes and only undergoes tension. The reason why these elements were used was to reduce the complexity and simulation time to model the suspension lines in addition to only allowing tension instead of compression similar to the behavior of strings. This process was repeated for each set of cascading suspension lines attached to every other rib as shown in Fig. 2.1 in addition to the control lines. A total of 64 1D seatbelt elements

Figure 2.6. Engineering drawing [4] of one set of cascading suspension lines (left) and the discretized suspension line using 1D seatbelt elements in HyperMesh (right).
elements were used to model the suspension and control lines. The initial uninflated model of the parachute system is shown in Fig. 2.7. It is important to note that the ends of the suspension and control ends shown in gray and red are not attached to the 4-corners of the simulated slider shown in black. This is due to creating an uninflated canopy with a rectangular planform instead of an arc-anhedral shape as shown in Fig. 1.1 where the curvature of the canopy allows the ends of the suspension and control lines to reach the 4-corners of the slider. This issue will be addressed later. Special considerations on the creation of the control lines are described in Section 3. After creating the canopy geometry, the material properties of the canopy system were defined.

2.3. Material Properties

In regards to the material properties of the model, the canopy is made of low permeability PIA-C-44378, type IV fabric [7] that was assumed to be isotropic with a
thickness of 0.0028 inches, mass density ($\rho$) of $5.0 \times 10^{-5}$ snail/inch$^3$ ($6.0 \times 10^{-4}$ slug/inch$^3$), Young’s modulus ($E$) of 68,000 psi, shear modulus ($G$) of 7,000 psi, and Poisson’s ratio ($\nu$) of 0.14. Treating the canopy fabric as isotropic was an appropriate assumption since the strains throughout the canopy fabric are small enough that the material will not behave in a non-linear fashion. In addition, various material properties such as breaking strength do not vary in the warp and filling direction of the fabric [4]. The suspension and control lines are made of braided polyester [8] and were modeled as solid lines with a diameter of 0.25 inches, linear density of $2.9 \times 10^{-3}$ snail/inch (36 slug/inch), breaking strain of 30%, and breaking force of 550 lbf. Based on these material properties and the model geometry described earlier, the boundary conditions for the canopy simulation were implemented.

2.4. Boundary Conditions

The boundary conditions for the simulations included prescribed displacements, applied pressure distributions, and fixtures. As noted earlier and shown in Fig. 2.7, the location of the endpoints of each suspension and control line are not at the correct position due to the method of beginning from a cut pattern geometry. Thus, a prescribed nodal displacement was used to relocate these endpoints to the correct position at the four corners of a simulated slider shown in black in Fig. 2.7 at the start of simulations and prior to the application of the pressure loading. Two constant pressure distributions were pursued in this project. In the first case, the inner surfaces of the canopy were subjected to a 0.013 psi (90 Pa) uniform pressure distribution corresponding to the stagnation pressure of a freestream velocity of 40 ft/s (12.2 m/s). This pressure distribution was mainly used for verifying the repeatability of results from a previous study [2] that employed a different pre-processing method. After verification, a more realistic pressure distribution was
applied to the canopy that consisted of different pressure patches in the chordwise and spanwise directions as shown in Fig. 2.8. This pressure distribution was based on a CFD study [6] for a rigid canopy model. Before applying this pressure loading, the endpoints of the suspension and control lines were relocated to the four corners of the slider in order to create the arc-anhedral shape of the canopy. After repositioning the endpoints, the pressure loading was increased linearly from 1 s to 1.5 s to allow sufficient time for the canopy half cells to inflate until the aforementioned pressure distributions were reached, and thereafter remained constant toward the completion of simulations.

![Figure 2.8](image)

Figure 2.8. Pressure distribution on top and bottom surfaces of the canopy. The leading edge is on top [6].
3. Control Line Implementation

After defining the model and boundary conditions, preliminary analysis of the initial inflated canopy simulations were conducted. A detailed inspection of the canopy indicated that the control lines as modeled by the 1D seatbelt elements had penetrated through the 2D element mesh of the canopy fabric during the simulations as shown in Fig. 3.1. The ‘D’ suspension lines, which are the fourth set of suspension line attached to the canopy starting from the leading edge on first half-cell were penetrating the canopy as well. Given that the control lines are attached to the trailing edge of canopy and the relatively lower loading near the trailing edge, the penetration of control lines would have a significant effect on the canopy geometry.

Several attempts were made to solve the contact issues present in the inflated model. Research into automobile crash simulations involving seatbelts led to the idea of incorporating the use of 2D seatbelt elements to improve contact between 2D canopy mesh, control lines, and suspension lines. A simple 2D strip of these seatbelt elements are shown in Fig. 3.2. The 2D seatbelt element behaves similarly to 1D seatbelt elements but is comprised of four node surfaces instead of two node line segments. In addition, these 2D
seatbelt elements have an actual width and thickness unlike 1D seatbelt elements that only have a diameter. These 2D elements are primarily used in contact simulations at the sacrifice of computational time and simulation stability.

![Figure 3.2. Simple strip comprised of 2D seatbelt elements.](image)

A highly simplified model consisting of a rectangular fabric supported by 1D and 2D seatbelt elements was created to observe the contact behavior of these elements with the 2D quad elements of the fabric. As shown in Fig. 3.3, 2D seatbelt elements (shown in green) were attached directly to two corners of the quad element piece while 1D seatbelt elements (shown in red) were attached to the other two corners. Two-way surface to surface contact cards were used between the 2D seatbelt elements and canopy quad elements while one-way node-to-surface contact cards were used between the 1D seatbelt elements and...
canopy elements. Application of pressure to the upper surface of the model resulted in a highly curved surface as shown in Fig. 3.3 on the right. The simulation revealed that there was no penetration of the 2D seatbelt elements while the 1D seatbelt elements penetrated the fabric elements even though the contact cards were applied.

Following the simplified case, a combination of 1D and 2D seatbelt elements were incorporated into the canopy model. The 2D seatbelt elements were used to model the control lines near the canopy trailing edge where contact would most likely occur. Since 1D seatbelt elements are more robust and stable [12] as compared to 2D seatbelt elements, 1D seatbelt elements were used further away from the canopy surface to improve simulation stability. A model of control lines consisting of 2D and 1D seatbelt elements is shown in Fig. 3.4. Nodes common between the 2D canopy mesh and 2D seatbelt elements were aligned to ensure proper matching between different element types. To address the penetration of the ‘D’ suspension lines connected to the two end panels of the canopy, the upper portion of these lines were modeled by 2D seatbelt elements, similar to the way control lines were modeled. The completed model resulted in 61,535 2D quadrilateral and triangular elements, 3,616 2D seatbelt elements, and 90 1D seatbelt elements. The material properties used for the 2D seatbelt elements are identical to the material properties for the 1D seatbelt elements.

Even though the contact issue was addressed, special care regarding the time step size of the simulation was required to maintain a stable solution. Furthermore, the time step size was dependent on the element size for LS-DYNA simulations. Since the upper portion of the control lines has a width of 2 2D seatbelt elements and had to be aligned with the mesh at the canopy trailing edge, a maximum element size of 0.125 inches that corresponds
to half the diameter of the control lines at the trailing edge was required. As a result, LS-
DYNA was allowed to automatically set the time step size for the simulations. This, in
turn, increased simulation times by seven-fold. This was a necessary trade-off since the
contact issues will be alleviated through the use of 2D seatbelt elements.

Figure 3.4. Zoomed in view of a control line consisting of 2D seatbelt elements (shown in
blue) and 1D elements (shown in red) near the canopy trailing edge.
4. Trial Cases using Classical Solutions

As noted previously, LS-DYNA provides various features that can be invoked in regards to shell elements and fabric materials. As a result, the effects of these features must be investigated before proceeding with the simulation of the canopy in order to provide confidence in the simulation results. To do this, classical cases such as a cantilever beam, cylindrical pressure vessel, and flat plate with fixed boundary conditions were investigated. The goal of these verification cases was to compare the stress and deflection results from LS-DYNA simulations for each case with their respective analytical solutions. In addition, various simulation options for fabric and shell elements in the LS-DYNA code were examined.

In this study, elastic and fabric material cases using LS-DYNA finite element code were examined using the *MAT_ELASTIC and *MAT_FABRIC cards, respectively. SolidWorks finite element analysis was also employed for some comparisons. The elastic cases considered included a cantilever beam, cylindrical pressure vessel, and flat plate with fixed boundary conditions. The fabric material cases considered included a cylindrical pressure vessel and flat plate with fixed boundary conditions. The elastic cases were used to determine the validity in the use of shell elements while the fabric material cases were used to examine the differences in the material and shell formulations. The elastic and fabric material cases are presented in sub-sections A and B, respectively.

4.1. Elastic Material Cases

4.1.1. Cantilever Beam

The first elastic case considered was a cantilever beam subjected to a prescribed uniform loading based on a known solution. The beam has a 5-inch square cross section
with a length of 20 inches. The Young’s Modulus and Poisson’s ratio for this case were chosen to be 314,000 psi and 0.27, respectively. Solid 8-node hexahedral elements were used for the linear LS-DYNA simulation while solid tetrahedral elements were used in SolidWorks with an element size of 0.125 inch. With a prescribed uniform loading distribution of 500 lbf/in, the analytical bending stress along the length of the beam was computed and compared to the numerical results from LS-DYNA along with SolidWorks simulation. The analytical bending stress [15] as a function of location of interest along the length of the cantilever beam and on the most outer surface can be found using

$$\sigma_x = \frac{wc}{2l}(l - x)^2$$

where \( w \) is the uniform loading distribution, \( c \) is the perpendicular distance from the neutral axis of the beam to the most outer surface, \( I \) is the second-area moment of inertia, \( l \) is

![Bending stress graph](image-url)

**Figure 4.1.** Bending stress results for a cantilever beam. The analytical solution is compared to LS-DYNA and SolidWorks simulation results.
Figure 4.2. Convergence plot for the maximum bending stress varying as a function of the number of elements used to mesh the cantilever beam.

the length of the beam, and \( x \) is the location of interest along the length of the beam. The results of this comparison are shown in Fig. 4.1 where analytical bending stress was plotted against bending stress was found to be maximum at the root and zero at the free end of the cantilever beam. Despite being a simple case, the numerical simulations from LS-DYNA and SolidWorks simulation are not able to capture the actual bending stress at the root of the cantilever beam due to stress singularities created from fixed restraints and Poisson’s effect. To demonstrate that there was a stress singularity in the simulation, a convergence plot for the maximum bending stress at the root of the cantilever as the beam was partitioned with a finer mesh is shown in Fig. 4.2. Since the maximum bending stress increases as more elements are used to partition the beam at upwards of \( 4 \times 10^6 \) elements, the existence of the stress singularity was verified. Even though there was a stress singularity, the numerical bending stress results away from the root of the beam begin to
match and overlap the analytical solution. In regards to the deflections, the analytical tip deflection [15] can be found using

$$y_{\text{max}} = \frac{wl^4}{8EI}$$

where $E$ is the Young’s Modulus. The analytical tip deflection was determined to be 0.611-inch while the tip deflections from LS-DYNA and SolidWorks were found to be 0.651-inch, resulting in a 6.5% discrepancy.

4.1.2. Cylindrical Pressure Vessel

The next elastic case that was considered was a thin walled cylindrical pressure vessel with open ends based on a known solution. The aluminum [15] pressure vessel has a wall thickness of 0.1-inch, radius of 10 inches, and a height of 20 inches. The Young’s Modulus and Poisson’s ratio for this case were chosen to be $1.0 \times 10^7$ psi and 0.3, respectively. 2D quad elements were used for the LS-DYNA simulation with an element size of 0.5 inch. With a prescribed pressure distribution of 0.013 psi (90 Pa), the hoop stress from both the analytical solution and LS-DYNA simulation in the pressure vessel was found to be 1.3 psi, resulting in no discrepancy.

4.1.3. Flat Plate with Fixed Boundary Conditions on Edges

The last elastic case that was considered was a flat circular plate with fixed boundary conditions around the edge of the plate based on a known solution [13]. The circular plate had a thickness of 0.2 inch and a radius of 20 inches. The Young’s Modulus and Poisson’s ratio for this case was chosen to be $E=3.0 \times 10^7$ psi and $v=0.3$, respectively. 2D quad and tri shell elements were used for the linear LS-DYNA simulation while solid tetrahedral elements were used in SolidWorks with an element size of 0.125 inch. Solid
elements were used to compare how accurate thin structures can be modelled with solid elements instead of shell elements. The analytical radial stress throughout the flat plate [9] can be found using

\[ \sigma_r = \frac{-3q}{8h^2}[a^2(1 + \nu) - r^2(3 + \nu)] \]

where \( q \) is the applied uniform pressure, \( h \) is the thickness of the plate, \( a \) is the radius of the plate, and \( r \) is the radial location of interest on the circular plate. With a prescribed uniform pressure of 1 psi over the entire top surface of the plate, the analytical radial stress along the radius of the plate was computed and compared to the numerical results from LS-DYNA along with SolidWorks simulation. After determining the analytical radial stress along with performing the simulations in LS-DYNA and SolidWorks, results indicated that there was an issue in regards to the modelling of the simulation.

Although the radial stress results indicated that there was an issue with LS-DYNA, the deflection results indicated otherwise. The maximum deflection at the center of the plate [9] given by

\[ \delta_{\text{max}} = \frac{qa^4}{64D} \]

where \( D \) is the flexural rigidity of the plate. The analytical deflection was determined to be \( 7 \times 10^{-3} \) inch while the LS-DYNA and SolidWorks deflection results were found to be \( 7.1 \times 10^{-3} \) and \( 7.2 \times 10^{-3} \) inch, respectively. This will result in a 2% and 3% discrepancy from the LS-DYNA and SolidWorks deflection results, respectively. These small discrepancies in the deflection of the plate and large differences in the radial stress resulted in further exploration of the LS-DYNA code.
From research [12] along with trial-and-error, it was determined that the card input for the number of integration points within the *SECTION_SHELL card may play a role in the differences in the radial stress. By default, LS-DYNA uses 2 integration points (IP) throughout the thickness of the shell element. Since this loading scenario is a bending problem, the default IP may not be enough to fully simulate the tension and compression throughout the thickness of the plate. To verify this claim, number of IP were increased from 2 – 9 throughout the thickness of the plate and compared the radial stress along the plate for each of these cases as shown in Fig. 4.3.

Figure 4.3. LS-DYNA radial stress results along the radius of the flat plate for different number of integration points (IP) throughout the thickness of the plate.
Figure 4.4. Radial stress results along the radius of the flat plate for the analytical solution and compared to LS-DYNA with 9 integration points and SolidWorks simulation results.

As the number of IP increases from a default IP of 2 (shown in dark red) to 9 IP (shown in orange), the differences in the radial stress plots becomes smaller with an approximate maximum radial stress difference of 2% from 7 IP to 9 IP. As shown in Fig. 4.4, the radial stress results from LS-DYNA with 9 IP are now nearly matching the analytical solution with a 2% discrepancy. After validating the use of shell elements in LS-DYNA for these elastic cases, the next set of verification cases were used to examine the differences results using different fabric materials and shell elements formulations.

4.2. Fabric Material Cases

4.2.1. Cylindrical Pressure Vessel

The first fabric material case considered was a cylindrical pressure vessel using identical geometry, loading, and material properties from the elastic case examined earlier but with the *MAT_FABRIC material card enabled instead of the *MAT_ELASTIC card.
With this case, the use of different fabric and shell element formulations were investigated. The first set of cases used the default fabric form of FORM=0, which is the least computationally expensive and most robust fabric material form. Using the default shell element form of ELFORM=2, the hoop stress in the pressure vessel described earlier was found to be 1.3 psi. Using the shell element form of ELFORM=5 for membrane structures, the hoop stress was also found to be 1.3 psi. The hoop stress from the elastic solution and those using the default fabric formulation were the same. The last set of cases used the latest fabric form of FORM=14, which is expected to closely match the behavior of real fabrics. The results for both shell formulations considered were unstable and produced no result. Changing various simulation parameters such as time step and dampening also did not produce stable results with FORM=14.

4.2.2. Flat Plate

The last fabric material case considered was a flat plate using identical geometry, boundary conditions, and material properties from the elastic case examined earlier but with the *MAT_FABRIC material card enabled instead of the *MAT_ELASTIC card. Similar to the cylindrical pressure vessel case with the *MAT_FABRIC card enabled, the use of different fabric and shell element formulations were investigated. The first set of cases used the default fabric form of FORM=0 and employed the two shell formulations. Using default shell element form of ELFORM=2, the maximum radial stress in the plate was found to be $1.5 \times 10^3$ psi with a maximum deflection of $2 \times 10^{-3}$ inch. Using the shell element form of ELFORM=5, the maximum radial stress in the plate was also found to be $1.5 \times 10^3$ psi with a maximum deflection of $2 \times 10^{-3}$ inch. The last set of case runs used the latest fabric form of FORM=14 and employed the two shell formulations. Similar to
the cylindrical pressure vessel, the results of these cases were unstable and produced no result. To determine if the number of IP play a role in the runs with a fabric flat plate, the number of IP throughout the thickness of the flat plate was changed. Based on these findings, there was no difference in the maximum radial stress and displacement results when the number of IP were changed for the fabric flat plate.

4.3. Summary of Trial Studies

From these verification cases, a number of important observations are be summarized below:

- Stress results near stress singularities will not match the expected analytical solution while stress results at a sufficient distance away from the stress singularity will match the expected analytical solution.

- Depending on the boundary conditions and location of interest, displacement results will not be affected by stress singularities.

- The number of integration points for shell elements in LS-DYNA may affect stress results if bending is to be expected. The displacement results, however, do not depend on the number of integration points.

- There are no differences in stress and displacement results when specifying either of the two shell formulations (FORM=2 or 5) for these simple cases with low loading considered here.

- The latest fabric material formulation of FORM=14 is not as robust as the default formulation and may produce unstable results.

- The stress and displacement results for fabric membranes are independent of the number of integration points.
• If computational solution time is a factor, specifying card parameters other than default values will increase solution times significantly.

Based on the findings of the verification cases, parachute canopy simulations were conducted using shell formulation FORM=2 with the fabric material card along with 9 IPs.
5. Results and Discussion

5.1 Inflation of the Baseline Canopy Model

To restrain the parachute system during the simulations, each of the four corners of the slider, which co-located the endpoint of the control and suspension lines, were fixed in space, as noted earlier. With the model of the parachute system established, the simulation of the structural deformation of the canopy was performed.

The inflation process described earlier from the initial to final geometry is shown in Fig. 5.1. The simulation began with an uninflated rectangular planform based on the cut-pattern of the canopy, see Fig. 5.1a. Then, the ends of suspension and control lines were repositioned to the correct location of a simulated slider at a time of 1 s as shown in Fig. 5.1b. Subsequently, a uniform pressure distribution of 0.013 psi (90 Pa) was ramped up between 1 and 1.5 s. The canopy half-cells started to inflate due to the prescribed pressure distribution at a time of 1.5 s, see Fig. 5.1c. The simulation was then allowed to run until the quasi-steady state model of the canopy was achieved in Fig. 5.1d. The geometry of the canopy at each development stage with an applied uniform pressure distribution was similar to the case with a distributed pressure loading shown earlier in Fig. 2.8. It is important to note that this inflation process does not necessarily simulate the physical inflation process, since an actual canopy does not start with the state shown in Fig. 5.1a. Certain canopy cells inflate as soon as the canopy unfolds.
To demonstrate the effects of incorporating control lines into the model, the inflated geometry of the canopy from the side is shown in Fig. 5.2. The inclusion of control lines, even without any retraction in Fig. 5.2b, resulted in the trailing edge remaining nearly level as opposed to the downward deflected trailing edge of the model in Fig. 5.2a. Based on the loading scenarios and the lengths of the suspension lines along with the un-retracted control lines, the simulation resulted in an arc-anhedral geometry as expected.
5.2. Control Line Retraction

To assess the effects of control line retraction on the geometry of the MC-4 canopy, five different cases were considered: 0, 13, 27, 40, and 53 inches of line retraction. The line retraction of 53 inches was considered the maximum and all other line retraction lengths were normalized with this value. Thus, the five cases correspond to length retractions of 0%, 25%, 50%, 75%, and 100%. To perform the control line retraction, the full length of the control line as specified in Ref. [4] was shortened in each line retraction scenario. For the case of 13 inches of control line retraction, 13 inches from both control lines were removed from the full control line length as specified in the MC-4 specifications [4] to simulate the final length of the control line after retraction. This process was repeated for each line retraction scenario in different simulation runs.

Side, rear, and top views of the inflated canopy with different control line retractions are shown in Figs. 5.3 – 5.5. Even though the trailing edge was not deflected for the case of no line retraction in Fig. 5.4, the trailing edge was not uniform due to the
presence of control lines. The orange side panel roughly maintained the cut-pattern shape of the rib. In regards to deflection, the trailing edge deflected progressively downwards as expected. Since the center rib was not attached to any control lines, it did not undergo as much deflection as the rest of the trailing edge. This created a circular pattern as shown in Fig. 5.5 for the six half-cells in the middle of the canopy. However, as shown in Figs. 5.3 and 5.5, the center rib did deflect downwards as the control lines retracted. This was due to the load path and the applied tension from the neighboring control lines.

![Figure 5.3. Rear view of the canopy with line retractions of (a) 0 (0%), (b) 13 (25%), (c) 27 (50%), (d) 40 (75%), and (e) 53 inches (100%).](image)

Figure 5.3. Rear view of the canopy with line retractions of (a) 0 (0%), (b) 13 (25%), (c) 27 (50%), (d) 40 (75%), and (e) 53 inches (100%).
Figure 5.4. Side view of inflated canopy with different line retraction from 0 (0%), 13 (25%), 27 (50%), 40 (75%), and 53 (100%) inches shown from left to right.

Figure 5.5. Top view of the canopy with line retractions of (a) 0 (0%), (b) 13 (25%), (c) 27 (50%), (d) 40 (75%), and (e) 53 inches (100%).
5.3. Global Measures

Three global measures as used in [2] were employed to compare the final quasi-steady state geometry of the canopy with the measurements extracted from an image of a MC-4 parachute system during steady flight as shown in Fig. 5.6. The measures extracted from the flight image had an estimated uncertainty of 5% based on the unknown orientation of the canopy and image data extraction error. The three global measures are shown in Fig. 5.7. The first measure in Fig. 5.7a represents the maximum spanwise distance between the outermost leading edge nodes. The second measure in Fig. 5.7b represents the height from the centerline leading edge node to the simulated slider location. The third measure in Fig. 5.7c represents the radius of a circle that is curve fitted to the far left and right leading edge nodes along with the centerline leading edge node.

Figure 5.6. Flight image data of a paratrooper using a MC-4 in steady flight.
Figure 5.7. Global measures: canopy span (a); height (b); and radius (c).

5.3.1. Baseline Model without Control Line Retraction and Uniform Pressure

The inflated canopy for the baseline case without control line retraction with a uniform pressure distribution of 0.013 psi (90 Pa) and the distributed pressure loading shown are Fig. 2.8. These two pressure loading distributions were considered since previous findings [2] showed that there was no significant difference between uniform and distributed pressure loading in regards to the canopy geometry [2]. In the case of a uniform pressure distribution of 0.013 psi (90 Pa), the span at the leading edge in the present simulations was found to be 265.2 inches as opposed to 266.6 inches in the flight image, resulting in a 0.5% discrepancy. The vertical distance from the center of leading edge to simulated slider was found to be 190.5 inches compared to 196 inches in the flight image, resulting in a 3% discrepancy. The canopy radius in our simulations was 197.1 inches as opposed to 196.5 inches in the image data, resulting in a 0.3% discrepancy. Similar results
were observed in the case of distributed pressure loading. Measurements in the span, height, and radius were found to be 257.9, 193.9, and 190.4 inches. These measures results in 3%, 1%, and 2% discrepancy from the flight image data, respectively. These differences were deemed acceptable due to the estimated 5% uncertainty in the flight image data and the relative viewing angle of the image. Uniform and distributed pressure loading cases of [2] without control lines were compared to these results and all three measures were within 2% of the current simulations with control lines. Henceforth, the distributed pressure loading was applied to the canopy for the remainder of the simulations.

5.3.2. Inflation of Model with a Prescribed Distributed Pressure Loading

The three global measures indicated earlier were extracted from the inflated canopy model with a distributed pressure loading and at different line retraction lengths. The canopy span, height, and radius are presented in Table 5.1 and 5.2 for different line retractions. Since the flight image data closely represents no control line retraction, comparisons can only be done with the baseline canopy model without control line retraction. The discrepancies between the flight image data and baseline case was found to be within 3%, 1%, and 3% for the spanwise, vertical, and radial measures, respectively. The span and radius measures of the canopy were found to increase from no control line retraction to 100% retraction by 1.9% and 2.8%, respectively. It was expected that as the span and radius increased due to control line retraction, the height measure would decrease slightly. However, results suggest that the height of the canopy increased slightly (0.6 in or 0.3%) due to control line retraction.

Based on classical airfoil theory, pressure distribution on an airfoil is expected to change as the effective angle of attack changes. A similar result will be expected as the
effective angle of attack of the canopy changes due to control line retraction. Therefore, an identical pressure distribution for each control line retraction case is not realistic. However, the global measures for the canopy with a uniform pressure loading of 0.013 psi (90 Pa) was within the same uncertainty as the distributed pressure loading with no control line retraction [2]. As a result, it may be reasonably assumed that the global leading edge geometry will remain the same as the trailing edge deflects and the pressure distribution will be altered due to control line retraction. With the global measures of the canopy model found to be within acceptable limits, the trailing edge deflection was investigated.

Table 5.1. Global measures of canopy without control line retraction.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Flight Image (±5%)</th>
<th>0% Line Retraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span [in]</td>
<td>266.6</td>
<td>257.9</td>
</tr>
<tr>
<td>Height [in]</td>
<td>196.0</td>
<td>193.9</td>
</tr>
<tr>
<td>Radius [in]</td>
<td>196.5</td>
<td>190.4</td>
</tr>
</tbody>
</table>

Table 5.2. Global measures of canopy at different control line retractions.

<table>
<thead>
<tr>
<th>Measures</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span [in]</td>
<td>257.9</td>
<td>259.1</td>
<td>260.4</td>
<td>261.5</td>
<td>262.9</td>
</tr>
<tr>
<td>Height [in]</td>
<td>193.9</td>
<td>194.1</td>
<td>194.0</td>
<td>194.1</td>
<td>194.5</td>
</tr>
<tr>
<td>Radius [in]</td>
<td>190.4</td>
<td>191.2</td>
<td>193.0</td>
<td>194.2</td>
<td>195.8</td>
</tr>
</tbody>
</table>

5.4. Trailing Edge Deflection

The position of nodes corresponding to the trailing edge of each rib shown in Fig. 5.8 were tracked as a function of control line retraction. The nodes were numbered from 0 to 7 corresponding to the centerline to the edge of canopy, respectively. The displacement of these trailing edge nodes referenced to the no control line retraction case is shown in Fig. 5.9 for the different control line retractions. A larger displacement was observed as the control line retraction increased, as expected. A control line retraction of 25% represented an average of almost 12.7-inch change in trailing edge deflection. The
displacement of the trailing edge nodes for rib locations 0, 1, and 2 remained within a 1.6-inch bracket for each line retraction case. This relatively small bracket for displacements is understandable since there are no control lines directly attached to these ribs. Rib location 3 was attached to a control line branch and represented a transition rib between no control line to control line attachment, resulting in noticeable increase in displacement between rib locations 3 and 4. The difference in the displacement between those locations was by as much as 5 inches for the 100% line retraction case. The trailing edge nodes attached to the control lines, which correspond to the trailing edge of rib locations 3 – 7, experienced a larger displacement compared to nodes without control line attachment. At rib location 4, the displacement increased from 12.2 inches at 25% line retraction to 50.2 inches at 100% line retraction. This was also common for the other outer rib locations. The displacements in Fig. 5.9 are also indicative of the behavior of the trailing edge shown in Figs. 5.3 – 5.5. The trailing edge at rib locations 0 – 2 was deflected less than the rib locations 4 – 7 in these figures.

Figure 5.8. Trailing edge rib locations with the labels starting from the center rib.
Figure 5.9. Trailing edge displacement at different ribs referenced to the no line retraction case.

Figure 5.10. Average trailing edge displacement as a function of line retraction. The solid line has a slope of one.

In order to compare the effective trailing edge deflection due to control line retraction, the displacements for rib locations 4 – 7 were averaged and are plotted in Fig. 5.10 as a function of the control line retraction. The solid line in this plot has a slope of one and it represents a one-to-one relationship between the average trailing edge displacement and the length of control line retracted. The best-fit line to the data in Fig. 5.10 would have
a slope of 0.98. This shows that the average displacement of the trailing edge nodes closely correspond to the length of control lines retracted.

5.5. Leading Edge Deflection

Similar to the set of trailing edge nodes at different rib locations shown in Fig. 5.8, a set of nodes on the leading edge of each rib was tracked. The centerline node was labeled 0 while the edge node was 7, as shown in Fig. 5.11. The displacement of these leading edge nodes referenced to the no control line retraction case is shown in Fig. 5.12 for the different control line retractions. Before performing the simulations, it was expected that the leading edge of the canopy would remain nearly stationary as control lines shortened. However, the data in Fig. 5.12 revealed that the leading edge of the canopy also deformed when control lines were retracted. At each rib location, the leading edge displacements increased as control line retraction increased. From the 25\% line retraction case, an approximate displacement of one inch was observed and increased to approximately 7 inches at 100\% line retraction for rib locations 4 – 6. In comparison, the height of each half cell is close to 22 inches.

In general, the results suggest that the leading edge nodes whose ribs are not directly connected to the control lines (rib locations 0 – 2) would undergo the least change as compared to the ribs that are attached to control lines, except for the edge rib. For each line retraction case, rib locations 4 – 6 had the largest displacements. Starting from the center rib and moving towards the edge, displacements increased slightly until rib location 3. Then, the displacement notably increased from rib location 3 to 4 and then remained nearly constant between locations 4 – 6. The displacement decreased between rib locations 6 and
7. The results suggest that control line retraction has a different effect on each half cell across the canopy span.

Figure 5.11. Leading edge rib locations with the labels starting from the center rib.

Figure 5.12. Leading edge displacement at different ribs referenced to the no line retraction case.

5.6. **In-Plane Stresses on the Canopy Fabric**

To assess the effects of the control line retraction on the canopy stresses, the five cases considered were 0, 13, 27, 40, and 53 inches of line retraction. As noted earlier, the line retraction of 53 inches was considered a maximum and all other line retraction lengths
were normalized with this value. Thus, the five cases correspond to length retractions of 0%, 25%, 50%, 75%, and 100%, respectively. The in-plane stress field for the canopy’s top and bottom surfaces were extracted from the simulation results for each line retraction case and presented in Figs. 5.13 – 5.22. In-plane stresses were investigated as the canopy was treated as a thin-walled structure where only in-plane stresses exist. In addition, the differences between the two shell formulations in LS-DYNA were found to have a negligible impact on the stress results in the recent investigations, as shown in Section 4.

5.6.1. Stress Contours on Canopy Top Surface

In general, stress singularities were found on the canopy top surface at key locations such as the control line attachment points and the leading edge as indicated by the red colored elements in Fig. 5.13. In addition, the in-plane stresses on the canopy were greater near the ¼-chord of each half-cell than the rest of the canopy and near the trailing edge of the canopy, as highlighted by the arrows in Fig. 5.13. This was expected since there was a higher prescribed pressure loading towards the leading edge. As the control line was progressively retracted, the in-plane stresses generally increased and the peak stresses near the ¼ chord became more pronounced as indicated by the change in different colored contour levels, see Figs. 5.13 – 5.17. It is important to note that the peak in-plane stress values in each of the contour plots are due to stress singularities as noted earlier. As a result, the contour plots should be examined in a qualitative manner based on the change in contour color levels. Also, a horizontal contour pattern was observed near the center of the canopy in Figs. 5.13 – 5.16 for each control line retraction scenario.
Figure 5.13. In-plane stress contour of the canopy top surface without line retraction. Stress values are in psi.

Figure 5.14. In-plane stress contour of the canopy top surface when control lines are retracted by 13 inches. Stress values are in psi.
Figure 5.15. In-plane stress contour of the canopy top surface when control lines are retracted by 27 inches.

This horizontal pattern occurred at the transition point between the 0.022 psi (150 Pa) and 0.016 psi (112 Pa) regions in the prescribed pressure loading on the top surface of the canopy. It is important to note that as the control line was progressively retracted, the

Figure 5.16. In-plane stress contour of the canopy top surface when control lines are retracted by 40 inches.
location of this horizontal demarcation did not move towards the trailing edge of the canopy. Instead, the stress field near the canopy trailing edge progressively spread forward closer to the center of the canopy as the control lines were retracted.

Figure 5.17. In-plane stress contour of the canopy top surface when control lines are retracted by 53 inches.

5.6.2. Stress Contours on Canopy Bottom Surface

The in-plane stress field for the canopy’s bottom surface was extracted and presented in a set of contour plots in Figs. 5.18 – 5.22. Similar to the top surface, stress singularities were observed at the suspension line attachment points on the right and left hand side of the canopy as highlighted by the arrows in Fig. 5.18. Unlike the top surface, the stress field on the bottom surface of the canopy did not appear to progressively change as the control lines were retracted. Stress values on the bottom surface of the canopy were also much lower when compared to the top surface due to the lower prescribed pressure on the lower surface. This was indicated by the contour legend where the majority of the stress
Figure 5.18. In-plane stress contour of the canopy bottom surface without control line retraction. Stress values are in psi. Note that the top surface is hidden.

Figure 5.19. In-plane stress contour of the canopy bottom surface when control lines are retracted by 13 inches.
Figure 5.20. In-plane stress contour of the canopy top surface when control lines are retracted by 27 inches.

Figure 5.21. In-plane stress contour of the canopy top surface when control lines are retracted by 40 inches.

field is light to dark blue. In addition, a chevron contour pattern was observed, see Fig. 5.18. This pattern may be a result of the suspension line attachment points of the middle ribs.
In-plane stresses at the ¼-Chord

To further examine the canopy stresses as the control lines were progressively retracted, the stress values near the ¼-chord of the canopy for each line retraction case were considered. The locations of interest were grouped and highlighted in red boxes in Fig. 5.23. It is important to note that this set of elements were all under a prescribed pressure loading of 0.022 psi (150 Pa). Instead of inspecting individual elements, the in-plane stresses within each rectangular area were spatially averaged and tabulated in Table 5.3 along with the respective variation for each control line retraction scenario. In general, higher in-plane stresses can be observed near the center of the canopy at half-cell areas 4 and 5 with progressively lower values away from the center. Since the canopy was symmetrically loaded, the average in-plane stresses are expected to also be symmetric. However, the tabulated results do not reveal perfect symmetry. Despite this issue, the spread or fluctuations for the in-plane stresses between symmetric regions are large enough that the majority of the stress results in the symmetric regions are overlapping or
Figure 5.23. Half-cell locations of interest for analyzing the canopy stresses highlighted in red rectangles.

Table 5.3. Average in-plane stress for half-cell areas 1 – 8 for all line retraction scenarios.

<table>
<thead>
<tr>
<th>Location</th>
<th>0% line retraction; in-plane stress [psi]</th>
<th>25% line retraction; in-plane stress [psi]</th>
<th>50% line retraction; in-plane stress [psi]</th>
<th>75% line retraction; in-plane stress [psi]</th>
<th>100% line retraction; in-plane stress [psi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Cell 1</td>
<td>151.7 ± 3.8</td>
<td>148.4 ± 3.5</td>
<td>150.6 ± 4.1</td>
<td>158.0 ± 4.5</td>
<td>165.4 ± 4.4</td>
</tr>
<tr>
<td>Half-Cell 2</td>
<td>156.2 ± 4.8</td>
<td>156.1 ± 4.4</td>
<td>158.9 ± 3.8</td>
<td>159.5 ± 4.4</td>
<td>157.8 ± 3.6</td>
</tr>
<tr>
<td>Half-Cell 3</td>
<td>158.5 ± 4.0</td>
<td>157.4 ± 3.8</td>
<td>160.2 ± 3.3</td>
<td>165.7 ± 3.9</td>
<td>166.9 ± 3.6</td>
</tr>
<tr>
<td>Half-Cell 4</td>
<td>162.0 ± 4.0</td>
<td>166.4 ± 4.5</td>
<td>175.5 ± 5.0</td>
<td>177.2 ± 4.2</td>
<td>183.3 ± 4.4</td>
</tr>
<tr>
<td>Half-Cell 5</td>
<td>161.2 ± 4.6</td>
<td>167.5 ± 5.2</td>
<td>169.7 ± 4.0</td>
<td>173.3 ± 4.1</td>
<td>183.7 ± 4.7</td>
</tr>
<tr>
<td>Half-Cell 6</td>
<td>157.0 ± 4.0</td>
<td>166.6 ± 5.1</td>
<td>165.8 ± 4.4</td>
<td>174.1 ± 4.1</td>
<td>176.1 ± 4.4</td>
</tr>
<tr>
<td>Half-Cell 7</td>
<td>153.4 ± 3.5</td>
<td>156.0 ± 3.6</td>
<td>158.9 ± 3.9</td>
<td>161.0 ± 3.9</td>
<td>158.9 ± 4.3</td>
</tr>
<tr>
<td>Half-Cell 8</td>
<td>151.7 ± 3.3</td>
<td>151.5 ± 3.7</td>
<td>153.1 ± 3.9</td>
<td>157.7 ± 4.1</td>
<td>170.0 ± 4.2</td>
</tr>
</tbody>
</table>

quite close. In regards to the effects of control line retraction, the average in-plane stresses for the center half-cells (4 and 5) increases by approximately 14% between the most extreme line retraction cases (0% and 100%). Furthermore, the symmetric half cells, such as 1 and 8, were observed to have comparable average in-plane stresses. This was expected since the applied pressure loading was symmetric across the middle rib of the canopy in addition to symmetric control line retraction.
In regards to peak in-plane stresses, the maximum in-plane stresses for all half-cell locations were extracted and are listed in Table 5.4. In comparison, the maximum in-plane stresses are approximately 60% greater than the spatially averaged stresses. In general, the maximum in-plane stresses for each half cell are comparable for the different control line retractions. These peak stresses were then compared to the material strength of the canopy fabric [7] corresponding to a percent elongation of the fabric of 20%. Assuming linear stress-strain behavior and using the Young’s Modulus [7] of 68,000 psi for the canopy fabric along with the maximum overall in-plane stress near the ¼ chord of the canopy, the maximum principal strain was found to be 0.4%. Based on this finding, the stresses experienced on the canopy fabric in regards to these simulations were found to be significantly below the breaking strain of the fabric material. Based on these stress fields and tabulated values, the stresses in canopy fabric were observed to increase as the control lines were progressively retracted.

Table 5.4. Max in-plane stresses for half-cell areas 1 – 8 for all line retraction scenarios.

<table>
<thead>
<tr>
<th>Location</th>
<th>0% line retraction; max in-plane stress [psi]</th>
<th>25% line retraction; max in-plane stress [psi]</th>
<th>50% line retraction; max in-plane stress [psi]</th>
<th>75% line retraction; max in-plane stress [psi]</th>
<th>100% line retraction; max in-plane stress [psi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Cell 1</td>
<td>251.8</td>
<td>254.5</td>
<td>239.1</td>
<td>251.8</td>
<td>251.8</td>
</tr>
<tr>
<td>Half Cell 2</td>
<td>232.2</td>
<td>232.9</td>
<td>242.6</td>
<td>234.8</td>
<td>232.2</td>
</tr>
<tr>
<td>Half Cell 3</td>
<td>269.6</td>
<td>278.0</td>
<td>264.1</td>
<td>273.8</td>
<td>269.6</td>
</tr>
<tr>
<td>Half Cell 4</td>
<td>264.5</td>
<td>277.7</td>
<td>277.2</td>
<td>268.1</td>
<td>268.1</td>
</tr>
<tr>
<td>Half Cell 5</td>
<td>274.3</td>
<td>277.2</td>
<td>277.5</td>
<td>274.3</td>
<td>274.3</td>
</tr>
<tr>
<td>Half Cell 6</td>
<td>264.4</td>
<td>264.9</td>
<td>270.4</td>
<td>266.6</td>
<td>266.6</td>
</tr>
<tr>
<td>Half Cell 7</td>
<td>266.7</td>
<td>263.7</td>
<td>242.3</td>
<td>266.7</td>
<td>234.8</td>
</tr>
<tr>
<td>Half Cell 8</td>
<td>243.0</td>
<td>240.7</td>
<td>261.5</td>
<td>243.0</td>
<td>243.0</td>
</tr>
</tbody>
</table>
In order to investigate how the stress varied as the control lines were retracted, the spatially averaged in-plane stresses for the symmetric half-cells, such as 1 and 8, were averaged to further reduce the effect of variations. The results of the spatially-averaged in-plane stresses for the specific areas of the canopy near the ¼-chord location are presented in Fig. 5.24. For all the specified areas, the in-plane stresses increased (nearly) linearly

![Figure 5.24. Average in-plane stresses as a function of control line retraction.](image)

![Figure 5.25. Maximum in-plane stresses as a function of control line retraction.](image)
with line retraction length, and the largest in-plane stresses were in the central two half-cells for all line retraction lengths considered.

In a similar fashion, the maximum in-plane stresses were averaged over the symmetric cells and are presented in Fig. 5.25. The data revealed that the maximum stresses did not increase with the length of line retraction and could be considered nearly constant. The central half-cells did experience greater stresses by approximately 10% compared to the other half-cells considered.

5.7. Quasi-steady State Nature of the Model

In order to verify that the canopy simulations achieved a quasi-steady state solution, the displacement of three distinct nodes on the edge of the canopy were tracked during the simulation time of 25 seconds. The tracked nodes span the top surface of the canopy along the chordwise direction at the leading edge and trailing edge along with a node located in the middle of the chord as shown in Fig. 5.26. As expected, the trailing edge node would undergo the most displacement of all the nodes tracked. Displacement plots of the nodes investigated as a function of simulation time are shown in Figs. 5.27 and 5.28 for the case of no line retraction and 100% line retraction for the most extreme cases considered.

Figure 5.26. Nodal points of interest for determining the quasi-steady state behavior of the simulation.
Based on this plots, the displacement of these nodes resemble that of a 1\textsuperscript{st} order system. As a result, steady state parameters can be obtained using the theory of 1\textsuperscript{st} order systems. In the case of no control line retraction, the time constants were calculated to be 2.8, 3.6, and 5.8 seconds for the leading edge, middle, and trailing edge nodes, respectively. To be within 5\% of the steady state value, a simulation of 8.4, 10.8, and 17.4 seconds were required for the leading edge, middle, and trailing edge nodes, respectively.

Figure 5.27. 1\textsuperscript{st} order behavior of displacement for the nodal points of interest for the case of no line retraction.

required for the leading edge, middle, and trailing edge nodes, respectively. Similarly for the case of 100\% line retraction, the time constants were calculated to be 2.6, 3.8, and 3.7 seconds for the leading edge, middle, and trailing edge nodes, respectively. To be within 5\% of the steady state value, a simulation of 7.9, 11.5, and 11.2 seconds were required for the leading edge, middle, and trailing edge nodes, respectively. Based on these results, the simulation time of 25 s will result in a quasi-steady state solution with converging results.
Figure 5.28. 1st order behavior of displacement for the nodal points of interest for the case of 53 inches of line retraction.
6. Conclusions

Numerical simulations of the MC-4 canopy were performed using LS-DYNA with a prescribed distributed pressure loading for different control line retractions. This study has shown that relatively accurate inflated canopies can be generated with no control line retraction since the simulated geometry was within the estimated uncertainty of the data extracted from the image of canopy in flight. Control line retractions up to 53 inches, corresponding to 100% line pull, were examined. The simulation results indicate that even though the trailing edge of canopy deforms substantially as a result of control line retraction, the canopy span and arc-anhedral, as measured by nodes on the leading edge, were minimally (less than 3%) affected. The trailing edge deflection increased with the extent of line retraction and was more pronounced toward the canopy edge. The average trailing edge displacement was approximately equal to the control line retraction. Moreover, the leading edge also deformed because of control line retraction. These findings suggest that as the control lines retract, the geometric specifications of each half-cell will change and result in altered aerodynamic characteristics.

In regards to the in-plane stresses on the canopy fabric, preliminary results suggest that the stresses on the canopy do not result in strains that exceed the minimum elongation of the fabric material before structural failure. In addition, the peak stresses on the canopy fabric are significantly greater than the spatially averaged stress results. Lastly, the average in-plane stresses on the canopy fabric was found to increase almost linearly due to progressive control line retraction while the peak stresses appear to not depend on the line retraction.
The significance of this work was to develop a tool for creating a database that could be used to characterize the effects of different suspension and control line retractions for the MC-4 canopy geometry. Despite having a general knowledge on how the control lines affect the canopy geometry, there are no current quantitative means of determining the canopy geometry due to variations in line pull scenarios. Furthermore, this tool can be used to determine the flight geometries of the canopy for parachute system control schemes after determining the aerodynamic behavior of the canopy using CFD studies.
7. Future Work

The present simulations may be beneficial to future investigations involving CFD and FSI simulations of MC-4 and other parachute systems. In addition, the simulations can be adapted for asymmetrical control line scenarios along with other maneuvering scenarios such as suspension line retraction to create a bluff body-like form to rapidly decrease the flight velocity. The geometries obtained here could also be used to perform CFD simulations for the trailing edge deflected cases to obtain more realistic pressure loadings. The results of this study may be further validated once quantitative experimental data become available.
References


