Chapter 7 Conclusions and Future Work

This chapter summarizes this entire study, presents conclusions, and provides ideas for future work.

7.1 Summary

Using numerical results, a thorough explanation was given of the effects of cylinder geometry, specifically, circular vs. elliptical cross sections, and geometric nonlinearities on cylinder responses. Also, the effects of orthotropy were studied using quasi-isotropic, axially-stiff, and circumferentially-stiff graphite-epoxy laminates. Displacements, reference surface strains and curvatures, and force and moment resultants were used to define cylinder responses. The Hashin failure theory and the maximum stress theory were used to assess the pressure capacity of elliptical composite cylinders. Interlaminar shear stresses were considered in the assessment of pressure capacity by integrating the geometrically linear equilibrium equations of elasticity in polar coordinates through the thickness at the cylinder wall. These interlaminar shear stresses together with the inplane (intralaminar) stresses were used in the failure theories. Failure pressure levels, failure location, and failure modes were studied.

7.2 Conclusions

The effects of elliptical geometry as discussed in chapter 2 include several key issues. For instance, responses for the elliptical case vary with both the x and s coordinate. This variation is seen in every elliptical response, either over the entire domain, or at the boundary. For the elliptical cylinder:

- axial responses are compressive at certain locations for axial displacement, axial strain, and the axial force resultant, despite the axial tensile effect of the internal pressure on the cylinder end plates
- the circumferential displacement and shear force resultant are not zero, whereas, both of these responses are zero for the circular cylinder
- the normal displacement can be negative
- the shear strain is as large, or larger, than axial and circumferential strain, whereas, it is zero for the circular cylinder
- the circumferential and twist curvatures are not zero at the midspan, whereas, both of these responses are zero at the midspan for the circular cylinder
- an ellipticity of 0.7 causes a change in sign of the response at the boundary for axial curvature, all moment resultants, and the shear force resultants as s varies from $s/C = 0$ to $s/C = 0.25$. It is felt less severe ellipses, e.g., an ellipticity of 0.90, may not experience these sign reversals.

The differences between the geometrically linear and nonlinear analyses considered here are strictly due to the nonlinear terms in the strain-displacement equations. Chapter 3 examines the differences between linear and nonlinear analyses created by these nonlinear terms. The effects of geometric nonlinearities seen in this chapter include several key issues. Between linear and nonlinear analyses:

- a smaller axial end displacement, Δ, is required to satisfy axial equilibrium
- the axial displacement displays an overall difference in magnitude

•the circumferential displacement has a shift of the location of the extreme value

•the normal displacement flattens at the crown of the cylinder.

Aside from the displacements, differences between linear and nonlinear analyses, if any exist, seem to split into two categories: those due to flattening of the crown of the cylinder, and those; involving a change in magnitude of the behavior at the boundary. Flattening of the crown of the cylinder is seen in:

•the circumferential strain

•the circumferential curvature

•the circumferential force resultant.

The change of the behavior at the boundary is seen in:

•the axial curvature

•the axial and circumferential transverse shear force resultants, $\overline{Q}_s$ and $\overline{Q}_x$.

The moment resultants show both behaviors, a flattening in the crown and a change of magnitude at the boundary. Also, two definitions of the transverse force resultants, $\overline{V}_s$ and $\overline{V}_x$, are introduced for the nonlinear case. There are significant differences between the circumferential transverse shear force resultant, $\overline{Q}_s$, and the circumferential transverse force resultant, $\overline{V}_s$.

In chapter 4 the focus is shifted from the influence of elliptical geometry and geometric nonlinearities to the influence of material orthotropy. Each laminate has a different response to internal pressure due to the percentages of fibers in the axial and circumferential directions. The axially-stiff, circumferentially-stiff, and quasi-isotropic laminates result in an overall difference in magnitude for the axial, circumferential, and normal displacements. In fact, the axially-stiff elliptical cylinder evaluated using nonlinear analysis contracts axially in response to internal pressure, whereas, for the other two cases there is axial extension. For some responses orthotropy mitigates the effect of ellipticity. For example:

- the circumferential strain behaves like that of a circular cylinder in the midspan region of the circumferentially-stiff laminate, namely being independent of circumferential location
- for the axially-stiff laminate, the axial strain displays less spatial variation with both *x* and *s* compared to the axial strains for the circumferentially-stiff and quasi-isotropic laminates.

The variation with s at the clamped boundary depends significantly on orthotropy for:

- the axial curvature
- the circumferential force resultant
- the circumferential moment resultant
- the transverse force resultants.

Compared to the circumferentially-stiff and quasi-isotropic laminates, for these responses, the axially-stiff laminate does not generally exhibit as much variation with *s*.

In chapter 5, an evaluation of material failure using the maximum stress and Hashin failure criteria is presented for elliptical cylinders by considering geometrically linear and nonlinear analyses and quasi-isotropic, axially-stiff, and circumferentially-stiff laminates. Also, the approach is discussed for computing the inplane stresses, and a method is presented for computing the interlaminar shear stresses that contribute to the failure criteria. The integral of the interlaminar shear stresses through the thickness are compared to the transverse shear stress resultant to verify the derivation of the interlaminar shear stresses. The difference between the integrated interlaminar shear stresses and the transverse shear stress resultant is considered to be negligible.

In chapter 6, the Hashin and maximum stress failure criteria and geometrically linear and nonlinear analyses are considered in order to predict the location of failure, mode of failure, and the pressure at failure. First matrix failure and first fiber failure are considered. Additionally, the concept of an accumulation of matrix cracks is introduced. Catastrophic failure is not expected at initial failure due to matrix cracking. Catastrophic failure due to fiber failure is more likely. For the geometrically linear analysis:

- the Hashin and maximum stress criteria both predict failure due to matrix cracks due to high values of σ_2 at very similar, if not identical, pressure levels and locations
- first fiber failure is predicted to be fiber compression for all cases at identical locations for the Hashin and maximum stress criteria
- pressures for first fiber failure are about twice as high as for matrix cracking pressures
- the contributions of the interlaminar shear stresses to failure were small.

For the geometrically nonlinear analysis:

- the Hashin and maximum stress criteria both predict failure due to matrix cracks due to high values of σ_2 at very similar, if not identical, pressure levels and locations
- slightly higher failure pressures at locations somewhat farther from the crown are predicted for the quasi-isotropic and axially-stiff laminates compared to the geometrically linear case
- slightly lower failure pressures but identical locations are predicted for the circumferentially-stiff laminate compared to the geometrically linear case
- first fiber failure for the Hashin criterion is predicted to be fiber compression for the axially-stiff and quasi-isotropic laminates at pressures higher than first fiber failure for the geometrically linear case

- first fiber failure for the Hashin criterion is predicted to be fiber tension for the circumferentially-stiff laminate at a higher pressure and different location than first fiber failure for the geometrically linear case
- first fiber failure for the maximum stress criterion is predicted to be fiber compression for all cases at higher pressures at locations farther away from $s/C = 0$ than first fiber failure predicted using a geometrically linear analyses.

For all cases, axially-stiff and quasi-isotropic laminates are predicted to fail due to bending effects and the circumferentially-stiff laminate is predicted to fail due to inplane effects. The differences in the predictions of the two failure criteria as expressed in the last three bulleted points is considered significant.

7.3 Future Work

7.3.1 Numerical

Future work will focus on a progressive failure analysis. This will mean moving beyond the first ply failure analysis and reaching the point of having a significant number of fibers fail. Since the initial failure will take place at certain circumferential, i.e., s/C, locations and not others, degraded material properties are to be incorporated only in the affected locations. This will make the analysis much more difficult than if material properties of the cylinder are the same at all locations. Therefore the finite element program STAGS will be used to study the progressive failure analysis. This will involve doing a sequence of analyses, each with a different distribution of material properties, the distributions reflecting the progressive degradation of material properties as the pressure increases.

7.3.2 Experimental

For the experimental phase of the work, existing elliptical cylinders will be prepared for pressure testing in the Structural Mechanics Branch of the NASA-Langley Research Center. This will involve C-scanning the cylinders for any material imperfections, then scanning the geometry to determine the exact shape of the cylinders. End fittings will have to be attached and strain gages mounted. The end fittings will be ones specially-designed for pressure testing. Testing to bursting failure will then take place.