Chapter 5 Conclusions and Recommendations

In this work, a number of different models were developed to predict the deformations of unsymmetric panels. The motivation behind each model differed, depending on the degree of asymmetry and whether the model considered thermal effects or mechanical effects. However, the common thread was the existence of laminate asymmetry. Chapter 2 discussed the warpages of autoclave cured large curved composite panels due to asymmetry arising from manufacturing anomalies. In this case the asymmetry was small. Three laminates were considered, a quasi-isotropic laminate, axially-stiff laminate, and a circumferentially-stiff laminate. These were intended to be of symmetric construction, but the manufacturing anomalies prevented perfectly symmetric construction. As a first step, models were developed to analyze the deformations of a perfect panels due to the orthotropic thermal expansion effects inherent in composite materials. These results were to be used as a baseline comparison for the laminates with manufacturing anomalies. Specifically, the thermal expansion coefficient through the thickness of a layer is much larger than the coefficient of thermal expansion in the fiber direction. It was found that orthotropic thermal expansion effects led to deformations that were not captured by conventional two-dimensional theories. The next section discussed deformations induced by a misaligned layer, a common manufacturing anomaly. Specifically, a 5° misalignment was applied to each of the 16 layers, one layer at a time, while keeping the remaining layers correctly oriented. It was found that layer misalignments led to large warpage deformations that far outweighed those induced by orthotropic thermal expansion effects. The through-thickness position, and the intended orientation of the layer, as well as the lamination sequence, were found to be important variable controlling the overall warpage due to ply misalignments. During the course of this phase of the investigation, it was discovered that geometric nonlinearites are important for this problem. The linear models predicted that warpage was evenly distributed over the whole laminate, whereas the nonlinear theory predicted that warpage was confined primarily to the edges. This led to another important discovery, namely, that warpage metrics that depended on particular positions of the laminate were misleading. Therefore a normalized average warpage metric that reduced the deformation of the whole panel to one position-independent number was developed. The next section investigated the deformations induced in large curved composite panels due to asymmetry introduced by ply thickness variations. Models were developed to investigate the effect of one 10% thicker layer in the three 16-layer laminates being considered. Like the ply misalignment investigation, only one of the 16 layers at a time was assumed to be thicker, while the remaining layers were of the same normal thickness. Due to the change in fiber volume fraction, the material properties of the thicker layer were modified. It was found that ply thickness variations led to magnitudes of deformation about 25-50% of those induced by ply misalignments. Again it was seen that the through-thickness position and orientation of the thicker ply was important. Also, geometric nonlinearites were important. Finally, warpage induced by nonuniform cooling of the laminate due to thermal gradients during cure was investigated. Six temperature distributions were investigated, each comprised of a 0.1°F/in. thermal gradient in the plane of the laminate. Due to the relatively thin nature of the laminates being considered, the temperature was assumed to be constant through the thickness of the laminate. It was found that inplane thermal gradients led to very small deformations. The deformations were negligible with respect to those induced by ply misalignments and ply thickness variations. Interestingly, geometric nonlinearities were found to be important to accurately predict the deformations induced by thermal gradients. Overall, for all the cases considered in Chapter 3, geometric nonlinearites were found to be important. Generally, the axially-stiff laminate was the most sensitive to circumferential warpage due to the lack of fibers in the circumferential direction to counter the deformations. A similar trend was not observed for circumferentially-stiff laminates in axial warpage. This can be attributed to the geometric stiffness induced by the initial panel curvature suppressing any tendencies for these laminates to deform in the axial direction. In summary, deformations of large curved composite panels due to manufacturing-induced asymmetries are most sensitive to ply misalignments followed by ply thickness variations. Thermal gradients and orthotropic thermal expansion effects were found to be negligible.

Chapter 3 discussed the deformations of severely unsymmetric composite plates caused by the temperature change from cure temperature to room temperature. The purpose of this phase of the study was to demonstrate that the magnitude of the out-of-plane deformations due to severe laminate asymmetry could be large. These results were to be a comparison to the cases considered in Chapter 4, where it was assumed severely unsymmetric laminates could be manufactured to be flat, perhaps with e-beam curing, and the bending-stretching coupling inherent in unsymmetric laminates be taken advantage of. Due to the nature of the problem being discussed, geometric nonlinearities were important. Four cross-ply laminates and three angle-ply laminates were discussed. Four-term and 14-term Rayleigh-Ritz models were developed, together with finite-element models to predict the deformed shapes of these laminates. Actual specimens were constructed and measured at NASA Langley Research Center for comparison with predictions. Results for all three models agreed well with experimental results. It was found that the 14-term Rayleigh-Ritz model was the best tool due to the physical insight provided by the analysis, the ability to find multiple stable configurations, and its computational efficiency compared to the finite-element models.

Once the manufacturing induced deformations discussed in Chapters 2 and 3 are eliminated so that dimensionally stable unsymmetric laminates can be manufactured, the response of these laminates due to mechanical loads needs to be investigated, particularly the response of severely unsymmetric laminates. Therefore, Chapter 4 discussed the deformations of unsymmetric composite plates due to inplane endshortening under various boundary conditions. Seven plates were considered in increasing levels of asymmetry, including, for comparison, an aluminum plate and two symmetric laminates. Each plate was evaluated with three boundary condition combinations, namely, clamped ends with clamped sides, clamped ends with simply-supported sides, and simply-supported ends and sides. Generally, the response depended on the laminate construction and boundary conditions applied along the ends and sides of the plate. The aluminum and symmetric cross-ply laminates had no out-of-plane deformations until classic buckling, or primary instability, and then exhibited two stable solutions. Each also exhibited a secondary instability that resulted in two stable solutions. It was found that the characteristics of the symmetric laminates showed similarities regardless of boundary conditions, while the unsymmetric laminates did not. Namely, the CL-CL boundary conditions for the unsymmetric laminates caused unique characteristics that were not exhibited by the CL-SS and SS-SS cases. This was attributed to the suppression of prebuckling deformations due to the clamped conditions along the plate boundaries discussed by Leissa [8]. However, the unbalanced unsymmetric laminate, the $[30_2/90/0]_{2T}$ laminate, did not follow this trend. Namely, all three boundary condition combinations for this laminate exhibited no classic buckling followed by secondary buckling behavior. This contradicts the findings of Leissa, since the clamped conditions applied for the CL-CL case failed to suppress the initial out-of-plane deformations, causing the laminate to make a transition from the flat state to a state with one half-wave in the two perpendicular plate directions, without undergoing bifurcation behavior. Overall, all cases considered became statically unstable at some point within the endshortening, thereby requiring a dynamic transient analysis to find alternate statically stable equilibrium solutions. Due to the nature of the problems considered in this section, geometrical nonlinearities are crucial for this analysis, as was the case with all the preceding chapters.

It is recommended that future work incorporate the effects of geometric imperfections in the plate. Preliminary investigations have shown that geometric imperfections can have a significant effect on the prebuckling, buckling, and postbuckling deformations of the plates discussed here. Most importantly, initial geometric imperfections will induce out-of-plane displacements from the onset of inplane endshortening in all plates, including isotropic and symmetric plates. This will prohibit the plate from exhibiting classic buckling, or primary instability. The consequences of including geometric imperfections in unsymmetric laminates under axial endshortening are not well understood. Due to the realities of manufacturing and the effects of manufacturing anomalies, such as those discussed in Chapter 2 and 3, geometric imperfections are inevitable. Therefore the effects of geometric imperfections warrants further investigation.

To investigate the mechanisms causing the various deformations seen in Chapter 4, a study of the distribution of stress resultants along the plate boundaries may be insightful. Namely, it would be of importance to know why certain laminates and boundary conditions exhibit certain shapes, and primary and secondary instabilities, while others do not. The unbalanced unsymmetric laminates, in particular, exhibits unique behavior that depends primarily on the boundary conditions. The distribution of stress resultants along the boundaries may lead to further understanding of the mechanisms responsible for this unique response.

Finally, the development of approximate classical solutions can contribute to verify the dynamic transient technique, namely the number and shapes of equilibrium solutions past points of instability. However, the relative complexity due to the bending-stretching coupling induced by the unsymmetric construction of the laminates makes this a formidable task, but worthy of future research efforts in investigating the deformations of unsymmetric composite panels.