

# Table of Contents

|   |           |
|---|-----------|
| <b>Chapter 1: Introduction</b>  | <b>1</b>  |
| <b>1.1 Motivation</b>   | <b>1</b>  |
| <b>1.2 Literature Review</b>  | <b>4</b>  |
| 1.2.1 Geometrically Nonlinear Finite Element Analysis   | 4         |
| 1.2.2 Cure Simulation and Process-Induced Deformation in<br>Thermosetting Composites  | 8         |
| 1.2.3 Convexity and Uncertainty   | 10        |
| 1.2.4 Optimization of Composite Stiffened Panels Using<br>Genetic Algorithms  | 12        |
| <b>1.3 Organization</b>   | <b>14</b> |
| <br>  |           |
| <b>Chapter 2: Nonlinear Finite Element Formulation for the<br/>Postbuckling Analysis of Stiffened Composite Panels with<br/>Imperfections</b> | <b>18</b> |
| <b>2.1 Variational Equation of Equilibrium</b>  | <b>20</b> |
| <b>2.2 Stiffness Formulation for a Rectangular Plate Element</b>  | <b>24</b> |
| 2.2.1 Strain-Displacement Relations   | 26        |
| 2.2.2 Stress-Strain Relations   | 27        |
| 2.2.3 Stress Resultant-Strain Relation  | 28        |
| 2.2.4 Finite Element Formulation  | 30        |
| 2.2.5 Evaluation of the Linear Stiffness Matrix $[K_o]$   | 32        |
| 2.2.6 Evaluation of the Initial Displacement Matrix $[K_L]$   | 34        |
| 2.2.7 Evaluation of the Initial Stress Stiffness Matrix $[K_\sigma]$  | 37        |
| <br>  |           |
| <b>Table of Contents</b>  | <b>iv</b> |

|   |           |
|---|-----------|
| 2.2.8 Applied Load Vector   | 38        |
| <b>2.3 Hybrid Numerical-Analytical Integration</b>  | <b>39</b> |
| <b>2.4 The Frontal Equation Solution Technique</b>  | <b>40</b> |
| <b>2.5 Incremental Procedure for Solutions of Nonlinear Discrete Problems</b>   | <b>42</b> |
| <b>2.6 Numerical Examples</b>   | <b>45</b> |
| 2.6.1 Large Deflection of an Uniformly Loaded Square Plate without Imperfections  | 45        |
| 2.6.2 Large Deflection of an Uniformly Loaded CCCC Square Plate with Initial Imperfection                                 | 48        |
| 2.6.3 Large Deflection of a Square Plate under a Concentrated Load with Two Opposite Edges Clamped and the Other Two Free | 49        |
| 2.6.4 Postbuckling Response and Failure Prediction of a Graphite-Epoxy Plates Loaded in Compression                       | 51        |
| <br>  |           |
| <b>Chapter 3: Optimum Design of Stiffened Composite Panels Using Genetic Algorithms</b>                                   | <b>56</b> |
| <b>3.1 Introduction</b>   | <b>56</b> |
| <b>3.2 Problem Description</b>  | <b>57</b> |
| <b>3.3 Optimization Formulation</b>   | <b>59</b> |
| <b>3.4 Implementation of the Genetic Algorithm</b>  | <b>61</b> |
| <b>3.5 Parent Selection</b>   | <b>64</b> |
| <b>3.6 Crossover</b>  | <b>65</b> |
| <b>3.7 Mutation</b>   | <b>66</b> |
| <b>3.8 Optimization Results</b>   | <b>67</b> |

|  |           |
|--|-----------|
| <b>Chapter 4: A Manufacturing Model for the Prediction of<br/>the Cured Profile of Epoxy Resin Composite Laminates</b> | <b>69</b> |
| <b>4.1 One-dimensional Cure Simulation</b>   | <b>70</b> |
| <b>4.2 Material Models</b>   | <b>75</b> |
| 4.2.1 Resin Modulus Variation  | 75        |
| 4.2.2 Lamina Mechanical Properties Variation   | 76        |
| <b>4.3 Chemical Shrinkage Strains</b>  | <b>79</b> |
| 4.3.1 Resin Chemical shrinkage   | 79        |
| 4.3.2 Lamina Chemical Shrinkage Strains  | 79        |
| <b>4.4 Lamina Thermal Expansion Strains</b>  | <b>80</b> |
| <b>4.5 Total Lamina Strain Increment</b>   | <b>80</b> |
| <b>4.6 Transformation of the Strain Increments</b>   | <b>81</b> |
| <b>4.7 Incremental Moment Resultant</b>  | <b>82</b> |
| <b>4.8 Finding the Curvatures</b>  | <b>83</b> |
| <b>4.9 Panel Profile Generation</b>  | <b>85</b> |
| 4.9.1 Panel Discretization   | 85        |
| 4.9.2 Determination of Panel Profile   | 86        |
| <b>4.10 Experimental Validation of the Suggested Model</b>   | <b>88</b> |
| <b>4.11 Generation of Imperfect Panels</b>   | <b>93</b> |
| 4.11.1 Numerical Example   | 93        |
| 4.11.2 Effect of Fiber Orientation on Cured Profile  | 96        |
| 4.11.3 Effect of the Number of Layers on the Final Panel Profile   | 97        |
| 4.11.4 Effect of the Position of the 45° Plies on the Final Profile  | 98        |

|  |            |
|--|------------|
| <b>Chapter 5: Convex and Probabilistic Models for the<br/>Uncertainties in Geometric Imperfections of Stiffened<br/>Composite Panels</b> | <b>100</b> |
| <b>5.1 The Design Problem</b>  | <b>105</b> |
| <b>5.2 Convex Models of Uncertainty</b>  | <b>109</b> |
| <b>5.3 Validation of the Convex Model Predictions</b>  | <b>113</b> |
| <b>5.4 Probabilistic Analysis of the Elastic Limit Load</b>  | <b>117</b> |
| <b>5.5 Concluding Remarks</b>  | <b>121</b> |
| <b>Chapter 6: Results and Discussion</b>   | <b>122</b> |
| <b>6.1 Results of the First Design Scheme</b>  | <b>126</b> |
| <b>6.2 Results of the Second Design Scheme</b>   | <b>131</b> |
| <b>Chapter 7: Conclusions</b>  | <b>133</b> |
| <b>7.1 Conclusions</b>   | <b>133</b> |
| <b>7.2 Future Work</b>   | <b>135</b> |
| <b>References</b>  | <b>136</b> |