EFFECT OF GEOMETRIC IMPERFECTIONS (WRINKLES) ON THE CIRCUMFERENTIAL STRENGTH OF A COMPOSITE POLYMER LINER FOR PRESSURE PIPES

by

Nancy Eduafoa Ampiah

A thesis submitted to the Department of Civil Engineering in conformity with the requirements for the degree of Master of Science (Engineering)

Queen’s University
Kingston, Ontario, Canada
(September, 2008)

Copyright ©Nancy Eduafoa Ampiah, 2008
ABSTRACT

The relining of deteriorated gravity flow and pressure pipes with polymeric liners is now popular practice. In the water industry, health concerns and challenges associated with re-opening water services in a lined small diameter pipe have limited the use of liners. Sanexen Environmental Services Inc. in Montreal, Canada, manufactures a cured-in-place liner system which can restore water service connections after lining from within the pipe, using a remote controlled robot.

The installation of the liner within cast iron water pipes can result in the formation of geometric imperfections (wrinkles) as the external diameter of the liner often exceeds the internal diameter of the host pipe. Previous studies have suggested that the wrinkles have a detrimental effect on the structural performance of the liner. In this study, experimental and analytical investigations were conducted to evaluate further the effect of the wrinkles on the circumferential (hoop) strength of the liner.

The experimental investigation involved testing 33-25 mm wide ring samples of the liner with and without wrinkles, using the split-disk test method which is defined by ASTM Standard D2290. The laboratory tests were conducted to examine the effects on the response of the liner of loading rate, cyclic loading, and presence of different wrinkle configurations. A series of two-tailed Mann-Whitney statistical tests were conducted on the obtained test data. The analytical investigation examined the behavior of two of the
three types of wrinkles observed in the liner using finite element models. The results from the models were evaluated using the experimental results.

This study confirmed that the wrinkles were a source of weakness in the liner as failure was initiated at the wrinkle in all the test samples. It also showed that their presence may or may not result in a reduction in the ultimate hoop tensile capacity of the liner depending on wrinkle pattern. The loading rate had no significant effect on the first cracking load of the resin within the wrinkle. However, lower ultimate hoop tensile capacities were observed at very slow loading rates. Under the 50-year cyclic loading, the resin within the wrinkle was susceptible to cracking while the jackets of the wrinkle remained intact.
ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisors, Dr. Amir Fam and Dr. Ian Moore who provided guidance and support during the course of my master’s research work.

I would also like to thank the technical support staff of the Civil Engineering Department whose assistance contributed towards the smooth running of the laboratory and analytical components of my research work. I am also grateful to all the faculty and staff members, my colleagues and friends who provided any form of help during my studies as a graduate student.

I would like to thank Kevin Bainbridge and the City of Hamilton, Canada, who provided the test samples and field information. This research work was funded by a strategic research grant from the Natural Sciences and Engineering Research Council of Canada.

I would also like to express my gratitude to my father, Ato, and my mother, Love, who to this point in my life, have always been and continue to be my strongest supporters, and have also taught me a lot of great life lessons. I would like to thank my siblings, Nelly, Theophilus, and Louisa, for their unconditional love and encouragement.
# TABLE OF CONTENTS

ABSTRACT.....................................................................................................................................ii

ACKNOWLEDGEMENTS............................................................................................................iv

TABLE OF CONTENTS.............................................................................................................. v

LIST OF TABLES..........................................................................................................................xi

LIST OF FIGURES......................................................................................................................xiii

NOTATION......................................................................................................................................xxii

CHAPTER 1 - INTRODUCTION................................................................................................... 1
  1.1 General ................................................................................................................................... 1
  1.2 Objectives ............................................................................................................................ 3
  1.3 Scope ...................................................................................................................................... 4
  1.4 Outline of Thesis .................................................................................................................... 6

CHAPTER 2 - LITERATURE REVIEW........................................................................................ 8
  2.1 Introduction ............................................................................................................................ 8
  2.2 Causes of Pipeline Deterioration ........................................................................................... 9
  2.3 Rehabilitation of Water Mains using Lining Techniques .................................................... 15
    2.3.1 Cured-In-Place Lining Method ..................................................................................... 16
    2.3.2 Other Lining Techniques .............................................................................................. 18
      2.3.2.1 Coatings ................................................................................................................. 18
        2.3.2.1.1 Cement-Mortar Lining .................................................................................... 18
        2.3.2.1.2 Reinforced cement-mortar lining ................................................................. 19
        2.3.2.1.3 Epoxy Lining .................................................................................................. 19
      2.3.2.2 Slip-Lining ............................................................................................................. 20
        2.3.2.2.1 Conventional Slip-Lining ................................................................................ 20
        2.3.2.2.2 Modified Slip-Lining ...................................................................................... 21
  2.4 Numerical and Experimental Examination of Sanexen’s Liner System ......................... 22
    2.4.1 Potential Limit States .................................................................................................... 23
    2.4.2 Constitutive Tests .......................................................................................................... 26
      2.4.2.1 Direct Tensile Tests ............................................................................................. 26
        2.4.2.1.1 Inner and Outer Polyester Jackets .............................................................. 26
4.2.1 Effect of Loading Rate ................................................................. 79
4.2.2 Effect of Cyclic Loading ................................................................. 82
4.2.3 Effect of the Presence of a Wrinkle and its Geometry ................. 87
  4.2.3.1 Test Results of Samples SW-1 to SW-5 ........................................ 87
  4.2.3.2 Test Results of Samples NW-1 to NW-5 ........................................ 89
  4.2.3.3 Effect of the Presence of a Wrinkle and its Shape and Size .......... 92
     4.2.3.3.1 Introduction ........................................................................... 92
     4.2.3.3.2 Effect of Wrinkle Depth (Amplitude) on $P_{cr}$ ..................... 93
     4.2.3.3.3 Effect of Angle $\theta$ of the Wrinkle on $P_{cr}$ ....................... 93
     4.2.3.3.4 Effect of Wrinkle Size and Pattern on $P_{max}$ ...................... 95

4.3 Statistical Test: Mann-Whitney Test ............................................. 97
  4.3.1 Introduction .............................................................................. 97
  4.3.2 Statistical Results ..................................................................... 99
     4.3.2.1 Effect of Loading Rate on First Cracking Load of Resin, $P_{cr}$ ... 99
     4.3.2.2 Effect of Loading Rate on Ultimate Load, $P_{max}$ .................... 99
     4.3.2.3 Effect of Cyclic Loading on Ultimate Load, $P_{max}$ ............ 101
     4.3.2.4 Effect of the Presence of a Wrinkle and its Geometry ............ 102
        4.3.2.4.1 Effect of Wrinkle Depth (Amplitude) on $P_{cr}$............... 102
        4.3.2.4.2 Effect of Wrinkle Angle $\theta$ on $P_{cr}$ .............................. 103
        4.3.2.4.3 Effect of Wrinkle Size and Pattern on $P_{max}$ .............. 104

CHAPTER 5 - ANALYTICAL MODELLING ............................................. 123
  5.1 Introduction .................................................................................. 123
  5.2 Statement of Problem ................................................................. 124
  5.3 Modeling of Wrinkle Type 1 and Non-wrinkled Liner ................. 126
     5.3.1 Overview .............................................................................. 126
     5.3.2 Material Properties ............................................................... 127
     5.3.3 Mesh and Kinematic Boundary Conditions ............................. 129
     5.3.4 Static Boundary Condition ..................................................... 131
     5.3.5 Modeling of Non-wrinkled Liner for Comparison with Wrinkle Type 1 131
  5.4 Numerical Results for Wrinkle Type 1 ....................................... 132
     5.4.1 Introduction .......................................................................... 132
     5.4.2 Numerical Results along Two Sections in Wrinkled Models (Type 1) 133
5.4.2.1 Numerical Result: Section AA ................................................................. 133
5.4.2.2 Numerical Result: Line of Symmetry ...................................................... 135
5.4.3 Effect of Jacket thickness ............................................................................ 136
5.5 Results for Non-wrinkled Liner and Comparison with Wrinkle Type 1 .......... 138
5.5.1 Introduction ................................................................................................. 138
5.5.2 Numerical Results along Two Sections in Non-Wrinkled Models ............... 139
  5.5.2.1 Numerical Results: Section AA ............................................................... 139
  5.5.2.2 Numerical Results: Line of Symmetry ..................................................... 140
5.5.3 Comparison of Results from Wrinkled (Type 1) and Non-wrinkled Analyses ... 141
5.6 Modeling of Wrinkle Type 2 and Non-wrinkled Liner ..................................... 142
  5.6.1 Overview .................................................................................................... 142
  5.6.2 Modeling of Wrinkle Type 2 ..................................................................... 143
  5.6.3 Static Boundary Condition ....................................................................... 144
  5.6.4 Modeling of Non-wrinkled Liner for Comparison with Wrinkle Type 2 ...... 144
5.7 Numerical Results for Wrinkle Type 2 and Non-wrinkled Liner ....................... 145
  5.7.1 Introduction ............................................................................................... 145
  5.7.2 Results from Wrinkled (Type 2) and Non-wrinkled Analyses ..................... 146
    5.7.2.1 Numerical Results: Stress Distribution ................................................... 146
    5.7.2.2 Numerical Results: Force-Displacement ................................................. 148
5.8 Comparison of Wrinkle Types 1 and 2 ........................................................... 149
  5.8.1 Introduction .............................................................................................. 149
  5.8.2 Numerical Results for Wrinkle Types 1 and 2 .......................................... 150
    5.8.2.1 Stress Distribution .............................................................................. 150
    5.8.2.2 Force-Displacement ............................................................................ 152
5.9 Comparison of Numerical and Experimental Results ...................................... 153
  5.9.1 Experimental Results ................................................................................ 153
  5.9.2 Objectives of Comparisons between Experimental and Numerical Results ... 155
  5.9.3 Evaluation of Numerical Results: Wrinkle Type 1 ..................................... 156
    5.9.3.1 Failure Mechanism ............................................................................. 156
    5.9.3.2 Stiffness ............................................................................................ 157
    5.9.3.3 Deflections ....................................................................................... 157
    5.9.3.4 Insight Gained from the Analysis of Wrinkle Type 1 ......................... 159
  5.9.4 Evaluation of Numerical Results: Wrinkle Type 2 ..................................... 160
5.9.4.1 Failure Mechanism ........................................................................................................ 160
5.9.4.2 Stiffness and Deflections .......................................................................................... 160
5.10 Approximation of the Force-Displacement Response for One Half of the Ring Samples
Using the Numerical Results and a Theoretical Equation .................................................. 162

CHAPTER 6 - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS .................. 191
6.1 Summary ........................................................................................................................ 191
6.2 Conclusions .................................................................................................................... 193
6.3 Recommendations for Future Work ................................................................................ 197

REFERENCES .................................................................................................................. 199

APPENDIX A - EXPERIMENTAL RESULTS .................................................................... 204

APPENDIX B - NUMERICAL RESULTS: FINITE ELEMENT CONVERGENCE STUDY .. 221
B. 1 OBJECTIVES AND OUTLINE OF METHODOLOGY .............................................. 222
B. 2 CONVERGENCE STUDY FOR WRINKLE TYPE 1: PROBLEM DEFINITION ..... 223
B. 3 KEY PARAMETERS ..................................................................................................... 224
B.3. 1 Material Properties .................................................................................................. 224
B.3. 2 Model Geometry ..................................................................................................... 224
B. 4 MODELING ................................................................................................................ 225
B. 5 RESULTS .................................................................................................................. 225
B.5. 1 Introduction ............................................................................................................. 225
B.5. 2 Effect of Spring Stiffness ...................................................................................... 226
B.5. 3 Effect of Number of Load Steps .......................................................................... 226
B. 6 CONVERGENCE STUDY FOR WRINKLE TYPE 2 ............................................... 227

APPENDIX C - CALCULATIONS ......................................................................................... 245
C. 1 INTRODUCTION ........................................................................................................ 246
C. 2 WRINKLE TYPE 1 ....................................................................................................... 246
C.2. 1 Determining applied stress, $p$ ............................................................................... 246
C.2. 2 Determining representative jacket thickness for analysis .................................. 247
C.2. 3 Determining Young’s moduli of jackets ................................................................. 248
C. 3 WRINKLE TYPE 2 ................................................................................................................. 249
  C.3. 1 Determining applied stress, \( p \) .................................................................................. 249
  C.3. 2 Determining representative jacket thickness for analysis ............................................. 250
  C.3. 3 Determining Young’s moduli of jackets ........................................................................ 251

APPENDIX D - NUMERICAL RESULTS: STRESS AND DISPLACEMENT CONTOURS. 253

APPENDIX E - NUMERICAL RESULTS: SUMMARY OF MATERIAL PROPERTIES ......268
LIST OF TABLES

Table 3.1: Half concrete disks mix proportions [From Mandal et al., 2005]........................................ 69
Table 4.1: Summary of test results used for the evaluation of the effect of loading rate............... 107
Table 4.2: Range of load values recorded for test samples LW-1 to LW-15............................... 107
Table 4.3: Summary of test results used for the evaluation of the effect of cyclic loading........ 108
Table 4.4: Range of load values recorded for test samples IW-1 to IW-5 and IW-6CM to IW-8CM ................................................................................................................................. 108
Table 4.5: Summary of test results used for the evaluation of the effect of the presence of a wrinkle and its geometry........................................................................................................ 109
Table 4.6: Range of load values recorded for test samples NW-1 to NW-5, SW-1 to SW-5, IW-1 to IW-5, and LW-1 to LW-5 ............................................................................................................................. 109
Table 4.7: Comparison between ultimate hoop tensile load for exhumed and fabricated liner... 110
Table 4.8: Average dimensions and recorded load values of ring samples ................................. 110
Table 5.1: Dimensions of wrinkle type 1 .................................................................................... 164
Table 5.2: Dimensions of the non-wrinkled finite element models for comparison with wrinkle type 1........................................................................................................................................ 164
Table 5.3: Displacement values from the numerical analysis of wrinkle type 1 ....................... 164
Table 5.4: Dimensions of wrinkle type 2 .................................................................................. 164
Table 5.5: Dimensions of the non-wrinkled finite element model for comparison with wrinkle type 2........................................................................................................................................ 165
Table 5.6: Displacement values from the numerical analysis of wrinkle type 2 ....................... 165
Table 5.7: Displacement values from experimental work involving wrinkle types 1 and 2 ...... 165
Table 5.8: Comparison of numerical and experimental displacement values ......................... 165
Table B. 1: Dimensions of wrinkle type 1 .................................................................................. 229
Table B. 2: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 1 ............................................................................................................................. 229
Table B. 3: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 1 ............................................................................................................................. 230
Table B. 4: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 1 ........................................................................................................................................ 231
Table B. 5: Effect of changes in spring stiffness on vertical displacement along location of springs in wrinkle type 1 ............................................................................................................................. 232
Table B. 6: Effect of number of load steps on results for wrinkle type 1 ........................................ 233
Table B. 7: Dimensions of wrinkle type 2 .................................................................................................. 234
Table B. 8: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 2 .................................................................................................................................................... 234
Table B. 9: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 2 .................................................................................................................................................... 235
Table B. 10: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 2 .................................................................................................................................................... 236
Table B. 11: Effect of changes in spring stiffness on vertical displacement along location of springs in wrinkle type 2 .................................................................................................................................................... 237
Table B. 12: Effect of number of load steps on results for wrinkle type 2 ........................................ 238
Table E. 1: Material properties of components of the composite liner and wrinkles .......................... 269
LIST OF FIGURES

Figure 2.1: (a) A section of metallic pipe with a corrosion pit, (b) Effect of tuberculation on a pipe [From Seica et al., 2002] .......................................................................................................................... 55

Figure 2.2: (a) Pulling resin impregnated liner into place, (b) Inflation and curing of liner with hot water [From Allouche et al., 2005] ............................................................................................................. 55

Figure 2.3: (a) LS1: Hoop tensile forces induced by internal pressure at locations where the host pipe has split, (b) LS2: Longitudinal wall bending in the liner wall at locations where it spans from a section of damaged host pipe to an intact section, (c) LS3: Longitudinal wall bending in the liner where it spans through a clamped section, (d) LS4: Overall or local bending in and stretching of the liner wall at ring fractures or joints, (e) LS5: Local bending in liner wall where it spans across a void, (f) LS6: Stresses in the vicinity of a water service connection [From Allouche et al., 2005] .......................................................................................... 56

Figure 2.4: Unfolding mechanism in a liner with a longitudinal fold [From Jaganathan et al., 2007] ................................................................................................................................................. 57

Figure 2.5: Defining the geometry of a longitudinal fold [From Jaganathan et al., 2007] ............................................................... 57

Figure 2.6: A split disk test fixture [From Kaynak et al., 2005] ........................................................................................................ 57

Figure 3.1: Liner with two wrinkles .......................................................................................................................... 70

Figure 3.2: Liner whose wrinkle has the smallest cross-sectional area observed ........................................................................ 70

Figure 3.3: Liner whose wrinkle has a cross-sectional area greater than the smallest wrinkle size, and less than the largest wrinkle size observed .................................................................................. 70

Figure 3.4: Liner whose wrinkle has the largest cross-sectional area observed .................................................. 71

Figure 3.5: Liner with no wrinkles ........................................................................................................................ 71

Figure 3.6: (a) A shorter length of a cast iron pipe section as delivered to the laboratory, (b) A cross-section of the cast iron pipe, (c) Cutting pipe section into shorter lengths of 250 mm, (d) Making a longitudinal cut on a side of a 250 mm pipe section, (e) Front view of a detached liner, (f) Cross-section of the detached liner, (g) Front view of a ring sample with a portion of its outer surface cleaned of polymeric resin residue and rust remnants ........................................................................ 72

Figure 3.7: A pair of half concrete disks after a preliminary test ........................................................................... 73

Figure 3.8: (a) Exerting force by clamping to enable an even distribution of the applied epoxy to smoothen the surface, (b) From left to right: A ring sample with rust and resin remnants intact, part of its surface completely cleaned of rust and resin remnants, and part of its surface coated with epoxy .......................................................................................................................... 73

xiii
Figure 3.9: Test setup in the laboratory ......................................................................................... 74
Figure 3.10: Schematic of test setup showing locations of strain gauges and LDSs in a ring sample with a wrinkle and in one with a perfect geometry.......................................................... 75
Figure 3.11: (a) Schematic of test setup showing dimensions of the H-shape sections and rectangular steel plates, both of which have a width of 40 mm, (b) Horizontal section, and (c) Vertical section through one half concrete disk, showing the typical arrangement of steel reinforcement.......................................................................................................................... 76
Figure 4.1: A labeled picture of a wrinkle similar to those in samples LW-1 to LW-15............. 111
Figure 4.2: (a) Load-stroke, (b) Load-average displacement graphs of sample LW-5 tested under monotonic conditions at a loading rate of 5 mm/min .......................................................... 111
Figure 4.3: Graphs of load-loading rate at first cracking of the resin within the wrinkle for samples (a) LW-1 to LW-14, and (b) LW-1 to LW-15, and (c) Graph of ultimate load-loading rate for samples LW-1 to LW-13............................................................................ 112
Figure 4.4: A ring sample with a wrinkle similar to those in samples LW-1 to LW-15, (a) before testing, and (b) after testing ............................................................................................................. 113
Figure 4.5: Typical failure mechanism observed in test samples LW-1 to LW-15 ..................... 114
Figure 4.6: A labeled picture of a wrinkle similar to those in samples IW-1 to IW-5 and IW-6C to IW-8C................................................................................................................................. 114
Figure 4.7: (a) Load-time graphs corresponding to the first 750 seconds of cyclic loading for samples IW-6C to IW-8C, (b) A ring sample before cyclic loading test, (c) An intact wrinkle after cyclic loading, and (d) A wrinkle with the resin component cracked after cyclic loading.................................................................................................................. 115
Figure 4.8: (a) Load-stroke, (b) Load-average displacement graphs for samples IW-6CM to IW-8CM tested under monotonic conditions at a loading rate of 5 mm/min............................. 116
Figure 4.9: (a) Load-stroke, (b) Load-average displacement graphs of sample IW-5 tested under monotonic conditions at a loading rate of 5 mm/min .......................................................... 117
Figure 4.10: (a) A ring sample with wrinkle type IW, before testing, and after testing with failure at (b) the wrinkle, and (c) at the opposite side of the wrinkle.............................................. 117
Figure 4.11: (a) A ring sample with wrinkle type SW, before testing, (b) A labeled picture of a wrinkle similar to those in samples SW-1 to SW-5 ................................................................. 118
Figure 4.12: (a) A picture of a wrinkle exhibiting failure type 1, (b) Load-stroke, (c) Load-average displacement graphs of sample SW-2 tested under monotonic conditions at a loading rate of 5 mm/min.................................................................................................................. 118
Figure 4.13: (a) A picture of a wrinkle exhibiting failure type 2, (b) Load-stroke, (c) Load-average displacement graphs of sample SW-4 tested under monotonic conditions at a loading rate of 5 mm/min.

Figure 4.14: A non-wrinkled ring sample (a) before testing, and (b) after testing.

Figure 4.15: (a) Load-stroke, (b) Load-average displacement graphs of sample NW-5 tested under monotonic conditions at a loading rate of 5 mm/min.

Figure 4.16: Schematic of wrinkle showing geometric parameters.

Figure 4.17: Effect of wrinkle size on (a) the load recorded at the first cracking of the resin within the wrinkle, and (b) on the ultimate load recorded.

Figure 4.18: (a) Defining the geometry of a wrinkle [From Jaganathan et al., 2007], (b) Representative geometry of a wrinkle in samples LW-1 to LW-5, (c) Representative geometry of a wrinkle in samples IW-1 to IW-5.

Figure 5.1: Labeled pictures of (a) wrinkle type 1, and (b) wrinkle type 2.

Figure 5.2: Schematic of wrinkle type 1.

Figure 5.3: Location of springs in wrinkle type 1.

Figure 5.4: Labeled finite element model of a liner section without a wrinkle.

Figure 5.5: Location of springs in a liner section without a wrinkle.

Figure 5.6: A labeled finite element mesh of wrinkle type 1.

Figure 5.7: Stress distribution at section AA in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.8: Horizontal displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.9: Vertical displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.10: Resultant displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.11: Force-displacement graphs corresponding to section AA in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.12: Stress distribution along line of symmetry in wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.13: A close up of the stress distribution along the inner and outer jackets at the line of symmetry in the wrinkled models (type 1) having three different jacket thicknesses.

Figure 5.14: Labeled finite element mesh of a liner section without a wrinkle.
Figure 5.15: Stress distribution at section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 ................................................................. 173
Figure 5.16: Horizontal displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 .............................................. 174
Figure 5.17: Vertical displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 ............................................. 174
Figure 5.18: Resultant displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 ............................................. 174
Figure 5.19: Force-displacement graphs corresponding to section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 ................................................. 175
Figure 5.20: Stress distribution along line of symmetry in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1 ............................................... 175
Figure 5.21: Force-displacement graphs for wrinkled (type 1) and non-wrinkled models having three different jacket thicknesses ................................................................................................. 176
Figure 5.22: Schematic of wrinkle type 2 .......................................................................................... 177
Figure 5.23: Location of springs in wrinkle type 2 .......................................................................... 177
Figure 5.24: Stress distribution at section AA in wrinkled model (type 2) with jacket thickness of 0.17 mm .................................................................................................................................................. 178
Figure 5.25: Stress distribution at section AA in non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2......................................................................................... 178
Figure 5.26: Stress distribution along line of symmetry in wrinkled model (type 2) with jacket thickness of 0.17 mm .................................................................................................................................................. 179
Figure 5.27: Stress distribution along line of symmetry in non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2 ................................................................. 179
Figure 5.28: Horizontal displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm ................................................................................................. 180
Figure 5.29: Vertical displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm ................................................................................................. 180
Figure 5.30: Resultant displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm ................................................................................................. 181
Figure 5.31: Force-displacement graphs for wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm ................................................................................................. 181
Figure 5.32: Stress distribution at section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 182
Figure 5.33: Stress distribution along line of symmetry in wrinkled model (type 1) with jacket thickness of 0.14 mm ................................................................. 183
Figure 5.34: Stress distribution along line of symmetry in wrinkled model (type 2) with jacket thickness of 0.14 mm ................................................................. 183
Figure 5.35: Stress distribution along line of symmetry in wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 183
Figure 5.36: Horizontal displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 184
Figure 5.37: Vertical displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 185
Figure 5.38: Resultant displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 185
Figure 5.39: Force-displacement graphs for wrinkle types 1 and 2 with jacket thickness of 0.14 mm ................................................................. 186
Figure 5.40: Experimental force-displacement graphs for wrinkled (type 1) and non-wrinkled samples ................................................................. 186
Figure 5.41: Experimental force-displacement graphs for wrinkled (type 2) and non-wrinkled samples ................................................................. 187
Figure 5.42: Experimental total load-average displacement graph for the wrinkled (type 1) sample showing the linear section plotted in Figure 5.40 ................................................................. 187
Figure 5.43: Experimental total load-average displacement graph for the wrinkled (type 2) sample showing the linear section plotted in Figure 5.41 ................................................................. 188
Figure 5.44: Experimental total load-average displacement graph for the non-wrinkled sample showing the linear section plotted in Figure 5.40 ................................................................. 188
Figure 5.45: Experimental total load-average displacement graph for the non-wrinkled sample showing the linear section plotted in Figure 5.41 ................................................................. 189
Figure 5.46: Experimental and lower and upper bound finite element force-displacement graphs for wrinkled (type 1 or wrinkle in sample IW-5) and non-wrinkled samples and models ............... 189
Figure 5.47: Experimental and lower and upper bound finite element force-displacement graphs for wrinkled (type 2 or wrinkle in sample SW-1) and non-wrinkled samples and models ............... 190
Figure A. 1: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-1 to LW-5 tested under monotonic conditions at a loading rate of 5 mm/min .............................................. 205

Figure A. 2: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-6 to LW-10 tested under monotonic conditions at a loading rate of 0.1 mm/min ....................................... 206

Figure A. 3: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-11 to LW-14, and LW-15 tested under monotonic conditions at loading rates of 100 mm/min and 250 mm/min, respectively ........................................................................................................... 207

Figure A. 4: Load-strain response at springlines of samples LW-1 to LW-5 tested under monotonic conditions at a loading rate of 5 mm/min .......................................................... 208

Figure A. 5: Load-strain response at springlines of samples LW-6 to LW-10 tested under monotonic conditions at a loading rate of 0.1 mm/min ......................................................... 209

Figure A. 6: Load-strain response at springlines of samples LW-11 to LW-14, and LW-15 tested under monotonic conditions at loading rates of 100 mm/min and 250 mm/min, respectively .......................................................................................................................... 210

Figure A. 7: (a) Load-stroke, (b) Load-average displacement graphs of samples IW-1 to IW-5 tested under monotonic conditions at a loading rate of 5 mm/min .............................................. 211

Figure A. 8: Load-strain response at springlines of samples IW-1 to IW-5 tested under monotonic conditions at a loading rate of 5 mm/min ............................................................................ 212

Figure A. 9: (a) Load-stroke, (b) Load-average displacement graphs of samples SW-1 to SW-5 tested under monotonic conditions at a loading rate of 5 mm/min .............................................. 213

Figure A. 10: Load-strain response at springlines of samples SW-1 to SW-5 tested under monotonic conditions at a loading rate of 5 mm/min .......................................................... 214

Figure A. 11: (a) Load-stroke, (b) Load-average displacement graphs of samples NW-1 to NW-5 tested under monotonic conditions at a loading rate of 5 mm/min .............................................. 215

Figure A. 12: Load-strain response at springlines of samples NW-1 to NW-5 tested under monotonic conditions at a loading rate of 5 mm/min .......................................................... 216

Figure A. 13: Load-strain response of samples NW-1 to NW-5 at a location 30° from one of the springlines ........................................................................................................... 217

Figure A. 14: Load-strain response of samples NW-1 to NW-5 at a location 60° from one of the springlines ........................................................................................................... 218

Figure A. 15: Load-strain response of samples NW-1 to NW-5 at a location 90° from one of the springlines (crown) ........................................................................................................... 219
Figure A. 16: Load-strain response of samples NW-1 to NW-5 at all the five strain gauged locations ...................................................................................................................................................................................... 220

Figure B. 1: (a) Wrinkle in test sample IW-5, (b) Finite element model of one half of the wrinkle in sample IW-5...................................................................................................................................................................................... 239

Figure B. 2: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 1 ...................................................................................................................................................................................... 239

Figure B. 3: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 1 ...................................................................................................................................................................................... 240

Figure B. 4: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 1 ...................................................................................................................................................................................... 240

Figure B. 5: Effect of changes in spring stiffness on average vertical displacement along location of springs in wrinkle type 1 ...................................................................................................................................................................................... 241

Figure B. 6: (a) Wrinkle in test sample SW-1, (b) Finite element model of one half of the wrinkle in sample SW-1 ...................................................................................................................................................................................... 241

Figure B. 7: Finite element mesh of wrinkle type 2 ...................................................................................................................................................................................... 242

Figure B. 8: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 2 ...................................................................................................................................................................................... 242

Figure B. 9: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 2 ...................................................................................................................................................................................... 243

Figure B. 10: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 2 ...................................................................................................................................................................................... 243

Figure B. 11: Effect of changes in spring stiffness on average vertical displacement along location of springs in wrinkle type 2 ...................................................................................................................................................................................... 244

Figure D. 1: Stress contours for wrinkled model (type 1) with jacket thickness of 0.14 mm...................................................................................................................................................................................... 254

Figure D. 2: Stress contours for wrinkled model (type 1) with jacket thickness of 0.3 mm...................................................................................................................................................................................... 254

Figure D. 3: Stress contours for wrinkled model (type 1) with jacket thickness of 0.5 mm...................................................................................................................................................................................... 255

Figure D. 4: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.14 mm...................................................................................................................................................................................... 255

Figure D. 5: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.3 mm...................................................................................................................................................................................... 256

Figure D. 6: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.5 mm...................................................................................................................................................................................... 256
Figure D. 7: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.14 mm ............................................................................................................................... 257
Figure D. 8: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.3 mm ................................................................................................................................. 257
Figure D. 9: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.5 mm ................................................................................................................................. 258
Figure D. 10: Stress contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1......................................................................................... .. 258
Figure D. 11: Stress contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1......................................................................................... .. 259
Figure D. 12: Stress contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1......................................................................................... .. 259
Figure D. 13: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1..................................................................... 260
Figure D. 14: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1..................................................................... 260
Figure D. 15: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1..................................................................... 261
Figure D. 16: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1..................................................................... 261
Figure D. 17: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1..................................................................... 262
Figure D. 18: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1..................................................................... 262
Figure D. 19: Stress contours for wrinkled model (type 2) with jacket thickness of 0.17 mm... 263
Figure D. 20: Stress contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2......................................................................................... .. 263
Figure D. 21: Horizontal displacement contours for wrinkled model (type 2) with jacket thickness of 0.17 mm ............................................................................................................................... 264
Figure D. 22: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2............................................................................. 264
Figure D. 23: Vertical displacement contours for wrinkled model (type 2) with jacket thickness of 0.17 mm ............................................................................................................................... 265
Figure D. 24: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2 .......................................................... 265

Figure D. 25: Stress contours for wrinkled model (type 2) with jacket thickness of 0.14 mm .... 266

Figure D. 26: Horizontal displacement contours for wrinkled model (type 2) with jacket thickness of 0.14 mm .................................................................................................................. 266

Figure D. 27: Vertical displacement contours for wrinkled model (type 2) with jacket thickness of 0.14 mm .................................................................................................................. 267
NOTATION

\( \alpha \) = Angle of wrinkles in ring samples LW-1 to LW-5
\( \beta \) = Angle of wrinkles in ring samples IW-1 to IW-5
\( \Delta \) = Amplitude of wrinkle measured from the outer circumference of the liner to the peak of the wrinkle
\( \Delta_{\text{avg}} \) = Average amplitude of wrinkles in a set of ring samples
\( \varepsilon \) = Axial strain
\( \lambda \) = Wavelength of wrinkle
\( \lambda_{\text{avg}} \) = Average wavelength of wrinkles in a set of ring samples
\( \theta \) = Angle of wrinkle with respect to a horizontal axis perpendicular to the peak of the wrinkle
\( \sigma \) = Axial stress
\( A \) = Cross-sectional area
\( A_{\text{avg}} \) = Average cross-sectional area of wrinkles in a set of ring samples. The cross-sectional area of each wrinkle is approximated as the area of a triangle whose height and base are the amplitude (\( \Delta \)) and wavelength (\( \lambda \)) of the wrinkle, respectively.
\( d \) = Depth (amplitude) of wrinkle as defined by Jaganathan et al. (2007)
\( E \) = Young’s modulus
\( E_{\text{inner jacket}} \) = Young’s modulus of inner polyester jacket in an analytical model
\( E_{\text{outer jacket}} \) = Young’s modulus of outer polyester jacket in an analytical model
\( L \) = Arc length along the average circumference of a ring sample
\( p \) = Stress applied to an analytical model
\( P \) = Applied load
\( P_{cr} \) = Load recorded at first cracking of the resin within a wrinkle
\( P_{\text{max}} \) = Ultimate load recorded
\( t \) = Thickness
\( t_4 \) = Total thickness of composite liner at Section AA in an analytical model
\( x \) = Thickness of resin at Section AA in an analytical model
\( y \) = Thickness of outer or inner polyester jacket in an analytical model
CHAPTER 1

INTRODUCTION

1.1 General

The availability of water to humans and all living things plays an important role in sustaining life on our planet. Most societies in our world have infrastructure such as pipelines which transmit water to the population. It is not only important that water is made available to people, but also necessary that it is of a quality which ensures the health of consumers is not put in jeopardy. The state of existing pipelines can influence the efficiency with which water is transmitted, as well as its quality. Ageing pipelines can undergo deterioration and subsequent breakdowns. The results of these processes include a reduction in the hydraulic efficiency and ability to preserve water quality, and the loss of structural integrity of a pipe.

The relining of deteriorated gravity flow and pressure pipes with polymeric liners has become a popular practice in recent years. Sanexen Environmental Services Inc. in Montreal, Canada, manufactures a cured-in-place liner system which is used for the rehabilitation of deteriorated cast iron water pressure pipes. The liner system can restore water service connections after lining from within the pipe, using a remote controlled robot. The polymer liner which is the focus of this study improves the structural performance of a deteriorated cast iron pipe, and can also maintain its hydraulic carrying capacity, and protect against further internal corrosion and leakage.
In the field, pipes do not have a uniform internal diameter along their lengths. During the installation of Sanexen’s polymer liner, the external circumference of the liner is normally oversized to accommodate the varying internal pipe diameter. This practice can result in the formation of longitudinal folds (wrinkles) in the installed liner. In this study, experimental and numerical investigations were conducted to examine the effect of these wrinkles on the circumferential (hoop) strength of the liner.

Previous numerical and experimental investigations have been conducted on samples of the liner with and without wrinkles, to characterize its mechanical properties. These investigations were carried out to obtain information on the tensile, flexural and creep properties of the liner, and on the behavior of the liner under static and cyclic internal pressures. Some experimental work has been performed by Jaganathan et al. (2007) to evaluate the effect of wrinkles on the circumferential properties of the liner under static internal pressure. However, there are no known tests to investigate the effect of internal pressure variation with time, and hence, loading rate, on a liner with a wrinkle. In this study, tests were conducted to investigate the effect of loading rate on the behavior of a liner with a wrinkle. Jaganathan et al. (2007) also performed finite element analysis to evaluate the effect of wrinkle geometry on the internal pressure rating of the liner. They defined the geometry of the wrinkle in terms of its angle and amplitude. In this study, experimental work was conducted to examine further the effect of wrinkle geometry and configuration on the liner performance. The geometry of the wrinkle was defined in terms of its angle, amplitude, size and pattern. Shanhai et al. (2007) conducted long-term cyclic
loading tests on liner samples without wrinkles. In the present study, long-term cyclic loading tests were conducted on liner samples with wrinkles.

The results from the investigations conducted in this research work could be used by engineers to assess the impact of wrinkles on the installed liner’s performance, once information on the wrinkle geometry is obtained. Such information can be obtained easily since the wrinkles can be observed as the remote controlled robot restores water service connections, following the liner installation.

1.2 Objectives

The main goal of this research work was to investigate the effect of wrinkles on the circumferential strength of Sanexen’s polymer liner. In this study, this goal was achieved by addressing the following:

1. Investigating the effect of wrinkles on the hoop capacity of the liner by comparing the ultimate loads recorded for ring samples of the liner with and without wrinkles.

2. Observing the failure mechanisms exhibited by ring samples of the liner with and without wrinkles, and recording the loads at which failure was initiated in these samples.

3. Examining the effects of the following parameters on the response of the liner:
   a. Rate of loading (by testing ring samples with wrinkles),
b. Cyclic loading (by testing ring samples with wrinkles), and
c. Presence and geometry of a wrinkle (by testing ring samples with and without wrinkles).

4. Developing analytical models of wrinkles and non-wrinkled liner sections to investigate further the behavior of the wrinkles. The results from the two sets of models were compared to examine the effect of wrinkles on the liner.

1.3 Scope

At present, there are limited established design methodologies for pressure pipe liner systems. The existing ASTM Standard F1216 provides some information on design methods and procedures for the rehabilitation of gravity flow and pressure pipes, using a cured-in-place liner system. Experimental and numerical investigations have been and are being carried out on Sanexen’s cured-in-place pressure pipe liner system to better understand its mechanical properties, and to obtain information for the development of limit states design methods. As stated earlier, the liner system is used for the rehabilitation of cast iron water pressure pipes. In the field, a lined water pressure pipe is subjected to internal pressure which leads to the development of circumferential (hoop) stresses in the wall of the liner. Hence, it is necessary to ensure that the liner is designed to withstand the hoop stresses that it will experience. Design methods related to internal water pressure can be established if the circumferential properties of the liner are known.
The design methods provided by the ASTM Standard F1216, do not consider the effect of geometric imperfections (wrinkles) on the circumferential capacity of the cured-in-place liner. In this study, the experimental and numerical investigations that are conducted, aim to determine the effect of wrinkles on the circumferential strength of Sanexen’s liner. For the experimental investigation, a series of tests are conducted on 25 mm wide ring samples of the liner with and without wrinkles. The method of testing is based on the split-disk test which is defined by ASTM Standard D2290. The effects of loading rate, cyclic loading, and the presence of a wrinkle and its geometry on the response of the liner are investigated. The effect of loading rate is evaluated by testing fifteen ring samples with identical wrinkles, at four different loading rates. To investigate the effect of cyclic loading, eight ring samples with identical wrinkles are tested. The effect of the presence of a wrinkle and its geometry is investigated by testing twenty ring samples. Ten of the twenty samples constituted of the five control samples for the cyclic loading tests, and five samples tested to evaluate the effect of loading rate. A series of two-tailed Mann-Whitney statistical tests are performed on the obtained test data.

An analytical investigation is also conducted to examine further the behavior of the wrinkles in the liner. Two different kinds of wrinkles observed in the liner are considered. The analytical work aims to evaluate the effect of the wrinkles on the response of the liner. Finite element models of the wrinkles and liner sections without wrinkles are constructed for the analysis. The behavior of one wrinkle is examined prior to the initiation of failure. For the other wrinkle type, the behavior up to the initiation of failure
is examined. The numerical results are evaluated by comparing them to the experimental results.

1.4 Outline of Thesis

The contents of this thesis are summarized below:

**Chapter 2**: presents a review of the experimental and analytical work conducted by other researchers to evaluate the mechanical properties of the liner and its constituents, and the effect of wrinkles on the response of the liner. A review of the split-disk test method is also presented.

**Chapter 3**: describes the experimental work conducted in this study. Descriptions of the wrinkles observed in the liner, preparation of the test samples, the test setup, instrumentation, test procedure, and the parameters investigated are provided.

**Chapter 4**: provides discussions on the results from the laboratory testing of ring samples of the liner. The discussions focus on the effects on the response of the liner of the three parameters investigated. The results of the two-tailed Mann-Whitney statistical tests conducted on the obtained test data are also discussed.

**Chapter 5**: presents discussions on the results from the two dimensional plane stress numerical analyses conducted to investigate further the behavior of the wrinkles. Information is provided on the analytical models, assumptions made, the types of analyses conducted, the numerical results, and their evaluation using experimental results.
Chapter 6: presents conclusions drawn from the experimental and numerical investigations conducted in this study, and recommendations for future research work involving the liner.

References.
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Buried pipes play an important role in any society. They can be used for transmission of the potable water which is essential to supporting life. During the service life of a pipe, the processes of ageing and deterioration can lead to poor structural and/or functional performance, and possible pipe failure. The ageing and deterioration processes are inevitable and can be initiated by environmental and operational conditions. Currently, the traditional method of pipe rehabilitation which involves the excavation of a deteriorated pipe and its replacement with a new pipe is avoided if possible. Trenchless rehabilitation techniques are employed if the level of deterioration in an old pipe does not require that it is replaced with a new pipe. In-place lining methods are one group of trenchless pipeline rehabilitation technologies that can be used for the repair of deteriorated water mains. The use of lining systems in the water industry is limited because of the challenges that are faced when re-opening water services in a lined small diameter pipe (< 0.5 m). A new cured-in-place liner system which is manufactured by Sanexen Environmental Services Inc. in Montreal, Canada, makes it possible to restore water service connections in a lined small diameter pipe from within the pipe using a remote controlled robot. The liner system which is the focus of this thesis is currently used for the rehabilitation of deteriorated water pressure pipes. Premier-Pipe Services
(International) Ltd. in the United Kingdom, and Karl Weiss Technologies in Berlin, Germany also manufacture cured-in-place liner systems which enable the re-opening of service connections from within the lined pipe using a robot.

In this chapter, the causes of pipe deterioration are discussed. A discussion is also presented on the cured-in-place lining technique and its use for the installation of Sanexen’s liner system. Other in-place lining methods are briefly described. Numerical analyses and laboratory tests that have been conducted on Sanexen’s cured-in-place pressure pipe liner to better understand its mechanical behavior and to provide information for the development of limit states design methods are presented. The split-disk method of testing which was used for the experimental investigation of the circumferential (hoop) strength of the liner is also discussed in detail.

2.2 Causes of Pipeline Deterioration

In the early 90s, the existing water pipes in the US were manufactured from materials such as metal, asbestos-cement, plastic, and concrete (Kirmeyer et al., 1994). The metallic pipes constituted more than two thirds of the existing water pipes and were made from cast iron and ductile iron. About 15% of the water pipes were manufactured from asbestos-cement and 18% from plastic, concrete and other materials. Kirmeyer et al. (1994) observed that the new pipes that were being installed were more likely to be manufactured from ductile iron, polyvinyl chloride (PVC) and reinforced or prestressed
concrete. Ductile iron seemed to be the material of choice, representing about 48% of the new pipes manufactured, 39% are PVC, and 12.5% are concrete. A survey of 21 Canadian cities by Rajani and McDonald (1995) showed that the distribution of pipe material types in the surveyed cities was similar to that observed in the US.

All pipelines begin to show signs of ageing after some years in service. Ageing pipelines are more susceptible to deterioration and subsequent breakdowns. Wrobel et al. (2004) identified the factors which had the most influence on the ageing process and the increased failure frequency of a pipeline as intensified vehicular traffic, changes in the properties of the transported medium, stray currents, changes in the underground water level, and soil contamination. Symptoms of ageing in underground pipelines include external and internal corrosion, excessive leakage through joints, fittings and connections, mechanical wear and abrasion of the wetted internal pipe surface, and root penetration and growth within the pipe (Koerner and Koerner, 1996). The symptoms associated with the ageing and deterioration processes can lead to reduced hydraulic efficiency and ability to preserve water quality, and the loss of structural integrity of a water main (Seica et al., 2002).

The pipe material has an influence on the observed deterioration mechanism. In PVC pipes, the deterioration mechanisms include chemical and mechanical degradation, and oxidation and biodegradation of plasticizers and solvents (Dorn et al., 1996). Kleiner and
Rajani (2001) noted that the long-term deterioration mechanisms were typically slower in PVC pipes than in metallic pipes. In asbestos-cement and concrete pipes, deterioration can occur through chemical processes that leach out the cement material or penetrate the concrete to form products that weaken the cement matrix (Rajani and Kleiner, 2001). Metallic and cement-based pipes can both undergo corrosion, an electrochemical process which is considered one of the leading causes of pipe deterioration and failure.

Environmental conditions such as aggressive soil, use of dissimilar metals and stray currents can cause corrosion in pipes (Rajani and Kleiner, 2003). Soil containing inorganic or organic acids, alkalis, or sulphates can initiate corrosion in concrete and metallic pipes (Rajani and Kleiner, 2001). The pH level of the soil can influence its corrosive potential. A low soil pH level indicates the presence of strong acids that can react with the pipe material and begin the process of corrosion. Low pH values in the soil can have the effect of reducing the pH of cement mortar which can lead to the corrosion of prestressing or reinforcing wire in a reinforced or pre-stressed concrete pipe (Dorn et al., 1996). A high soil pH level indicates an alkaline soil environment and can also promote microbiological corrosion because it provides favorable conditions that enable different kinds of anaerobic bacteria to thrive (Seica et al., 2002). The corrosive potential of soil increases with increasing sulphide concentration. In the presence of aggressive sulphate-reducing bacteria which metabolize sulphates into sulphides, soil that contains sulphates can cause microbiological corrosion in metallic pipes (Seica et al., 2002).
The electric resistivity of a soil can influence its ability to promote stray current corrosion in a pipe. Stray currents are the electrons that deviate from direct current (DC) circuits through earth and other metallic structure paths (Kale and Sanders, 2000). Moist soil that contains a high concentration of salts has a low resistivity and can easily conduct electric current which increases its potential to cause corrosion in a pipe (Seica et al., 2002). Rajani and Kleiner (2003) observed that pipes installed in clayey and silty soils or in marshy environments were more prone to corrosion than those installed in well-drained soils such as sand and gravels. A possible explanation for this observation is that the electric resistivity of sand is greater than 20000 $\Omega$.cm while that of clay is less than 500 $\Omega$.cm, thus making the latter an extremely aggressive soil (METALogic, 1998). Pipes buried in the vicinity of high voltage overhead electric power transmission lines or transit systems are prone to stray current corrosion (Nielsen, 2005). Kale and Sanders (2000) identified trains and running rails as some of the sources of stray currents on a DC operated transit system. They noted that once the stray currents were deposited into the soil and discharged onto the pipe surface, anodic and cathodic areas were created on the pipe structure with the anodic areas becoming susceptible to corrosion.

The use of dissimilar metals along the length of a pipe can also initiate corrosion. Rajani and Kleiner (2003) observed that in cases where a deteriorated segment of an old cast iron pipe was replaced with a new ductile iron pipe segment, a higher corrosion rate was detected in the ductile iron pipe. An explanation given for this was that the new ductile
iron pipe acted as a sacrificial anode to the cast iron pipe, thus protecting the cast iron pipe from corrosion while its resistance to corrosion is minimized.

Corrosion results in wall thinning and the formation of corrosion pits in metallic pipes. Figure 2.1 (a) shows a picture of a pipe section with a corrosion pit in its wall. Corrosion pits can grow from the outer or inner surface of the pipe wall until the pipe is fully perforated, making it possible for water leakage to occur (Rajani and Kleiner, 2003). Corrosion pits act as stress concentrators and crack initiators and can weaken the structural resistance of a pipe (Seica et al., 2002). The effects of corrosion are more easily noticed in ductile iron pipes than in cast iron pipes. In cast iron pipes, corrosion occurs in the form of graphitization where the iron component is leached out leaving behind an intact graphite matrix. The intact graphite matrix can obscure the corrosion pits formed by maintaining the original shape of the cast iron pipe while its structural resistance declines (Seica et al., 2002). It acts as a plug which prevents water leakage until it is displaced by a disturbing phenomenon such as water hammer or soil movement (Rajani and Kleiner, 2003). Tuberculation which is a by product of corrosion and consists of materials deposited within the pipe from the corroded pipe wall can lead to a significant reduction in the internal cross-sectional area of a pipe (Seica et al., 2002). The effect of tuberculation on a pipe is illustrated in Figure 2.1 (b).
The internal environment of a pipe can also cause corrosion and contribute to its functional deterioration. The characteristics of the transmitted water can provide conditions that are suitable for the occurrence of internal corrosion. The chemical properties of the water such as its pH, amount of dissolved oxygen, free chlorine residual, and alkalinity, as well as its temperature and microbiological activity can influence internal corrosion (Rajani and Kleiner, 2001). Both poorly and overtreated water can deposit solids within a pipe. Poorly treated water can deposit solids such as sand, silts or organic materials within a pipe (AWWA, 2001). Perforations in the pipe wall which are formed when corrosion pits grow deeper and larger can also serve as points of entry for solids into the pipe. In the case of overtreated water, the deposited solids can contain substances such as alum, lime or calcium carbonates (AWWA, 2001). Solid deposits can cause mechanical wear and abrasion of the internal pipe surface as they are transported through the pipe. A buildup of solids can lead to a reduction in the pipe’s interior cross-sectional area and flow capacity. Tuberculation, erosion, and crevice corrosion which can occur in the interior of a pipe provide breeding grounds for bacteria and also result in the reduction of the effective internal pipe diameter (Rajani and Kleiner, 2001). Some bacteriological activities can lead to the development of slimes which can cause pipe fouling, and water taste and odor problems (AWWA, 2001). Although internal pipe processes such as corrosion, solid deposition and bacterial activities may not have a significant impact on the structural deterioration of a pipe, their effect on water quality and hydraulic performance can be profound.
2.3 Rehabilitation of Water Mains using Lining Techniques

The processes of ageing and deterioration in pipelines are inevitable. However, there are rehabilitation methods which can be employed to improve poor performance and/or prevent pipe failure caused by deterioration and ageing. In the past, the typical rehabilitation technique for deteriorated pipelines involved excavation, pipe removal, pipe replacement, backfilling and the restoration of the site to its original condition (Koerner & Koerner, 1996). Over the past few years, new and improved rehabilitation techniques have been developed for the repair of deteriorated pipelines. Wrobel et al. (2004) noted that the current rehabilitation techniques are mainly trenchless methods. In their opinion, trenchless methods are more efficient because unlike the traditional method of pipeline rehabilitation, they substantially minimize or eliminate trenching, protect the natural environment and considerably reduce costs. The minimization or elimination of trenching associated with the use of trenchless rehabilitation techniques is possible because access to the deteriorated pipeline is only required at discrete locations (Koerner and Koerner, 1996).

There are many trenchless technologies that can be used for the rehabilitation of water pipelines. In the case of potable water pipes, it is necessary to ensure that the materials or pipes used for the purpose of rehabilitation do not pose any health risk to the population. In-place lining methods are one group of the trenchless pipeline rehabilitation technologies available in the market. Lining methods can prevent the occurrence of tuberculation within a corroded pipe, and can also protect the interior of a pipe from
corrosion caused by the corrosive chemical components of the transported water (Seica et al., 2002).

In the next sections, a number of in-place lining techniques used for the rehabilitation of water mains are discussed. A discussion on the cured-in-place lining technique and its use for the installation of a new polymer liner which is the focus of this thesis is presented. The other lining methods are briefly described. It should be noted that one or more of the lining methods can be used for the purpose of rehabilitation.

### 2.3.1 Cured-In-Place Lining Method

In recent years, the relining of deteriorated gravity flow and pressure pipes with polymeric liners has become a popular practice (Zhu and Hall, 2001). A method of pipe rehabilitation that uses polymeric liners is the cured-in-place pipe (CIPP) lining technique. The CIPP lining technique involves the insertion of a polymer fiber tube or hose impregnated or coated with a thermoset resin system into an existing pipe. Polyester, vinyl ester or epoxy can be used as the thermoset resin system. After the insertion of the lining tube into the host pipe, the resin is cured under ambient conditions or by the heat produced from steam or hot water. The cured resin adheres the lining tube to the host pipe. In general, CIPP lining techniques produce only a minor reduction in the internal cross-section of the host pipe (Koerner & Koerner, 1996).
The CIPP lining method is widely used for the rehabilitation of wastewater and gas pipelines (AWWA, 2001). In the potable water industry, its use is limited mostly due to health concerns. As stated earlier, it is necessary to ensure that the lining system used for pipe rehabilitation does not pose any health risks. The implementation of CIPP liners requires approval from relevant health authorities (AWWA, 2001). Another possible reason for the limited use of the CIPP lining technique may be due to the difficulty associated with re-opening water services after a small diameter water pipe has been lined (Allouche et al., 2005).

Currently, a new cured-in-place liner system which is manufactured by Sanexen Environmental Services Inc. in Montreal, Canada, makes it possible to restore water service connections in a lined small diameter pipe from within the pipe using a remote controlled robot. The liner is used for the rehabilitation of deteriorated cast iron water pressure pipes. The liner system which is the focus of this thesis is made of two concentric, tubular, plain woven polyester jackets, with the inner jacket bonded onto a polyurethane elastomer. The polyurethane elastomer is compatible with potable water and is designed to maintain the water tightness of the liner. The polyester jackets are impregnated with a polymeric resin which adheres the liner to the host pipe after installation. In the field, the liner is installed within a deteriorated cast iron pipe using the CIPP lining technique. After the insertion of the liner into the host pipe, it is inflated and cured by the pressure applied by hot water at a temperature of 55°C. Figure 2.2 shows the installation process of the liner and also illustrates the CIPP lining technique.
2.3.2 Other Lining Techniques

In this section, the methods of coating and slip-lining which can also be used for the rehabilitation of water mains are briefly described.

2.3.2.1 Coatings

In the water industry, cement-mortar and epoxy are coating materials that can be used for pipe rehabilitation. Koerner and Koerner (1996) advised against using coatings to solve chronic pipe problems. They also suggested that it was necessary to fill cracks and holes in the walls of the host pipe prior to the application of a coating material.

2.3.2.1.1 Cement-Mortar Lining

At present, cement-mortar is not only applied to deteriorated water pipes but also to new ductile-iron and most steel water pipes before installation (AWWA, 2001). Prior to lining, the inner wall of the existing pipe is cleaned and dried. A section of the pipe is cut by sawing in a cast iron pipe or by torching in a steel pipe to provide an entry location for the lining machine. The lining machine applies cement-mortar to the inner pipe wall as it is winched through the existing pipe. The lined surface is smoothened by rotating trowels which are a part of the lining machine. After the lining is completed, the removed pipe section is reconnected to the exiting pipe by mechanical coupling and butt straps in cast iron and steel pipes, respectively. Cement-mortar lining protects the interior pipe material from aggressive environments (Rajani and Kleiner, 2003). It can protect the pipe against
oxidation, a process that can initiate corrosion and cause pitting in metallic pipes (AWWA, 2001).

2.3.2.1.2 Reinforced cement-mortar lining

The method of reinforced cement-mortar lining varies slightly from the cement-mortar lining technique. It can be used in pipelines that are large enough to allow access by working personnel. This method involves the application of two layers of cement-mortar which are separated by a wire mesh. The first layer of cement-mortar is applied to the inner wall of the host pipe without troweling. A wire mesh is placed against the first coat of lining, and the second layer of cement-mortar is applied over the wire mesh and troweled. The reinforced cement-mortar lining technique can be used to restore the structural integrity of steel pipes which have undergone extensive corrosion (AWWA, 2001).

2.3.2.1.3 Epoxy Lining

As stated earlier, epoxy can be used as the lining material for the rehabilitation of water mains. Prior to the application of the epoxy resin, the inner wall of the host pipe is cleaned and rid of existing corrosion buildup. The application head and hoses of the lining machine are pulled to one end of the pipe and winched back to the opposite end while the epoxy resin is sprayed onto the dried inner pipe wall. Once the epoxy is cured,
2.3.2.2 Slip-Lining

In this section, the conventional and modified methods of slip-lining are described.

2.3.2.2.1 Conventional Slip-Lining

The conventional slip-lining method involves the insertion of a flexible thermoplastic pipe into a deteriorated host pipe. Its use in the water industry is not as widespread as the other lining techniques (AWWA, 2001). The common material used for the flexible pipe is high-density polyethylene (HDPE). Koerner & Koerner (1996) attribute the reason for this to the desirable properties that HDPE offers which includes flexibility, high modulus, toughness, and corrosion resistance. Other materials that can be used for the manufacture of the flexible pipe include polypropylene (PP) or polybutylene, fiber reinforced polyethylene, and polyvinyl chloride (PVC).

This method requires the excavation of access pits to provide an entry location for and to enable the transfer of the thermoplastic pipe into place within the existing pipe. At least two access pits, one on either end of the deteriorated pipe section are required. The length of thermoplastic pipe required for rehabilitation is obtained by butt fusing the ends of shorter flexible pipe sections. The thermoplastic pipe is pulled through the existing pipe
by means of a winch cable attached to a bullet-shaped pulling head on the leading end of the liner pipe. Slip-lining enables the creation of a new pipe system within an old deteriorated pipe without the need for extensive excavation and replacement of the old system (AWWA, 2001). It can be used to fix severe structural problems such as extensive transverse cracking, longitudinal cracking, and joint deterioration (Koerner & Koerner, 1996). However, unlike some lining techniques, the liner pipe does not turn well in elbows and the effective cross-sectional area of the new pipe system is significantly reduced (AWWA, 2001).

2.3.2.2 Modified Slip-Lining

The modified slip-lining technique involves the insertion of a temporarily deformed flexible thermoplastic tube into a host pipe. The initially reduced size of the thermoplastic pipe allows sufficient clearance for insertion. A variety of thermoplastic pipe thicknesses can be used when the modified slip-lining technique is implemented. As stated earlier, the use of the conventional slip-lining method leads to a reduced effective cross-sectional area of the rehabilitated pipe system which in turn reduces flow capacity. When thin thermoplastic pipes are used during the modified slip-lining technique, the lack of joints (since there is no need for the butt fusion process) and the increased smoothness of the pipe’s interior surface improve the flow capacity of the deteriorated pipe despite the reduction in the effective cross-sectional area (AWWA, 2001).
2.4 Numerical and Experimental Examination of Sanexen’s Liner System

Allouche et al. (2005) noted that there are many lining systems available for the rehabilitation of deteriorated gravity flow sewers. However, their use in smaller diameter water distribution pipes is not as widespread. They attributed this to the problems encountered when re-opening water services in a lined small diameter pipe. As described earlier, the challenges associated with restoring water service connections in a lined small diameter pipe can be eliminated when Sanexen’s liner system is used.

The City of Hamilton in Ontario, Canada, has investigated the possibility of using Sanexen’s liner system for the repair of its deteriorated cast iron water pressure pipes. The city undertook a pilot project in which a 1000 m long section of a 75 year old cast iron watermain was lined with the liner. The 150 mm diameter watermain had characteristics and a failure rate that were similar to a large number of pipes in the city’s network. The City of Toronto in Ontario, Canada, was also involved in a pilot project in which sections of iron pipe were lined with the liner. Other cities such as Kingston and London in Ontario, Canada, have also undertaken pilot projects involving the liner.

Currently, there are limited established design methodologies for pressure pipe liner systems. Thus, numerical analyses and laboratory tests are being conducted on Sanexen’s cured-in-place pressure pipe liner to better understand its mechanical behavior and to provide information for the development of limit states design methods. A series of tests
have been conducted to evaluate the tensile and flexural properties of the liner, as well as its behavior when it is subjected to static and cyclic internal pressures, and creep. In the next sections findings from numerical analyses and laboratory tests that have been conducted on samples of the liner and on lined pipe sections are presented and discussed.

2.4.1 Potential Limit States

Allouche et al. (2005) classified the liner system as an independent pressure pipe liner. On the basis of this classification, they identified internal water pressure, earth loads, and nonuniform ground movements as loading cases whose effects could significantly influence the performance of the liner system. They suggested that the liner could easily support the external earth loads because of its wall thickness. Thus, considering the effects of internal water pressure and nonuniform ground movements, they identified six potential limit states that can influence the stability of the liner during its service life. The six limit states are illustrated in Figure 2.3.

Allouche et al. (2005) used finite element analyses to investigate the longitudinal and local bending that occurs in the liner under different conditions. The behavior of the liner when it spans from a damaged section of cast iron pipe into an intact section of cast iron pipe, through a restriction, and across circular perforations (graphitized zones) in the cast iron pipe wall were evaluated. These conditions are denoted by the limit state designations, LS2, LS3, and LS5 in Figures 2.3 (b), (c), and (e), respectively.
For the conditions defined by LS2 and LS3, the finite element analyses showed that the longitudinal bending produced circumferential tension that was slightly greater than the tensile stress produced in the liner when it was in unconfined hoop tension. The analyses also showed that the longitudinal bending generated longitudinal bending stress that was about 20% higher than the hoop stress in unconfined tension. It was noted that the length of the restriction did not have any significant influence on both the peak circumferential and longitudinal tensions. The results from the analyses led Allouche et al. (2005) to suggest that it was reasonable to use unconfined tension tests to characterize the strength of the liner, with a factor of safety considered to account for the additional stresses.

In the case of the liner spanning a cast iron pipe with circular perforations in its wall, the finite element analyses showed that circular perforations with radii of 10 mm and 20 mm produced tensile bending stresses that were less than the tension produced in the liner under unconfined hoop tension. For perforations with radii of 30 mm and greater, an opposite effect was observed. Perforations with radii of 30 mm and 40 mm generated tensile bending stresses that were about 30% and 200% greater than the tension produced in the liner under unconfined hoop tension.

Shanhai et al. (2007) also evaluated the effect of the size of a circular defect and the defect shape on the short-term liner burst pressure using finite element analysis. The circular defects considered in the analysis had diameters ranging from 40 mm to 200 mm.
The results from the 3-D finite element model showed that the liner burst pressure decreased to about a third of its initial value when the diameter of the circular defect increased from 40 mm to 100 mm. There was no significant change in the burst pressure between circular defect diameters of 100 mm and 200 mm.

To evaluate the effect of the defect shape on the liner burst pressure, defects with square, rectangular and ellipse geometries were also considered. The cross sectional area of all the defects investigated was 9 in² (5806 mm²). The result from the numerical analysis confirmed the composite nature of Sanexen’s liner system. Shanhai et al. (2007) observed that the orientation of the ellipse and rectangular shaped defects had a significant influence on the estimated liner burst pressure. They attributed this to the different stiffness values in the longitudinal and circumferential directions of the liner as a result of its composite nature. Based on the results, Shanhai et al. (2007) suggested that in elongated defects, the effective stiffness of the liner was governed by the stiffness in the short dimension of the defect. They noted that the predicted burst pressure for an elongated defect with its long dimension oriented in the longitudinal direction was substantially lower than the value predicted for a circular defect with the same cross sectional area. Based on this observation, Shanhai et al. (2007) suggested that it was conservative to assume a square shaped defect for design purposes. They stated that further experimental work was required to investigate the appropriate geometry-related safety factor for a non-square defect.
2.4.2 Constitutive Tests

Simple short-term tests have been conducted to evaluate the key mechanical properties of the liner and its constituents. The data obtained from these tests can be used for defining the properties of the liner during numerical analyses. In the next sections, constitutive tests that have been conducted are discussed.

2.4.2.1 Direct Tensile Tests

2.4.2.1.1 Inner and Outer Polyester Jackets

Brown et al. (2007) conducted a series of direct uniaxial tension tests to characterize the mechanical properties of the inner and outer polyester jackets of the composite liner. The tests aim to establish the stress-strain curves of the two components in both the longitudinal and circumferential directions.

Flat rectangular coupons were fabricated from the inner and outer polyester jackets provided in their original form (pre-cured state). The coupons had dimensions of 25 x 225 mm and were prepared using procedures that conformed to the ASTM D3039/3039M-00 standard for the preparation of fiber reinforced polymer (FRP) flat coupons. From the section of the outer polyester jacket provided, fourteen coupons were prepared in the longitudinal direction and seven coupons in the transverse direction. Seven of the fourteen coupons prepared in the longitudinal direction had the
circumferential polyester strands removed. Seven coupons each were also prepared from
the inner polyester jacket in the longitudinal and transverse directions. To enable
effective gripping in the testing machine, both ends of the coupons were embedded in 50
mm long tabs fabricated from the glass fiber woven fabric, Tyfo SHE-51A, impregnated
with Tyfo S Epoxy resin.

For the inner polyester jacket, a linear load-strain response was exhibited by the coupons
cut in both the longitudinal and circumferential directions. The tensile stiffnesses were
estimated as 588 N/mm and 1530 N/mm in the longitudinal and circumferential
directions, respectively. For the outer polyester jacket, the coupons cut in the longitudinal
direction with the circumferential strands intact exhibited a bilinear strain hardening
behavior. The strain hardening behavior was observed between strains of 15 % and 20 %.
Brown et al. (2007) attributed this behavior to the plain-weave of the polyester fibers
within the outer jacket. Brown et al. (2007) stated that the plain-weave nature of the
polyester fibers caused the straightening and thus stiffening of the longitudinal polyester
strands to occur later in the test at strains between 15 % and 20 %. The tensile stiffnesses
before and after the strain hardening behavior were estimated as 194 N/mm and 833
N/mm, respectively.

In the case of the coupons cut in the longitudinal direction with the circumferential
strands removed, the plain-weave effect was eliminated. A linear load-strain behavior
was exhibited by these coupons. Brown et al. (2007) observed that for these coupons, the longitudinal polyester fibers were almost fully elongated prior to testing. Thus, the straightening and stiffening of the fibers occurred shortly after the test had begun. The tensile stiffness of 982 N/mm determined for these coupons was slightly greater than but relatively close to the value of 833 N/mm determined after the strain hardening behavior had occurred in the coupons with the circumferential strands intact. The coupons cut in the circumferential direction also exhibited a linear load-strain behavior. The tensile stiffness was determined to be 2270 N/mm. The tests showed that in both the longitudinal and circumferential directions, the outer polyester jacket was stiffer than the inner polyester jacket. They also showed that the polyester jackets were stiffer in the circumferential direction than in the longitudinal direction.

2.4.2.1.2 Polymeric Resin

Brown et al. (2007) also conducted direct uniaxial tension tests to evaluate the behavior of the polymeric resin. In the field, hot water with a temperature of about 55 °C is used to cure and also provide pressure for the inflation of the installed liner. The tests were conducted to examine the effect of curing temperature on the resin’s stress-strain behavior. Type IV dumbbell shaped coupons of the resin were fabricated following procedures that conformed to ASTM D638-03. Five coupons were prepared and cured at each of the four curing temperatures of 20 °C, 40 °C, 55 °C, and 70 °C.
The test results showed that at all four curing temperatures, the resin exhibited a linear stress-strain behavior to a strain of at least 2 %. It was observed that the mechanical properties of the resin increased up to a curing temperature of 55 °C. The tensile strength increased by 28 % as the curing temperature increased from 20 °C to 55 °C. Between the curing temperatures of 20 °C and 55 °C, the tensile modulus increased from 1832 MPa to 2356 MPa. A tensile modulus of 2307 MPa was recorded at the curing temperature of 70 °C. Brown et al. (2007) noted that it was necessary to conduct further tests on coupons of the resin cured at temperatures slightly less and greater than 55 °C to determine the approximate temperature at which the increase in mechanical properties ceases.

2.4.2.1.3 Composite Polymer Liner

Allouche et al. (2005) reported on the short-term longitudinal uniaxial tensile behavior of the liner. Tensile tests were conducted on uniaxial test specimens which were cut in the longitudinal direction from the liner. The liner samples from which the test specimens were prepared were obtained from lined cast iron pressure pipes exhumed from a field site in Hamilton City. To ensure effective gripping in the testing machine, the ends of the test specimens were built up using epoxy resin. The test result showed that in the longitudinal direction, the liner had a bi-liner stress-strain response to uniaxial tension. The longitudinal uniaxial modulus was determined to be 2000 MPa at axial tension strains less than 1.3 %. At strains greater than 1.3 %, the modulus was determined to be 180 MPa.
Brown et al. (2007) also conducted direct uniaxial tension tests to investigate the stress-strain response of coupons of the liner extracted from the exhumed lined cast iron pipes, and from samples of the liner fabricated in the laboratory. The main purpose of this test series was to investigate the behavior of the composite liner in the circumferential direction. The tubular nature of the exhumed liner made it impossible to obtain flat rectangular coupons in the circumferential direction. To solve this problem, flat sections of the composite liner were fabricated in the laboratory from samples of the inner and outer polyester jackets provided in their original form, and the polymeric resin prepared in the laboratory. The lined cast iron pipes were exhumed from a field site in Hamilton City. The test coupons had the same dimensions as the inner and outer polyester jacket test coupons, and were prepared and tested following the same procedure described in Section 2.4.2.1.1.

Five coupons were cut in the longitudinal direction from both the exhumed and the fabricated polymer liner for testing. Both sets of coupons showed similar strength and behavior. The stress-strain curves appeared to be bilinear. For all coupons, a linear stress-strain response was observed between strains of 0% to 1%, 4% to 8%, and 9% to 13%. The moduli values corresponding to these three ranges of strains were determined to be 2019 MPa, 115 MPa, and 180 MPa for the coupons prepared from the exhumed liner sample. Moduli values of 2017 MPa, 135 MPa, and 190 MPa were determined for the coupons obtained from the fabricated liner sample. The longitudinal moduli values of
2019 MPa and 2017 MPa determined for strains less than 1 % were relatively close to the value of 2000 MPa reported by Allouche et al. (2005) for strains less than 1.3 %.

For both sets of coupons, a stiffening phase was observed between strain values of 8% and 9%. The tests showed that in the longitudinal direction, the coupons could resist a stress of at least 49 MPa which corresponds to a strain of 13%. The similar behavior observed for the two sets of coupons cut in the longitudinal direction served as a validation for Brown et al. (2007) that the circumferential behavior of the polymer liner could be inferred from coupons cut in the transverse direction from the fabricated liner.

Tests were conducted on five coupons cut in the transverse direction from the composite liner fabricated in the laboratory. The result from the tests showed a stress-strain response similar to that observed for the coupons cut in the longitudinal direction. A linear response was observed at strains between 0% to 0.5%, 2% to 5%, and 6 to 8%. The moduli values corresponding to these three ranges of strains were estimated as 3040 MPa, 480 MPa and 720 MPa. The tests also showed that in the circumferential direction, the coupons were capable of resisting a stress of at least 67 MPa which corresponds to a strain of 8%. Brown et al. (2007) noted that the composite liner was about 45% stiffer and stronger in the circumferential direction than in the longitudinal direction. Based on the observations made during the tests, they also suggested that the initial stiffness of the
liner was controlled by the resin. Following the cracking of the resin, the entire load was then resisted by the two polyester jackets.

Shanhai et al. (2007) also conducted uniaxial tensile tests on coupons of the liner. The coupons were prepared from liner material removed from a section of cast iron pipe that was exhumed from a field site in Hamilton City. A total of ten coupons were cut in the longitudinal and circumferential directions of the liner. The coupons were prepared and tested in accordance with ASTM D638-00. The experimentally determined Poisson’s ratio of the liner was approximately 0.3 in both the longitudinal and circumferential directions. The initial yield stresses in the longitudinal and circumferential directions were determined to be 3413.85 lb/in² (23.5 MPa) and 2786.8 lb/in² (19.2 MPa), respectively. The circumferential and longitudinal Young’s moduli were determined to be 325600 lb/in² (2245 MPa) and 256500 lb/in² (1769 MPa), respectively.

Knight and Sarrami (2006) also reported on the behavior of the liner when it is subjected to direct tension. A series of direct tension tests were carried out on samples of the liner in accordance with ASTM D638-03. The purpose of the tests was to verify Sanexen’s reported mechanical properties. Type I dumb-bell shaped test specimens were cut from laboratory cured cylinders and flat plates manufactured and cured by Sanexen. The specimens from the cylinders were cut along the longitudinal axis while that from the flat
plates were cut parallel and perpendicular to the machine direction noted by the manufacturer.

Sanexen considers the 0.5 mm thick polyurethane elastomer bonded to the inner surface of the liner as a non-structural component. The mechanical properties of the liner were estimated for two cases of the liner depth, the measured and corrected specimen depths which included and excluded the thickness of the polyurethane elastomer, respectively. Knight and Sarrami (2006) indicated that there was no information provided on whether Sanexen’s reported mechanical properties were based on the corrected or measured specimen depth.

The test results showed that the tensile moduli, peak tensile stresses and strains determined using the mean corrected specimen depth were approximately equal to the values reported by Sanexen. The tensile moduli determined using the mean measured specimen depth were about 13% lower than the values reported by Sanexen. Knight and Sarrami (2006) noted that the two sets of specimens cut from the flat plates exhibited similar tensile properties. The secant tensile modulus for the specimens cut in the longitudinal direction from the cylinders was determined to be 2340 MPa at a strain of 0.5%. The peak tensile stresses determined for all the three sets of specimens using the mean corrected depth exceeded the minimum ASTM F1216 value of 21 MPa (for field cured specimens for pressure pipes) by a factor greater than three. With the exception of
the specimens cut parallel to the machine direction of the flat plates, all the specimens attained a peak strain of about 20%. The former attained a peak strain of 10.9%.

### 2.4.2.2 Flexural Tests

Knight and Sarrami (2006) also reported on the flexural behavior of the liner. A series of flexural tests were conducted on rectangular test specimens in accordance with ASTM D790-03. Three sets of test specimens were cut from cylinders and flat plates with span to depth ratios of at least 16. The test specimens were cut in the same directions from the cylinders and the flat plates as described in Section 2.4.2.1.3.

Test results showed that for all three sets of specimens, the flexural moduli determined using the measured and corrected specimen depths were about 30% and 8% lower than the value reported by Sanexen, respectively. Even though Sanexen’s reported flexural modulus exceeded the minimum ASTM F1216 value of 1724 MPa recommended for field cured specimens for pressure pipes, the results from the laboratory tests proved otherwise. The only exception to this was in the case of the corrected depth flexural modulus determined for the specimens cut from the cylinders. For all three sets of specimens, both the measured and corrected depth flexural strengths exceeded the minimum ASTM F1216 value of 31 MPa.
2.4.3 Creep Behavior of Liner

Polymeric materials can undergo creep when subjected to a sustained load over a period of time (Pomeroy, 1978). The study of the behavior of the liner material under creep conditions is important because its stress evolution and expected life are significantly influenced by its resistance to creep (Zhu and Hall, 2001). Under sustained loading, a reduction in the strength of the composite polymer liner can occur with time (Pomeroy, 1978). Pomeroy (1978) noted that the creep response of a composite material was not only influenced by the time under the sustained load, but also by the fibre (e.g. woven fabrics) orientation relative to the applied stress. Shanhai et al. (2007) used finite element analysis to investigate the long-term creep behavior of the liner installed in a cast iron host pipe with circular defects. The eight-parameter creep model of the ADINA finite element software was used for the purpose of the analysis. This model was chosen because it best represented the experimental creep data obtained from testing coupons of the liner. The diameter of the circular defects ranged from 100 mm to 200 mm. A constant pressure of 200 lb/in\(^2\) (1379 kPa) was applied in the analysis. The effect of creep on the liner was described in terms of the predicted displacement at the center of the circular defects after 5000 hours. Shanhai et al. (2007) reported that creep had the effect of increasing the predicted displacement at the center of the circular defects by values as high as 70\% to 105\%. The percentage increase in the displacement of the liner due to the creep effect increased with decreasing defect size. The results from the finite element analysis led Shanhai et al. (2007) to suggest that it was necessary to consider the effect of creep strain in the design of structural liners used for pressure pipe rehabilitation.
Knight and Sarrami (2006) also reported on the long-term flexural creep performance of the liner. Knowledge of a liner’s flexural creep behavior is needed when designing for resistance to buckling under external pressures such as sustained groundwater pressure and/or transferred soil pressure (Gumbel, 1998). Flexural creep tests were conducted on the liner in accordance with ASTM D2990-01. The test specimens were cut from flat plates with a span to depth ratio of 16. The flexural test load was applied over 1.2 years and had a magnitude that was a quarter of the yield stress determined using ASTM D790. The liner was observed to have a linear creep rate (defined as the slope of the creep modulus versus the log load application time) during the first 100 hours of load application. Beyond this time period, the creep rate increased at a constant rate. Analysis of the test results led to the characterization of the liner as a material which begins to experience tertiary creep at about 100 hours of load application.

2.4.4 Parallel Plate Loading Tests

The parallel plate loading test can be used to determine the stiffness of a liner material. A liner’s ability to carry loads such as soil, live and groundwater loads, vacuum and construction loads can be determined if its stiffness is known (Jeyapalan, 2005). Allouche et al. (2005) conducted parallel plate loading tests on the liner to evaluate its circumferential properties. The tests were conducted on short lengths of the liner removed from lined cast iron pipes which were exhumed from a field site in Hamilton City. Each test specimen was subjected to compression through rigid plates at its crown
and invert in accordance with ASTM D2412. The average moduli were determined using elastic ring theory. The initial modulus which was estimated as 1500 MPa decreased to about 600 MPa as loading progressed. Allouche et al. (2005) attributed the decreasing modulus observed at higher strains to the yielding of the extreme fibers at the springlines, crown and invert, and progressively through more of the specimen during loading.

Knight and Sarrami (2006) also discussed the results from ring deflection tests conducted on cylinders of the liner. The purpose of the tests was to investigate the liner’s unrestrained loading and unloading behavior. The tests also conformed to ASTM D2412. Three test specimens were each subjected to two cycles of loading and unloading. Each load cycle involved loading the specimen until it experienced a vertical deflection of 40 mm, and then unloading it afterwards. One of the test specimens was loaded till failure during the second load cycle. The source of loading for all three specimens was a line load.

The test results for all three specimens showed that during the first loading cycle, the load-strain response remained linear from the start of the test till a vertical strain of approximately 5% was reached. The vertical strain of 5 % corresponded to a line load of 1250 N. Beyond this strain, the liner showed a non-linear load-strain response. The behavior of the liner during the second loading cycle was similar to that observed during the first loading cycle. In the specimen tested to failure, a crack was observed to develop
on the left side of the cylinder at a vertical strain of about 94%. The test specimens regained most of their initial shape after the line load was removed. Based on the observations made during the tests, Knight and Sarrami (2006) suggested that the liner was a highly flexible material which was capable of surviving a catastrophic event such as a collapsed line due to a line vacuum. They also noted that further testing was needed to examine the effect of multiple load cycles on the behavior of the liner.

2.4.5 Behavior of the Liner under Static Internal Pressure

In this section, experimental and numerical evaluations that have been conducted to determine the effect of geometric imperfections on the pressure rating of the liner are discussed. In the field, pipes do not have a uniform internal diameter along their lengths. Thus, when a cured-in-place-pipe liner is used for the purpose of rehabilitation there is the tendency to oversize the circumference of the liner in order to accommodate the varying internal pipe diameter. Oversizing the liner has the advantage of eliminating gaps between the liner and the host pipe and hence minimizing the likelihood of buckling under external pressure (Jaganathan et al., 2007). However, oversizing can result in the formation of longitudinal folds in the liner. In the following sections, studies which have identified the detrimental effect of longitudinal folds on the structural performance of the liner are discussed.
2.4.5.1 Effect of Longitudinal Folds on Pressure Rating

Jaganathan et al. (2007) carried out short-term burst tests on two lined cast-iron pipe specimens to establish the pressure rating of the liner. The tests were conducted in accordance with ASTM D3139-98. The internal pressure was applied in increments of 340 kPa with the pressure held at each increment for at least 5 minutes. One of the test specimens had a longitudinal fold in the liner while the other had none. The specimens were tested in a custom-made pressure cell which could generate internal pressure of up to 5 MPa. Water was used as the pressurizing medium for the tests.

One of the pressure tests was conducted on a 900 mm long cast iron pipe with an internal diameter of 152 mm. The pipe was rehabilitated with a liner which had a longitudinal fold. A rectangular gap with length and width of 300 mm and 75 mm, respectively, was machined in the cast iron pipe to expose the longitudinal fold in the liner. The longitudinal fold was centered about the machined gap. Three pairs of linear variable displacement transducers (LVDTs) were installed at three locations on the outer surface of the liner, in the immediate vicinity of the longitudinal fold. At each of the three locations, one LVDT was placed on either side of the longitudinal fold. During the test, the radial displacements of the liner were measured by the LVDTs. The liner ruptured along the longitudinal fold at an internal pressure of 2137 kPa. The load-displacement curve obtained for the specimen showed that yielding of the liner occurred at a pressure of about 1300 kPa.
Jaganathan et al. (2007) used finite element analysis to evaluate further the behavior of the liner tested in the laboratory. Two finite element models were constructed for the analysis. One of the models had dimensions and characteristics that were similar to that of the liner tested in the laboratory. The other model had a perfect circular geometry with no longitudinal fold. The former model confirmed the experimental result and observations. It predicted that the maximum stress and strain values occurred along the outer section of the longitudinal fold. As stated earlier, the liner failed by rupture along the longitudinal fold during the laboratory test. The finite element analysis estimated the failure pressure as 2000 kPa. This value differed from the experimental failure pressure of 2137 kPa by -6.5%. The finite element analysis estimated the failure pressure of the liner with the perfect geometry as 6000 kPa. Jaganathan et al. (2007) identified the high stress concentration that developed along the longitudinal fold as the cause of the premature failure observed in the model with the imperfection. The finite element analysis also showed that under increasing internal pressure, an unfolding mechanism occurred in the liner with the longitudinal fold. Figure 2.4 illustrates this unfolding mechanism in the liner. Jaganathan et al. (2007) attributed the drastic reduction in the internal pressure resisting capacity of a liner with a longitudinal fold to the high stress concentration and the unfolding of the liner.

The second pressure test was conducted on a section of lined cast iron pipe which constituted a fire hydrant tee with two bells. This section of cast iron pipe was rehabilitated with a liner without a longitudinal fold. The fire hydrant feed pipe was
machined off to expose an oval shaped section of the liner with dimensions of 200 mm and 150 mm in width and length, respectively. A total of five LVDTs were installed along the major and minor axes of the exposed liner. During the test, the loud cracking noises that were heard as the liner expanded were attributed to the breaking of the stiff resin layer coating which covered the liner’s outer wall. At pressures greater than 3500 kPa, the noises were attributed to the partial failure of the glass fiber reinforcement. The test was halted when an internal pressure of 3790 kPa was reached. The liner did not fail at this internal pressure value. The load-displacement curve obtained for the specimen showed that yielding of the liner occurred at a pressure of about 1650 kPa. This value was slightly greater than the yield pressure value of 1300 kPa recorded for the specimen with the longitudinal fold.

Jaganathan et al. (2007) conducted finite element analysis to investigate the behavior of the liner tested in the laboratory. The finite element model predicted a failure pressure of 4960 kPa. For both the analytical model and test specimen, the highest displacement value was recorded at the center of the exposed liner. The maximum stress and strain values in the model were predicted along the edge of the exposed liner. The model also showed that the initial rupture of the liner occurred in this region. This observation confirmed the prediction made by Allouche et al. (2005) that the structural performance of the liner can be influenced by the presence of circular voids in the host pipe.
2.4.5.2 Effect of Geometry of Longitudinal Fold on Critical Internal Pressure

Jaganathan et al. (2007) used finite element analysis to establish a theoretical relationship between the dimensions of the longitudinal fold and the critical internal pressure for the liner. They characterized the geometry of the fold by its depth (amplitude), \( d \), and its angle, \( \theta \), with respect to a horizontal axis perpendicular to the bottom of the fold. Figure 2.5 illustrates the two parameters used to characterize the geometry of the longitudinal fold. For the purpose of the study, the angle and depth of the fold were varied from 30° to 90° and from 7 mm to 20 mm, respectively. The radius of curvature at the tip of the fold, the thickness of the liner, and the internal diameter of the cast iron pipe were fixed. In the finite element model, a section of the liner which was 75 mm wide and 300 mm long was exposed by a gap in the cast iron pipe. The fold was located at the center of the gap. Based on this study, Jaganathan et al. (2007) established that the pressure rating of the liner was significantly influenced by changes in the depth and angle of the fold. The study revealed that the pressure rating of the liner was inversely proportional to both the depth and angle of the fold. Jaganathan et al. (2007) noted that the pressure rating of the liner decreased as the depth of the fold increased. They also noted that for a given depth of fold, the minimum pressure rating occurred when the angle of fold was 90°.

2.4.6 Behavior of Liner under Cyclic Internal Pressure

Shanhai et al. (2007) reported on the effect of cyclic loading on the long-term burst pressure of the liner installed in a deteriorated host pipe. Cyclic loading tests were carried
out on four PVC pipe specimens with internal diameters of 6 in (152 mm). The pipe specimens were lined with Sanexen’s composite liner and had gaps with different diameters. The condition of a cast iron host pipe was simulated by encasing the PVC pipe specimens in several steel rings machined to a diameter that was greater than the PVC pipe’s spigot. A circular opening was machined in the steel ring to expose the opening in the host pipe. The pipe specimens were subjected to internal pressure that alternated between 60 lb/in² (414 kPa) and 120 lb/in² (827 kPa). The response of the liner was recorded by LVDTs and strain gauges.

Shanhai et al. (2007) compared the experimental data recorded over 600 hours or 100000 loading cycles to the results from a finite element analysis in which the liner was subjected to a monotonic pressure of 120 lb/in² (827 kPa). Measurements of the displacement and strain at the center of a 100 mm gap in the liner were considered for the comparison. Shanhai et al. (2007) observed that there was a close agreement between the displacement values obtained from the experimental data and the numerical results. This was not the case for the strain values where the experimentally recorded values were generally lower that the numerically predicted values. Shanhai et al. (2007) attributed this observation to a lower primary strain. They noted that the secondary creep strain gain under the constant pressure of 120 lb/in² (827 kPa) was similar in magnitude to that for a base pressure of 60 lb/in² (414 kPa) with cyclic loading of up to 120 lb/in² (827 kPa). This observation led Shanhai et al. (2007) to conclude that for design purposes, the fatigue effect due to cyclic loading can be accounted for by determining the secondary
creep gain based on the expected peak pressure value which is the maximum surge pressure.

2.5 Split-Disk Method of Testing

When in service, hollow tubular structures such as pipes and pressure vessels are generally subjected to internal pressure which leads to the development of hoop stresses (Kaynak et al., 2005). It is necessary to ensure that such structures are designed to withstand the hoop stresses that they will experience. Test methods such as the pressurized filament-wound vessel test, the pressurized ring test, and the split-disk test can be used to evaluate the hoop properties of a material. Of the test methods, the split-disk test is considered as the simplest. In the case of filament wound materials it can be used to test the “as wound” ring specimen (Yoon et al., 1997). When compared to the pressure tests, it requires smaller and simpler specimens, and eliminates the possibility of the pressurizing medium leaking or even seeping into the material being tested (Jones et al., 1996). The split-disk test will be used in this thesis for the evaluation of the hoop strength of the composite liner. In the following sections, a description of the split-disk test, its limitations, and studies undertaken to investigate means of increasing the reliability of the split-disk test results are presented and discussed.
2.5.1 Description of the Split-Disk Test Method

The split-disk test is used to determine the apparent hoop tensile strength of plastic or reinforced plastic pipes. This method of testing is defined by ASTM Standard D2290 and it involves subjecting a ring specimen fitted over a pair of half disks to tension. The sample is loaded under tension when the two half disks are stretched apart. A typical split-disk test fixture is shown in Figure 2.6.

The term “apparent” rather than “true” is used to describe the tensile strength obtained from the test because of the effect of the bending moment that is imposed at the split between the test fixture during testing (Kaynak et al., 2005). Yoon et al. (1997) identified the rotation of the test fixture as the cause of the bending that occurred in the width direction of the ring specimen being tested. Shlitsa and Novikova (1983) noted that the bending moment produced the concentration of circumferential normal stresses and the occurrence of shear stresses within the ring specimen at the locations near the line of separation of the half disks. They suggested that the development of these stresses could cause the premature failure of the ring specimen and thus the underestimation of its hoop tensile strength.

Yoon et al. (1997) attributed the effects of this local bending, and the friction between the ring specimen and the test fixture as possible reasons for the split-disk test not being suitable for the determination of the hoop tensile modulus. However, some researchers
have suggested that with the correct test setup, the split-disk test can also be used to make a reasonable measurement of the tensile modulus of a material.

2.5.2 Effects of Modifications to the Typical Split-Disk Test Fixture

Modifications to the typical split-disk test fixture aim at minimizing the occurrence of local bending and/or the presence of friction. As stated earlier, the rotation of the test fixture during loading introduces bending in the width direction of the ring specimen. The effect of the local bending is more pronounced around the split disk edges at high load levels (Yoon et al., 1997). The resulting non-uniform stress distribution in the width direction leads to the underestimation of the failure load of the ring specimen (Yoon et al., 1997).

In addition to the occurrence of the local bending, the existence of rolling friction between the split disks and the ring specimen can make this test unsuitable for the determination of the tensile modulus of a ring specimen. Jones et al. (1996) noted that there will always be some degree of rolling friction between the split disks and the ring specimen because the surfaces of both cannot be perfectly smooth. They stated that indentation of the contacting surfaces of the split disks and the ring specimen was an additional source of contribution to the rolling friction.
Jones et al. (1996) conducted tests on ring specimens prepared from a filament-wound material. For their tests, the original split-disk test fixture was modified to reduce the effect of friction. The half disks were manufactured such that they could accommodate a set of silver steel needle rollers along their outer surfaces. The needle rollers served as the interface between the half disks and the ring specimen, thus reducing rolling friction. Results from the analytical analyses conducted to evaluate the effects of this modified test fixture led Jones et al. (1996) to suggest that even though there was significant bending stresses at the split line, there was also the rapid decay of these stresses so that the majority of the ring specimen was in a uniform state of stress.

In their study, Yoon et al. (1997) tested four different types of fiber reinforced materials using a modified split-disk test fixture which aimed at eliminating rotation and hence reducing the local bending in the width direction of the ring specimen. The fiber reinforced materials consisted of three types of carbon fiber reinforced materials (T300, T800, and T1000) and one type of glass fiber reinforced material (S2). Yoon et al. (1997) modified the original split-disk test fixture by attaching pin holes at the horizontal matching surfaces of the half disks. Through the pin holes it was possible to keep the two half disks aligned during loading. To ensure that the other parts of the modified test fixture did not rotate out of plane of the disks, the test fixture was rigidly fixed to the loading ram. Friction between the test fixture and the ring specimen was minimized by applying graphite powders over the surface of the half disks.
Yoon et al. (1997) tested five to seven ring specimens prepared from each of the four fiber reinforced materials. Results from the tests showed that the measured hoop tensile strengths were lower than the theoretically predicted strengths by approximately 13-21%. Tests were also conducted on ring specimens prepared from one of the carbon fiber reinforced materials (T800) to investigate the extent to which the modified test fixture improved the accuracy of the experimentally determined tensile strength. This was achieved by testing ring specimens of the carbon reinforced material using both the modified and the original split-disk test fixtures. The measured tensile strengths were 16.7 % and 24.4 % lower than the theoretically predicted strength when the modified and the original test fixtures were used, respectively. Yoon et al. (1997) confirmed through their investigation that the rotation of the test fixture and the presence of friction have the effect of reducing the tensile strength determined from a split-disk test.

2.5.3 Increasing the Accuracy of the Measured Tensile Modulus

As stated earlier, the split-disk test may not be a suitable method for the determination of the tensile modulus. The distribution of the circumferential strain in the ring specimen is influenced by the local bending at the disk edges and the friction between the specimen and the test fixture (Yoon et al., 1997). In this section, tests conducted to investigate a means to improve the reliability of the tensile modulus determined from a split-disk test are discussed. In the discussions that follow, a location of 0° on the outer surface of a ring
specimen corresponds to the springline of the specimen. In the split-disk test fixture, this location corresponds to the split line (i.e. the place of separation of the two half disks).

Yoon et al. (1997) conducted tests on ring specimens prepared from the carbon fiber reinforced material T300, and the glass fiber reinforced material S2. Eight strain gages were installed along the outer surface of the ring specimen at locations of 0°, 7.5°, 15°, 30°, 45°, 60°, 75°, and 90°. The modified test fixture described in Section 2.5.2 was used for the tests. Graphite powder was applied over the contact surface between the test fixture and the ring specimen to reduce friction. The effect of friction was further eliminated by subjecting each of the ring specimens to one cycle of loading and unloading while maintaining the same loading speed. This decision was based on the fact that the frictional effect is the same in magnitude but opposite for the loading and unloading paths. Thus, the frictional effects during loading and unloading will counteract each other. The tensile modulus at the location of each strain gage was determined as the average of the loading and unloading moduli.

The effects of friction were evident in the test results. At each strain gage location, the load-strain curve formed a hysteresis loop and the loading and unloading paths had different slopes. Yoon et al. (1997) noted that there was a relationship between the location of the strain gage and the size of the hysteresis loop formed. They observed that there was greater hysteresis as the strain gage location moved further from the split disk.
edges. Further from the split disk edges, the contact area between the test fixture and the ring specimen increases. This increases the effect of friction and hence the greater hysteresis observed. For both sets of specimens, the highest tensile modulus corresponded to the strain gage installed at the split disk edges. Its value was about twice the value determined at other gage locations. Yoon et al. (1997) suggested that this was caused by the local bending that occurred at the split disk edges.

Excluding the tensile modulus determined at the split disk edges, the moduli values for the seven remaining strain gage locations had percentage errors ranging between 0.6 % and 7.3 % for the carbon fiber reinforced specimen, and 1.4 % and 13.8 % for the glass fiber reinforced specimen. The least percentage errors of 0.6 % and 1.4 % were determined at the strain gage locations of 30° and 60°, respectively. From the test results, it can be suggested that the best location for the determination of the tensile modulus depends on the type of material being investigated.

Shlitsa and Novikova (1983) also conducted tests on ring specimens prepared from glass and carbon fiber-reinforced plastics (FRP) using a typical split-disk test fixture. Five or six ring specimens were tested for each set of tests conducted. Strain gages were installed at locations of ±12°, ±18°, ±30°, ±45°, and ±60° along the outer surface of the ring specimens. Test results showed that the best measurement of the elastic modulus occurred for the glass FRP at a strain gage location of ±30° and for the carbon FRP at a
strain gage location of \( \pm 45^\circ \). Shlitsa and Novikova (1983) stated that similar conclusions were drawn from a more thorough study on carbon, boron, organic and high modulus glass FRP.

The studies discussed in this section show that it is possible to obtain a reasonable measurement of the tensile modulus of a ring specimen from a split-disk test if the location for the measurement of deformations is properly selected.

2.5.4 Effects of Other Parameters on the Split-Disk Test Results

In the previous sections, the discussions pointed out that the local bending that occurred at the split disk edges played a role in the underestimation of the measured tensile strength of a ring specimen. From the discussions, it is also known that the location for strain measurements can affect the accuracy of the inferred tensile modulus. Shlitsa and Novikova (1983) noted that it was necessary to evaluate the effect that other factors such as the geometric parameters of the ring specimen, and the initial gap between the ring specimen and the half disks had on the measured tensile strength and modulus. In their study, Shlitsa and Novikova (1983) conducted split-disk tests on ring specimens prepared from carbon, boron, organic and high-modulus glass fiber-reinforced plastics (FRP). Five or six ring specimens were tested for each set of tests conducted. In the next sections, the effect of some parameters on the measured tensile strength and modulus of elasticity are discussed.
2.5.4.1 Effect of the Initial Gap

Shlitsa and Novikova (1983) defined the size of the initial gap as the difference between the inside diameter of the ring specimen and the half disks, as assembled before loading. The ring specimens tested were prepared from carbon, boron, organic and high-modulus glass fiber-reinforced plastics (FRP). The size of the initial gap investigated ranged from about 0.1 mm to 4 mm. Test results showed that the size of the initial gap had no effect on the inferred tensile modulus. In the case of the tensile strength, the carbon FRP ring specimens showed a significant decrease in strength when the initial gap was increased.

Shlitsa and Novikova (1983) also observed that the presence of an initial gap before the start of testing had an effect on the load-deformation response. When an initial gap exists, the graph of the load-deformation response exhibits a nonlinear section at the start of the loading which is followed by a linear section till the end of loading. An increase in the initial gap resulted in the widening of the non-linear section of the load-deformation graph. The linear section of the graph was used for the determination of the tensile modulus.

2.5.4.2 Effect of the Thickness of Ring Specimen

To investigate the effect of the specimen thickness on the measured strength and modulus, ring specimens were prepared from carbon, boron, organic and high-modulus glass fiber-reinforced plastics (FRP) and tested. The thickness of the specimens ranged
from 0.6 mm to 8 mm. Test results showed that the sample thickness had no effect on the inferred tensile modulus. The only exception to this was in the case of the 8 mm thick glass FRP ring specimens, where the inferred tensile modulus was overestimated. It was determined that the strength of the ring specimen was influenced by its thickness. The strength was observed to decrease with increasing specimen thickness. An exception to this was in the case of the organic FRP ring specimens where there was no decrease in strength for the range of specimen thickness investigated.

2.5.4.3 Effect of the Width of Ring Specimen

Tests were conducted on ring specimens prepared from carbon and organic FRP to evaluate the effect of specimen width on the measured strength and modulus. The specimen width ranged from about 6 mm to 26 mm. The test results showed that for a specimen width in the range of 6 mm to 20 mm, the width had no influence on the measured strength and modulus. However, a specimen width greater than 20 mm led to underestimated results. Shlitsa and Novikova (1983) noted that further testing was needed to determine the optimal width of ring specimens of composite materials with an oblique fiber reinforcement arrangement.

A review of the studies conducted on the split-disk test method has shown that the split-disk test is a very simple test which also has limitations. Its limitations can influence the
reliability of the measured results. However, the accuracy of the measured results can be improved if the test parameters are properly selected.
Figure 2.1: (a) A section of metallic pipe with a corrosion pit, (b) Effect of tuberculation on a pipe [From Seica et al., 2002]

Figure 2.2: (a) Pulling resin impregnated liner into place, (b) Inflation and curing of liner with hot water [From Allouche et al., 2005]
Figure 2.3: (a) LS1: Hoop tensile forces induced by internal pressure at locations where the host pipe has split, (b) LS2: Longitudinal wall bending in the liner wall at locations where it spans from a section of damaged host pipe to an intact section, (c) LS3: Longitudinal wall bending in the liner where it spans through a clamped section, (d) LS4: Overall or local bending in and stretching of the liner wall at ring fractures or joints, (e) LS5: Local bending in liner wall where it spans across a void, (f) LS6: Stresses in the vicinity of a water service connection [From Allouche et al., 2005]
Figure 2.4: Unfolding mechanism in a liner with a longitudinal fold
[From Jaganathan et al., 2007]

Figure 2.5: Defining the geometry of a longitudinal fold [From Jaganathan et al., 2007]

Figure 2.6: A split disk test fixture [From Kaynak et al., 2005]
CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 General

A series of tests were conducted to evaluate the effect of geometric imperfections on the circumferential strength of Sanexen’s composite polymer liner. The geometric imperfections investigated were in the form of longitudinal folds and are referred to as wrinkles in this thesis. These wrinkles were formed as a result of the larger diameter of the liner relative to the inner diameter of the host cast iron pipe. The test samples were obtained from exhumed lined cast iron pipes. The method of testing was based on the split-disk test which is defined by ASTM Standard D2290. A series of tests were conducted to investigate the effects of three parameters. Generally, three to five similar specimens were tested for every case to establish repeatability of test results and obtain a reliable average. The first set of tests was carried out to determine the effect of loading rate on the liner. For this evaluation, fifteen ring samples were tested under monotonic loading conditions at four different rates of loading. The second set of tests was carried out to evaluate the response of the liner to cyclic loading. For this investigation, three ring samples were subjected to the same cyclic loading pattern, which was selected to represent service conditions in practice. A set of five ring samples which were subjected to monotonic loading only served as the control set for the cyclic loading tests. Upon completion of the cyclic loading tests, each of the three ring samples was subjected to
monotonic loading to failure. The effects of the presence of a wrinkle and its geometry were also evaluated as the third parameter of this study. This chapter provides detailed descriptions of the wrinkles observed in the liner, preparation of the test samples from the exhumed lined cast iron pipes, preliminary tests conducted to determine the type of test setup to use, instrumentation, test procedure and the parameters investigated.

3.2 Description of Wrinkles in the Liner

The composite polymer liner examined in this thesis is manufactured by Sanexen Environmental Service Inc. in Montreal, Canada. The city of Hamilton in Ontario, Canada, was involved in a pilot project aimed at investigating the possibility of using Sanexen’s cured-in-place polymer liner for the rehabilitation of its deteriorated cast iron water pressure pipes. The liner samples tested in the laboratory were obtained from lined cast iron pipes exhumed from a field site in Hamilton.

As discussed in Section 2.4.5, oversizing the circumference of the liner in order to accommodate the varying internal pipe diameter can result in the formation of longitudinal folds, which are referred to as wrinkles. An inspection of the lined cast iron pipe sections delivered to the laboratory for testing revealed different patterns of wrinkles along the length of the pipe sections. Figures 3.1 to 3.4 show some of the different patterns of wrinkles that were observed. Figure 3.5 shows a ring sample with a perfect geometry (i.e. free of wrinkles).
As described in Section 2.3.1, the liner is composed of two plain woven polyester jackets, namely, the inner and outer jackets, and polymeric resin. In Figure 3.2, only the inner jacket is wrinkled inward whereas the outer jacket is not wrinkled. In Figure 3.3, both the inner and outer jackets are deformed inward within the wrinkle. A line drawn through the peak of the wrinkle produces two almost symmetric parts. In Figure 3.4, both the inner and outer jackets are deformed inward within the wrinkle. A line drawn through the peak of the wrinkle produces two asymmetric parts. Additional information on the cross-sectional area of the wrinkles observed in the liners shown in Figures 3.2 to 3.4 will be provided in Chapter 4.

3.3 Preparation of Ring Samples from Lined Cast Iron Pipe Sections

To obtain the ring samples that were needed for testing, the lined cast iron pipes were cut into shorter sections with lengths of about 250 mm. A longitudinal cut was made along two opposite sides on each section. The longitudinal cuts made it possible to detach the cast iron pipe from the liner. Each detached liner section was washed to remove traces of rust and dirt deposited onto its outer surface from the cast iron pipe, and the solids deposited onto its inner surface. The ring samples were obtained by cutting the cleaned liner into 25 mm wide sections. The locations along the outer surface of the ring samples where the strain gages were attached were completely cleaned of the polymeric resin residue produced during the installation of the liner, and any rust remnant, using a belt sander. Figures 3.6 (a) to (g) show pictures that illustrate these preparation processes.
3.4 Preliminary Tests and Lessons Learned

Ring samples of the liner were tested using the split-disk test method. Tests were conducted on two ring samples each of which had two wrinkles. Figure 3.1 shows a picture of a ring sample similar to the two ring samples tested. Specially fabricated concrete disks were used in the split-disk test. Concrete was chosen because it can be molded to accommodate the different patterns of the wrinkles. In both tests, the two half concrete disks cracked before the complete rupture of the liner. Figure 3.7 shows a picture of one of the two sets of the half concrete disks that were used for the preliminary test. In Figure 3.7, it can be seen that the cracks in the concrete disks have propagated from the points of contact between the wrinkles and the concrete disks. This may have occurred because of the higher stress concentration at these locations. The tests may have been successful if the wrinkles were located 180° apart from each other. Such an orientation would have made it possible to locate the wrinkles at the split between the two half disks, thus eliminating the locations of high stress concentration.

Tests were also conducted on ring samples with only one wrinkle. Two different locations of the wrinkle were considered during the tests. The wrinkle was placed at the split between the two half disks (the split disk edge or springline) or 90° from the split disk edge (the crown). In the case where the wrinkle was located at the crown, the half concrete disk in contact with the wrinkle cracked before the complete rupture of the liner. The explanation for this observation is the same as that given in the previous paragraph, namely, stress concentrations. However, testing was successful when the wrinkle was
located at the springline. This orientation made it possible to eliminate regions of high stress concentration. Based on the observations made during the preliminary tests, a decision was made to conduct the tests on ring samples with only one wrinkle, and also to orient the ring samples such that the wrinkle was located at the split between the two half concrete disks.

It should be noted that if the half disks were manufactured from steel instead of concrete, tests involving ring samples with more than one wrinkle would have been possible. It would also not be necessary to orient the samples such that the wrinkle was located at the springline. Although steel is a stronger material than concrete and will not have been susceptible to cracking, concrete was the better choice for the manufacture of the half disks for a number of reasons. As can be seen in Figures 3.1 to 3.4, the interior cross-section of the liner varies with the type of wrinkle observed. Compared to steel, concrete could easily be molded to fit the exact interior cross-section of the ring samples, as indicated before. It was also a lower cost material, and hence, half disks could be manufactured as needed.

For each pattern of wrinkle in the ring samples tested, one or more sets of half concrete disks were manufactured. Information on the mix proportions of the concrete disks is provided in Table 3.1. The concrete disks were molded in 55 mm wide lined cast iron pipe sections (with the different types of wrinkles observed) which were placed over a
flat glass surface during pouring of the concrete. The two half disks were separated by a 2
mm thick rectangular steel plate which was placed at the location of the split between the
two halves, prior to the pouring of concrete. When the 55 mm wide lined pipe section had
been filled to a depth of 45 mm with concrete (i.e. 10 mm above the flat glass surface), a
steel reinforcement cage was placed on either side of the rectangular steel plate, and the
pouring of the concrete was continued until the pipe section was completely filled. This
was followed by smoothing of the concrete surface. Once the concrete disks had cured, a
longitudinal cut similar to that described in Section 3.3, was made along two opposite
sides on each 55 mm wide lined pipe section to enable the detachment of the lined pipe
section from the half concrete disks, and the removal of the rectangular steel plate. The
same steps were followed during the fabrication of the concrete disks for liner samples
without wrinkles.

3.5 Test Specimens and Parameters Investigated

3.5.1 Effect of Loading Rate

A set of tests was conducted to evaluate the effect of loading rate on the behavior of the
liner. A total of fifteen ring samples were tested at loading rates of 0.1 mm/min, 5
mm/min, 100 mm/min and 250 mm/min. For each of the loading rates of 0.1 mm/min and
5 mm/min, five samples were tested. Four samples were tested at a loading rate of 100
mm/min, and one sample at 250 mm/min. Figure 3.4 shows a ring sample that is similar
to the fifteen samples tested. In terms of size, the wrinkles in the fifteen samples had the
largest cross-sectional areas observed. Results from the five samples tested at a loading rate of 5 mm/min were also used for the evaluation of the effects of the presence of a wrinkle and its geometry.

3.5.2 Effect of Cyclic Loading

A set of tests was also carried out to investigate the effect of cyclic loading. For the purpose of this investigation, a total of eight ring samples were tested. Three of the eight samples were subjected to cyclic loading with loads alternating between 1.2 kN and 2.5 kN. The lower and upper load limits were established based on information provided on the operational water pressure and periodical surges observed in the water distribution systems in Hamilton City, and neglecting the effect of wrinkles on the hoop force. The operational water pressure and the periodical surges were estimated to be in the range of 350 to 420 kPa and 560 to 770 kPa, respectively. Each of the three samples was subjected to at least 50,000 load cycles at a loading frequency of approximately 5 seconds (i.e. 0.2 Hz). The 50,000 load cycles are equivalent to about 50 years of service. Upon completion of the cyclic loading tests, the samples were tested to failure under monotonic loading conditions at a loading rate of 5 mm/min. The other five samples, which served as control, were subjected to monotonic loading only at a loading rate of 5 mm/min. Figure 3.3 shows a ring sample that is similar to the eight samples tested. In terms of size, the wrinkles in the eight samples had cross-sectional areas that were smaller than those observed in the fifteen samples tested to evaluate the effect of loading rate. Test results
for the five control samples used in this part of the study were also used for the evaluation of the effects of the next parameter, namely, presence of a wrinkle and its geometry.

### 3.5.3 Effect of the Presence of a Wrinkle and its Geometry

The evaluation of the effect of wrinkle geometry on the behavior of the liner considered three different types of wrinkles, two of which have already been described (see Figures 3.3 and 3.4). Figure 3.2 shows a ring sample with the third type of wrinkle that was investigated. Five samples similar to that shown in Figure 3.2 were subjected to monotonic loading at a loading rate of 5 mm/min. In terms of size, the wrinkles in these five samples had the smallest cross-sectional areas observed. Test results for these five samples were also used for the evaluation of the effect of the presence of a wrinkle.

Monotonic loading tests were also carried out on five samples of the liner with perfect geometries (i.e. no wrinkles). The five samples served as control for the tests performed to evaluate the effects of the presence of a wrinkle and its geometry. Figure 3.5 shows a ring sample that is similar to the five samples tested. One of the five samples was tested to failure while the other four samples were initially tested to a maximum load of approximately 10 kN. After the initial loading and unloading, the four samples were subjected to monotonic loading for a second time until failure occurred. All the five samples were tested at a loading rate of 5 mm/min.
3.6 Instrumentation and Data Acquisition

The instrumentation was similar for all tests carried out. Electric resistance strain gauges were used for the measurement of the circumferential strains and were HBM Type 6/120LD20, 6 mm long. As described in Section 3.3, the locations along the outer circumference of the ring samples where the strain gauges were to be installed were completely cleaned of rust and polymeric resin remnants, using a belt sander. Other surface preparations followed this step, before the installation of the strain gauges. Each sand papered location was coated with a film of epoxy, thin enough just to smoothen the uneven surface of the liner. The epoxy constituted of M-Bond adhesive resin GA-2 and M-Bond type 10-A curing agent. The epoxy coated surface was covered with a thin plastic sheet, followed by a 2.4 mm thick silicon gum pad, a wooden block, and then clamped to ensure an even distribution of the epoxy. This process is illustrated in Figure 3.8 (a). Figure 3.8 (b) also shows the surface of a ring sample just after it has been detached from the cast iron pipe, completely cleaned of rust and resin remnants using the belt sander, and with a coat of cured epoxy. After the epoxy had cured, the coated surfaces were sand papered with grid 100 sandpaper, followed by grid 400A sandpaper. The strain gauges were installed on the epoxy coated surfaces of the ring samples using HBM Type 1-X60 strain gauge adhesive.

The relative displacement between the upper and lower halves of the concrete disks was measured using four SLS130 Linear Displacement Sensors (LDSs) with a stroke of 25 mm to give a reliable average. The LDSs were secured by aluminum brackets attached to
the surfaces of the half disks, using 5 minute epoxy. Figure 3.9 shows a test setup with the LDSs installed. A schematic of the test setup with the location of each of the four LDSs and the strain gauges labeled is also shown in Figure 3.10. In all the tests, the shafts of the LDSs were retracted by about 20 mm.

The cyclic loading tests and one monotonic loading test involving one of the ring samples with a perfect geometry were conducted using an Instron model 1350 testing machine with a load capacity of 100 kN. For the cyclic loading tests, the load and time data were recorded using the DT Measure Foundry program. The load and stroke data for the monotonic loading test performed in the Instron testing machine were recorded using the StrainSmart Version 4.11 software. All other tests were conducted using a Zwick/Roell material testing machine (MTM) with a loading capacity of 20 kN. The load and stroke data from the MTM were recorded using the TestXpert V11.0 Master software. For all the tests, the data from the strain gauges and the four LDSs were recorded using the StrainSmart Version 4.11 software.

3.7 Test Setup and Procedure

The ring samples were tested using a technique that was based on the split-disk method of testing. The test fixture used for all the tests is shown in Figure 3.9. Prior to testing, the samples were fitted onto the concrete disk such that they were centered on its outer circumference. As shown in Figure 3.10, each half disk was secured by an H-shape
section made from mild steel. The H-shape sections were connected through hinges (by means of bolts and nuts) to rectangular mild steel plates, which were fitted into the grips of the testing machine. In Figure 3.11, the dimensions of the H-shape sections and rectangular mild steel plates, and the typical arrangement of steel reinforcement in the half concrete disks are shown. The fabrication of the reinforced concrete disks was described in Section 3.4. With the exception of the cyclic loading tests which were conducted under load control, all other tests were stroke controlled. The dimensions of the ring samples were measured with a digital caliper. Measurements of width and thickness were made at locations along the circumference of the samples.
Table 3.1: Half concrete disks mix proportions [From Mandal et al., 2005]

<table>
<thead>
<tr>
<th>Concrete mix proportions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete strength, $f'_c$ (MPa)</td>
<td>81</td>
</tr>
<tr>
<td>7-day strength (MPa)</td>
<td>39 – 41</td>
</tr>
<tr>
<td>Cement (kg/m$^3$)</td>
<td>505</td>
</tr>
<tr>
<td>Water (kg/m$^3$)</td>
<td>145</td>
</tr>
<tr>
<td>Silica fume (kg/m$^3$)</td>
<td>63</td>
</tr>
<tr>
<td>Gravel/stone (kg/m$^3$)</td>
<td>1136</td>
</tr>
<tr>
<td>Sand (kg/m$^3$)</td>
<td>701</td>
</tr>
<tr>
<td>High-range water reducing admixture (kg/m$^3$)</td>
<td>24</td>
</tr>
<tr>
<td>Water to cement ratio, w/c</td>
<td>0.25</td>
</tr>
</tbody>
</table>

1 A compression test was conducted on three 100 mm x 200 mm concrete cylinders. The 7-day strength represents the average strength of the three concrete cylinders. The compression test was conducted for each new batch of concrete mix, and thus, the range of values presented in the table.
2 Type 30 Portland Cement was used
3 The diameter of the stones used was no more than 10 mm
4 A superplasticizer was used. For a unit volume (1 m$^3$) of concrete, 8 kg of the superplasticizer was used instead of the suggested 24 kg.
Figure 3.1: Liner with two wrinkles

Figure 3.2: Liner whose wrinkle has the smallest cross-sectional area observed

Figure 3.3: Liner whose wrinkle has a cross-sectional area greater than the smallest wrinkle size, and less than the largest wrinkle size observed
Figure 3.4: Liner whose wrinkle has the largest cross-sectional area observed

Figure 3.5: Liner with no wrinkles
Figure 3.6: (a) A shorter length of a cast iron pipe section as delivered to the laboratory, (b) A cross-section of the cast iron pipe, (c) Cutting pipe section into shorter lengths of 250 mm, (d) Making a longitudinal cut on a side of a 250 mm pipe section, (e) Front view of a detached liner, (f) Cross-section of the detached liner, (g) Front view of a ring sample with a portion of its outer surface cleaned of polymeric resin residue and rust remnants
Figure 3.7: A pair of half concrete disks after a preliminary test

Figure 3.8: (a) Exerting force by clamping to enable an even distribution of the applied epoxy to smoothen the surface, (b) From left to right: A ring sample with rust and resin remnants intact, part of its surface completely cleaned of rust and resin remnants, and part of its surface coated with epoxy
Figure 3.9: Test setup in the laboratory
Figure 3.10: Schematic of test setup showing locations of strain gauges and LDSs in a ring sample with a wrinkle and in one with a perfect geometry.
Notes: All dimensions are in mm

The vertical reinforcement bars were welded to the horizontal reinforcement bars.

Figure 3.11: (a) Schematic of test setup showing dimensions of the H-shape sections and rectangular steel plates, both of which have a width of 40 mm, (b) Horizontal section, and (c) Vertical section through one half concrete disk, showing the typical arrangement of steel reinforcement.
CHAPTER 4
TEST RESULTS AND DISCUSSION

4.1 General

In this chapter, the results of all the tests conducted are presented and analyzed. As discussed in Chapter 3, a series of tests were conducted to evaluate the effect of geometric imperfections (wrinkles) on the circumferential strength of Sanexen’s composite polymer liner. The method of testing was based on the split-disk test. Ring samples were tested to evaluate the effects of three parameters on the behavior of the liner. During testing, each ring sample with a wrinkle was oriented such that the wrinkle was located at the split between the two half concrete disks (the springline). The load-stroke, load-average displacement and load-strain graphs were obtained for the ring samples tested. The discussions in this chapter are based on these test results and the visual observations made during testing. A series of two-tailed Mann-Whitney statistical tests were conducted on the measured load values at a level of significance, \( \alpha \) of 0.05. In the following sections, the effects of the presence of a wrinkle and its geometry, loading rate, and cyclic loading on the behavior of the liner, and the results of the statistical tests are discussed.
4.2 Test Results and Effects of Various Parameters

In this section, the results of all the tests performed are presented and discussed. The discussions focus mostly on the load-stroke and load-average displacement graphs obtained. The load-strain behavior of the samples is briefly discussed. In the graphs used for the discussions, the load represents the total load applied to the ring sample. The stroke represents the crosshead displacement of the testing machine. The average displacement represents the average value recorded by the four Linear Displacement Sensors (LDSs). The strain represents the circumferential strain measured by a strain gauge installed at the specified location along the outer surface of the ring sample. In the graphs, it is noted that the average displacement values are lower than the stroke values at any given load. This is expected because the LDSs measure only the relative displacement between the upper and lower halves of the concrete disks while the stroke reflects the total measured displacements that include those of the entire split-disk test fixture, the grips and other components of the testing apparatus.

It should be noted that no measures were taken to minimize the friction between the half concrete disks and the inner surface of the ring samples tested. As described in Section 3.4 of Chapter 3, the concrete disks used in the split-disk tests were molded in lined cast iron pipe sections. The outer surface of the concrete disks was thus, textured due to the woven nature of the inner jacket of the liner (see Section 2.3.1 of Chapter 2). The textured outer and inner surfaces of the concrete disks and ring samples, respectively, imply that friction existed between the two surfaces during testing. As discussed in
Chapter 2, Yoon et al. (1997) determined through experimental investigations that the presence of friction between the ring specimen and half disks had the effect of reducing the tensile strength measured from the split-disk test. Hence, it is possible that the measured load values presented and discussed in the following sections are underestimated.

4.2.1 Effect of Loading Rate

The water demand on a municipal pipeline is not constant. It can vary in the course of the day and with season (Henry and Heinke, 1996). The water demand is defined as the volume of water consumed by a population over a time interval. It is directly related to the water flow rate within a pipe. Water loses energy as it flows through a pipe (Hwang, 1981). Hwang (1981) identified friction between the flowing water and the pipe walls as one of the causes of major energy loss. This energy loss results in head loss along the pipe length. The head loss is directly related to the water flow rate, and thus, water demand, and also to the internal pressure variation with time, and hence, the rate of loading (Hwang, 1981). As stated in Chapter 3, fifteen ring samples were tested to investigate the effect of loading rate on the behavior of the composite polymer liner. The ring samples are identified as LW-1 to LW-15. Figure 4.1 shows a labeled picture of a wrinkle similar to those in samples LW-1 to LW-15. A series of tests were conducted under stroke control, at loading rates of 0.1 mm/min, 5 mm/min, 100 mm/min, and 250 mm/min. Figures 4.2 (a) and (b) which are based on test sample LW-5 show the typical load-stroke and load-average displacement graphs that were obtained for the tested
samples. Figures A.1 to A.6 of Appendix A show the load-stroke, load-average displacement, and load-strain graphs obtained for all the fifteen test samples. A summary of the test results is presented in Tables 4.1 and 4.2. The results summarized in Table 4.1 are plotted in Figures 4.3 (a) to (c).

Thirteen of the fifteen samples were tested to failure. All thirteen samples failed at the wrinkle. Two samples (LW-14 and LW-15, see Table 4.1) were not tested to failure because of a malfunction of the testing machine. However, the load at which the first cracking of the resin within the wrinkle occurred was obtained. In all the samples, signs of failure began with the cracking of the resin. The crack was initiated at a location along the outer surface of the wrinkle, and propagated through the resin towards the outer jacket. This was followed by the rupture of the outer jacket, then the cracking of the resin between the inner and outer jackets, and finally the rupture of the inner jacket. Figures 4.1 and 4.4 (a) and (b) show a labeled picture of a wrinkle similar to those in samples LW-1 to LW-15, and a ring sample before and after testing, respectively. The observed sequence of failure mechanism is illustrated in Figure 4.5. The behavior of the wrinkle during testing confirmed the unfolding mechanism predicted by the finite element analysis performed by Jaganathan et al. (2007) on a liner with a wrinkle subjected to increasing internal pressure (see Section 2.4.5.1). The initiation of failure at the wrinkle in the test samples indicates that the wrinkle is a source of weakness in the liner as suggested by findings of earlier research work (see Section 2.4.5).
In Figures 4.2 (a) and (b), the drops in the load values occurred during the cracking of the resin within the wrinkle with the first drop being the longest as it represents first cracking. In Table 4.2, the range of load values recorded at the loading rates of 0.1 mm/min, 5 mm/min and 100 mm/min as well as the average values are presented. From Table 4.2, it can be seen that for a given loading rate, the difference between the maximum and minimum load values recorded at the first cracking of the resin can be significant. This is not the case for the maximum and minimum ultimate load values. The graph in Figure 4.3 (a) represents the load values recorded at the first cracking of the resin for the three loading rates of 0.1 mm/min, 5 mm/min and 100 mm/min. From the graph, it can be seen that the recorded load values fall within a similar range. The load value of 5294 N recorded at the first cracking of the resin for sample LW-15 which was tested at a loading rate of 250 mm/min also falls in the range of values recorded for the other three loading rates as shown in Figure 4.3 (b). If failure of the liner is defined as the occurrence of the first cracking of the resin within the wrinkle, then it is reasonable to suggest that the loading rate has no significant effect on the hoop tensile capacity of the liner. In Figure 4.3 (c), the ultimate load values plotted for the loading rates of 5 mm/min and 100 mm/min fall within a similar range. However, the ultimate load values for the loading rate of 0.1 mm/min are lower than that for the loading rates of 5 mm/min and 100 mm/min. It appears that at loading rates less than 5 mm/min, the ultimate hoop tensile capacity of the liner is dependent on the loading rate. This suggests that the effect of very slow loading rates as well as sustained loads over a long period of time would likely
reduce the ultimate hoop tensile capacity of the liner and would need to be studied further.

Figures A.4 to A.6 of Appendix A represent the load-strain graphs of samples LW-1 to LW-15. In the samples, the strain gauge installed at the wrinkle was in contact with the resin (see Figure 4.1). The graphs correspond to the start of the test until the first cracking of the resin within the wrinkle occurs. A similar load-strain response was observed in all samples. The behavior generally shows that the strains at the wrinkled and non-wrinkled sides are not equal. This is expected because of the different wall thicknesses at both sides as well as the different proportions of fabric and resin within the wall thickness.

4.2.2 Effect of Cyclic Loading

In the field, surge pressures can be generated in a pressure pipe as a result of the opening and closing of valves, the starting and stopping of pumps, changes in flow demand, and the presence of trapped air within a pipe (Shanhai et al., 2007). As stated in Section 3.5 of Chapter 3, periodical pressure surges estimated to be in the range of 560 kPa to 770 kPa occur in the pipelines in Hamilton City. Tests were conducted on eight ring samples to evaluate the response of the liner to cyclic loading. The ring samples are identified as IW-1 to IW-5 and IW-6C to IW-8C. Figure 4.6 shows a labeled picture of a wrinkle similar to those in samples IW-1 to IW-5 and IW-6C to IW-8C. Five of the eight samples (IW-1 to IW-5) served as control for the cyclic loading tests and were subjected to monotonic loading only at a loading rate of 5 mm/min. The remaining three samples (IW-6C to IW-
8C) were subjected to 50,000 load cycles at a loading frequency of approximately 5 seconds (i.e. 0.2 Hz). The 50,000 cycles represent approximately a 50-year design life, assuming three surge events occur daily (Shanhai et al., 2007). Based on the information provided about the operational water pressure and the periodical pressure surges, loads alternating between 1.2 kN and 2.5 kN were applied to samples IW-6C to IW-8C in the form of triangular waves. Upon completion of the cyclic loading tests, the three samples were tested to failure under monotonic loading conditions at a loading rate of 5 mm/min. The control samples (IW-1 to IW-5) were tested under stroke control. Samples IW-6C to IW-8C were subjected to cyclic loading under load control. After the cyclic loading tests, the three samples were tested to failure under stroke control.

In Figure 4.7 (a), the load-time graphs of samples IW-6C to IW-8C corresponding to the first 750 seconds of cyclic loading are presented. In Sample IW-6C, no signs of failure were observed during and after testing, however, both samples IW-7C and IW-8C showed signs of cracking at the wrinkle. In sample IW-7C, the resin within the wrinkle cracked during the first loading cycle. The crack was initiated at a location along the outer surface of the wrinkle and propagated through the resin towards the outer jacket. During testing, the resin between the two jackets also underwent cracking. In sample IW-8C, the cracking of the resin within the wrinkle led to a sudden increase in the relative displacement between the upper and lower halves of the concrete disk, in the vicinity of the wrinkle. This sudden increase in displacement was captured by the two Linear Displacement Sensors (LDSs) installed on either surface of the concrete disk in the
vicinity of the wrinkle (i.e. LDSs 1 and 3, see Figure 3.10), and occurred about 18 hours into the test. At the end of the tests, an inspection of samples IW-7C and IW-8C revealed that most of the resin had cracked and had become detached from the jackets, yet both the inner and outer jackets in both samples remained intact. These observations suggest that the polyester jackets of a wrinkle in the liner can remain intact under the 50-year cyclic loading. However, the resin within the wrinkle is susceptible to cracking. Figures 4.7 (b) to (d) show pictures of a ring sample prior to the cyclic loading test, and of ring samples that illustrate the two types of observations that were made in the samples at the end of the tests, respectively.

Figure 4.8 presents the load-stroke and load-average displacement graphs obtained for samples IW-6C to IW-8C, which were tested to failure under monotonic loading conditions following the cyclic loading tests. In the graphs, samples IW-6C, IW-7C, and IW-8C are identified as IW-6CM, IW-7CM, and IW-8CM, respectively. A summary of the results for the monotonic loading tests conducted on samples IW-6CM to IW-8CM is presented in Tables 4.3 and 4.4. In Figure 4.8, the graphs for sample IW-6CM show drops in the load values. The drops reflect cracking of the resin within the wrinkle as indicated earlier. The failure mechanism observed in sample IW-6CM was similar to that observed in samples LW-1 to LW-15 in Section 4.2.1. As described earlier, the resin within the wrinkles of samples IW-7CM and IW-8CM underwent cracking during the cyclic loading tests. Therefore, in Figure 4.8, the load-deformation graphs for these two samples show fairly smooth curves since they were precracked. It is clear then that the
resin within the region of the wrinkle affects significantly the initial part of the load-displacement behavior.

As stated earlier, samples IW-1 to IW-5 served as control for the cyclic loading tests and were subjected to monotonic loading only at a loading rate of 5 mm/min (i.e. similar to samples LW-1 to LW-5). Figures 4.9 (a) and (b), which are based on test sample IW-5, show the typical load-stroke and load-average displacement graphs that were obtained for samples IW-1 to IW-5. Figures A.7 and A.8 of Appendix A show the load-stroke and load-average displacement, and load-strain graphs obtained for all the five test samples, respectively. A summary of the test results is presented in Tables 4.3 and 4.4.

All five samples were tested to failure. Samples IW-2, IW-4 and IW-5 failed at the wrinkle. In samples IW-1 and IW-3, failure occurred at the opposite side of the wrinkle where the liner had a perfect (i.e. non-wrinkled) geometry. Figures 4.10 (a) to (c) show pictures of a ring sample before testing, and of ring samples which illustrate the two types of observations that were made in the samples at the end of the tests. In all the samples, signs of failure began with the cracking of the resin within the wrinkle. The crack was initiated at a location along the outer surface of the wrinkle, and propagated through the resin towards the outer jacket. The failure mechanism observed in the three samples which failed at the wrinkle was similar to that observed in samples LW-1 to LW-15 discussed in Section 4.2.1. Both the inner and outer jackets at the wrinkle of samples IW-1 and IW-3 were still intact when rupture occurred at the other side.
In Figures 4.9 (a) and (b), the drops in the load values occurred during the cracking of the resin as illustrated before. A similar load-deformation response was exhibited by all the five samples irrespective of the observed failure mechanism (see Figure A.7 of Appendix A). From Table 4.3, it can be seen that the lowest load values corresponding to the first cracking of the resin ($P_{cr}$) were recorded for samples IW-1 and IW-3 in which failure occurred at the opposite side of the wrinkle. The highest ultimate load value ($P_{max}$) of 12003 N was recorded for sample IW-3. The fourth highest ultimate load value of 10292 N was recorded for sample IW-1. The small number of samples that exhibited the two types of failure mechanisms observed makes it impossible to determine the extent to which the observed failure mechanisms influence the ultimate load values recorded. The load-strain graphs of samples IW-1 to IW-5 are presented in Figure A.8 of Appendix A. In Figure A.8, the graphs correspond to the start of the test until the first cracking of the resin within the wrinkle occurs. As indicated earlier, the strains at both sides of the samples were quite different. The explanation for this observation is the same as that given for samples LW-1 to LW-15 in Section 4.2.1.

From Table 4.4, it can be seen that samples IW-6CM to IW-8CM and control samples IW-1 to IW-5 have ultimate load values which fall in the ranges of 8823 N to 10858 N, and 8929 N to 12003 N, respectively. Sample IW-4 appears to show a significantly lower strength than the other four control samples. It appears to be more similar to samples LW-1 to LW-5 (see Table 4.5). If it is excluded, the ultimate load values recorded for the four remaining control samples fall in the range of 10292 N to 12003 N. Based on the
average values (see Table 4.4), it maybe concluded that the 50-year cyclic loading could possibly cause a reduction of about 10 % in the ultimate hoop tensile strength of the liner.

4.2.3 Effect of the Presence of a Wrinkle and its Geometry

Four sets of five ring samples were tested under stroke control, to evaluate the effect of the presence of a wrinkle and its geometry on the behavior of the composite polymer liner. Two sets of the ring samples which are identified as samples LW-1 to LW-5, and IW-1 to IW-5 have already been discussed in Sections 4.2.1 and 4.2.2, respectively. Figures 4.1 and 4.6 show labeled pictures of wrinkles similar to those in samples LW-1 to LW-5 and IW-1 to IW-5, respectively. The wrinkles in the third set of samples which are identified as samples SW-1 to SW-5 had the smallest cross-sectional areas observed in this liner. The fourth set of samples which are identified as samples NW-1 to NW-5 had perfect geometries (i.e. no wrinkles) and served as control samples. All the samples were tested under monotonic loading conditions at a loading rate of 5 mm/min. The following sections will focus on series SW and NW as well as general assessment of the wrinkles based on all four sets.

4.2.3.1 Test Results of Samples SW-1 to SW-5

Figure 4.11 shows a labeled picture of a wrinkle similar to those in samples SW-1 to SW-5. Wrinkle type SW is characterized by a small size and with the inner jacket only being wrinkled. In Figures 4.12 and 4.13, the typical load-stroke and load-average displacement
graphs that were obtained for the tested samples are presented. Figures A.9 and A.10 of Appendix A show the load-stroke and load-average displacement, and load-strain graphs obtained for all the five test samples, respectively. A summary of the test results is presented in Tables 4.5 and 4.6.

In samples SW-1 to SW-5, two types of failure mechanisms were observed and these are defined as types 1 and 2. Failure occurred at the wrinkle in all the five samples. Failure type 1 began with the cracking of the resin at a location along the boundary between the resin and the outer unwrinkled jacket. The crack then propagated through the resin towards the inner wrinkled jacket. This was followed by the rupture of the outer jacket, and finally the rupture of the inner jacket. Figure 4.12 (a) shows a picture of a wrinkle exhibiting failure type 1. Samples SW-1, SW-2 and SW-3 exhibited failure type 1. Figures 4.12 (b) and (c) which are based on sample SW-2 represent the typical load-stroke and load-average displacement graphs obtained for the test samples that exhibited failure type 1. It is noted that the drop in the load due to the first cracking of the resin is quite small relative to other cases discussed previously, with larger wrinkles and with both jackets wrinkled.

Failure type 2 began with the rupture of the outer unwrinkled jacket, followed by detachment of the uncracked resin from the inner wrinkled jacket, and finally rupture of the inner jacket. Figure 4.13 (a) shows a picture of a wrinkle exhibiting failure type 2. Samples SW-4 and SW-5 exhibited failure type 2. Figures 4.13 (b) and (c) which are
based on sample SW-4 represent the typical load-stroke and load-average displacement graphs obtained for the test samples that exhibited failure type 2. In Figures 4.13 (b) and (c), there are no significant drops in the loads. Based on the graphs presented in Figures 4.12 (b) and (c) and Figures 4.13 (b) and (c), it appears that for small wrinkles of this type of configuration, failure types (1 or 2) do not have a significant effect on the load-displacement responses, and generally, there is a clear bilinear trend with reduction of stiffness but no major drop in load due to cracking as was shown in other types of wrinkles before.

In Figure A.10 of Appendix A, the load-strain graphs of samples SW-1 to SW-5 are presented. A similar load-strain response was observed in all the five samples irrespective of the exhibited failure mechanism. In samples SW-1 to SW-5, the installed strain gauges were in contact with the outer jacket. In each sample, a strain gauge was installed at the wrinkle and at the opposite side of the wrinkle. At both locations, a bilinear load-strain response was observed. It is interesting to note that the strains at the wrinkled side show a near yielding behavior at about 6 kN, which is within the range at which the outer jacket likely failed at the wrinkle or when the resin cracked.

### 4.2.3.2 Test Results of Samples NW-1 to NW-5

As stated earlier, five samples (NW-1 to NW-5) without wrinkles (i.e. non-wrinkled samples), which served as control specimens, were also tested. Sample NW-5 was tested to failure while the other four samples (NW-1 to NW-4) were initially tested to a
maximum load of approximately 10 kN. After the initial loading and unloading, the four samples were subjected to monotonic loading for a second time until failure occurred. The test results for samples NW-1 to NW-5 are summarized in Tables 4.5 and 4.6. The load values presented correspond to the loads recorded at failure. Figures 4.14 (a) and (b) show pictures of a sample before and after testing. Figures 4.15 (a) and (b), which are based on test sample NW-5, show the typical load-stroke and load-average displacement graphs. The load-stroke and load-average displacement graphs for all the five samples are presented in Figure A.11 of Appendix A. As discussed earlier in Section 2.4.2.1.3 of Chapter 2, Brown et al. (2007) conducted direct uniaxial tension tests on flat coupons cut in the transverse direction from a liner fabricated in the laboratory. In Table 4.7, the failure load values for the flat coupons and the ring samples tested in this study are compared. Strain gauges were installed at five locations along the outer surface of each ring sample. The strain gauges installed at the opposite split disk edges (springlines) were approximately 180° apart. The three remaining strain gauges were installed along the outer surface of each ring sample at locations of 30°, 60°, and 90°. Figures A.12 to A.15 of Appendix A show the load-strain graphs obtained at the five different locations along the outer surface of each ring sample. In Figure A.16, the load-strain responses at the five strain gauged locations are plotted in a single graph for each ring sample. In Figures A.11 to A.16, the load-stroke, load-average displacement and load-strain graphs for samples NW-1 to NW-4 correspond to the first loading (i.e. up to 10 kN only).
All the five samples exhibited a bilinear load-deformation response. After testing to failure, an inspection of the samples revealed that in samples NW-1, NW-3 and NW-4, the polyurethane elastomer bonded to the inner surface of the liner was ruptured. In samples NW-2 and NW-5, the elastomer was stretched but was not ruptured. In Table 4.7, the lowest ultimate load values recorded correspond to samples NW-2 and NW-5 in which the elastomer was not ruptured. As stated earlier in Section 2.4.2.1.3 of Chapter 2, Sanexen considers the elastomer as a non-structural component of the liner. Based on the experimental results, it can be suggested that the elastomer has some contribution to the hoop tensile strength of the liner. In Table 4.7, the flat coupons, which are identified as Coupons #3 to #7 (Brown et al., 2007), have widths and thicknesses that are similar to those of ring samples NW-1 to NW-5. Also, both sets of samples were tested at a loading rate of 5 mm/min. At failure, the elastomer in all the five flat coupons was not ruptured. From Table 4.7, it can be seen that the ultimate load values for Coupons #3 to #7 fall in the range of 9211 N to 10673 N. The ultimate load values of 10161 N and 10554 N for samples NW-2 and NW-5 in which the elastomer was not ruptured also fall in the specified range. Based on the experimental results, it is reasonable to suggest that the curvature effect is quite insignificant and that the circumferential properties of field-installed polymer liners can be inferred from flat coupons fabricated in the laboratory.

Figures A.12 to A.15 of Appendix A show the load-strain graphs obtained at five different locations along the outer surface of each ring sample. The load-strain graphs at the springlines of the ring samples are presented in Figure A.12. As described in Section
2.5 of Chapter 2, local bending can occur at the split disk edges of the test fixture during loading. In Figure A.12, this is evident in the negative strains recorded at the springlines of the ring samples. In general, at all the five strain gauged locations the liner exhibits a non linear behavior as load increases (see Figures A.12 to A.15).

### 4.2.3.3 Effect of the Presence of a Wrinkle and its Shape and Size

#### 4.2.3.3.1 Introduction

In this section, the wrinkle size is defined as the cross-sectional area of the wrinkle. It is approximated as the area of a triangle whose height and base are the amplitude (Δ) and wavelength (λ) of the wrinkle, respectively, as shown in Figure 4.16. The amplitude and wavelength of the wrinkles in the ring samples were measured with a digital caliper. The shape of the wrinkle is defined in terms of its amplitude (Δ), and angle (θ) with respect to a horizontal axis perpendicular to the peak of the wrinkle. The pattern of the wrinkle is described in terms of the proximity of the inner jacket to the outer jacket. Figures 4.17 (a) and (b) illustrate the effect of the wrinkle size on the load recorded at the first cracking of the resin within the wrinkle, and on the ultimate load of the liner. The load values plotted in Figures 4.17 (a) and (b) are presented in Table 4.5. The average cross-sectional areas of the wrinkles are presented in Table 4.6. In Figures 4.17 (a) and (b), a trendline is drawn through the average of the load values recorded for the four sets of ring samples tested. The average load values are summarized in Table 4.6. In each of the three sets of
samples with a wrinkle, the first signs of failure began with the cracking of the resin within the wrinkle or the rupture of the outer jacket at the wrinkle.

4.2.3.3.2 Effect of Wrinkle Depth (Amplitude) on $P_{cr}$

In Table 4.6 and Figure 4.17 (a), it can be seen that the load values recorded at the first cracking of the resin ($P_{cr}$) in samples SW-1 to SW-3, are generally higher than that recorded for samples IW-1 to IW-5 and LW-1 to LW-5. Finite element analysis performed by Jaganathan et al. (2007) established that the internal pressure rating of a liner with a wrinkle was influenced by the amplitude (depth, $d$) of the wrinkle (see Section 2.4.5.2 of Chapter 2). The amplitude of the wrinkle is defined in Figure 4.18 (a). Jaganathan et al. (2007) noted that the internal pressure rating of a liner with a wrinkle, increased with decreasing wrinkle amplitude. The internal pressure rating of the liner is directly related to its hoop tensile strength. In Table 4.8, the lowest average amplitude ($\Delta_{avg}$) of 10.0 mm in this study corresponds to samples SW-1 to SW-5. Based on the reported theoretical relationship, the higher load values recorded at the first cracking of the resin in samples SW-1 to SW-3 is expected because of the lower amplitudes of their wrinkles.

4.2.3.3.3 Effect of Angle $\theta$ of the Wrinkle on $P_{cr}$

In Table 4.6 and Figure 4.17 (a), it can be seen that the load values recorded at the first cracking of the resin ($P_{cr}$) in samples LW-1 to LW-5 are generally higher than that
recorded for samples IW-1 to IW-5. In Table 4.6, the average $P_{cr}$ values for samples IW-1 to IW-5 and LW-1 to LW-5 are 3564 N and 5401 N, respectively. Jaganathan et al. (2007) also reported that the internal pressure rating of a liner with a wrinkle was influenced by the angle ($\theta$) of the wrinkle. For a given amplitude of wrinkle, they noted that the minimum internal pressure rating occurred when the angle of the wrinkle was 90°. The angle of the wrinkle is defined in Figures 4.16 and 4.18 (a). Based on this theoretical relationship, the internal pressure rating, and thus the hoop tensile strength of a liner with a given amplitude of wrinkle, is expected to decrease as the angle of the wrinkle increases. Figures 4.18 (b) and (c) show wrinkles similar to those in samples LW-1 to LW-5 and IW-1 to IW-5, respectively. In Table 4.8, it can be seen that the two sets of samples have average wrinkle amplitudes of 15.9 mm and 16.1 mm which are approximately equal. In Figure 4.18, the angles of the wrinkle in samples LW-1 to LW-5 and IW-1 to IW-5 are labeled as ($\alpha$) and ($\beta$), respectively. The angle ($\beta$) of the wrinkle in samples IW-1 to IW-5 is greater than the angle ($\alpha$) of samples LW-1 to LW-5. Based on the theoretical relationship reported by Jaganathan et al. (2007), the higher load values recorded at the first cracking of the resin in samples LW-1 to LW-5 can be attributed to the lower angle of the wrinkles in the samples.

It is also reasonable to attribute the higher $P_{cr}$ values recorded for samples LW-1 to LW-5 to the size of the wrinkles in the samples. The average cross-sectional areas of the wrinkles in samples IW-1 to IW-5 and LW-1 to LW-5 are 176 mm² and 227 mm², respectively. The higher average cross-sectional area recorded for samples LW-1 to LW-
5 suggests that the cross-sectional area in the direction of the load is also higher. As such, the stress level is lower and hence cracking occurred at a higher load.

In Table 4.6, samples NW-1 to NW-5, which have no wrinkles, have the highest load values and average load value recorded at failure, as also shown in Figure 4.17 (a). If failure in the three sets of samples with wrinkles is defined as the occurrence of the first cracking of the resin within the wrinkles, then it is reasonable to suggest that the presence of a wrinkle in the liner has significantly decreased its hoop tensile capacity.

4.2.3.3.4 Effect of Wrinkle Size and Pattern on $P_{\text{max}}$

In Table 4.6, the ranges of ultimate load values ($P_{\text{max}}$) recorded for the three sets of samples with wrinkles and for samples NW-1 to NW-5 which have no wrinkles are presented. The average $P_{\text{max}}$ values are also presented in the table. In Table 4.6 and Figure 4.17 (b), the lowest ultimate load values correspond to samples LW-1 to LW-5 which have the highest average cross-sectional area of 227 mm$^2$. Figure 4.17 (b) also shows that the ultimate load values recorded for samples SW-1 to SW-5 and IW-1 to IW-5 which have average cross-sectional areas of 56 mm$^2$ and 176 mm$^2$, respectively, fall within a similar range as that recorded for samples NW-1 to NW-5. In Table 4.8, the average $P_{\text{max}}$ values for the three sets of samples with wrinkles increase as the average cross-sectional area of the wrinkles decreases. The average $P_{\text{max}}$ values for samples SW-1 to SW-5 and NW-1 to NW-5 are approximately equal.
An explanation for the similar range of ultimate load values recorded for samples SW-1 to SW-5 and NW-1 to NW-5 can be made on the basis of the size and pattern of the wrinkles in samples SW-1 to SW-5. It is possible that the small size of the wrinkles combined with the fact that the outer jacket was not wrinkled at all, have minimized or eliminated the detrimental effects of the wrinkle on the ultimate load. The resin in this wrinkle was completely confined between the two jackets. A confirmation of this can be seen in Figures A.9 and A.11 of Appendix A which represent the load-deformation graphs obtained for samples SW-1 to SW-5 and NW-1 to NW-5, respectively. In the figures, both sets of samples exhibit a bilinear load-deformation response, with insignificant change in behavior at first cracking.

An explanation for the similar range of ultimate load values recorded for samples IW-1 to IW-5 and NW-1 to NW-5 can be made on the basis of the failure mechanism observed in samples IW-1 to IW-5 during testing. Failure was influenced by the pattern of the wrinkles in samples IW-1 to IW-5, where the two jackets were in close proximity (see Figure 4.6). After the occurrence of the first cracking of the resin within the wrinkle, the unfolded wrinkled springline, after straightening, resembled the opposite side springline which had a perfect geometry, in that both jackets at the wrinkle acted together in resisting the applied load. Thus, failure in ring samples IW-1 to IW-5 could have equal chance of occurrence at either springline, just as was observed in ring samples NW-1 to NW-5. This is indeed confirmed by the occurrence of failure at the springline with the perfect geometry which was opposite the wrinkled springline in samples IW-1 and IW-3
This important observation suggests that the pattern of wrinkle of both jackets, relative to each other is as important as the overall size of the wrinkle, with regard to their effects on $P_{\text{max}}$.

In Table 4.6 and Figure 4.17 (b), the ultimate load values recorded for samples LW-1 to LW-5 are lower than that for samples NW-1 to NW-5. An explanation for this observation can be made on the basis of the pattern of the wrinkles in these samples. As can be seen from Figure 4.1, the jackets in the wrinkles of samples LW-1 to LW-5 are separated by a greater amount of resin and are further apart than those in samples IW-1 to IW-5 (see Figure 4.6). This implies that after the occurrence of the first cracking of the resin within the wrinkle, both jackets act separately in resisting the applied load. As separate components (i.e. each with a different amplitude of wrinkle), the jackets will not share the load equally, and hence, will have a reduced resistance to the applied load. In samples LW-1 to LW-5 failure occurred at the wrinkle. The reduced load resistance of the jackets in the wrinkle is confirmed by the fact that failure never occurred at the other side of the springline, with the perfect geometry.

### 4.3 Statistical Test: Mann-Whitney Test

#### 4.3.1 Introduction

A series of two-tailed Mann-Whitney tests were conducted to confirm the suggestions made on the basis of the experimental results which were presented and discussed in
Section 4.2. The measured load values were considered for the analysis. All the statistical tests discussed in the next sections were conducted at a level of significance, $\alpha$ of 0.05. In each test, the null hypothesis which was the hypothesis tested, assumed that the two sets of test samples considered exhibited similar hoop capacities. The alternative hypothesis assumed that the null hypothesis was not true. Based on one of the two sets of samples considered, a test statistic was determined, and was used to establish whether the null hypothesis should be accepted or rejected. The statistical decision made was then compared to the experimental based decision. It should be noted that the acceptance of the null hypothesis does not imply that the null hypothesis is true but rather implies that on the basis of the test samples considered, the null hypothesis has not been shown to be false, meaning there is no evidence to suggest that the two sets of samples exhibit different hoop capacities (Conover, 1980). The rejection of the null hypothesis, and hence, the acceptance of the alternative hypothesis implies that the former is false while the later is true (Conover, 1980). When the null hypothesis is rejected, it is rejected at the level of significance, $\alpha$ of 0.05 considered for this analysis (Conover, 1980). In the following sections, the outcome of the two-tailed Mann-Whitney tests conducted to confirm the experimental based decisions suggested in Section 4.2 is presented and discussed.
4.3.2 Statistical Results

4.3.2.1 Effect of Loading Rate on First Cracking Load of Resin, $P_{cr}$

In Section 4.2.1, the first cracking load of the resin within the wrinkles, $P_{cr}$ measured for samples tested at loading rates of 0.1 mm/min, 5 mm/min and 100 mm/min were similar (see Tables 4.1 and 4.2, and Figure 4.3 (a)). Based on this observation, it was suggested that the loading rate had no significant effect on $P_{cr}$. A series of two-tailed Mann-Whitney tests were conducted to determine if the samples tested at the three different loading rates exhibited similar $P_{cr}$ values as suggested in Section 4.2.1. Three tests were conducted in which the $P_{cr}$ values of the samples tested at 5 and 0.1 mm/min, 5 and 100 mm/min, and 0.1 and 100 mm/min were compared. The test statistics for the three tests were based on the samples tested at 0.1 mm/min, 100 mm/min, and 100 mm/min, respectively. Each of the three statistical tests showed that the $P_{cr}$ values of the two sets of samples compared were similar. The results imply that there is no evidence to suggest that the $P_{cr}$ values of the samples tested at the loading rates of 0.1 mm/min, 5 mm/min and 100 mm/min differ, and hence, the $P_{cr}$ values are similar as suggested earlier. This confirms the suggestion that the loading rate has no significant effect on $P_{cr}$.

4.3.2.2 Effect of Loading Rate on Ultimate Load, $P_{max}$

In Section 4.2.1, the ultimate load ($P_{max}$) values measured for samples tested at loading rates of 5 mm/min and 100 mm/min were similar. However, the $P_{max}$ values of samples
tested at a loading rate of 0.1 mm/min were lower than that of those tested at 5 mm/min and 100 mm/min (see Tables 4.1 and 4.2, and Figure 4.3 (c)). Based on this observation, it was suggested that slow loading rates (i.e. loading rates less than 5 mm/min) would likely reduce the ultimate hoop tensile capacity of the liner.

A two-tailed Mann-Whitney test was conducted to determine if the samples tested at the loading rates of 5 mm/min and 100 mm/min exhibited similar $P_{\text{max}}$ values as suggested in Section 4.2.1. In the test, the $P_{\text{max}}$ values of the samples tested at 5 and 100 mm/min were compared. The test statistic for this test was based on the samples tested at 100 mm/min. The statistical result showed that the $P_{\text{max}}$ values of the two sets of samples were similar. The result implies that there is no evidence to suggest that the $P_{\text{max}}$ values of the samples tested at the loading rates of 5 mm/min and 100 mm/min differ, and hence, the $P_{\text{max}}$ values are similar as suggested earlier.

Two-tailed Mann-Whitney tests were also conducted to determine if the samples tested at the loading rate of 0.1 mm/min exhibited similar $P_{\text{max}}$ values as those tested at the loading rates of 5 mm/min and 100 mm/min. Two tests were conducted in which the $P_{\text{max}}$ values of the samples tested at 0.1 and 5 mm/min, and 0.1 and 100 mm/min were compared. The test statistics for the tests were based on the samples tested at 0.1 mm/min. The statistical tests showed that the $P_{\text{max}}$ values of the samples tested at 0.1 mm/min were not similar to that of those tested at 5 mm/min and 100 mm/min. The test statistic determined in each of
the two tests also showed that the $P_{\text{max}}$ values of the samples tested at 0.1 mm/min were likely lower than that of those tested at 5 mm/min and 100 mm/min. This confirms the suggestion that slow loading rates would likely reduce the ultimate hoop tensile capacity of the liner.

4.3.2.3 Effect of Cyclic Loading on Ultimate Load, $P_{\text{max}}$

In Section 4.2.2, the average ultimate load ($P_{\text{max}}$) value obtained for samples subjected to the 50-year cyclic loading prior to monotonic loading was lower than that obtained for samples subjected to monotonic loading only (see Tables 4.3 and 4.4). Based on this observation, it was suggested that the 50-year cyclic loading could cause a reduction in the ultimate hoop tensile strength of the liner.

A two-tailed Mann-Whitney test was conducted to determine if the samples subjected to the 50-year cyclic loading exhibited similar $P_{\text{max}}$ values as those subjected to monotonic loading only. In the test, the $P_{\text{max}}$ values of the two sets of samples were compared. The test statistic for this test was based on the samples subjected to the 50-year cyclic loading, and tested to failure under monotonic loading conditions following the cyclic loading tests. The statistical result suggested that the $P_{\text{max}}$ values of the two sets of samples were similar. This does not confirm the suggestion that the 50-year cyclic loading could cause a reduction in the ultimate hoop tensile strength of the liner. It is important to note that the statistical result implies that there is no evidence to suggest that the $P_{\text{max}}$ values of the
two sets of samples differ. Considering that only three samples were subjected to the 50-year cyclic loading, it may be necessary to test at least five samples to establish if this long-term cyclic loading condition causes any significant reduction in the ultimate hoop tensile strength of the liner.

4.3.2.4 Effect of the Presence of a Wrinkle and its Geometry

4.3.2.4.1 Effect of Wrinkle Depth (Amplitude) on \( P_{cr} \)

In Section 4.2.3.3.2, the loads measured at the first cracking of the resin within the wrinkles (\( P_{cr} \)) in samples SW-1 to SW-3 were generally higher than that measured for samples IW-1 to IW-5 and LW-1 to LW-5 (see Tables 4.5 and 4.6, and Figure 4.17 (a)). Sample types IW and LW had wrinkle amplitudes that were higher than sample type SW. Based on this experimental observation and result from a finite element analysis performed by Jaganathan et al. (2007), a suggestion was made that samples with lower wrinkle amplitudes exhibited higher \( P_{cr} \) values.

Two-tailed Mann-Whitney tests were conducted to determine if sample type SW exhibited similar \( P_{cr} \) values as sample types IW and LW. Two tests were conducted in which the \( P_{cr} \) values of sample types SW and IW, and SW and LW were compared. The test statistic for each of the two tests was based on sample type SW. The statistical test showed that the \( P_{cr} \) values of sample types SW and IW were not similar. The test statistic
determined in the test also showed that the $P_{cr}$ values of sample type SW were likely higher than that of sample type IW. This confirms the suggestion that samples of type SW which have lower wrinkle amplitudes than samples of type IW, exhibit higher $P_{cr}$ values.

The statistical result for sample types SW and LW suggested that the two sets of samples exhibited similar $P_{cr}$ values. This does not confirm the suggestion that samples with lower wrinkle amplitudes are expected to exhibit higher $P_{cr}$ values. It is important to note that this statistical result implies that there is no evidence to suggest that the $P_{cr}$ values of the two sets of samples differ. This is expected because as can be seen in Figure 4.17 (a), a number of sample type LW exhibit $P_{cr}$ values that are lower than, and also similar to that of sample type SW. Despite this contradiction it is still reasonable to suggest that samples with lower wrinkle amplitudes exhibit higher $P_{cr}$ values since there is enough experimental evidence and also numerical proof that this is generally the case.

4.3.2.4.2 Effect of Wrinkle Angle $\theta$ on $P_{cr}$

In Section 4.2.3.3.3, the loads measured at the first cracking of the resin within the wrinkles ($P_{cr}$) in samples LW-1 to LW-5 were generally higher than that measured for samples IW-1 to IW-5 (see Tables 4.5 and 4.6, and Figure 4.17 (a)). Sample types LW and IW had similar wrinkle amplitudes, with samples of type LW having the lower wrinkle angles (see Figure 4.18). Based on the experimental observations and result from
a finite element analysis performed by Jaganathan et al. (2007), a suggestion was made that for samples with similar wrinkle amplitudes, the samples with lower wrinkle angles exhibited higher $P_{cr}$ values.

A two-tailed Mann-Whitney test was conducted to determine if sample types LW and IW exhibited similar $P_{cr}$ values. In the test, the $P_{cr}$ values of sample types LW and IW were compared. The test statistic was based on sample type LW. The statistical result suggested that the two sets of samples exhibited similar $P_{cr}$ values. This does not confirm the suggestion that for a given wrinkle amplitude, samples with lower wrinkle angles are expected to exhibit higher $P_{cr}$ values. It is important to note that this statistical result implies that there is no evidence to suggest that the $P_{cr}$ values of the two sets of samples differ. This is expected because as can be seen in Figure 4.17 (a), a number of sample type IW exhibit $P_{cr}$ values that are lower than, and also similar to that of sample type LW. It may be necessary to test more samples to establish the effect of wrinkle angle on $P_{cr}$.

### 4.3.2.4.3 Effect of Wrinkle Size and Pattern on $P_{max}$

As described earlier, sample types SW, IW and LW had wrinkles while sample type NW had no wrinkles. The wrinkles in sample types SW, IW and LW varied in terms of size and pattern. In Section 4.2.3.3.4, the ultimate load ($P_{max}$) values measured for sample types NW, SW and IW were similar. However, the $P_{max}$ values measured for sample type LW were lower than that for sample type NW (see Tables 4.5 and 4.6, and Figure 4.17
(b). Based on these experimental observations, it was suggested that the presence of a wrinkle may or may not cause a reduction in the ultimate hoop tensile capacity of the liner depending on the wrinkle pattern.

A series of two-tailed Mann-Whitney tests were conducted to determine if sample types NW, SW, and IW exhibited similar $P_{\text{max}}$ values as suggested in Section 4.2.3.3.4. Three tests were conducted in which the $P_{\text{max}}$ values of sample types NW and SW, NW and IW, and SW and IW were compared. The test statistics for the three tests were based on samples types SW, IW, and IW, respectively. Each of the three statistical tests showed that the $P_{\text{max}}$ values of the two sets of samples compared were similar. The results imply that there is no evidence to suggest that the $P_{\text{max}}$ values of sample types NW, SW, and IW differ, and hence, the $P_{\text{max}}$ values of the three sets of samples are similar as suggested earlier. This confirms the suggestion that the presence of the wrinkle may not cause a reduction in the ultimate hoop tensile capacity of the liner depending on the wrinkle pattern.

A two-tailed Mann-Whitney test was also conducted to determine if sample types NW and LW exhibited similar $P_{\text{max}}$ values. In the test, the $P_{\text{max}}$ values of the two sets of samples were compared. The test statistic was based on sample type LW. The statistical result showed that the $P_{\text{max}}$ values of sample types NW and LW were not similar. The test statistic also showed that the $P_{\text{max}}$ values of sample type LW were likely lower than that
of sample type NW. This confirms the suggestion that the presence of the wrinkle may cause a reduction in the ultimate hoop tensile capacity of the liner depending on the wrinkle pattern.
### Table 4.1: Summary of test results used for the evaluation of the effect of loading rate

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Δ (mm)</th>
<th>λ (mm)</th>
<th>Outer Diameter¹ (mm)</th>
<th>Loading Rate (mm/min)</th>
<th>Pcr (N)</th>
<th>Pmax (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW-1</td>
<td>16.03</td>
<td>26.15</td>
<td>155</td>
<td>5</td>
<td>6391</td>
<td>8573</td>
</tr>
<tr>
<td>LW-2</td>
<td>15.92</td>
<td>25.47</td>
<td>156</td>
<td>5</td>
<td>3311</td>
<td>8491</td>
</tr>
<tr>
<td>LW-3</td>
<td>15.81</td>
<td>32.79</td>
<td>158</td>
<td>5</td>
<td>4787</td>
<td>8546</td>
</tr>
<tr>
<td>LW-4</td>
<td>15.82</td>
<td>-</td>
<td>155</td>
<td>5</td>
<td>6329</td>
<td>8627</td>
</tr>
<tr>
<td>LW-5</td>
<td>15.81</td>
<td>30.09</td>
<td>155</td>
<td>5</td>
<td>6189</td>
<td>9626</td>
</tr>
<tr>
<td>LW-6</td>
<td>15.66</td>
<td>26.10</td>
<td>159</td>
<td>0.1</td>
<td>4916</td>
<td>7869</td>
</tr>
<tr>
<td>LW-7</td>
<td>17.46</td>
<td>28.07</td>
<td>158</td>
<td>0.1</td>
<td>5449</td>
<td>7168</td>
</tr>
<tr>
<td>LW-8</td>
<td>17.02</td>
<td>27.23</td>
<td>158</td>
<td>0.1</td>
<td>5541</td>
<td>7685</td>
</tr>
<tr>
<td>LW-9</td>
<td>17.06</td>
<td>32.41</td>
<td>157</td>
<td>0.1</td>
<td>3207</td>
<td>7621</td>
</tr>
<tr>
<td>LW-10</td>
<td>18.45</td>
<td>29.13</td>
<td>159</td>
<td>0.1</td>
<td>7014</td>
<td>8071</td>
</tr>
<tr>
<td>LW-11</td>
<td>18.18</td>
<td>30.81</td>
<td>157</td>
<td>100</td>
<td>5991</td>
<td>9714</td>
</tr>
<tr>
<td>LW-12</td>
<td>17.17</td>
<td>28.33</td>
<td>158</td>
<td>100</td>
<td>5150</td>
<td>8666</td>
</tr>
<tr>
<td>LW-13</td>
<td>18.39</td>
<td>27.98</td>
<td>158</td>
<td>100</td>
<td>4566</td>
<td>9109</td>
</tr>
<tr>
<td>LW-14</td>
<td>19.67</td>
<td>31.47</td>
<td>158</td>
<td>100</td>
<td>4763</td>
<td>N/A</td>
</tr>
<tr>
<td>LW-15</td>
<td>17.58</td>
<td>27.69</td>
<td>158</td>
<td>250</td>
<td>5294</td>
<td>N/A</td>
</tr>
</tbody>
</table>

¹ Outer diameter of the composite polymer liner

Notes:

Δ = Amplitude of wrinkle measured from the outer circumference of the liner to the peak of the wrinkle

λ = Wavelength of wrinkle

Pcr = Load recorded at first cracking of the resin within the wrinkle

Pmax = Ultimate load recorded

---

### Table 4.2: Range of load values recorded for test samples LW-1 to LW-15

<table>
<thead>
<tr>
<th>Loading Rate (mm/min)</th>
<th>Minimum Pcr (N)</th>
<th>Maximum Pcr (N)</th>
<th>Avg. Pcr (N)</th>
<th>Minimum Pmax (N)</th>
<th>Maximum Pmax (N)</th>
<th>Avg. Pmax (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3207</td>
<td>7014</td>
<td>5225</td>
<td>7168</td>
<td>8071</td>
<td>7683</td>
</tr>
<tr>
<td>5</td>
<td>3311</td>
<td>6391</td>
<td>5401</td>
<td>8491</td>
<td>9626</td>
<td>8773</td>
</tr>
<tr>
<td>100</td>
<td>4566</td>
<td>5991</td>
<td>5095</td>
<td>8666</td>
<td>9714</td>
<td>9163</td>
</tr>
</tbody>
</table>

Notes:

Pcr = Load recorded at first cracking of the resin within the wrinkle

Pmax = Ultimate load recorded
Table 4.3: Summary of test results used for the evaluation of the effect of cyclic loading

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Δ (mm)</th>
<th>λ (mm)</th>
<th>Outer Diameter (mm)</th>
<th>P_{cr} (N)</th>
<th>P_{max} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IW-1</td>
<td>16.38</td>
<td>21.96</td>
<td>150</td>
<td>3143</td>
<td>10292</td>
</tr>
<tr>
<td>IW-2</td>
<td>16.31</td>
<td>22.65</td>
<td>151</td>
<td>4024</td>
<td>11604</td>
</tr>
<tr>
<td>IW-3</td>
<td>17.04</td>
<td>23.09</td>
<td>150</td>
<td>2489</td>
<td>12003</td>
</tr>
<tr>
<td>IW-4</td>
<td>15.28</td>
<td>21.60</td>
<td>152</td>
<td>4399</td>
<td>8929</td>
</tr>
<tr>
<td>IW-5</td>
<td>15.29</td>
<td>20.24</td>
<td>150</td>
<td>3763</td>
<td>11057</td>
</tr>
<tr>
<td>IW-6CM</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>5304</td>
<td>10730</td>
</tr>
<tr>
<td>IW-7CM</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10858</td>
</tr>
<tr>
<td>IW-8CM</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>8823</td>
</tr>
</tbody>
</table>

1 The sample failed at the location with perfect geometry (i.e. the opposite side of the wrinkle)
2 The sample did not show any signs of cracking at the wrinkle during the cyclic loading test.
3 The resin within the wrinkle cracked during the first loading cycle. At the end of the cyclic loading test, both the inner and outer polyester jackets remained intact.
4 The resin within the wrinkle cracked about 18 hours into the cyclic loading test. At the end of the cyclic loading test, both the inner and outer polyester jackets remained intact.
5 Outer diameter of the composite polymer liner

Notes: Δ = Amplitude of wrinkle measured from the outer circumference of the liner to the peak of the wrinkle
λ = Wavelength of wrinkle
P_{cr} = Load recorded at first cracking of the resin within the wrinkle
P_{max} = Ultimate load recorded

---

Table 4.4: Range of load values recorded for test samples IW-1 to IW-5 and IW-6CM to IW-8CM

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Minimum P_{cr} (N)</th>
<th>Maximum P_{cr} (N)</th>
<th>Avg. P_{cr} (N)</th>
<th>Minimum P_{max} (N)</th>
<th>Maximum P_{max} (N)</th>
<th>Avg. P_{max} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IW-1 – IW-5</td>
<td>2489</td>
<td>4399</td>
<td>3564</td>
<td>8929</td>
<td>12003</td>
<td>11239</td>
</tr>
<tr>
<td>IW-6CM – IW-8CM</td>
<td>5304</td>
<td>5304</td>
<td>5304</td>
<td>8823</td>
<td>10858</td>
<td>10137</td>
</tr>
</tbody>
</table>

1 Average P_{max} value based on control samples IW-1 to IW-3 and IW-5
2 Average P_{cr} value based on sample IW-6CM only

Notes: P_{cr} = Load recorded at first cracking of the resin within the wrinkle
P_{max} = Ultimate load recorded
Table 4.5: Summary of test results used for the evaluation of the effect of the presence of a wrinkle and its geometry

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wrinkle type</th>
<th>$\Delta$ (mm)</th>
<th>$\Delta_{avg}$ (mm)</th>
<th>$\lambda$ (mm)</th>
<th>$\lambda_{avg}$ (mm)</th>
<th>Outer diameter$^3$ (mm)</th>
<th>$P_{cr}$ (N)</th>
<th>$P_{max}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-1$^1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>158</td>
<td>N/A</td>
<td>13108</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NW-2$^2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>156</td>
<td>N/A</td>
<td>10161</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NW-3$^3$</td>
<td>None</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>155</td>
<td>N/A</td>
<td>11935</td>
</tr>
<tr>
<td>NW-4$^4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>157</td>
<td>N/A</td>
<td>11465</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NW-5$^2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>160</td>
<td>N/A</td>
<td>10554</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW-1</td>
<td>Inner</td>
<td>9.99</td>
<td>11.94</td>
<td>153</td>
<td>6039</td>
<td>11971</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW-2</td>
<td>jacket</td>
<td>9.97</td>
<td>10.00</td>
<td>154</td>
<td>6372</td>
<td>10761</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW-3</td>
<td>only</td>
<td>10.09</td>
<td>10.27</td>
<td>153</td>
<td>N/A</td>
<td>12349</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW-4</td>
<td></td>
<td>10.07</td>
<td>10.71</td>
<td>154</td>
<td>N/A</td>
<td>11176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-1</td>
<td>Both</td>
<td>16.38</td>
<td>21.96</td>
<td>150</td>
<td>3143</td>
<td>10292</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-2</td>
<td>jackets</td>
<td>17.04</td>
<td>16.1</td>
<td>150</td>
<td>2489</td>
<td>12003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-3</td>
<td></td>
<td>15.28</td>
<td>21.60</td>
<td>152</td>
<td>4399</td>
<td>8929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-4</td>
<td></td>
<td>15.29</td>
<td>20.24</td>
<td>150</td>
<td>3763</td>
<td>11057</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-5</td>
<td></td>
<td>16.03</td>
<td>26.15</td>
<td>155</td>
<td>6391</td>
<td>8573</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW-1</td>
<td>Both</td>
<td>15.92</td>
<td>25.47</td>
<td>156</td>
<td>3311</td>
<td>8491</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW-2</td>
<td>jackets</td>
<td>15.81</td>
<td>15.9</td>
<td>158</td>
<td>4787</td>
<td>8546</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW-3</td>
<td></td>
<td>15.82</td>
<td>-</td>
<td>155</td>
<td>6329</td>
<td>8627</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW-4</td>
<td></td>
<td>15.81</td>
<td>30.09</td>
<td>155</td>
<td>6189</td>
<td>9626</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- $\Delta$ = Amplitude of wrinkle measured from the outer circumference of the liner to the peak of the wrinkle
- $\lambda$ = Wavelength of wrinkle
- $P_{cr}$ = Load recorded at first cracking of the resin within the wrinkle
- $P_{max}$ = Ultimate load recorded

Table 4.6: Range of load values recorded for test samples NW-1 to NW-5, SW-1 to SW-5, IW-1 to IW-5, and LW-1 to LW-5

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$A_{avg}$ (mm$^2$)</th>
<th>Minimum $P_{cr}$ (N)</th>
<th>Maximum $P_{cr}$ (N)</th>
<th>Avg. $P_{cr}$ (N)</th>
<th>Minimum $P_{max}$ (N)</th>
<th>Maximum $P_{max}$ (N)</th>
<th>Avg. $P_{max}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-1 - NW-5</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10161</td>
<td>13108</td>
<td>11445</td>
</tr>
<tr>
<td>SW-1 - SW-5</td>
<td>56</td>
<td>6039</td>
<td>6432</td>
<td>6281</td>
<td>10761</td>
<td>12349</td>
<td>11701</td>
</tr>
<tr>
<td>IW-1 - IW-5</td>
<td>176</td>
<td>2489</td>
<td>4399</td>
<td>3564</td>
<td>8929</td>
<td>12003</td>
<td>10777</td>
</tr>
<tr>
<td>LW-1 - LW-5</td>
<td>227</td>
<td>3311</td>
<td>6391</td>
<td>5401</td>
<td>8491</td>
<td>9626</td>
<td>8773</td>
</tr>
</tbody>
</table>

Notes:
- $A_{avg}$ = Average cross-sectional area of wrinkles
- $P_{cr}$ = Load recorded at first cracking of the resin within the wrinkle
- $P_{max}$ = Ultimate load recorded
Table 4.7: Comparison between ultimate hoop tensile load for exhumed and fabricated liner

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Ultimate Load, $P_{\text{max}}$ (N)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-1</td>
<td>13108</td>
<td></td>
</tr>
<tr>
<td>NW-2</td>
<td>10161</td>
<td></td>
</tr>
<tr>
<td>NW-3</td>
<td>11935</td>
<td>Exhumed</td>
</tr>
<tr>
<td>NW-4</td>
<td>11465</td>
<td></td>
</tr>
<tr>
<td>NW-5</td>
<td>10554</td>
<td></td>
</tr>
<tr>
<td>Coupon #3(^1)</td>
<td>10120</td>
<td></td>
</tr>
<tr>
<td>Coupon #4(^1)</td>
<td>10673</td>
<td></td>
</tr>
<tr>
<td>Coupon #5(^1)</td>
<td>10206</td>
<td>Fabricated (flat coupon)</td>
</tr>
<tr>
<td>Coupon #6(^1)</td>
<td>10640</td>
<td></td>
</tr>
<tr>
<td>Coupon #7(^1)</td>
<td>9211</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) From Brown et al. (2007), fabricated flat coupons

Table 4.8: Average dimensions and recorded load values of ring samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$A_{\text{avg}}$ (mm(^2))</th>
<th>$\Delta_{\text{avg}}$ (mm)</th>
<th>Average $P_{cr}$ (N)</th>
<th>Average $P_{\text{max}}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-1 - NW-5</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>11445</td>
</tr>
<tr>
<td>SW-1 - SW-5</td>
<td>56</td>
<td>10.0</td>
<td>6281</td>
<td>11701</td>
</tr>
<tr>
<td>IW-1 - IW-5</td>
<td>176</td>
<td>16.1</td>
<td>3564</td>
<td>10777</td>
</tr>
<tr>
<td>LW-1 - LW-5</td>
<td>227</td>
<td>15.9</td>
<td>5401</td>
<td>8773</td>
</tr>
</tbody>
</table>

Notes:
- $\Delta_{\text{avg}}$ = Average amplitude of the wrinkles
- $A_{\text{avg}}$ = Average cross-sectional area of the wrinkles
- Average $P_{cr}$ = Average of load values recorded at first cracking of the resin within the wrinkles
- Average $P_{\text{max}}$ = Average of ultimate load values recorded
Figure 4.1: A labeled picture of a wrinkle similar to those in samples LW-1 to LW-15

Figure 4.2: (a) Load-stroke, (b) Load-average displacement graphs of sample LW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure 4.3: Graphs of load-loading rate at first cracking of the resin within the wrinkle for samples (a) LW-1 to LW-14, and (b) LW-1 to LW-15, and (c) Graph of ultimate load-loading rate for samples LW-1 to LW-13
Figure 4.4: A ring sample with a wrinkle similar to those in samples LW-1 to LW-15, (a) before testing, and (b) after testing
Figure 4.5: Typical failure mechanism observed in test samples LW-1 to LW-15

Figure 4.6: A labeled picture of a wrinkle similar to those in samples IW-1 to IW-5 and IW-6C to IW-8C
Figure 4.7: (a) Load-time graphs corresponding to the first 750 seconds of cyclic loading for samples IW-6C to IW-8C, (b) A ring sample before cyclic loading test, (c) An intact wrinkle after cyclic loading, and (d) A wrinkle with the resin component cracked after cyclic loading.
Figure 4.8: (a) Load-stroke, (b) Load-average displacement graphs for samples IW-6CM to IW-8CM tested under monotonic conditions at a loading rate of 5 mm/min.
Figure 4.9: (a) Load-stroke, (b) Load-average displacement graphs of sample IW-5 tested under monotonic conditions at a loading rate of 5 mm/min

Figure 4.10: (a) A ring sample with wrinkle type IW, before testing, and after testing with failure at (b) the wrinkle, and (c) at the opposite side of the wrinkle
Figure 4.11: (a) A ring sample with wrinkle type SW, before testing, (b) A labeled picture of a wrinkle similar to those in samples SW-1 to SW-5

Figure 4.12: (a) A picture of a wrinkle exhibiting failure type 1, (b) Load-stroke, (c) Load-average displacement graphs of sample SW-2 tested under monotonic conditions at a loading rate of 5 mm/min
Figure 4.13: (a) A picture of a wrinkle exhibiting failure type 2, (b) Load-stroke, (c) Load-average displacement graphs of sample SW-4 tested under monotonic conditions at a loading rate of 5 mm/min.

Figure 4.14: A non-wrinkled ring sample (a) before testing, and (b) after testing.
Figure 4.15: (a) Load-stroke, (b) Load-average displacement graphs of sample NW-5 tested under monotonic conditions at a loading rate of 5 mm/min

Figure 4.16: Schematic of wrinkle showing geometric parameters
Figure 4.17: Effect of wrinkle size on (a) the load recorded at the first cracking of the resin within the wrinkle, and (b) on the ultimate load recorded.
Figure 4.18: (a) Defining the geometry of a wrinkle [From Jaganathan et al., 2007], (b) Representative geometry of a wrinkle in samples LW-1 to LW-5, (c) Representative geometry of a wrinkle in samples IW-1 to IW-5
CHAPTER 5

ANALYTICAL MODELLING

5.1 Introduction

In earlier chapters, the formation and different patterns of wavy imperfections (wrinkles) observed in Sanexen’s composite polymer liner, and their effect on the circumferential strength of the liner were discussed. In this chapter, the two dimensional plane stress numerical analyses that were conducted to investigate further the behavior of the wrinkles are presented and discussed. The finite element analysis package ABAQUS Version 6.5-1 was used to conduct all the numerical analyses. Two types of wrinkles referred to as types 1 and 2 were considered for the analyses. The geometry of the wrinkled finite element models was based on that of the wrinkles in two ring samples tested in the laboratory. Non-wrinkled rings with similar dimensions as the wrinkled ones were also modeled. The numerical results for the wrinkled and non-wrinkled models were compared. The accuracy of the numerical results was evaluated using experimental results. The experimental results referenced in this chapter are from the split-disk tests conducted on ring samples of the composite liner (see Chapter 4), and the direct uniaxial tension tests conducted by Brown et al. (2007) on flat coupons of the composite liner and its components (see Chapter 2). Results from the tests conducted by Brown et al. (2007) on flat coupons representing the circumferential direction were considered. The numerical analyses conducted and discussed in this chapter, aimed to evaluate the behavior of the wrinkles, their effect on the response of the liner, and the relationship
between the circumferential properties determined from the direct uniaxial tension and split-disk tests. In the following sections, the geometries of the wrinkled and non-wrinkled models, properties of their components, assumptions made, the types of analyses conducted, the numerical results, and their evaluation will be presented and discussed.

5.2 Statement of Problem

In Chapter 4, the results from the series of split-disk tests conducted on ring samples of the liner with three different patterns of wrinkles were discussed. Discussions were also provided on the results from the laboratory testing of ring samples of the liner without wrinkles. The two dimensional plane stress numerical analyses conducted on the wrinkles in the liner, focused on two different patterns of wrinkles which are shown in Figure 5.1, and will be referred to as wrinkle types 1 and 2 in this chapter. The geometry of wrinkle types 1 and 2 was based on that of the wrinkles in test samples IW-5 (see Section 4.2.2) and SW-1 (see Section 4.2.3), respectively. The purpose of the numerical analyses was to investigate further the behavior of the wrinkles in the composite liner.

As stated in earlier chapters, the composite liner and the wrinkles consist of three components, namely, the inner and outer woven polyester jackets and the polymeric resin (see Figure 5.1). The material properties of the three components are summarized in Appendix E, and are discussed in this chapter. The inner jacket is bonded onto a
polyurethane elastomer. In each analysis, one half of the wrinkle was constructed for evaluation. The jackets were modeled with the same thickness, and the effect of the polyurethane elastomer was not considered. The jackets were characterized as solid materials with uniform properties over their thicknesses, and not as woven fabrics. The approximation of the jackets as uniform solids involved assigning a representative jacket thickness, and determining the Young’s modulus of each jacket. This approximation raised two concerns: the approach to use for the selection of the representative jacket thickness, and the effect of this choice of jacket thickness on the numerical results.

In the analyses, the approach used for the selection of the jacket thickness incorporated results from the direct uniaxial tension tests conducted by Brown et al. (2007). This approach is described in Section 5.4.3, and is illustrated using calculations presented in Appendix C. Its reliability is determined by comparing the calculated results with the measured results from the split-disk tests. Discussions on the comparisons are presented in Section 5.9. To investigate the effect of the choice of jacket thickness on the numerical results, three finite element models of wrinkle type 1 with the same dimensions but different jacket thicknesses were constructed and analyzed. The results from the analysis of the three wrinkled models are discussed in Section 5.4.

An analysis was also conducted to enable the comparison of the behavior of wrinkle types 1 and 2. Finite element models of the wrinkles with the same dimensions and jacket
thickness were constructed for the analysis. A series of analyses involving finite element models of liner sections without wrinkles (i.e. non-wrinkled liners) were also conducted. These analyses were performed to enable the evaluation of the effect of the wrinkle on the liner. In all the analyses conducted and discussed in this chapter, the effect of the polyurethane elastomer bonded onto the inner jacket was not considered, and both the inner and outer jackets had the same thicknesses. Further studies may be needed to examine the effects of the elastomer and unequal jacket thicknesses on the behavior of the wrinkle. A unit width was considered in all the analyses.

5.3 Modeling of Wrinkle Type 1 and Non-wrinkled Liner

5.3.1 Overview

Figure 5.1 (a) shows the typical geometry of wrinkle type 1 in an actual test sample. As described earlier in Section 3.2 of Chapter 3, the wrinkle consists of three components, namely, the inner and outer polyester jackets, and the polymeric resin. In the finite element model of the wrinkle, the properties of each of the three components were based on the results from direct uniaxial tension tests conducted by Brown et al. (2007). The inner and outer jackets were modeled with the same thickness. One half of the wrinkle was constructed for the analysis. The kinematic and static boundary conditions applied in the analysis were based on the behavior of the wrinkle during laboratory testing. In the next sections, the modeled geometry of the wrinkle, properties of its components, the
applied kinematic and static boundary conditions, and the assumptions made will be presented and discussed.

To evaluate the effect of the wrinkle on the liner, there was the need for an analysis involving a liner section without a wrinkle. Thus, a non-wrinkled liner section was also constructed and analyzed. The dimensions of the non-wrinkled liner section were similar to those of the wrinkled. The results from the analyses of the wrinkled and non-wrinkled finite element models were compared. Details for the non-wrinkled liner section will also be provided.

5.3.2 Material Properties

As stated earlier, the wrinkle consists of three components, namely, the inner and outer polyester jackets, and the polymeric resin. As discussed in Section 2.4.2 of Chapter 2, Brown et al. (2007) conducted direct uniaxial tension tests on flat coupons prepared from each of the three components. The load/stress-strain behaviors of the three components were determined from the tests. The experimentally determined properties were used as a basis for the analytical modeling.

Brown et al. (2007) established that both the inner and outer jackets exhibited a linear load-strain behavior under direct uniaxial tension. They estimated the circumferential tensile stiffnesses of the inner and outer jackets as 1530 N/mm and 2270 N/mm,
respectively. In the models, the Young’s modulus of each jacket was obtained by dividing its experimentally determined circumferential tensile stiffness by the jacket thickness.

Brown et al. (2007) conducted direct uniaxial tension tests on flat coupons of the resin cured at four different temperatures. They observed that under direct uniaxial tension, the resin generally exhibited a linear stress-strain response from the start of loading until a strain of about 2 %, and a nonlinear response at strains greater than 2 %. For the analytical modeling, the experimentally determined properties of the resin cured at a temperature of 55 °C were used. These properties were chosen because in the field, the installed liner is cured using hot water with a temperature of about 55 °C. In the models, the resin had an elastic region with a Young’s modulus of 2356 MPa, and a yield stress of 36 MPa. At stresses between 36 MPa and 61 MPa, the resin was modeled to have strain increments with a sum total of 0.022 mm/mm. Each of the three components of the wrinkle had a Poisson’s ratio of 0.3. This Poisson’s ratio value was based on the results from uniaxial tensile tests conducted by Shanhai et al. (2007) on coupons cut in the transverse direction, from samples of the same type of liner extracted from a lined cast iron water main.
5.3.3 Mesh and Kinematic Boundary Conditions

The idealized geometry of the wrinkle was based on a sine function which took into account the amplitude ($\Delta$) and wavelength ($\lambda$) of the wrinkle (see Figure 4.16). Based on an assumption of symmetry, one half of the wrinkle was constructed for the analysis. Figure 5.1 (a) shows the typical geometry of wrinkle type 1 in an actual test sample. In wrinkle type 1, both the inner and outer jackets are deformed inward. A closer look at Figure 5.1 (a) shows that wrinkle type 1 is not exactly symmetric about a vertical line drawn through its peak. Such a line produces two parts (halves), one of which has the inner and outer jackets almost touching, and hence a non-uniform resin thickness between the two jackets, and the other in which the two jackets are separated by resin with an almost uniform thickness. The assumption of symmetry was based on the latter half. In the latter, a greater amount of resin is present. As discussed in Chapter 4, failure in ring samples with wrinkles identical to wrinkle type 1 always began with the cracking of the resin within the wrinkle. This implies that the excess resin within the wrinkle may be a source of weakness. Therefore, the analytical model was constructed considering the half with the greater amount of resin which was almost uniform in thickness. Figure 5.2 shows a labeled finite element model of wrinkle type 1. The geometry of wrinkle type 1 was based on that of the wrinkle in test sample IW-5. The dimensions of the wrinkle are summarized in Table 5.1.

Three wrinkled models with three different jacket thicknesses (0.14 mm, 0.3 mm and 0.5 mm) but the same dimensions were constructed and analyzed to evaluate the behavior of
wrinkle type 1, and also the sensitivity of the model approach to the choice of jacket thickness. In the models, the inner and outer jackets had the same thickness. The three components of the liner were all modeled as solid materials. The wrinkled models were discretized into six-noded modified quadratic plane stress triangular elements referred to as CPS6M. The elements had two translational degrees of freedom at each node. The resulting meshes constituted of elements whose aspect ratios were no more than three.

As described earlier in Chapter 3, each ring sample was fitted onto two half concrete disks and subjected to tensile load during testing. Ring samples with wrinkles were oriented such that the wrinkle was located at the split between the two half concrete disks. The left boundary of the finite element models was restrained against horizontal movement as shown in Figure 5.2. This boundary condition best described the behavior of the wrinkle during testing. In the models, the part of the ring sample in contact with the half disks was restrained against vertical movement by springs. It should be noted that in the laboratory, the part of the sample in contact with the concrete disks was likely restrained from movement in the radial direction. The decision to restrain vertical movement only in the models was made because it was easier to model springs providing vertical instead of radial restraints. The location of the springs in the models is shown in Figure 5.3. A detailed discussion on the convergence study conducted to determine the stiffness of the spring elements used is presented in Appendix B.
5.3.4 Static Boundary Condition

In the analyses involving wrinkle type 1 (based on sample IW-5), a stress of 9.35 MPa was applied over ten load steps. The location of the applied stress, \( p \) is shown in Figure 5.2. A convergence study conducted to determine the number of load steps used in the analyses is presented in Appendix B. As described in Chapter 4, failure in sample IW-5 (see Section 4.2.2) began with the cracking of the resin within the wrinkle. In the analyses, the applied stress of 9.35 MPa corresponded to the load recorded at the first cracking of the resin in sample IW-5 during laboratory testing. A calculation that shows how the stress value of 9.35 MPa was determined is presented in Section C.2.1 of Appendix C.

5.3.5 Modeling of Non-wrinkled Liner for Comparison with Wrinkle Type 1

Three non-wrinkled models with three different jacket thicknesses but the same dimensions were also constructed and analyzed. The dimensions of the non-wrinkled models were similar to those of the three wrinkled models discussed earlier. A labeled finite element model of a liner section without a wrinkle is shown in Figure 5.4. The results from the analysis of the non-wrinkled models were compared to that of the wrinkled models. The dimensions of the non-wrinkled models are summarized in Table 5.2.
The material properties of the inner and outer jackets, and the resin in the models were the same as those discussed in Section 5.3.2. The inner and outer jackets had the same thickness. The models were discretized using the solid element CPS6M (see Section 5.3.3). The resulting meshes constituted of triangular elements whose aspect ratios were no more than three. The kinematic boundary conditions were similar to those discussed in Section 5.3.3. Figures 5.4 and 5.5 show the locations of the horizontal restraints and springs in a non-wrinkled model, respectively. A stress of 9.35 MPa was applied over ten load steps in all the analyses. The location of the applied stress, \( p \) is shown in Figure 5.4.

5.4 Numerical Results for Wrinkle Type 1

5.4.1 Introduction

As stated earlier, wrinkle type 1 refers to a wavy imperfection whose inner and outer jackets are both deformed inward. A schematic of this wrinkle is shown in Figure 5.2. A series of analyses were conducted to investigate the behavior of wrinkle type 1, and also the sensitivity of the model approach to the choice of jacket thickness. Three jacket thicknesses (0.14 mm, 0.3 mm and 0.5 mm) were considered for the analyses. The dimensions of all three models are summarized in Table 5.1. A calculation that shows how the jacket thickness of 0.14 mm was determined is presented in Section C.2.2 of Appendix C. The analysis involving the wrinkled model with the jacket thickness of 0.14 mm, resulted in an ABAQUS warning message regarding the distortion of some elements...
of the model. As discussed earlier in Section 5.3.3, the wrinkled models were discretized using triangular elements. The triangular elements are less sensitive to distortion (ABAQUS Analysis User’s Manual, 2004). Hence, the effect of this condition (i.e. the ABAQUS warning message) on the accuracy of the results would likely be minimal.

The plots provided for each of the models represent the stress and/or displacement results along two sections, namely, section AA and the line of symmetry (BC). In the wrinkled models, section AA represents the location of the applied stress (see Figures 5.2 and 5.6). The line of symmetry in the wrinkled models is shown in Figure 5.2. The results were obtained from the stress and displacement contours for each model. The stress and displacement contours correspond to the last load step in the analyses unless stated otherwise. In the next sections, the discussions are based on the graphs obtained from the numerical analysis of the wrinkled models. The effect of the choice of jacket thickness on the results is also discussed.

5.4.2 Numerical Results along Two Sections in Wrinkled Models (Type 1)

5.4.2.1 Numerical Results: Section AA

The stress distributions along section AA in the three wrinkled models are plotted in Figure 5.7. The horizontal, vertical and resultant displacements along section AA are also plotted in Figures 5.8 to 5.10, respectively. The displacement values in these graphs correspond to one half of the wrinkle as shown in Figure 5.2. In Figures 5.7 to 5.10, the
horizontal (x-axis) origin represents the outer surface of the inner jacket at section AA (see Figure 5.6). The values plotted in Figures 5.7 to 5.10, were obtained from the stress and displacement contours which are presented in Figures D.1 to D.9 of Appendix D.

The force-displacement graphs corresponding to Section AA in the three wrinkled models are presented in Figure 5.11. The force values in Figure 5.11 were determined from stress distribution graphs similar to those in Figure 5.7. Figure 5.7 corresponds to the last load step in the analysis. To determine the force values, the average stress over each of the three components of the liner at section AA was determined. Each of the three average stress values was multiplied by the thickness over which it acts to obtain three force values. The sum of the three force values represents the force at a given average displacement in the graphs. In Figure 5.11, the average displacement at a given force represents the average value of the resultant displacements along section AA, multiplied by two to account for the other half of the wrinkle.

In Figure 5.7, it can be seen that along section AA, the stresses in both jackets decrease as the jacket thickness increases. The stresses are generally higher in the jackets with the lowest thickness (0.14 mm), than those calculated for thicknesses of 0.3 mm and 0.5 mm. The higher stress values observed in the jackets with the thickness of 0.14 mm is expected because there is a lower cross-sectional area resisting the same applied stress. In Figure 5.7, it can also be seen that at section AA, the stress in the resin is not influenced by the choice of jacket thickness. Figures 5.8 to 5.10 also show that the wrinkled models
which have the same amplitude but different jacket thicknesses, exhibit a similar
distribution of displacements along section AA. In Figure 5.11, it can be seen that the
stiffness of the wrinkled models, slightly increases with decreasing choice of jacket
thickness. A lower value of jacket thickness in the model leads to increases in resin
thickness. Thus, it can be suggested that prior to cracking of the resin, the stiffness of a
liner with a wrinkle is primarily influenced by the resin.

5.4.2.2 Numerical Results: Line of Symmetry

The stress distributions along the line of symmetry (see Figure 5.2) in the three wrinkled
models are plotted in Figures 5.12 and 5.13. In these graphs, the horizontal (x-axis) origin
represents point B in Figure 5.6. Figure 5.12 represents the stress distribution between
points B and C (see Figure 5.6). The values plotted in Figures 5.12 and 5.13 were
obtained from the stress contours which are presented in Figures D.1 to D.3 of Appendix
D.

In Figure 5.13, it can be seen that along the line of symmetry, the stresses in both jackets
decrease as the jacket thickness increases. The stresses are generally higher in the jackets
with the lowest thickness (0.14 mm), than those calculated for thicknesses of 0.3 mm and
0.5 mm. The explanation for this observation is the same as that given in Section 5.4.2.1.
In Figure 5.12, it can also be seen that along the line of symmetry, the stress in the resin
is not influenced by the choice of jacket thickness.
Figure 5.12 also shows that in the models, the stress in the resin increases as the vertical distance below B becomes greater and approaches point C (see Figure 5.6). This stress distribution implies that the peak stress occurs near point C, and hence, cracking of the resin will begin at the outer surface of the wrinkle, with the crack propagating through the resin towards the inner wrinkled jacket (i.e. towards point B).

5.4.3 Effect of Jacket thickness

In the finite element analysis, the inner and outer jackets which are woven fabrics were represented as solid materials with uniform properties over their thicknesses. Brown et al. (2007) conducted direct uniaxial tension tests in which the circumferential tensile stiffnesses of the jackets were measured. The approximation of the jackets (which had the same thickness) as uniform solids involved assigning a representative jacket thickness, and determining the solid modulus of each jacket by dividing its measured stiffness value by the assigned jacket thickness. The approach to use for the selection of the representative jacket thickness, and the implications of this choice of jacket thickness on the numerical results (i.e. the calculated stresses and deflections) were two concerns in the analysis of the wrinkles.

In the analysis, the approach used for the selection of the jacket thickness involved two steps. First, the resin thickness was calculated so that the total calculated stiffness of the three liner components in the model matched the measured stiffness of the composite
liner sample. Then, the jacket thickness was determined based on two assumptions: that the total thickness of the inner and outer jackets, and the resin in the model matched the measured total thickness for the composite liner sample, and that the inner and outer jackets thicknesses were equal. A calculation that shows how the representative jacket thickness of 0.14 mm for wrinkle type 1 was determined is presented in Section C.2.2 of Appendix C.

The analysis of wrinkle type 1 aimed to evaluate the behavior of the wrinkle, and also the implications of the choice of jacket thickness on the numerical results. The results from the analysis which involved three wrinkled models with three different jacket thicknesses but the same dimensions (see Table 5.1) have already been discussed in Section 5.4.2. A schematic and a labeled finite element mesh of wrinkle type 1 are shown in Figures 5.2 and 5.6, respectively. Figures 5.7, 5.12 and 5.13 show the stress distributions along section AA and the line of symmetry in the wrinkled models, respectively. Figures 5.8 to 5.10 show the horizontal, vertical and resultant displacements along section AA in the wrinkled models, respectively.

As stated earlier, Figures 5.8 to 5.10 show that the three wrinkled models with different jacket thicknesses, exhibit a similar distribution of displacements along section AA. In Figures 5.7, 5.12 and 5.13, it can be seen that the stresses in the jackets are significantly influenced by the choice of jacket thickness. In the figures, the stresses in the jackets
increase with decreasing choice of jacket thickness. However, the stress in the resin is not influenced by the choice of jacket thickness. These results imply that the choice of jacket thickness in the model has a minimal effect on the calculated deflections in the composite liner system. The results also imply that the choice of jacket thickness in the model greatly influences the calculated stresses in the jackets, but has no significant effect on that in the resin of the composite liner system.

5.5 Results for Non-wrinkled Liner and Comparison with Wrinkle Type 1

5.5.1 Introduction

In the next sections, the discussions are based on the graphs obtained from the numerical analysis of the non-wrinkled finite element models. Three jacket thicknesses (0.14 mm, 0.3 mm and 0.5 mm) were considered for the analysis. The dimensions of all three models are summarized in Table 5.2. The plots provided for each of the models represent the stress and/or displacement results along two sections, namely, section AA and the line of symmetry. In the non-wrinkled models, section AA represents the location of the applied stress (see Figures 5.4 and 5.14). The line of symmetry in the non-wrinkled models is shown in Figure 5.4.

The results from the analysis of the non-wrinkled models were compared with that of the wrinkled models (type 1) which have already been discussed in Section 5.4. The purpose of the comparison was to evaluate the effect of the wrinkle on the liner. Discussions will
be provided on the similarities and differences between the results for the non-wrinkled and wrinkled models. Details for the construction of both sets of models were presented in Section 5.3.

5.5.2 Numerical Results along Two Sections in Non-Wrinkled Models

5.5.2.1 Numerical Results: Section AA

The stress distributions along section AA in the three non-wrinkled models are plotted in Figure 5.15. The horizontal, vertical and resultant displacements along section AA are also plotted in Figures 5.16 to 5.18, respectively. The displacement values in these graphs correspond to one half of the non-wrinkled liner section as shown in Figure 5.4. In Figures 5.15 to 5.18, the horizontal (x-axis) origin represents the outer surface of the inner jacket at section AA (see Figure 5.14). The values plotted in Figures 5.15 to 5.18 were obtained from the stress and displacement contours which are presented in Figures D.10 to D.18 of Appendix D.

The force-displacement graphs corresponding to Section AA in the three non-wrinkled models are presented in Figure 5.19. The force values in Figure 5.19 were determined from stress distribution graphs similar to those in Figure 5.15. Figure 5.15 corresponds to the last load step in the analysis. The force values were determined by following the same procedure described earlier in Section 5.4.2.1 for the wrinkled models. In Figure 5.19, the average displacement at a given force represents the average value of the resultant
displacements along section AA, multiplied by two to account for the other half of the non-wrinkled liner section.

In Figure 5.15, it can be seen that at section AA, the stress in the resin is not influenced by the choice of jacket thickness, just as was observed in the wrinkled models. Figure 5.18 shows that the non-wrinkled models which have the same total thickness but different jacket thicknesses, exhibit a similar distribution of resultant displacements along section AA. In Figure 5.19, it can be seen that the stiffness of the non-wrinkled models, increases with decreasing choice of jacket thickness, just as was observed in the wrinkled models. A lower value of jacket thickness in the model leads to increases in resin thickness. Thus, it can be suggested that the stiffness of a liner without a wrinkle is also influenced primarily by the resin.

5.5.2.2 Numerical Results: Line of Symmetry

The stress distributions along the line of symmetry in the three non-wrinkled models are plotted in Figure 5.20. In these graphs, the horizontal (x-axis) origin represents point B in Figure 5.14. The values plotted in Figure 5.20 were obtained from the stress contours which are presented in Figures D.10 to D.12 of Appendix D.

In Figure 5.20, it can be seen that along the line of symmetry, the stresses in both jackets decrease as the jacket thickness increases. The stresses are generally higher in the jackets with the lowest thickness (0.14 mm), than those calculated for thicknesses of 0.3 mm and
0.5 mm. The explanation for this observation is the same as that given in Section 5.4.2.1. In Figure 5.20, it can also be seen that along the line of symmetry, the stress in the resin is not influenced by the choice of jacket thickness, just as was observed in the wrinkled models.

5.5.3 Comparison of Results from Wrinkled (Type 1) and Non-wrinkled Analyses

The discussions in this section are based on the results from the numerical analyses of the wrinkled and non-wrinkled finite element models, which were presented and discussed earlier in Sections 5.4.2 and 5.5.2, respectively. Figure 5.21 shows the force-displacement graphs corresponding to Section AA in all the finite element models. The displacement values corresponding to a force of approximately 43 N/mm are summarized in Table 5.3.

The analyses involving both the wrinkled and non-wrinkled models showed that the stress in the resin was not influenced by the choice of jacket thickness. Based on this observation, it is reasonable to suggest that the behavior of the resin in the liner is not influenced by the jackets. In both sets of models, it was also observed that a lower value of jacket thickness which leads to increases in resin thickness, resulted in an increase in the stiffness of the liner. Based on this observation, it is also reasonable to suggest that the stiffness of the liner is influenced primarily by the resin. Figure 5.21 shows that for each of the three jacket thicknesses investigated, the wrinkled model exhibits a stiffer response than the non-wrinkled model. This is expected because in the wrinkled models, there is a greater mass of resin which implies a stiffer system.
5.6 Modeling of Wrinkle Type 2 and Non-wrinkled Liner

5.6.1 Overview

Figure 5.1 (b) shows the typical geometry of wrinkle type 2 in an actual test sample. As can be seen in the figure, the wrinkle consists of three components, namely, the inner and outer jackets, and the resin. In the finite element model of the wrinkle, the properties of each of the three components were based on the results from direct uniaxial tension tests conducted by Brown et al. (2007). The inner and outer jackets were modeled with the same thickness. One half of the wrinkle was constructed for the analysis. The kinematic and static boundary conditions applied in the analysis were based on the behavior of the wrinkle during laboratory testing. In the next sections, the modeled geometry of the wrinkle, properties of its components, the applied kinematic and static boundary conditions, and the assumptions made will be presented and discussed.

To evaluate the effect of wrinkle type 2 on the liner, an analysis involving a non-wrinkled liner section with similar dimensions as the wrinkle, was conducted. The results for the wrinkled and non-wrinkled finite element models were compared. Details for the non-wrinkled liner section will also be provided.
5.6.2 Modeling of Wrinkle Type 2

The idealized geometry of the wrinkle was based on a sine function which took into account the amplitude ($\Delta$) and wavelength ($\lambda$) of the wrinkle (see Figure 4.16). Based on an assumption of symmetry, one half of the wrinkle was constructed for the analysis. Figure 5.1 (b) shows the typical geometry of wrinkle type 2 in an actual test sample. In wrinkle type 2, only the inner jacket is wrinkled inward whereas the outer jacket is not wrinkled. Figure 5.22 shows a labeled finite element model of wrinkle type 2. The geometry of wrinkle type 2 was based on that of the wrinkle in test sample SW-1. The dimensions of the wrinkle are summarized in Table 5.4.

The material properties of the inner and outer jackets, and the resin in the model were the same as those discussed in Section 5.3.2. The inner and outer jackets had the same thickness. The model was discretized using the solid element CPS6M (see Section 5.3.3). The resulting mesh constituted of triangular elements whose aspect ratios were no more than three. The kinematic boundary conditions were similar to those discussed in Section 5.3.3. Figures 5.22 and 5.23 show the locations of the horizontal restraints and springs in the wrinkled model, respectively. A discussion on the convergence study conducted to determine the stiffness of the spring elements used is presented in Section B.6 of Appendix B.
5.6.3 Static Boundary Condition

In the analysis involving wrinkle type 2 (based on sample SW-1), a stress of 14.32 MPa was applied over fifteen load steps. The location of the applied stress, \( p \) is shown in Figure 5.22. A convergence study conducted to determine the number of load steps used in the analysis is presented in Section B.6 of Appendix B. As described in Chapter 4, failure in sample SW-1 (see Section 4.2.3.1) began with the cracking of the resin within the wrinkle. In the analysis, the applied stress of 14.32 MPa corresponded to a load value recorded prior to the first cracking of the resin in sample SW-1, during laboratory testing. A calculation that shows how the stress value of 14.32 MPa was determined is presented in Section C.3.1 of Appendix C.

5.6.4 Modeling of Non-wrinkled Liner for Comparison with Wrinkle Type 2

A non-wrinkled model with similar dimensions as the wrinkled model was also constructed and analyzed. A labeled finite element model of a liner section without a wrinkle is shown in Figure 5.4. The results from the analysis of the non-wrinkled model were compared to that of the wrinkled model. The dimensions of the non-wrinkled model are summarized in Table 5.5.

The material properties of the inner and outer jackets, and the resin in the model were the same as those discussed in Section 5.3.2. The inner and outer jackets had the same thickness. The model was discretized using the solid element CPS6M (see Section 5.3.3).
The resulting mesh constituted of triangular elements whose aspect ratios were no more than three. The kinematic boundary conditions were similar to those discussed in Section 5.3.3. Figures 5.4 and 5.5 show the locations of the horizontal restraints and springs in a non-wrinkled model, respectively. A stress of 14.32 MPa was applied over fifteen load steps in the analysis. The location of the applied stress, \( p \) is shown in Figure 5.4.

### 5.7 Numerical Results for Wrinkle Type 2 and Non-wrinkled Liner

#### 5.7.1 Introduction

As stated earlier, wrinkle type 2 refers to a wavy imperfection in which the inner jacket is wrinkled inward, and the outer jacket is not wrinkled. A labeled finite element model of this wrinkle is shown in Figure 5.22. The dimensions of the wrinkled model are summarized in Table 5.4. A jacket thickness of 0.17 mm was considered for the analysis. A calculation that shows how the jacket thickness was determined is presented in Section C.3.2 of Appendix C. A non-wrinkled model with similar dimensions as the wrinkled model was also analyzed. A schematic of a non-wrinkled model is shown in Figure 5.4. The dimensions of the non-wrinkled model are summarized in Table 5.5. In the following sections, the results from the analysis of both the wrinkled and non-wrinkled finite element models are presented and discussed. The plots provided for each model represent the stress and/or displacement results along two sections, namely, section AA and the line of symmetry.
In both the wrinkled and non-wrinkled models, section AA represents the location of the applied stress. Figures 5.6 and 5.22 show the location of the applied stress in the wrinkled model. Figure 5.6 is based on a finite element mesh for wrinkle type 1. The location of the applied stress in the non-wrinkled model is shown in Figures 5.4 and 5.14. Both figures are based on a non-wrinkled liner section whose dimensions are the same as those of the non-wrinkled models compared to wrinkle type 1 in Section 5.4. The line of symmetry in the non-wrinkled and wrinkled models is shown in Figures 5.4 and 5.22, respectively.

5.7.2 Results from Wrinkled (Type 2) and Non-wrinkled Analyses

5.7.2.1 Numerical Results: Stress Distribution

The stress distributions along section AA in the wrinkled and non-wrinkled models are plotted in Figures 5.24 and 5.25, respectively. The horizontal (x-axis) origin in these graphs represents the outer surface of the inner jacket at section AA (see Figures 5.6 and 5.14). The stress distributions along the line of symmetry in the wrinkled and non-wrinkled models are plotted in Figures 5.26 and 5.27, respectively. The horizontal origin in these graphs represents point B as shown in Figures 5.6 and 5.14. The stress values plotted for the wrinkled and non-wrinkled models were obtained from the stress contours which are presented in Figures D.19 and D.20, respectively, of Appendix D.
Figure 5.26 shows that in the wrinkled model, the stress in the resin increases as the vertical distance below B becomes greater and approaches point C (see Figure 5.6). This stress distribution implies that the peak stress occurs near point C, and hence, cracking of the resin will begin at a location along the boundary between the resin and the outer unwrinkled jacket, with the crack propagating through the resin towards the inner wrinkled jacket (i.e. towards point B).

Based on the results from direct uniaxial tension tests conducted by Brown et al. (2007) on flat coupons of the fabricated composite liner, they reported that during loading, load was transferred from the resin to the inner and outer jackets once the response of the resin, and hence, the liner, became nonlinear. This transfer of load continued until the resin cracked, after which the entire load was resisted by the jackets only. In sample SW-1, prior to the first cracking of the resin within the wrinkle, the liner exhibited a nonlinear response. The load-average displacement graph for sample SW-1 is presented in Figure A.9 (b) of Appendix A. In the graph, the first cracking of the resin is indicated by the first drop in the load, which occurs at a load value of approximately 6kN. As described in Section C.3.1 of Appendix C, the stress of 14.32 MPa applied in the analysis, corresponds to the highest total load recorded in the first linear section that follows the nonlinear section at the start of the loading, in the load-average displacement graph for sample SW-1. The specified total load is less than the load recorded at the first cracking of the resin within the wrinkle. In Figures 5.26 and 5.27, it can be seen that in both jackets, the stress at the jacket-resin boundary is the highest. It is possible that the transfer
of stresses from the resin to the jackets which occurs as the liner begins to exhibit a nonlinear response, is responsible for the stress distributions observed in the jackets.

5.7.2.2 Numerical Results: Force-Displacement

The horizontal, vertical and resultant displacements along section AA of the wrinkled and non-wrinkled models are plotted in Figures 5.28 to 5.30, respectively. The displacement values in these graphs correspond to one half of the non-wrinkled liner and the wrinkle as shown in Figures 5.4 and 5.22, respectively. The horizontal (x-axis) origin in Figures 5.28 to 5.30 is the same as that in Figures 5.24 and 5.25, which was described earlier in Section 5.7.2.1. The values plotted in Figures 5.28 to 5.30, were obtained from the displacement contours which are presented in Figures D.21 to D.24 of Appendix D. The graphs show that the wrinkled and non-wrinkled models exhibit a similar distribution of displacements along section AA.

The force-displacement graphs corresponding to Section AA in the wrinkled and non-wrinkled models are presented in Figure 5.31. The force values in Figure 5.31 were determined from stress distribution graphs similar to those in Figures 5.24 and 5.25 for the wrinkled and non-wrinkled models, respectively. Figures 5.24 and 5.25 correspond to the last load step in the analysis. The force values were determined by following the same procedure described earlier in Section 5.4.2.1. In Figure 5.31, the average displacement at a given force represents the average value of the resultant displacements along section AA, multiplied by two to account for the other half of the wrinkle or non-wrinkled liner.
section. The displacement values corresponding to a force of approximately 63 N/mm are summarized in Table 5.6. Figure 5.31 shows that the wrinkled model exhibits a stiffer response than the non-wrinkled model. This is expected because in the wrinkled model, there is a greater mass of resin. In Section 5.4.2, the results from the analysis of wrinkle type 1 led to the suggestion that the stiffness of the liner was mainly influenced by the resin. Hence, the greater mass of resin in the wrinkled model implies a stiffer system.

5.8 Comparison of Wrinkle Types 1 and 2

5.8.1 Introduction

An analysis was conducted to enable the comparison of the behavior of wrinkle types 1 and 2. A finite element model of each type of wrinkle, with a jacket thickness of 0.14 mm was considered. The dimensions of the models for both wrinkles are the same as those summarized in Table 5.1. A stress of 9.35 MPa was applied over ten load steps in the analysis. As stated earlier in Section 5.3.4, the stress of 9.35 MPa corresponds to the load recorded at the first cracking of the resin in wrinkle type 1. It should be noted that it is not known whether this stress causes the cracking of the resin in wrinkle type 2.

In the next sections, the results from the analysis are presented and discussed. The numerical results for wrinkle type 1 with a jacket thickness of 0.14 mm, have already been discussed in detail in Section 5.4.2. The plots provided for each model represent the stress and/or displacement results along two sections, namely, section AA and the line of
symmetry. In the models, section AA represents the location of the applied stress. Figures 5.2 and 5.6 which are based on wrinkle type 1, show the location of the applied stress in the wrinkled models. The line of symmetry in the wrinkled models is shown in Figure 5.2. In the next sections, the amplitude of the wrinkle is the composite liner thickness at the line of symmetry. The wrinkle pattern is described in terms of the proximity of the inner jacket to the outer jacket.

5.8.2 Numerical Results for Wrinkle Types 1 and 2

5.8.2.1 Stress Distribution

The stress distributions along section AA in the wrinkled models are plotted in Figure 5.32. The horizontal (x-axis) origin in these graphs represents the outer surface of the inner jacket at section AA (see Figure 5.6). Figures 5.33 and 5.34 show the stress distributions along the line of symmetry in wrinkle types 1 and 2, respectively. The stress distributions along the line of symmetry in both types of wrinkles are plotted in Figure 5.35. In these graphs, the horizontal origin represents point B in Figure 5.6. The stress values plotted for wrinkle type 2 were obtained from the stress contours which are presented in Figure D.25 of Appendix D.

In Section 5.4, the analysis of wrinkle type 1 which involved wrinkled models with the same geometry but different jacket thicknesses, led to the suggestion that the behavior of the resin was not influenced by the choice of jacket thickness. In Figure 5.32, it can be
seen that the stress in the resin of the wrinkles which have the same geometry, is not influenced by the pattern of the wrinkles. Based on this observation, it can be suggested that the stress distribution in the resin is not influenced by the wrinkle pattern.

In Figure 5.35, it can be seen that along the line of symmetry, the wrinkles mostly have similar levels of stress in the resin. In Chapter 4, two of the three types of wrinkles evaluated, types LW and IW, had average amplitudes ($\Delta_{avg}$) which were almost equal, but different wrinkle patterns. Wrinkle type IW (see Figure 4.6) had jackets which were in closer proximity than those in wrinkle type LW (see Figure 4.1). The ultimate load values ($P_{max}$) of the ring samples with wrinkle type IW were generally higher than that recorded for the samples with wrinkle type LW (see Table 4.5). Figures 5.33 to 5.35 show that the stress level in the jackets is influenced by the wrinkle pattern. In wrinkle type 1 where the jackets are in close proximity, the stress in the jackets is almost evenly distributed. In wrinkle type 2 where the jackets are further apart, the stress level in the outer jacket is significantly higher than that in the inner jacket. The stress level in the outer jacket of wrinkle type 2 is extremely high compared to that in both jackets of wrinkle type 1 (see Figure 5.35). Based on this observation, it is reasonable to suggest that in wrinkles with similar amplitudes, the wrinkle pattern has an effect on the stress level and distribution in the jackets. Jackets in closer proximity have lower and more evenly distributed stresses, and are likely to withstand higher load levels before failure of the jackets occur, following the cracking of the resin. This explains the observations made in Chapter 4.
where higher ultimate load values were recorded for samples with wrinkle type IW, than for samples with wrinkle type LW.

5.8.2.2 Force-Displacement

The horizontal, vertical and resultant displacements along section AA of the wrinkled models are plotted in Figures 5.36 to 5.38, respectively. The displacement values in these graphs correspond to one half of the wrinkles. The horizontal (x-axis) origin in Figures 5.36 to 5.38 is the same as that in Figure 5.32, which was described earlier in Section 5.8.2.1. The displacement values plotted for wrinkle type 2 were obtained from the displacement contours which are presented in Figures D.26 and D.27 of Appendix D. The graphs show that both types of wrinkles exhibit a similar distribution of displacements along section AA.

The force-displacement graphs corresponding to Section AA in the wrinkled models are presented in Figure 5.39. The force values for wrinkle type 2 were determined from stress distribution graphs similar to that in Figures 5.32. Figure 5.32 corresponds to the last load step in the analysis. The force values were determined by following the same procedure described earlier in Section 5.4.2.1. In Figure 5.39, the average displacement at a given force represents the average value of the resultant displacements along section AA, multiplied by two to account for the other half of the wrinkle.
Figure 5.39 shows that at high load levels, wrinkle type 2 exhibits a stiffer response than wrinkle type 1. As stated earlier, the applied stress corresponds to the load that causes the first cracking of the resin in wrinkle type 1. The effect of the applied stress on the resin in wrinkle type 2 is not known. It is possible that a greater stress than that applied in the analysis is required to crack the resin in wrinkle type 2. Thus, while the resin in wrinkle type 1 approaches crack initiation and gradually loses its ability to contribute most of the liner’s stiffness, the resin in wrinkle type 2 remains intact and continues to contribute most of the liner’s stiffness. Based on this observation, it is possible that in wrinkles with similar amplitudes, the wrinkle pattern has an influence on the load level at which the first cracking of the resin occurs.

5.9 Comparison of Numerical and Experimental Results

5.9.1 Experimental Results

The discussions in this section are based on the experimental results for ring samples IW-5, SW-1 and NW-1 which were tested to failure under tension in the laboratory. In Sections 5.4, 5.5, and 5.7, the numerical results from the analysis of wrinkle types 1 and 2 were discussed, respectively. As stated earlier, the geometries of the finite element models of wrinkle types 1 and 2 were based on that of the wrinkles in samples IW-5 and SW-1, respectively. The experimental results for the two wrinkled ring samples are used in the next sections to evaluate the numerical results from the analysis of wrinkle types 1 and 2. In Chapter 4, the experimental results of five samples (NW-1 to NW-5) without
wrinkles were presented and discussed. The load-average displacement graphs for all the five non-wrinkled samples were presented in Figure A.11 (b) of Appendix A. The experimental result for sample NW-1 is used in the next sections for the evaluation of the numerical results from all the analyses involving the non-wrinkled models.

The experimental force-displacement graphs for the wrinkled samples IW-5 and SW-1 are shown in Figures 5.40 and 5.41, respectively. In both figures, the experimental force-displacement graph for the non-wrinkled sample NW-1 is also plotted. For the wrinkled samples, the graphs correspond to the wrinkled springline. For the non-wrinkled sample, the graph corresponds to one of the springlines. In the graphs, the average displacement value at a given force represents the average of the values recorded by the four Linear Displacement Sensors (LDSs) installed during testing (see Chapter 3).

In Figure 5.40, the graph for the wrinkled springline corresponds to the linear section which follows the nonlinear section at the start of loading, up to the first cracking of the resin within the wrinkle, in the load-average displacement graph for sample IW-5 (see Figure 5.42). The load at the first cracking of the resin is approximately 43 N/mm. In Figure 5.41, the graph for the wrinkled springline corresponds to the first linear section which follows the nonlinear section at the start of loading, in the load-average displacement graph for sample SW-1 (see Figure 5.43). The highest load in the first linear section of the load-deformation graph is approximately 63 N/mm. This load is less than the load recorded at the first cracking of the resin.
In Figures 5.40 and 5.41, the graphs for the non-wrinkled springline correspond to the first linear section that follows the nonlinear section at the start of loading, in the load-average displacement graph for sample NW-1 (see Figures 5.44 and 5.45, respectively). The highest load in each of the graphs for the non-wrinkled springline is the same as that for the wrinkled springline. The nonlinear sections at the start of loading are caused by the lack of fit in the testing apparatus. As the load increases and the ring samples are stretched, the lack of fit in the testing apparatus is eliminated. This is confirmed by the linear response that follows the nonlinear response at the start of loading. The load applied in the finite element analyses is thus estimated from the load corresponding to the linear response only in the load-average displacement graphs. The displacement values corresponding to a force of approximately 43 N/mm in Figure 5.40, and 63 N/mm in Figure 5.41, are summarized in Table 5.7 for wrinkle types 1 and 2, respectively.

5.9.2 Objectives of Comparisons between Experimental and Numerical Results

In the following sections, the discussions are based on the results obtained from the numerical and experimental analyses. The discussions focus on the similarities and differences between the numerical and experimental results. The experimental results from the split-disk tests have already been discussed in Section 5.9.1. The results from the direct uniaxial tension tests conducted by Brown et al. (2007) will also be referenced in the discussions. The numerical results are from the analysis of wrinkle types 1 and 2, and have already been discussed in Sections 5.4, 5.5, and 5.7, respectively. The numerical
and experimental results will be compared to determine if the failure mechanisms observed during the laboratory testing of the samples were predicted by the finite element models. The calculated and measured stiffnesses and deflections will also be compared. The reliability of the approach used for the selection of the representative jacket thickness (see Section 5.4.3) will also be determined based on the calculated and measured deflections.

5.9.3 Evaluation of Numerical Results: Wrinkle Type 1

5.9.3.1 Failure Mechanism

The results from the numerical analysis of wrinkle type 1 were discussed in detail in Sections 5.4 and 5.5. The distribution of stress along the line of symmetry in the wrinkled finite element models (see Figure 5.12) conformed to the failure mechanism observed at the wrinkled springline in sample IW-5 during testing. As described earlier in Chapter 4, failure in sample IW-5 occurred at the wrinkled springline, and began with the cracking of the resin within the wrinkle. The crack was initiated at a location along the outer surface of the wrinkle, and propagated through the resin towards the outer jacket. This failure mechanism indicates that during testing, the stress within the resin increased away from the inner jacket, towards the outer surface of the wrinkle. This is predicted in Figure 5.12, in which the stress in the resin increases as the vertical distance below B becomes greater and approaches point C (see Figure 5.6).
5.9.3.2 Stiffness

The force-displacement graphs for both the wrinkled and non-wrinkled models (see Figures 5.11 and 5.19) predicted that the stiffness of the liner was controlled by the intact resin. In both sets of models, as the thickness of the resin increased with decreasing choice of jacket thickness, the liner’s stiffness also increased. This observation implied that the stiffness of the liner was influenced primarily by the resin. The force-displacement response supports findings reported by Brown et al. (2007), which suggested that the liner’s stiffness was initially controlled by the intact resin, until the response of the resin and hence the liner, became nonlinear. The force-displacement graphs for the numerical and experimental analyses involving wrinkle type 1 are shown in Figures 5.21 and 5.40, respectively. Figure 5.21 shows that the wrinkled models exhibit stiffer responses than the non-wrinkled models. This behavior is confirmed in Figure 5.40, in which a stiffer response is exhibited at the springline of the wrinkled sample, than at the springline of the non-wrinkled sample.

5.9.3.3 Deflections

In Figures 5.21 and 5.40, the force-displacement graphs for the numerical and experimental analyses involving wrinkle type 1 are shown, respectively. A summary of the displacement values corresponding to a force of approximately 43 N/mm is presented in Table 5.3 for the wrinkled and non-wrinkled finite element models. In the table, the difference between the displacement values for the wrinkled and non-wrinkled models is
also presented. In Table 5.7, the displacement values for the wrinkled and non-wrinkled test samples, and the difference between the two values are presented. In the table, the displacement values for wrinkle type 1 also correspond to a force of approximately 43 N/mm. The total displacements measured in the experiments are for the whole liner and hence, will be considerably greater than those calculated in the analyses which are just for the region in the vicinity of the wrinkles. However, the difference in displacement for the wrinkled and non-wrinkled specimens should be similar because they reflect the additional stiffness provided by the wrinkles.

In Table 5.8, it can be seen that the analysis indicated a displacement change from 0.02 mm to 0.03 mm, while the measured change was 0.04 mm (see Table 5.7). It appears, then, that the best numerical model is that with the thickest jacket (of 0.5 mm), where the effect of the wrinkle on the calculated displacement is within 33% of the measured change in displacement. For the thinnest jacket choice (of 0.14 mm), this error increases to 50%. It should be noted that the circumferential properties of the liner and its individual components, which were determined from the direct uniaxial tension tests conducted by Brown et al. (2007), were used in the calculation of the jacket thickness of 0.14 mm. In that calculation (see Section C.2.2 of Appendix C), an assumption was made that the combined behavior of the individual liner components, conformed to the behavior of the composite liner. Based on the results in Table 5.8, in which the highest percentage difference corresponds to the models with the jacket thickness of 0.14 mm, it
is possible that this assumption is not reasonable, and hence, the approach used for the selection of the representative jacket thickness is not reliable.

Another possible explanation for the observed deviation can be made on the basis of the properties of the jackets in the finite element models. As discussed in earlier sections, the jackets were characterized as uniform solid materials, and not as woven fabrics. Another explanation can also be made on the basis of the type of restraint provided by the spring elements in the models. As described earlier in Section 5.3.3, the part of the liner in contact with the half concrete disks may have been restrained from movement in the radial direction during testing. However, in the finite element models, the movement of these parts was restrained in the vertical direction only.

5.9.3.4 Insight Gained from the Analysis of Wrinkle Type 1

The stress results for different assumptions of jacket thickness showed that the analysis could accurately predict the failure mechanism observed in the laboratory during testing. The stress results also showed that the choice of jacket thickness had a significant impact on the stress levels in the jackets, but not that in the resin which is known to contribute most of the liner’s stiffness prior to cracking. The finite element models could not accurately predict the measured deflection. While the analysis does not provide deflections accurately, it is useful for estimating the stresses in the intact resin, and the failure mechanism.
5.9.4 Evaluation of Numerical Results: Wrinkle Type 2

5.9.4.1 Failure Mechanism

The results from the numerical analysis of wrinkle type 2 were discussed in detail in Section 5.7. The distribution of stress along the line of symmetry in the wrinkled finite element model (see Figure 5.26) conformed to the failure mechanism observed at the wrinkled springline in sample SW-1 during testing. As described earlier in Chapter 4, two types of failure mechanisms (types 1 and 2) were observed in samples SW-1 to SW-5 (see Section 4.2.3.1). Sample SW-1 exhibited failure type 1 which occurred at the wrinkled springline, and began with the cracking of the resin at a location along the boundary between the resin and the outer unwrinkled jacket. The crack then propagated through the resin towards the inner wrinkled jacket. This failure mechanism indicates that during testing, the stress within the resin increased away from the wrinkled inner jacket, towards the inner surface of the outer unwrinkled jacket. This is predicted in Figure 5.26, in which the stress in the resin increases with increasing vertical distance below B (i.e. the peak tension occurs near point C, see Figure 5.6).

5.9.4.2 Stiffness and Deflections

The force-displacement graphs for the numerical and experimental analyses involving wrinkle type 2 are shown in Figures 5.31 and 5.41, respectively. Figure 5.31 shows that the wrinkled model exhibits a stiffer response than the non-wrinkled model. This behavior is confirmed in Figure 5.41, in which a stiffer response is exhibited at the
springline of the wrinkled sample, than at the springline of the non-wrinkled sample. A summary of the displacement values corresponding to a force of approximately 63 N/mm is presented in Tables 5.6 and 5.7 for the wrinkled and non-wrinkled finite element models and test samples, respectively. In the tables, the difference between the displacement values for the wrinkled and non-wrinkled models and test samples is also presented. As seen in the tables, the total displacements measured in the experiments are considerably greater than those calculated in the analysis. This is expected because the measured displacements correspond to the whole liner while the calculated displacements correspond to the region in the vicinity of the wrinkle.

The difference in displacement for the wrinkled and non-wrinkled specimens reflects the additional stiffness provided by the wrinkles, and hence, should be similar. This is not the case for wrinkle type 2 (see Tables 5.6 and 5.7). The deviation of the difference between the numerical displacement values from that between the experimental displacement values, is expressed as a percentage and presented in Table 5.8. The percentage difference of about 93 % in Table 5.8, is extremely high and shows that the finite element models were not successful in predicting the exact displacement values corresponding to the applied force. The jacket thickness of 0.17 mm was calculated using the same assumption as that used in the calculation of the jacket thickness of 0.14 mm in Section 5.9.3.3 (see Section C.3.2 of Appendix C). As stated earlier in Section 5.9.3.3, it is possible that this assumption is not reasonable, and hence, the approach used for the selection of the representative jacket thickness is not reliable. While the finite element
models with the jacket thickness of 0.14 mm predicted a difference in displacement within 50% of the measured change in displacement in wrinkle type 1, the models with the jacket thickness of 0.17 mm made a prediction that deviated from the measured change by 93% in wrinkle type 2 (see Table 5.8). Based on this observation, it is possible that the different patterns of wrinkles require different approaches for the selection of a representative jacket thickness which can accurately predict the measured deflections. Other possible explanations for the observed deviation can be made on the basis of the properties of the jackets in the finite element models, and the type of restraint provided by the spring elements used in the models. These explanations have already been given in Section 5.9.3.3.

5.10 Approximation of the Force-Displacement Response for One Half of the Ring Samples Using the Numerical Results and a Theoretical Equation

The numerical analyses of the wrinkles and the non-wrinkled liner sections considered the region in the vicinity of the wrinkles. These analyses assumed that there was zero slip in the sections of the ring samples that were not modeled. In Figures 5.46 and 5.47, the numerical results for the representative jacket thicknesses of 0.14 mm and 0.17 mm for wrinkle types 1 and 2, respectively, and the non-wrinkled liner models to which they were compared are referred to as the lower bound. These numerical results were presented and discussed in Sections 5.4, 5.5 and 5.7.
In Figures 5.46 and 5.47, the plots referred to as the upper bound correspond to one half of the ring samples that were considered in the numerical analyses. The upper bound displacement at a given force represents the sum of the displacement value obtained from the numerical analysis of the wrinkled or non-wrinkled finite element model, and the displacement value corresponding to the sections within one half of the ring sample which were not modeled. The displacement value for the latter was determined using the equation of deformation, \( \Delta = \frac{PL}{EA} \). The upper bound force-displacement response assumes that there is zero friction, and hence, full slip in the system. It also assumes that there is zero slip at the vertical axis of symmetry (i.e. the crown and invert of the ring samples).

In Figures 5.46 and 5.47, the difference between the upper bound displacement values for the wrinkled and non-wrinkled models was similar to that of the lower bound. This theoretical calculation serves as a check for the numerical results presented earlier for wrinkle types 1 and 2. In Figures 5.46 and 5.47, the experimental force-displacement graphs for the ring samples with wrinkle types 1 and 2, and the non-wrinkled ring sample are also presented. These graphs were presented and discussed in earlier sections. A comparison between the upper bound and experimental force-displacement responses in both figures shows that the upper bound plots could not accurately predict the experimental responses, but are closer to them.
Table 5.1: Dimensions of wrinkle type 1

<table>
<thead>
<tr>
<th></th>
<th>Finite element model</th>
<th>Test sample IW-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>75</td>
<td>75.25</td>
</tr>
<tr>
<td>Wavelength (mm)</td>
<td>10.16</td>
<td>10.12</td>
</tr>
<tr>
<td>Thickness at line of symmetry, amplitude (mm)</td>
<td>15.3</td>
<td>15.29</td>
</tr>
<tr>
<td>Thickness at location of applied stress, $p$ (mm)</td>
<td>4.6</td>
<td>4.55$^1$</td>
</tr>
</tbody>
</table>

$^1$The average of thicknesses measured at three different locations along the circumference of the ring sample. Each of the three locations was about an inch from the wrinkled springline. Along the width of the ring sample, the measurements were taken at two locations which were close to the two edges of the sample, and at one location which was mid width.

Table 5.2: Dimensions of the non-wrinkled finite element models for comparison with wrinkle type 1

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>75</td>
</tr>
<tr>
<td>Thickness at line of symmetry (mm)</td>
<td>4.6</td>
</tr>
<tr>
<td>Thickness at location of applied stress, $p$ (mm)</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 5.3: Displacement values from the numerical analysis of wrinkle type 1

<table>
<thead>
<tr>
<th>Polyester jacket thickness (mm)</th>
<th>Displacement (Non-wrinkled model) (mm)</th>
<th>Displacement (Wrinkled model) (mm)</th>
<th>Difference in displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.089</td>
<td>0.069</td>
<td>0.02</td>
</tr>
<tr>
<td>0.30</td>
<td>0.095</td>
<td>0.072</td>
<td>0.023</td>
</tr>
<tr>
<td>0.50</td>
<td>0.102</td>
<td>0.075</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 5.4: Dimensions of wrinkle type 2

<table>
<thead>
<tr>
<th></th>
<th>Finite element model</th>
<th>Test sample SW-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>77</td>
<td>76.71</td>
</tr>
<tr>
<td>Wavelength (mm)</td>
<td>6.20</td>
<td>6.20</td>
</tr>
<tr>
<td>Thickness at line of symmetry, amplitude (mm)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Thickness at location of applied stress, $p$ (mm)</td>
<td>4.4</td>
<td>4.43$^1$</td>
</tr>
</tbody>
</table>

$^1$The average of thicknesses measured at three different locations along the circumference of the ring sample. Each of the three locations was about an inch from the wrinkled springline. Along the width of the ring sample, the measurements were taken at two locations which were close to the two edges of the sample, and at one location which was mid width.
Table 5.5: Dimensions of the non-wrinkled finite element model for comparison with wrinkle type 2

<table>
<thead>
<tr>
<th>Dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>77</td>
</tr>
<tr>
<td>Thickness at line of symmetry (mm)</td>
<td>4.4</td>
</tr>
<tr>
<td>Thickness at location of applied stress, ( p ) (mm)</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Table 5.6: Displacement values from the numerical analysis of wrinkle type 2

<table>
<thead>
<tr>
<th>Polyester jacket thickness (mm)</th>
<th>Displacement (Non-wrinkled model) (mm)</th>
<th>Displacement (Wrinkled model) (mm)</th>
<th>Difference in displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>0.083</td>
<td>0.072</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Table 5.7: Displacement values from experimental work involving wrinkle types 1 and 2

<table>
<thead>
<tr>
<th>Wrinkle Type</th>
<th>Displacement (Non-wrinkled sample) (mm)</th>
<th>Displacement (Wrinkled sample) (mm)</th>
<th>Difference in displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.23</td>
<td>1.19</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>1.77</td>
<td>1.62</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 5.8: Comparison of numerical and experimental displacement values

<table>
<thead>
<tr>
<th>Wrinkle Type</th>
<th>Polyester jacket thickness (mm)</th>
<th>Difference in displacement (finite element model) (mm)</th>
<th>% difference in numerical and experimental displacements (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.14</td>
<td>0.02</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>0.023</td>
<td>42.5</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.027</td>
<td>32.5</td>
</tr>
<tr>
<td>2</td>
<td>0.17</td>
<td>0.011</td>
<td>92.7</td>
</tr>
</tbody>
</table>
Figure 5.1: Labeled pictures of (a) wrinkle type 1, and (b) wrinkle type 2

Figure 5.2: Schematic of wrinkle type 1
Figure 5.3: Location of springs in wrinkle type 1

Figure 5.4: Labeled finite element model of a liner section without a wrinkle
Figure 5.5: Location of springs in a liner section without a wrinkle

Figure 5.6: A labeled finite element mesh of wrinkle type 1
Figure 5.7: Stress distribution at section AA in wrinkled models (type 1) having three different jacket thicknesses

Figure 5.8: Horizontal displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses
Figure 5.9: Vertical displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses

Figure 5.10: Resultant displacement along section AA in wrinkled models (type 1) having three different jacket thicknesses
Figure 5.11: Force-displacement graphs corresponding to section AA in wrinkled models (type 1) having three different jacket thicknesses
Figure 5.12: Stress distribution along line of symmetry in wrinkled models (type 1) having three different jacket thicknesses

Figure 5.13: A close up of the stress distribution along the inner and outer jackets at the line of symmetry in the wrinkled models (type 1) having three different jacket thicknesses
Figure 5.14: Labeled finite element mesh of a liner section without a wrinkle

Figure 5.15: Stress distribution at section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1
Figure 5.16: Horizontal displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1

Figure 5.17: Vertical displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1
Figure 5.18: Resultant displacement along section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1

Figure 5.19: Force-displacement graphs corresponding to section AA in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1
Figure 5.20: Stress distribution along line of symmetry in non-wrinkled models (having three different jacket thicknesses) for comparison with wrinkle type 1

Figure 5.21: Force-displacement graphs for wrinkled (type 1) and non-wrinkled models having three different jacket thicknesses
Figure 5.22: Schematic of wrinkle type 2

Figure 5.23: Location of springs in wrinkle type 2
Figure 5.24: Stress distribution at section AA in wrinkled model (type 2) with jacket thickness of 0.17 mm

Figure 5.25: Stress distribution at section AA in non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2
Figure 5.26: Stress distribution along line of symmetry in wrinkled model (type 2) with jacket thickness of 0.17 mm

Figure 5.27: Stress distribution along line of symmetry in non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2
Figure 5.28: Horizontal displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm

Figure 5.29: Vertical displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm
Figure 5.30: Resultant displacement along section AA in wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm

Figure 5.31: Force-displacement graphs for wrinkled (type 2) and non-wrinkled models with jacket thickness of 0.17 mm
Figure 5.32: Stress distribution at section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm
Figure 5.33: Stress distribution along line of symmetry in wrinkled model (type 1) with jacket thickness of 0.14 mm

Figure 5.34: Stress distribution along line of symmetry in wrinkled model (type 2) with jacket thickness of 0.14 mm
Figure 5.35: Stress distribution along line of symmetry in wrinkle types 1 and 2 with jacket thickness of 0.14 mm

Figure 5.36: Horizontal displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm
Figure 5.37: Vertical displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm

Figure 5.38: Resultant displacement along section AA in wrinkle types 1 and 2 with jacket thickness of 0.14 mm
Figure 5.39: Force-displacement graphs for wrinkle types 1 and 2 with jacket thickness of 0.14 mm

Figure 5.40: Experimental force-displacement graphs for wrinkled (type 1) and non-wrinkled samples
Figure 5.41: Experimental force-displacement graphs for wrinkled (type 2) and non-wrinkled samples

Figure 5.42: Experimental total load-average displacement graph for the wrinkled (type 1) sample showing the linear section plotted in Figure 5.40
Figure 5.43: Experimental total load-average displacement graph for the wrinkled (type 2) sample showing the linear section plotted in Figure 5.41

Figure 5.44: Experimental total load-average displacement graph for the non-wrinkled sample showing the linear section plotted in Figure 5.40
Figure 5.45: Experimental total load-average displacement graph for the non-wrinkled sample showing the linear section plotted in Figure 5.41

Figure 5.46: Experimental and lower and upper bound finite element force-displacement graphs for wrinkled (type 1 or wrinkle in sample IW-5) and non-wrinkled samples and models
Figure 5.47: Experimental and lower and upper bound finite element force-displacement graphs for wrinkled (type 2 or wrinkle in sample SW-1) and non-wrinkled samples and models
CHAPTER 6
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Experimental and analytical investigations were conducted to examine the effect of geometric imperfections (wrinkles) on the circumferential strength of a composite polymer liner. The polymer liner is manufactured by Sanexen Environmental Services Inc. in Montreal, Canada, and is used for the rehabilitation of deteriorated water pressure pipes. The experimental work involved the testing of liner samples with three different wrinkle patterns. The analytical work evaluated two of the three wrinkle patterns observed in the test samples.

A series of tests were conducted to examine the effects of three parameters on the response of the liner. The method of testing was based on the split-disk test which is defined by ASTM Standard D2290. Ring samples of the liner with widths of 25 mm were tested. To examine the effect of loading rate, fifteen ring samples with identical wrinkles were tested at loading rates of 0.1 mm/min, 5 mm/min, 100 mm/min, and 250 mm/min. Eight samples with identical wrinkles were tested to investigate the effect of cyclic loading equivalent to 50 years. Three of the eight samples were subjected to cyclic loading, and then tested to failure under monotonic loading conditions upon completion.
of the cyclic loading tests. The five remaining samples which served as control were tested to failure under monotonic loading conditions only.

A total of twenty ring samples were tested to investigate the effect of the presence of a wrinkle and its geometry. Five of the twenty ring samples did not have wrinkles (the “non-wrinkled” samples), and served as a control. The remaining fifteen samples consisted of three sets of five samples with wrinkles, each set with a different wrinkle geometry and cross-sectional area. Two of the three sets of samples were the control samples tested to evaluate the effect of cyclic loading, and the samples tested at 5 mm/min to investigate the effect of loading rate. During testing, each ring sample with a wrinkle was oriented such that the wrinkle was located at the split between the two half concrete disks of the split-disk test fixture. A series of two-tailed Mann-Whitney statistical tests were conducted on the obtained load data to enable a comparison between the experimental and statistical based conclusions. The statistical tests were conducted at a level of significance, $\alpha$ of 0.05.

The analytical component of this study investigated the behavior of two of the three types of wrinkles observed in the test samples. It aimed to investigate further the behavior of the wrinkles, their effect on the response of the liner, and the relationship between the circumferential properties determined from the direct uniaxial tension tests conducted by Brown et al. (2007) and the split-disk tests conducted in this study. The wrinkles in two ring test samples, IW-5 and SW-1 were analyzed. These wrinkles were referred to as
wrinkle types 1 and 2, respectively. In all the finite element models, the properties of the three components of the liner system were based on the circumferential results from the direct uniaxial tension tests conducted by Brown et al. (2007).

To determine the effect of the wrinkles on the response of the liner, models for liner sections without wrinkles were also constructed and analyzed. The relationship between the circumferential properties determined from the direct uniaxial tension and split-disk tests was explored through the approach used for the selection of a representative jacket thickness for each wrinkle examined. The two types of wrinkles were also compared in an analysis in which both wrinkles were modeled with the same dimensions and jacket thickness, and subjected to the same stress. The calculated results were evaluated using experimental results reported by Brown et al. (2007) as well as results from the split-disk tests. The success of the analytical work was measured through the ability of the finite element models to predict the failure mechanisms observed in the wrinkles during testing, and the measured stiffnesses and deflections.

6.2 Conclusions

The following conclusions were drawn from the experimental work conducted in this study:
1. In a liner without a wrinkle, the monotonic load-deformation response is a bi-linear smooth response. In wrinkled liners, the response is also bi-linear but exhibits load drops.

2. The wrinkle is a source of weakness in the liner. During laboratory testing, failure was initiated at the wrinkle in all the test samples.

3. The presence of a wrinkle can result in cracking of resin within the liner and a load drop of about 67% of the ultimate load. The load then rises again. The wrinkle, however, may or may not cause a reduction in the ultimate hoop tensile capacity of the liner depending on the wrinkle pattern. In samples with similar amplitudes of wrinkles, the ultimate load values for the samples in which the two jackets were in close proximity, were higher than those for the samples in which the two jackets were further apart by about 19%.

4. The loading rate has no significant effect on the first cracking load of the resin within the wrinkle. At loading rates between 0.1 and 250 mm/min, the first cracking load of the resin within the wrinkle varied by a maximum of 6%.

5. The polyester jackets of a wrinkle in the liner can remain intact under the 50-year cyclic loading. However, the resin within the wrinkle is susceptible to cracking. At the end of the cyclic loading tests, the polyester jackets of the wrinkle in the three samples subjected to the 50-year cyclic loading remained intact, whereas the resin in two of the three samples cracked.

6. When tested to failure under monotonic loading following the cyclic loading test, a fairly smooth load-deformation graph without load drops was obtained for the
two samples in which the resin within the wrinkle had cracked during cyclic loading. For the sample in which the resin remained intact throughout the cyclic loading, the load-deformation graph in subsequent monotonic loading had a number of load drops indicating cracking of the resin within the wrinkle.

7. The polyurethane elastomer bonded onto the inner polyester jacket contributes to the hoop tensile strength of the liner by about 15%. In the samples without wrinkles, higher ultimate load values were recorded for samples in which the elastomer was ruptured than for those in which it was stretched but not ruptured when the liner failed.

8. The circumferential properties of field-installed polymer liners can be inferred from flat liner coupons fabricated in the laboratory. In all the flat liner coupons fabricated in the laboratory by Brown et al. (2007), the polyurethane elastomer did not rupture at failure. The ultimate load values recorded for the ring samples without wrinkles in which the elastomer was not ruptured at failure, were similar to those recorded for the flat liner coupons.

The conclusions presented below were drawn from the analytical investigation, and apply to a liner system exhibiting a linear response.

1. The stiffness of the liner is mainly influenced by the resin. In the analysis in which the same stress was applied to three wrinkled models with the same dimensions but different jacket thicknesses, the stiffness of the models slightly increased with decreasing jacket thickness. A lower value of jacket thickness in
the models led to an increase in the resin thickness, and the stiffness of the system. The same observations were made in the three non-wrinkled models.

2. The wrinkle provides additional stiffness to the liner system. This was also the case for the ring test samples on which the analytical investigation was based.

3. In wrinkles with similar amplitudes, the wrinkle pattern (i.e. the proximity of the inner jacket to the outer jacket) has an effect on the stress level and distribution in the jackets. The model in which the jackets were in closer proximity had lower and more evenly distributed stresses in the jackets. This was not the case for the model in which the jackets were further apart. For this model, the stress level in the outer jacket was significantly higher than that in the inner jacket and the other model.

4. In a wrinkle and the liner system in general, the response of the resin is independent of the jackets. When the same stress was applied to wrinkled models with the same dimensions and wrinkle pattern but different jacket thicknesses, or with the same dimensions and jacket thickness but different wrinkle patterns, the stress levels in the resin were similar in both sets of models. The same observation was made in the non-wrinkled models.

5. The models were successful in predicting the failure locations observed in the wrinkles. They, however, underestimated deflections in general.
6.3 Recommendations for Future Work

The experimental and analytical investigations conducted in this study raised a number of issues that may need to be addressed through further studies. The following are some suggestions for future work:

1. Examining the effect of very slow loading rates (i.e. loading rates less than 5 mm/min) as well as sustained loads over a long period of time, on the ultimate hoop tensile capacity of the liner. The experimental results showed that the ultimate load values recorded for the loading rate of 0.1 mm/min were lower than that for the loading rates of 5 mm/min and 100 mm/min. The ultimate load values recorded for the loading rates of 5 mm/min and 100 mm/min were similar.

2. Subjecting at least five ring samples with the same type of wrinkle to the 50-year cyclic loading, to establish if this long-term loading condition causes any significant reduction in the hoop tensile strength of the liner. In this study, only three samples with wrinkles were subjected to the 50-year cyclic load.

3. Testing liner samples without wrinkles to investigate their response to different loading rates. In this study, liner samples with wrinkles were tested for this purpose.

4. Determining a more reliable approach to use for the selection of a representative jacket thickness. In this study, the finite element models with the representative jacket thicknesses could not accurately predict the measured deflections.
5. Conducting analytical work to determine the effect of the polyurethane elastomer bonded onto the inner jacket, on the response of the liner system. The effect of the elastomer was not considered in the analytical component of this study.

6. Conducting analytical work to investigate the behavior of the third kind of wrinkle observed in the test samples but not examined in the analytical work conducted in this study.
REFERENCES


APPENDIX A

EXPERIMENTAL RESULTS
Figure A. 1: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-1 to LW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 2: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-6 to LW-10 tested under monotonic conditions at a loading rate of 0.1 mm/min
Figure A. 3: (a) Load-stroke, (b) Load-average displacement graphs of samples LW-11 to LW-14, and LW-15 tested under monotonic conditions at loading rates of 100 mm/min and 250 mm/min, respectively.
Figure A. 4: Load-strain response at springlines of samples LW-1 to LW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 5: Load-strain response at springlines of samples LW-6 to LW-10 tested under monotonic conditions at a loading rate of 0.1 mm/min
Figure A. 6: Load-strain response at springlines of samples LW-11 to LW-14, and LW-15 tested under monotonic conditions at loading rates of 100 mm/min and 250 mm/min, respectively
Figure A. 7: (a) Load-stroke, (b) Load-average displacement graphs of samples IW-1 to IW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 8: Load-strain response at springlines of samples IW-1 to IW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 9: (a) Load-stroke, (b) Load-average displacement graphs of samples SW-1 to SW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 10: Load-strain response at springlines of samples SW-1 to SW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 11: (a) Load-stroke, (b) Load-average displacement graphs of samples NW-1 to NW-5 tested under monotonic conditions at a loading rate of 5 mm/min.
Figure A. 12: Load-strain response at springlines of samples NW-1 to NW-5 tested under monotonic conditions at a loading rate of 5 mm/min
Figure A. 13: Load-strain response of samples NW-1 to NW-5 at a location 30° from one of the springlines
Figure A. 14: Load-strain response of samples NW-1 to NW-5 at a location 60° from one of the springlines
Figure A. 15: Load-strain response of samples NW-1 to NW-5 at a location 90° from one of the springlines (crown)
Figure A. 16: Load-strain response of samples NW-1 to NW-5 at all the five strain gauged locations
APPENDIX B

NUMERICAL RESULTS: FINITE ELEMENT CONVERGENCE STUDY
B. 1 OBJECTIVES AND OUTLINE OF METHODOLOGY

The numerical analyses conducted in this thesis investigated the behavior of two types of wrinkles in the liner. The wrinkles were constructed as two dimensional plane stress finite element models. The static and kinematic boundary conditions applied to the models were discussed in detail in Sections 5.3 and 5.6 of Chapter 5. Spring elements were used to provide vertical restraint in some parts of the models. In the analyses, stress was applied over a number of load steps. A convergence study was conducted to determine the stiffness of the spring elements used, and the number of load steps to use for the analyses. The finite element analysis package ABAQUS Version 6.5-1 was used to conduct the convergence study discussed in this appendix.

The convergence study was based on two types of wrinkles referred to as types 1 and 2. In Sections B.2 to B.5, the study involving wrinkle type 1 is discussed in detail. The study involving wrinkle type 2 is presented in a summary in Section B.6. The convergence study for each wrinkle was conducted in two parts. In the first part of the study, a series of analyses were performed to evaluate the effect of changes in the spring stiffness on four parameters. The spring stiffness values used in each analysis ranged between 1 N/mm to 1024000 N/mm. Based on the results from the first part of the study, a spring stiffness value was chosen for use in subsequent analyses. In the second part of the study, a series of analyses were conducted to determine the number of load steps to use for the analysis. The effect of changes in the number of load steps on four parameters was investigated. The four parameters were the same as those evaluated in the first part of
the study. Based on the results from the second part of the study, the total number of load steps for use in subsequent analyses was chosen. In the following sections, the convergence study conducted for wrinkle types 1 and 2 is presented and discussed.

**B. 2 CONVERGENCE STUDY FOR WRINKLE TYPE 1: PROBLEM DEFINITION**

The wrinkle in test sample IW-5 is referred to as wrinkle type 1. A two dimensional model of this wrinkle was considered for the convergence study discussed in the next sections. The study was conducted to determine the stiffness of the spring elements used, and the number of load steps to use for the numerical analysis. A stress, $p$ of 9.35 MPa was applied in each analysis conducted for the convergence study. This stress value corresponded to the load at which first cracking of the resin within wrinkle type 1 occurred during laboratory testing. The effect of changes in the spring stiffness and number of load steps on four parameters was investigated. The spring stiffness value for use in subsequent analyses was chosen such that at spring stiffness values greater than the chosen value, there was no significant change in each of the four evaluated parameters. The number of load steps used in subsequent analyses was chosen such that an increased computational efficiency could be achieved.
B. 3 KEY PARAMETERS

B.3. 1 Material Properties

The inner and outer polyester jackets of the liner were modeled as linear elastic isotropic materials with Young’s modulus of 5100 MPa and 7567 MPa, respectively. Both polyester jackets had a thickness of 0.3 mm. The polymeric resin was modeled as an elastic-plastic material with a Young’s modulus of 2356 MPa, a yield stress of 36 MPa, and a total strain increment of 0.022 mm/mm occurring at stresses between 36 MPa and 61 MPa. Each of the three constituents of the liner had a Poisson’s ratio of 0.3. These parameter choices are discussed in detail in Section 5.3.2 of Chapter 5.

B.3. 2 Model Geometry

The finite element model was constructed such that its dimensions were similar to that of the wrinkle in test sample IW-5. One half of the wrinkle in sample IW-5 was constructed for the study, based on an assumption of symmetry at the left hand boundary of the mesh (see Figure B.1). The geometry of the wrinkle in the actual test sample, and in the finite element model is shown in Figure B.1. A labeled model of the wrinkle is shown in Figure 5.2 of Chapter 5. The dimensions of the wrinkle are summarized in Table B.1. A stress, \( p \) of 9.35 MPa which corresponds to half of the total load recorded at the first cracking of the resin within the wrinkle was applied in the analysis. A calculation that shows how the applied stress of 9.35 MPa was determined is presented in Section C.2.1 of Appendix C.
B. 4 MODELING

The two dimensional analysis was performed using the finite element package ABAQUS Version 6.5-1. The finite element model of the wrinkle was discretized into 6 noded quadratic plane stress triangular elements. Figure 5.6 of Chapter 5 shows the finite element mesh that was used for the analysis. The left boundary of the model (mid-wrinkle) was restrained against horizontal movement as shown in Figure 5.2 of Chapter 5. In the laboratory, sample IW-5 was fitted onto two half concrete disks and subjected to tensile load during testing. In the finite element model, the part of the sample in contact with the half disks was restrained against vertical movement by springs. Figure 5.3 of Chapter 5 shows the location of the springs in the model.

B. 5 RESULTS

B.5.1 Introduction

The results from the convergence study are summarized in Tables B.2 to B.6 and Figures B.2 to B.5, and are discussed in the next sections. In the Tables and Figures, Section AA refers to the location where the stress of 9.35 MPa was applied. The critical stress at the mid-wrinkle represents the stress at point C (i.e. the last node along the mid-wrinkle). The specified locations are labeled in Figure 5.6 of Chapter 5. In Table B.3 and Figure B.3, the displacement values correspond to a full wrinkle (i.e. the other half of the wrinkle is accounted for by doubling displacements calculated in the circumferential direction).
B.5. 2 Effect of Spring Stiffness

A numerical analysis was performed to investigate the effect of changes in the spring stiffness on four parameters. The average force/width value and the resultant displacement at section AA, the critical stress at mid-wrinkle, and the average vertical displacement along the location of the springs were the four parameters investigated. A summary of the results for this analysis is presented in Tables B.2 to B.5. The values in the tables are plotted in Figures B.2 to B.5. The study showed that at a spring stiffness value greater than or equal to 16000 N/mm, there was no significant change in each of the four parameters. The average vertical displacement along the location of the springs was also negligible at these spring stiffnesses. Thus, a spring stiffness of 16000 N/mm was chosen for use in subsequent analyses.

B.5. 3 Effect of Number of Load Steps

A numerical analysis was conducted to evaluate the effect of changes in the number of load steps on four parameters. The four parameters were the same as that stated in Section B.5.2. A spring stiffness of 16000 N/mm was used for the analysis. A stress of 9.35 MPa was applied over 10 and 100 load steps. A summary of the results for this analysis is presented in Table B.6. The study showed that for the given applied stress, the number of load steps had no significant effect on the four parameters investigated. Thus, a total of 10 load steps was chosen to increase computational efficiency.
B. 6 CONVERGENCE STUDY FOR WRINKLE TYPE 2

A convergence study similar to that conducted for the two dimensional model of the wrinkle in sample IW-5 (wrinkle type 1), was conducted for a two dimensional model of the wrinkle in test sample SW-1 (wrinkle type 2). The purpose of the study was to determine the stiffness of the spring elements used, and the number of load steps to use for the numerical analysis. The finite element model was constructed such that its dimensions were similar to that of the wrinkle in test sample SW-1. One half of the wrinkle in sample SW-1 was constructed for the study.

The properties of the three constituents of the liner were similar to that described in Section B.3.1. However, both polyester jackets had a thickness of 0.17 mm, and the Young’s modulus of each jacket was modified to account for the chosen thickness. The geometry of the wrinkle in the actual test sample and in the finite element model is shown in Figure B.6. A labeled model of the wrinkle is shown in Figure 5.22 of Chapter 5. Figure B.7 shows the finite element mesh that was used for the analysis. The location of the springs in the model is shown in Figure 5.23 of Chapter 5. The dimensions of the wrinkle are summarized in Table B.7. A stress, $p$ of 14.32 MPa was applied in the analysis. This stress corresponded to a load value recorded prior to the first cracking of the resin within wrinkle type 2. Calculations that show how the applied stress of 14.32 MPa, and the jacket thickness of 0.17 mm were determined, are presented in Section C.3 of Appendix C.
The results from the convergence study are summarized in Tables B.8 to B.12 and Figures B.8 to B.11. In the Tables and Figures, Section AA refers to the location where the stress of 14.32 MPa was applied. The critical stress at the mid-wrinkle represents the stress at point C (i.e. the last node along the mid-wrinkle). The specified locations are labeled in Figure B.7. In Table B.9 and Figure B.9, the displacement values correspond to a full wrinkle (i.e. the other half of the wrinkle is accounted for by doubling displacements calculated in the circumferential direction).

The study showed that at a spring stiffness value greater than or equal to 16000 N/mm, there was no significant change in each of the four parameters investigated. The average vertical displacement along the location of the springs was also negligible at these spring stiffnesses. Thus, a spring stiffness of 16000 N/mm was chosen for use in subsequent analyses. An analysis was also conducted to evaluate the effect of changes in the number of load steps on the four parameters investigated. A spring stiffness of 16000 N/mm was used for the analysis. A stress of 14.32 MPa was applied over 15 and 100 load steps. A summary of the results for this analysis is presented in Table B.12. The study showed that for the given applied stress, the number of load steps had no significant effect on the four parameters investigated. Thus, a total of 15 load steps was chosen to increase computational efficiency.
Table B. 1: Dimensions of wrinkle type 1

<table>
<thead>
<tr>
<th></th>
<th>Finite element model</th>
<th>Test sample IW-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>75</td>
<td>75.25</td>
</tr>
<tr>
<td>Thickness at mid-wrinkle, amplitude (mm)</td>
<td>15.3</td>
<td>15.29</td>
</tr>
<tr>
<td>Thickness at location of applied stress, $p$ (mm)</td>
<td>4.6</td>
<td>4.55</td>
</tr>
</tbody>
</table>

Table B. 2: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 1

<table>
<thead>
<tr>
<th>Spring Stiffness (N/mm)</th>
<th>Force/width (N/mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.01645169</td>
<td>13.2072</td>
</tr>
<tr>
<td>2</td>
<td>42.04101785</td>
<td>13.1565</td>
</tr>
<tr>
<td>4</td>
<td>42.08922290</td>
<td>13.0569</td>
</tr>
<tr>
<td>8</td>
<td>42.18295870</td>
<td>12.8633</td>
</tr>
<tr>
<td>15.625</td>
<td>42.35213247</td>
<td>12.5138</td>
</tr>
<tr>
<td>31.25</td>
<td>42.66490002</td>
<td>11.8678</td>
</tr>
<tr>
<td>62.5</td>
<td>43.18498368</td>
<td>10.7934</td>
</tr>
<tr>
<td>125</td>
<td>43.95246588</td>
<td>9.2081</td>
</tr>
<tr>
<td>250</td>
<td>44.92709782</td>
<td>7.1948</td>
</tr>
<tr>
<td>500</td>
<td>45.96905463</td>
<td>5.0424</td>
</tr>
<tr>
<td>1000</td>
<td>46.89088586</td>
<td>3.1382</td>
</tr>
<tr>
<td>2000</td>
<td>47.56203798</td>
<td>1.7518</td>
</tr>
<tr>
<td>4000</td>
<td>47.97241468</td>
<td>0.9041</td>
</tr>
<tr>
<td>5000</td>
<td>48.06008666</td>
<td>0.7230</td>
</tr>
<tr>
<td>6000</td>
<td>48.11911715</td>
<td>0.6011</td>
</tr>
<tr>
<td>7000</td>
<td>48.16153811</td>
<td>0.5134</td>
</tr>
<tr>
<td>8000</td>
<td>48.19341977</td>
<td>0.4476</td>
</tr>
<tr>
<td>9000</td>
<td>48.21821136</td>
<td>0.3964</td>
</tr>
<tr>
<td>10000</td>
<td>48.23795643</td>
<td>0.3556</td>
</tr>
<tr>
<td>11000</td>
<td>48.25409049</td>
<td>0.3223</td>
</tr>
<tr>
<td>12000</td>
<td>48.26758401</td>
<td>0.2944</td>
</tr>
<tr>
<td>13000</td>
<td>48.27885637</td>
<td>0.2711</td>
</tr>
<tr>
<td>14000</td>
<td>48.28863176</td>
<td>0.2509</td>
</tr>
<tr>
<td>15000</td>
<td>48.29693145</td>
<td>0.2338</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>48.30432952</strong></td>
<td><strong>0.2185</strong></td>
</tr>
<tr>
<td>32000</td>
<td>48.35877204</td>
<td>0.1060</td>
</tr>
<tr>
<td>64000</td>
<td>48.38549441</td>
<td>0.0508</td>
</tr>
<tr>
<td>128000</td>
<td>48.39861324</td>
<td>0.0237</td>
</tr>
<tr>
<td>256000</td>
<td>48.40518339</td>
<td>0.0101</td>
</tr>
<tr>
<td>512000</td>
<td>48.40849554</td>
<td>0.0033</td>
</tr>
<tr>
<td>1024000</td>
<td>48.41009223</td>
<td>0</td>
</tr>
</tbody>
</table>
Table B. 3: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 1

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Average resultant displacement (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.886649739</td>
<td>1005.1774</td>
</tr>
<tr>
<td>2</td>
<td>0.454751391</td>
<td>466.8315</td>
</tr>
<tr>
<td>4</td>
<td>0.243367913</td>
<td>203.3495</td>
</tr>
<tr>
<td>8</td>
<td>0.144796200</td>
<td>80.4833</td>
</tr>
<tr>
<td>15.625</td>
<td>0.104369252</td>
<td>30.0926</td>
</tr>
<tr>
<td>31.25</td>
<td>0.088704096</td>
<td>10.5665</td>
</tr>
<tr>
<td>62.5</td>
<td>0.083329591</td>
<td>3.8674</td>
</tr>
<tr>
<td>125</td>
<td>0.081440522</td>
<td>1.5127</td>
</tr>
<tr>
<td>250</td>
<td>0.080733617</td>
<td>0.6316</td>
</tr>
<tr>
<td>500</td>
<td>0.080452157</td>
<td>0.2808</td>
</tr>
<tr>
<td>1000</td>
<td>0.080332843</td>
<td>0.1320</td>
</tr>
<tr>
<td>2000</td>
<td>0.080278800</td>
<td>0.0647</td>
</tr>
<tr>
<td>4000</td>
<td>0.080252887</td>
<td>0.0324</td>
</tr>
<tr>
<td>5000</td>
<td>0.080247722</td>
<td>0.0259</td>
</tr>
<tr>
<td>6000</td>
<td>0.080244278</td>
<td>0.0216</td>
</tr>
<tr>
<td>7000</td>
<td>0.080241817</td>
<td>0.0186</td>
</tr>
<tr>
<td>8000</td>
<td>0.080239957</td>
<td>0.0163</td>
</tr>
<tr>
<td>9000</td>
<td>0.080238478</td>
<td>0.0144</td>
</tr>
<tr>
<td>10000</td>
<td>0.080237348</td>
<td>0.0130</td>
</tr>
<tr>
<td>11000</td>
<td>0.080236400</td>
<td>0.0118</td>
</tr>
<tr>
<td>12000</td>
<td>0.080235617</td>
<td>0.0108</td>
</tr>
<tr>
<td>13000</td>
<td>0.080234948</td>
<td>0.0100</td>
</tr>
<tr>
<td>14000</td>
<td>0.080234374</td>
<td>0.0093</td>
</tr>
<tr>
<td>15000</td>
<td>0.080233852</td>
<td>0.0086</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>0.080233417</strong></td>
<td><strong>0.0081</strong></td>
</tr>
<tr>
<td>32000</td>
<td>0.080230130</td>
<td>0.0040</td>
</tr>
<tr>
<td>64000</td>
<td>0.080228504</td>
<td>0.0020</td>
</tr>
<tr>
<td>128000</td>
<td>0.080227643</td>
<td>0.0009</td>
</tr>
<tr>
<td>256000</td>
<td>0.080227209</td>
<td>0.0004</td>
</tr>
<tr>
<td>512000</td>
<td>0.080227000</td>
<td>0.0001</td>
</tr>
<tr>
<td>1024000</td>
<td>0.080226913</td>
<td>0</td>
</tr>
</tbody>
</table>
Table B. 4: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 1

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Critical stress at mid-wrinkle (MPa)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.48843</td>
<td>1.3967</td>
</tr>
<tr>
<td>2</td>
<td>7.48752</td>
<td>1.3844</td>
</tr>
<tr>
<td>4</td>
<td>7.48574</td>
<td>1.3603</td>
</tr>
<tr>
<td>8</td>
<td>7.48235</td>
<td>1.3144</td>
</tr>
<tr>
<td>15.625</td>
<td>7.47642</td>
<td>1.2341</td>
</tr>
<tr>
<td>31.25</td>
<td>7.46611</td>
<td>1.0945</td>
</tr>
<tr>
<td>62.5</td>
<td>7.45077</td>
<td>0.8868</td>
</tr>
<tr>
<td>125</td>
<td>7.43192</td>
<td>0.6315</td>
</tr>
<tr>
<td>250</td>
<td>7.41373</td>
<td>0.3852</td>
</tr>
<tr>
<td>500</td>
<td>7.40016</td>
<td>0.2015</td>
</tr>
<tr>
<td>1000</td>
<td>7.39213</td>
<td>0.0928</td>
</tr>
<tr>
<td>2000</td>
<td>7.38817</td>
<td>0.0391</td>
</tr>
<tr>
<td>4000</td>
<td>7.38646</td>
<td>0.0160</td>
</tr>
<tr>
<td>5000</td>
<td>7.38617</td>
<td>0.0121</td>
</tr>
<tr>
<td>6000</td>
<td>7.38598</td>
<td>0.0095</td>
</tr>
<tr>
<td>7000</td>
<td>7.38586</td>
<td>0.0079</td>
</tr>
<tr>
<td>8000</td>
<td>7.38577</td>
<td>0.0066</td>
</tr>
<tr>
<td>9000</td>
<td>7.38571</td>
<td>0.0058</td>
</tr>
<tr>
<td>10000</td>
<td>7.38565</td>
<td>0.0050</td>
</tr>
<tr>
<td>11000</td>
<td>7.38561</td>
<td>0.0045</td>
</tr>
<tr>
<td>12000</td>
<td>7.38558</td>
<td>0.0041</td>
</tr>
<tr>
<td>13000</td>
<td>7.38555</td>
<td>0.0037</td>
</tr>
<tr>
<td>14000</td>
<td>7.38553</td>
<td>0.0034</td>
</tr>
<tr>
<td>15000</td>
<td>7.38551</td>
<td>0.0031</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>7.38549</strong></td>
<td><strong>0.0028</strong></td>
</tr>
<tr>
<td>32000</td>
<td>7.38538</td>
<td>0.0014</td>
</tr>
<tr>
<td>64000</td>
<td>7.38532</td>
<td>0.0005</td>
</tr>
<tr>
<td>128000</td>
<td>7.38530</td>
<td>0.0003</td>
</tr>
<tr>
<td>256000</td>
<td>7.38529</td>
<td>0.0001</td>
</tr>
<tr>
<td>512000</td>
<td>7.38528</td>
<td>0.0000</td>
</tr>
<tr>
<td>1024000</td>
<td>7.38528</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
Table B. 5: Effect of changes in spring stiffness on vertical displacement along location of springs in wrinkle type 1

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Average vertical displacement (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.435269154</td>
<td>598498.3044</td>
</tr>
<tr>
<td>2</td>
<td>0.217626308</td>
<td>299187.7800</td>
</tr>
<tr>
<td>4</td>
<td>0.108805897</td>
<td>149533.9107</td>
</tr>
<tr>
<td>8</td>
<td>0.054397808</td>
<td>74709.8852</td>
</tr>
<tr>
<td>15.625</td>
<td>0.027850259</td>
<td>38200.7104</td>
</tr>
<tr>
<td>31.25</td>
<td>0.013929738</td>
<td>19056.6936</td>
</tr>
<tr>
<td>62.5</td>
<td>0.006978152</td>
<td>9496.6131</td>
</tr>
<tr>
<td>125</td>
<td>0.003512050</td>
<td>4729.9012</td>
</tr>
<tr>
<td>250</td>
<td>0.001786897</td>
<td>2357.4070</td>
</tr>
<tr>
<td>500</td>
<td>0.000928722</td>
<td>1177.2131</td>
</tr>
<tr>
<td>1000</td>
<td>0.000501140</td>
<td>589.1861</td>
</tr>
<tr>
<td>2000</td>
<td>0.000287436</td>
<td>295.2933</td>
</tr>
<tr>
<td>4000</td>
<td>0.000180293</td>
<td>147.9459</td>
</tr>
<tr>
<td>5000</td>
<td>0.000158798</td>
<td>118.3842</td>
</tr>
<tr>
<td>6000</td>
<td>0.000144447</td>
<td>98.6483</td>
</tr>
<tr>
<td>7000</td>
<td>0.000134184</td>
<td>84.5347</td>
</tr>
<tr>
<td>8000</td>
<td>0.000126479</td>
<td>73.9389</td>
</tr>
<tr>
<td>9000</td>
<td>0.000120482</td>
<td>65.6910</td>
</tr>
<tr>
<td>10000</td>
<td>0.000115680</td>
<td>59.0881</td>
</tr>
<tr>
<td>11000</td>
<td>0.000111750</td>
<td>53.6824</td>
</tr>
<tr>
<td>12000</td>
<td>0.000108472</td>
<td>49.1752</td>
</tr>
<tr>
<td>13000</td>
<td>0.000105698</td>
<td>45.3595</td>
</tr>
<tr>
<td>14000</td>
<td>0.000103319</td>
<td>42.0877</td>
</tr>
<tr>
<td>15000</td>
<td>0.000101256</td>
<td>39.2510</td>
</tr>
<tr>
<td>16000</td>
<td><strong>0.000099451</strong></td>
<td><strong>36.7682</strong></td>
</tr>
<tr>
<td>32000</td>
<td>0.000085890</td>
<td>18.1192</td>
</tr>
<tr>
<td>64000</td>
<td>0.000079095</td>
<td>8.7746</td>
</tr>
<tr>
<td>128000</td>
<td>0.000075694</td>
<td>4.0967</td>
</tr>
<tr>
<td>256000</td>
<td>0.000073992</td>
<td>1.7561</td>
</tr>
<tr>
<td>512000</td>
<td>0.000073140</td>
<td>0.5855</td>
</tr>
<tr>
<td>1024000</td>
<td>0.000072715</td>
<td>0</td>
</tr>
</tbody>
</table>
Table B. 6: Effect of number of load steps on results for wrinkle type 1

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Force/width at section AA (N/mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>48.30432952</td>
<td>0.00012577</td>
</tr>
<tr>
<td>100</td>
<td>48.30426876</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Avg. resultant displacement at section AA (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.080233417</td>
<td>0.00004335</td>
</tr>
<tr>
<td>100</td>
<td>0.080233452</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Critical stress at mid-wrinkle (MPa)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.38549</td>
<td>0.00027080</td>
</tr>
<tr>
<td>100</td>
<td>7.38551</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Avg. vertical displacement(^1) (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.000099451</td>
<td>0.00054660</td>
</tr>
<tr>
<td>100</td>
<td>0.000099450</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^1\) The average vertical displacement along the location of the springs
Table B. 7: Dimensions of wrinkle type 2

<table>
<thead>
<tr>
<th></th>
<th>Finite element model</th>
<th>Test sample SW-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius of ring sample (mm)</td>
<td>77</td>
<td>76.71</td>
</tr>
<tr>
<td>Thickness at mid-wrinkle, amplitude (mm)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Thickness at location of applied stress, p (mm)</td>
<td>4.4</td>
<td>4.43</td>
</tr>
</tbody>
</table>

Table B. 8: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 2

<table>
<thead>
<tr>
<th>Spring Stiffness (N/mm)</th>
<th>Force/width (N/mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.66829091</td>
<td>11.7144</td>
</tr>
<tr>
<td>2</td>
<td>59.68266325</td>
<td>11.6932</td>
</tr>
<tr>
<td>4</td>
<td>59.71158526</td>
<td>11.6504</td>
</tr>
<tr>
<td>8</td>
<td>59.76849060</td>
<td>11.5662</td>
</tr>
<tr>
<td>15.625</td>
<td>59.87431159</td>
<td>11.4096</td>
</tr>
<tr>
<td>31.25</td>
<td>60.08153524</td>
<td>11.1030</td>
</tr>
<tr>
<td>62.5</td>
<td>60.46112466</td>
<td>10.5414</td>
</tr>
<tr>
<td>125</td>
<td>61.10446696</td>
<td>9.5895</td>
</tr>
<tr>
<td>250</td>
<td>62.07244283</td>
<td>8.1572</td>
</tr>
<tr>
<td>500</td>
<td>63.30722763</td>
<td>6.3302</td>
</tr>
<tr>
<td>1000</td>
<td>64.60418085</td>
<td>4.4113</td>
</tr>
<tr>
<td>2000</td>
<td>65.71816394</td>
<td>2.7630</td>
</tr>
<tr>
<td>4000</td>
<td>66.51575234</td>
<td>1.5829</td>
</tr>
<tr>
<td>8000</td>
<td>67.01055214</td>
<td>0.8508</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>67.28898629</strong></td>
<td><strong>0.4388</strong></td>
</tr>
<tr>
<td>32000</td>
<td>67.43683142</td>
<td>0.2201</td>
</tr>
<tr>
<td>64000</td>
<td>67.51297843</td>
<td>0.1074</td>
</tr>
<tr>
<td>128000</td>
<td>67.55159189</td>
<td>0.0503</td>
</tr>
<tr>
<td>256000</td>
<td>67.57084797</td>
<td>0.0218</td>
</tr>
<tr>
<td>512000</td>
<td>67.58068437</td>
<td>0.0072</td>
</tr>
<tr>
<td>1024000</td>
<td>67.58556158</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

234
Table B. 9: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 2

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Average resultant displacement (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.208759677</td>
<td>1475.9984</td>
</tr>
<tr>
<td>2</td>
<td>0.612926194</td>
<td>699.1421</td>
</tr>
<tr>
<td>4</td>
<td>0.318337032</td>
<td>315.0524</td>
</tr>
<tr>
<td>8</td>
<td>0.176796355</td>
<td>130.5097</td>
</tr>
<tr>
<td>15.625</td>
<td>0.115285084</td>
<td>50.3104</td>
</tr>
<tr>
<td>31.25</td>
<td>0.090125419</td>
<td>17.5068</td>
</tr>
<tr>
<td>62.5</td>
<td>0.081479335</td>
<td>6.2339</td>
</tr>
<tr>
<td>125</td>
<td>0.078566368</td>
<td>2.4360</td>
</tr>
<tr>
<td>250</td>
<td>0.077512310</td>
<td>1.0617</td>
</tr>
<tr>
<td>500</td>
<td>0.077087000</td>
<td>0.5072</td>
</tr>
<tr>
<td>1000</td>
<td>0.076895503</td>
<td>0.2575</td>
</tr>
<tr>
<td>2000</td>
<td>0.076801187</td>
<td>0.1345</td>
</tr>
<tr>
<td>4000</td>
<td>0.076752142</td>
<td>0.0706</td>
</tr>
<tr>
<td>8000</td>
<td>0.076726090</td>
<td>0.0366</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>0.076712342</strong></td>
<td><strong>0.0187</strong></td>
</tr>
<tr>
<td>32000</td>
<td>0.076705181</td>
<td>0.0093</td>
</tr>
<tr>
<td>64000</td>
<td>0.076701529</td>
<td>0.0046</td>
</tr>
<tr>
<td>128000</td>
<td>0.076699665</td>
<td>0.0021</td>
</tr>
<tr>
<td>256000</td>
<td>0.076698716</td>
<td>0.0009</td>
</tr>
<tr>
<td>512000</td>
<td>0.076698277</td>
<td>0.0003</td>
</tr>
</tbody>
</table>
| 1024000                | 0.076698026                        | 0           
Table B. 10: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 2

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Critical stress at mid-wrinkle (MPa)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.9803</td>
<td>-0.6114</td>
</tr>
<tr>
<td>2</td>
<td>59.9777</td>
<td>-0.6071</td>
</tr>
<tr>
<td>4</td>
<td>59.9728</td>
<td>-0.5988</td>
</tr>
<tr>
<td>8</td>
<td>59.9630</td>
<td>-0.5824</td>
</tr>
<tr>
<td>15.625</td>
<td>59.9454</td>
<td>-0.5529</td>
</tr>
<tr>
<td>31.25</td>
<td>59.9125</td>
<td>-0.4977</td>
</tr>
<tr>
<td>62.5</td>
<td>59.8574</td>
<td>-0.4053</td>
</tr>
<tr>
<td>125</td>
<td>59.7780</td>
<td>-0.2721</td>
</tr>
<tr>
<td>250</td>
<td>59.6866</td>
<td>-0.1188</td>
</tr>
<tr>
<td>500</td>
<td>59.6105</td>
<td>0.0089</td>
</tr>
<tr>
<td>1000</td>
<td>59.5707</td>
<td>0.0757</td>
</tr>
<tr>
<td>2000</td>
<td>59.5645</td>
<td>0.0861</td>
</tr>
<tr>
<td>4000</td>
<td>59.5755</td>
<td>0.0676</td>
</tr>
<tr>
<td>8000</td>
<td>59.5896</td>
<td>0.0439</td>
</tr>
<tr>
<td>16000</td>
<td><strong>59.6007</strong></td>
<td><strong>0.0253</strong></td>
</tr>
<tr>
<td>32000</td>
<td>59.6077</td>
<td>0.0136</td>
</tr>
<tr>
<td>64000</td>
<td>59.6117</td>
<td>0.0069</td>
</tr>
<tr>
<td>128000</td>
<td>59.6139</td>
<td>0.0032</td>
</tr>
<tr>
<td>256000</td>
<td>59.6150</td>
<td>0.0013</td>
</tr>
<tr>
<td>512000</td>
<td>59.6155</td>
<td>0.0005</td>
</tr>
<tr>
<td>1024000</td>
<td>59.6158</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
Table B. 11: Effect of changes in spring stiffness on vertical displacement along location of springs in wrinkle type 2

<table>
<thead>
<tr>
<th>Spring stiffness (N/mm)</th>
<th>Average vertical displacement (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.598138609</td>
<td>2043478.4255</td>
</tr>
<tr>
<td>2</td>
<td>0.299043739</td>
<td>1021601.8675</td>
</tr>
<tr>
<td>4</td>
<td>0.149496652</td>
<td>510664.7770</td>
</tr>
<tr>
<td>8</td>
<td>0.074723517</td>
<td>255197.6280</td>
</tr>
<tr>
<td>15.625</td>
<td>0.038235104</td>
<td>130532.6547</td>
</tr>
<tr>
<td>31.25</td>
<td>0.019095300</td>
<td>65140.3014</td>
</tr>
<tr>
<td>62.5</td>
<td>0.009528343</td>
<td>32454.1873</td>
</tr>
<tr>
<td>125</td>
<td>0.004749533</td>
<td>16127.0803</td>
</tr>
<tr>
<td>250</td>
<td>0.002366554</td>
<td>7985.4813</td>
</tr>
<tr>
<td>500</td>
<td>0.001182325</td>
<td>3939.4888</td>
</tr>
<tr>
<td>1000</td>
<td>0.000596728</td>
<td>1938.7577</td>
</tr>
<tr>
<td>2000</td>
<td>0.000308484</td>
<td>953.9557</td>
</tr>
<tr>
<td>4000</td>
<td>0.000166869</td>
<td>470.1192</td>
</tr>
<tr>
<td>8000</td>
<td>0.000097185</td>
<td>232.0385</td>
</tr>
<tr>
<td><strong>16000</strong></td>
<td><strong>0.000062767</strong></td>
<td><strong>114.4478</strong></td>
</tr>
<tr>
<td>32000</td>
<td>0.000045698</td>
<td>56.1289</td>
</tr>
<tr>
<td>64000</td>
<td>0.000037204</td>
<td>27.1101</td>
</tr>
<tr>
<td>128000</td>
<td>0.000032969</td>
<td>12.6394</td>
</tr>
<tr>
<td>256000</td>
<td>0.000030854</td>
<td>5.4143</td>
</tr>
<tr>
<td>512000</td>
<td>0.000029797</td>
<td>1.8042</td>
</tr>
<tr>
<td>1024000</td>
<td>0.000029269</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
Table B. 12: Effect of number of load steps on results for wrinkle type 2

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Force/width at section AA (N/mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>67.28898629</td>
<td>0.00013323</td>
</tr>
<tr>
<td>100</td>
<td>67.28889664</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Avg. resultant displacement at section AA (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.076712342</td>
<td>0.00000841</td>
</tr>
<tr>
<td>100</td>
<td>0.076712335</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Critical stress at mid-wrinkle (MPa)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>59.6007</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>59.6007</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of load steps</th>
<th>Avg. vertical displacement¹ (mm)</th>
<th>% Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.0000627671</td>
<td>0.00032002</td>
</tr>
<tr>
<td>100</td>
<td>0.0000627673</td>
<td>0</td>
</tr>
</tbody>
</table>

¹ The average vertical displacement along the location of the springs
Figure B. 1: (a) Wrinkle in test sample IW-5, (b) Finite element model of one half of the wrinkle in sample IW-5

Figure B. 2: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 1
Figure B. 3: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 1

Figure B. 4: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 1
Figure B. 5: Effect of changes in spring stiffness on average vertical displacement along location of springs in wrinkle type 1

Figure B. 6: (a) Wrinkle in test sample SW-1, (b) Finite element model of one half of the wrinkle in sample SW-1
Figure B. 7: Finite element mesh of wrinkle type 2

Figure B. 8: Effect of changes in spring stiffness on average force/width value at section AA of wrinkle type 2
Figure B. 9: Effect of changes in spring stiffness on average resultant displacement at section AA of wrinkle type 2

Figure B. 10: Effect of changes in spring stiffness on critical stress at line of symmetry in wrinkle type 2
Figure B. 11: Effect of changes in spring stiffness on average vertical displacement along location of springs in wrinkle type 2
C. 1 INTRODUCTION

In each of the numerical analyses conducted to evaluate the behavior of wrinkle types 1 and 2, a stress was applied over a number of load steps. The applied stresses corresponded to load values recorded during the laboratory testing of two ring samples of the liner. In the next sections, calculations that show how the applied stress values were determined are presented. In the finite element models, the inner and outer jackets of the liner were represented as solid materials with uniform properties over their thicknesses. To approximate the jackets (which had the same thickness) as uniform solids, there was the need to assign a representative jacket thickness and Young’s moduli. The assigned jacket thickness and Young’s moduli were calculated using results from the direct uniaxial tension tests conducted by Brown et al. (2007). Calculations that show how the assigned jacket thicknesses and Young’s moduli were determined are also presented in the next sections.

C. 2 WRINKLE TYPE 1

C.2. 1 Determining applied stress, $p$

- In the laboratory, half of the total load recorded at the first cracking of the resin is approximately 43 N/mm at the wrinkled springline

- The force value of 43 N/mm is obtained by dividing the total load recorded by 2, and then by the sample width at the wrinkled springline in sample IW-5
- The linear section of the load-average displacement graph up to first cracking of the resin is used for the determination of the force of 43 N/mm. The non-linear section of the graph at the start of loading is ignored (see Figure A.7 (b) of Appendix A).
- A unit width is considered in all the numerical analyses.

In the equations below,

\[
\text{thickness} = \text{thickness at section AA where the stress, } p \text{ is applied} = 4.6 \text{ mm (based on sample IW-5)}
\]

At the first cracking of the resin, at mid-wrinkle of the finite element model

\[
\text{Stress, } p = \frac{\text{force}}{\text{area}} = \frac{\text{force}}{\text{width} \times \text{thickness}}
\]

\[
\frac{\text{force}}{\text{width}} = \text{Stress} \times \text{thickness}
\]

\[
43 \frac{N}{\text{mm}} = \text{Stress} \times 4.6 \text{ mm}
\]

\[
\text{Stress, } p = 9.35 \text{ MPa}
\]

**C.2.2 Determining representative jacket thickness for analysis**

In the calculation below, the variables in the equations are defined as follows:

\[x = \text{thickness of resin at section AA}\]

\[y = \text{thickness of outer or inner polyester jacket at section AA}\]
\[ t_4 = \text{total thickness of liner at section AA (based on sample IW-5)} = 4.6 \text{ mm} \]

\[
\begin{align*}
Force &= \sum_{i=1}^{3} \sigma_i t_i = \sum_{i=1}^{3} E_i (\varepsilon \cdot t_i) = \varepsilon \sum_{i=1}^{3} E_i t_i = \varepsilon E t \\
\varepsilon E_i t_i &= \text{force per unit width of inner jacket} \\
\varepsilon E_i t_2 &= \text{force per unit width of outer jacket} \\
\varepsilon E_i t_3 &= \text{force per unit width of resin} \\
\varepsilon E_i t_4 &= \text{force per unit width of fabricated composite liner}
\end{align*}
\]

\[
\begin{align*}
\varepsilon E_i t_4 &= \varepsilon \left( E_1 t_1 + E_2 t_2 + E_3 t_3 \right) \\
3040 \frac{N}{mm^2} \times 4.6mm &= 1530 \frac{N}{mm} + 2270 \frac{N}{mm} + \left( 2356 \frac{N}{mm^2} \cdot x(mm) \right) \\
x (\text{thickness of resin}) &= 4.32mm
\end{align*}
\]

\[ t_4 = x + 2y \]
\[ 4.6mm = 4.32mm + 2y \]
\[ y (\text{thickness of outer or inner polyester jacket}) = 0.14mm \]

**C.2. 3 Determining Young’s moduli of jackets**

- **Young’s modulus of inner jacket** (\( E_{\text{inner jacket}} \))

  Circumferential tensile stiffness = 1530 N/mm

  \[ y (\text{thickness of inner jacket}) = 0.14 \text{ mm} \]

  \[
  E_{\text{inner jacket}} = \frac{\text{Circumferential tensile stiffness}}{y(\text{thickness of inner jacket})}
  \]
\[
\frac{1530 N / mm}{0.14 mm} = 10929 MPa
\]

\[E_{\text{inner jacket}} = 10929 MPa\]

- **Young’s modulus of outer jacket** \((E_{\text{outer jacket}})\)

  Circumferential tensile stiffness = 2270 N/mm

  \[y \text{ (thickness of outer jacket)} = 0.14 \text{ mm}\]

  \[E_{\text{outer jacket}} = \frac{\text{Circumferential tensile stiffness}}{y \text{(thickness of outer jacket)}}\]

  \[= \frac{2270 N / mm}{0.14 mm} = \frac{2270 N / mm}{0.14 mm}\]

  \[E_{\text{outer jacket}} = 16214 MPa\]

**C. 3 WRINKLE TYPE 2**

**C.3. 1 Determining applied stress, \(p\)**

- The stress applied in the analysis of wrinkle type two corresponds to the highest total load recorded in the first linear section that follows the nonlinear section at the start of the loading, in the load-average displacement graph for sample SW-1 (see Figure A.9 (b) of Appendix A)
- In the laboratory, half of this total load is approximately 63 N/mm at the wrinkled springline.

- The force value of 63 N/mm is obtained by dividing the total load recorded by 2, and then by the sample width at the wrinkled springline in sample SW-1.

- This force is less than the force recorded at the first cracking of the resin.

- A unit width is considered in all the numerical analyses.

In the equations below,

\[
\text{thickness} = \text{thickness at section AA where the stress, } p \text{ is applied} = 4.4 \text{ mm (based on sample SW-1)}
\]

At mid-wrinkle of the finite element model

\[
\text{Stress, } p = \frac{\text{force}}{\text{area}}
\]

\[
= \frac{\text{force}}{\text{width} \times \text{thickness}}
\]

\[
\frac{\text{force}}{\text{width}} = \text{Stress} \times \text{thickness}
\]

\[
63 \frac{N}{mm} = \text{Stress} \times 4.4 \text{ mm}
\]

\[
\text{Stress, } p = 14.32 \text{ MPa}
\]

**C.3.2 Determining representative jacket thickness for analysis**

In the calculation below, the variables in the equations are defined as follows:
\[ x = \text{thickness of resin at section AA} \]

\[ y = \text{thickness of outer or inner polyester jacket at section AA} \]

\[ t_4 = \text{total thickness of liner at section AA (based on sample SW-1)} = 4.4 \text{ mm} \]

\[ \text{Force} = \sum_{i=1}^{3} \sigma_i t_i = \sum_{i=1}^{3} E_i (\varepsilon_i \cdot t_i) = \varepsilon \sum_{i=1}^{3} E_i t_i = \varepsilon \overline{E} t \]

\[ \varepsilon E_i t_i = \text{force per unit width of inner jacket} \]

\[ \varepsilon E_i t_i = \text{force per unit width of outer jacket} \]

\[ \varepsilon E_i t_i = \text{force per unit width of resin} \]

\[ \varepsilon E_4 t_4 = \text{force per unit width of fabricated composite liner} \]

\[ \varepsilon E_4 t_4 = \varepsilon (E_i t_1 + E_2 t_2 + E_3 t_3) \]

\[ 3040 \frac{N \text{ mm}^2}{mm^2} \times 4.4 \text{ mm} = 1530 \frac{N \text{ mm}}{mm} + 2270 \frac{N \text{ mm}}{mm} + \left( 2356 \frac{N}{mm^2} \cdot x(mm) \right) \]

\[ x(\text{thickness of resin}) = 4.06 \text{ mm} \]

\[ t_4 = x + 2y \]

\[ 4.4 \text{ mm} = 4.06 \text{ mm} + 2y \]

\[ y(\text{thickness of outer or inner polyester jacket}) = 0.17 \text{ mm} \]

C.3.3 Determining Young’s moduli of jackets

- Young’s modulus of inner jacket (\( E_{\text{inner jacket}} \))

  Circumferential tensile stiffness = 1530 N/mm

  \[ y(\text{thickness of inner jacket}) = 0.17 \text{ mm} \]
\[ E_{\text{inner jacket}} = \frac{\text{Circumferential tensile stiffness}}{y(\text{thickness of inner jacket})} \]
\[ = \frac{1530 \text{ N/mm}}{0.17 \text{ mm}} \]

\[ E_{\text{inner jacket}} = 9000 \text{ MPa} \]

- **Young’s modulus of outer jacket** \((E_{\text{outer jacket}})\)

Circumferential tensile stiffness = 2270 N/mm

\[ y (\text{thickness of outer jacket}) = 0.17 \text{ mm} \]

\[ E_{\text{outer jacket}} = \frac{\text{Circumferential tensile stiffness}}{y(\text{thickness of outer jacket})} \]
\[ = \frac{2270 \text{ N/mm}}{0.17 \text{ mm}} \]

\[ E_{\text{outer jacket}} = 13353 \text{ MPa} \]
APPENDIX D

NUMERICAL RESULTS: STRESS AND DISPLACEMENT

CONTOURS
Figure D. 1: Stress contours for wrinkled model (type 1) with jacket thickness of 0.14 mm

Figure D. 2: Stress contours for wrinkled model (type 1) with jacket thickness of 0.3 mm
Figure D. 3: Stress contours for wrinkled model (type 1) with jacket thickness of 0.5 mm

Figure D. 4: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.14 mm
Figure D. 5: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.3 mm

Figure D. 6: Horizontal displacement contours for wrinkled model (type 1) with jacket thickness of 0.5 mm
Figure D. 7: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.14 mm

Figure D. 8: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.3 mm
Figure D. 9: Vertical displacement contours for wrinkled model (type 1) with jacket thickness of 0.5 mm

Figure D. 10: Stress contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1
Figure D. 11: Stress contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1

Figure D. 12: Stress contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1
Figure D. 13: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1

Figure D. 14: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1
Figure D. 15: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1

Figure D. 16: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.14 mm) for comparison with wrinkle type 1
Figure D. 17: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.3 mm) for comparison with wrinkle type 1

Figure D. 18: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.5 mm) for comparison with wrinkle type 1
Figure D. 19: Stress contours for wrinkled model (type 2) with jacket thickness of 0.17 mm

Figure D. 20: Stress contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2
Figure D. 21: Horizontal displacement contours for wrinkled model (type 2) with jacket thickness of 0.17 mm

Figure D. 22: Horizontal displacement contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2
Figure D. 23: Vertical displacement contours for wrinkled model (type 2) with jacket thickness of 0.17 mm

Figure D. 24: Vertical displacement contours of non-wrinkled model (with jacket thickness of 0.17 mm) for comparison with wrinkle type 2
Figure D. 25: Stress contours for wrinkled model (type 2) with jacket thickness of 0.14 mm

Figure D. 26: Horizontal displacement contours for wrinkled model (type 2) with jacket thickness of 0.14 mm
Figure D. 27: Vertical displacement contours for wrinkled model (type 2) with jacket thickness of 0.14 mm
APPENDIX E

NUMERICAL RESULTS: SUMMARY OF MATERIAL PROPERTIES
Table E. 1: Material properties of components of the composite liner and wrinkles

<table>
<thead>
<tr>
<th>Component of wrinkle</th>
<th>Wrinkle Type</th>
<th>Tensile stiffness (N/mm)</th>
<th>Polyester jacket thickness (mm)</th>
<th>Young’s Modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Yield stress (MPa)</th>
<th>Stress Strain increment (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner polyester jacket</td>
<td>1</td>
<td>1530</td>
<td>0.14</td>
<td>10929</td>
<td>0.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.30</td>
<td>5100</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td>3060</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Outer polyester jacket</td>
<td>1</td>
<td>2270</td>
<td>0.14</td>
<td>16214</td>
<td>0.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>0.30</td>
<td>7567</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td>4540</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Polymeric resin</td>
<td>1 &amp; 2</td>
<td>N/A</td>
<td>N/A</td>
<td>2356</td>
<td>0.3</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.022</td>
</tr>
</tbody>
</table>