NOMENCLATURE

GFRE	Glass Fiber Reinforced Epoxy
M_1	The first method of specimens manufacturing
M_2	The second method of specimens manufacturing
S-N curve	Conventional stress-log life fatigue curve
V_f	Fiber volume fraction
M	Applied bending moment
T	Applied torsional moment
M_m	Mean value of applied bending moment
M_a	Amplitude value of applied bending moment
T_m	Mean value of applied torsional moment
T_a	Amplitude value of applied torsional moment
P	The value of applied pressure
P_{max}	The maximum value of applied pressure
d_i	Inner diameter of the specimen
d_o	Outer diameter of the specimen
I	Second moment of area
J	Second polar second moment of area
ω	Angular velocity
θ	Fiber orientations angle
σ_x	Normal global stress component in (x) direction
σ_y	Normal global stress component in (y) direction
τ_{xy}	Global shear stress component in (x-y) plane
σ_b	Bending stress
σ_h	Hoop stress
σ_l	Longitudinal stress
σ_{max}	The maximum normal global stress component
σ_{min}	The minimum normal global stress component
σ_a	Amplitude normal global stress component
σ_m	Mean normal global stress component
σ_1	Local stress component in the fiber direction

obeikandl.com

σ_2	Local stress component in the perpendicular direction to the fiber
σ_3	Local shear stress component
S_U	Ultimate global static bending strength
S_{US}	Ultimate global static shear strength
S_H	Ultimate global static hoop strength
S_L	Ultimate global static longitudinal strength
S_f	Bending fatigue strength
F_1	Local strength in the fiber direction
F_2	Local strength in the perpendicular direction to the fiber
F_6	Local shear strength
F_{1t}	Local tension component in directions (1)
F_{1c}	Local compression component in directions (1)
F_{1t}	Local tension component in directions (2)
F_{1c}	Local compression component in directions (2)
N	Nuber of cycles to failure
SWT	The Smith-Watson-Topper parameter
Ψ	The modified fatigue strength ratio
R.D.	Relative damage
G.R.D.	Goodman's relative damage

oberkandl.com

TABLES OF CONTENTS

Acknowledgment
Abstract **i**
Nomenclature **iv**
Table of Contents **vi**
List of Tables **xii**
List of Figures **xviii**
1 Introduction **1**
1.1 Composite Materials History 1
1.2 Definition of Composite Materials 1
1.3 Classifications of composite Materials 2
1.3.1 Particulate composites 2
1.3.2 Flake composites 2
1.3.3 Fiber composites 3
1.4 Fibers and Matrix 3
1.4.1 Matrix Materials 3
1.4.2 Functions of a Matrix 4
1.4.3 Properties of a Matrix 4
1.4.4 General types of Matrix Materials 5
1.4.5 Fibers Materials 6
1.4.5.1 Functions of Fibers 6
1.4.6 General types of Fibers 6
1.5 The Mechanics Behavior of Composite Materials 7
1.5.1 Isotropic Material 7
1.5.2 Orthotropic Material 7
1.5.3 Anisotropic Material 7
1.6 Lamina and Laminates 8
1.7 Failure Modes of Composite Materials 9
1.7.1 Microcracking of the matrix 10

obeikandl.com

1.7.2 Fiber pull out and Debonding (separation of fibers &matrix) 11
1.7.3 Delamination 12
1.7.4 Breaking of fibers 12
1.8 Manufacture of Composite Materials 12
1.8.1 Open Mold Process 13
1.8.1.1 Wet Lay-up/Hand Lay-up 13
1.8.1.2 Spray Lay-up 13
1.8.1.3 Filament Winding 14
1.8.2 Closed Mold Process 15
1.8.2.1 Vacuum Bag Processing 15
1.8.2.2 Injection Molding 16
1.8.3 Continuous Processes 16
1.8.3.1 Pultrusion 16
1.9 Applications of composite Materials 17
1.9.1 Glass fiber reinforced epoxy (GFRE) pipes 17
1.10 Advantages and disadvantages of Composite Materials 19
1.10.1 Advantages of Composite Materials 19
1.10.2 Disadvantages of Composite Materials 20
2 Literature Review 21
2.1 Introduction 21
2.2 Fatigue Damage Model and Failure mechanisms of Composite pipes 21
2.3 Biaxial loading of Composite pipes 28
2.4 Fatigue behavior of GFRE Composite pipes 32
2.5 Factors Affecting the Fatigue Behavior of Composite Materials 34
2.5.1 Effect of Type of Loading 35
2.5.2 Effect of loading frequency 38
2.5.3 Effect of volume fraction Vf 39
2.5.4 Effect of fiber orientation 40
2.5.5 Effect of mean stress and stress ratio 43
2.5.6 Effect of Environmental factors 45
2.5.7 Effect of size and stress gradient 48
2.5.8 Effect of surface finish 49

obeikandl.com

2.5.9 Effect of Stress concentration 49
2.6 Fatigue failure criteria 49
2.7 The Smith-Watson-Topper (SWT) parameter 51
2.8 Fatigue Strength Ratio 54
2.9 Aim of The Present Work 56
3 Analytical study 58
3.1 Introduction 58
3.2 The Global Stress State 58
3.3 The local Stress State 60
3.3.1 The [0,90°]3s specimens 62
3.3.2 The $[\pm 45°]_{3s}$ specimens 62
3.3.3 The local stresses for completely reversed pure bending or completely reversed pure torsion moment 62
3.3.4 The local stresses for pure internal pressure (open and closed cylinder) 64
3.3.5 The local stresses for combined completely reversed bending plus internal pressure (open and closed cylinder) 64
3.4 Stresses description in multilayer thick-walled tube 65
3.4.1 Stress Calculations of the First Method of Manufacturing 66
3.4.2 Stress Calculations of the Second Method of Manufacturing 67
4 Experimental Work 70
4.1 Introduction 70
4.2 Test Specimens 70
4.2.1 Materials 70
4.2.2 Shape and dimensions 70
4.2.3 Thin/ Thick walled check 71
4.2.4 Specimens Manufacturing 72
4.2.4.1 First Manufacturing Method M_1 73
4.2.4.2 Second Manufacturing Method M_2 73
4.2.5 Specimens Closure System 74
4.3 Testing Machine 74
4.3.1 Load measuring system 75
4.3.2 Testing procedure 75

opelkanal.com

4.3.2.1 For pure bending and pure torsion moments test 75
4.3.2.2 For pure hydrostatic internal pressure test 76
4.3.2.3 For combined bending and internal pressure test 77
5 Test Results 83
5.1 Introduction 83
5.2 Static Tests 83
5.2.1 Pure Bending and Pure Torsion static Testes 83
5.2.2 Internal Pressure Tests 84
5.3 Fatigue Tests 85
5.3.1 The first group 85
5.3.1.1 Pure bending fatigue test 85
5.3.1.2 Pure Torsion fatigue test 88
5.3.2 The second group 91
5.3.2.1 The combined completely reversed bending and internal pressure 91
6 Discussions 99
6.1 Introduction 99
6.2 Effect of Fiber Orientation and Method of Manufacturing 99
6.2.1 Static tests 99
6.2.1.1 Effect of Fiber Orientation 99
6.2.1.2 Effect of manufacture method 104
6.2.1.3 Effect of hydraulic oil absorption 105
6.2.1.4 Static Failure Modes 105
6.2.2 Fatigue tests 108
6.2.2.1 Completely Reversed Pure Bending or Torsion Tests 108
6.2.2.1.1 Effect of Fiber Orientation 111
6.2.2.1.2 Effect of manufacture method 112
6.2.2.1.3 Failure Modes 114
6.2.2.2 Combined Completely Reversed Bending and Internal Pressure Tests 116
6.2.2.2.1 Effect of Fiber Orientation 122
6.2.2.2.2 Effect of manufacture method 123
6.2.2.2.3 Effect of Pressure ratio (P_r) 123

openkandil.com

6.2.2.2.4 Failure Modes 126
6.3 Effect of Mean Stress 128
6.4 Validity of SWT Parameter 137
6.4.1 Validity of modified SWT Parameter 139
6.5 Validity of Modified Fatigue Strength Ratio (Ψ) 145
6.6 Applicability of failure criteria 148
6.6.1 Selecting Suitable Failure Criteria 148
6.6.2 Failure Criteria for The Present Work 149
6.6.3 The relative damage for $[0,90°]_{3s}$ specimens 149
6.6.4 The relative damage for $[\pm 45°]_{3s}$ specimens 150
6.6.5 Modification of Failure Criteria 158
6.6.5.1 The main principals for selecting the new term 162
6.6.6 Confirmation of Modified Failure Criteria 164
7 Artificial Neural Network 173
7.1 Introduction 173
7.2 The Key Elements of Neural Networks 174
7.3 Training methods 175
7.3.1 Supervised learning 175
7.3.2 Unsupervised learning 176
7.4 Network Architectures 176
7.4.1 Single Layer of Neurons 176
7.4.2 Multiple Layers of Neurons 176
7.5 Mean Square Error 177
7.6 Neural Networks in the Field of fatigue failure of Composite Materials 178
7.7 Neural network to study the effect of Pressure ratio 180
7.7.1 A feed-forward Neural Network, FFNN 180
7.7.2 Generalized regression Neural Network, GRNN 186
7.7.3 Radial Basis Neural Network, RBNN 191
7.8 Neural System Validation and Reliability 195
7.9 Conclusion 196
7.10 The Use Present Artificial Neural Network in Predicting Non-experimental Data 197

openkandi.com

8 Conclusions & Suggestions for future work **203**
8.1 Conclusions 203
8.2 Suggestions for Future Work 204
References **206**
Appendix (1): Specimens Code **221**
Appendix (2) The Failure Modes **222**
Appendix (3): Tables of Results and Calibration **242**
Appendix (4): Stresses in thick walled and multilayer tubes **273**

Obeikandl.com

LIST OF TABLES

Table 3.1: The local stresses for completely reversed pure bending 63

Table 3.2: The local stresses for completely reversed pure torsion 63

Table 3.3: The local stresses for internal pressure only 64

Table 3.4: The local stresses for combined completely reversed bending plus internal pressure (open and closed cylinder) 65

Table 4.1.The specimen specifications 71

Table 4.2.The average and standard deviation value of specimen wall thickness-to-diameter ratios 72

Table 5.1: Static bending and torsional tests 84

Table 5.2: Static Pressure tests 85

Table 5.3: Fatigue Constants (a) and (b) for Completely Reversed Pure Bending Under $P_r = 0$ 88

Table 5.4: Fatigue Constants (c) and (d) for Completely Reversed Pure Torsion 91

Table 5.5: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure of Closed Cylinder Under $P_r = 0.25$ 98

Table 5.6: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure of Closed Cylinder Under $P_r = 0.5$ 98

Table 5.7: Fatigue Constants (a) and (b) for Completely Reversed Bending plus Internal Pressure of Closed Cylinder Under $P_r = 0.75$ 98

Table 6.1: Fatigue Constants (a) and Average values of (b) for tested specimens 122

Table 6.2: Fatigue Constants (a) as a function of pressure ratio (P_r) 124

Table 6.3: The Hoop-amplitude relation for M_1, $[0,90°]_{3s}$ specimens 132

Table 6.4: The Hoop-amplitude relation for M_1, $[\pm 45°]_{3s}$ specimens 132

Table 6.5: The Hoop-amplitude relation for M_2, $[0,90°]_{3s}$ specimens 132

Table 6.6: The Hoop-amplitude relation for M_2, $[\pm 45°]_{3s}$ specimens 132

Table 6.7: Values of constants $(\boldsymbol{a_1})$ and $(\boldsymbol{b_1})$ for the (SWT) parameter 138

Table 6.8: The ratio between the constant $(\boldsymbol{a_1})$ to the static ultimate strength (S_u) 139

Table 6.9: Values of constants $(\boldsymbol{a_2})$ and $(\boldsymbol{b_2})$ for Modified Fatigue Strength Ratio (Ψ) 145

obeikandl.com

Table 6.10: Selected Failure criteria for $[0, 90°]_{3s}$ and $[\pm45°]_{3s}$ specimens Subjected to combined completely reversed pure bending plus internal pressure Stresses 149

Table 7.1: percentage error of fatigue constant (a) values at P_r=0.25 196

Table 7.2: Mean square error (MSE) values at $P_r = 0.75$ 196

Table 7.3: Fatigue Constant (a) and (b) for M_1, $[0,90°]_{3s}$ specimens tested 199

Table 7.4: Fatigue Constant (a) and (b) for M_1, $[\pm45°]_{3s}$ specimens tested 200

Table 7.5: Fatigue Constant (a) and (b) for M_2, $[0,90°]_{3s}$ specimens tested 200

Table 7.6: Fatigue Constant (a) and (b) for M_2, $[\pm45°]_{3s}$ specimens tested 200

Table A2.1: The failure modes of M_1, $[0,90°]_{3s}$ specimens under completely reversed pure bending 222

Table A2.2: The failure modes of M_2, $[0,90°]_{3s}$ specimens under completely reversed pure bending 223

Table A2.3: The failure modes of M_1, $[\pm45°]_{3s}$ specimens under completely reversed pure bending 224

Table A2.4: The failure modes of M_2, $[\pm45°]_{3s}$ specimens under completely reversed pure bending 225

Table A2.5: The failure modes of M_1, $[0,90°]_{3s}$ specimens under completely reversed pure torsion 226

Table A2.6: The failure modes of M_2, $[0,90°]_{3s}$ specimens under completely reversed pure torsion 227

Table A2.7: The failure modes of M_1, $[\pm45°]_{3s}$ specimens under completely reversed pure torsion 228

Table A2.8: The failure modes of M_2, $[\pm45°]_{3s}$ specimens under completely reversed pure torsion 229

Table A2.9: The failure modes of M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.25$ 230

Table A2.10: The failure modes of M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.25$ 231

Table A2.11: The failure modes of M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0.25$ 232

Table A2.12: The failure modes of M_2, $[\pm45°]_{3s}$ specimens Under $P_r = 0.25$ 233

Table A2.13: The failure modes of M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.5$ 234

Table A2.14: The failure modes of M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.5$ 235

Table A2.15: The failure modes of M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0.5$ 236

Table A2.16: The failure modes of M_2, $[\pm45°]_{3s}$ specimens Under $P_r = 0.5$ 237

Table A2.17: The failure modes of M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.75$ 238

Table A2.18: The failure modes of M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.75$ 239

Table A2.19: The failure modes of M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0.75$ 240

obeikandl.com

Table A2.20: The failure modes of M_2, $[\pm 45°]_{3s}$ specimens Under $P_r = 0.75$ 241
Table A3.1.Properties of used hydraulic oil 242
Table A3.2.Properties of used materials 242
Table A3.3: The bending moment loading system specification 243
Table A3.4: The bending moment loading system Calculation 243
Table A3.5: The torsion loading system specification 244
Table A3.6: The torsion loading system Calculation 244
Table A3.7: Static Bending Test Data of M_1, $[0,90°]_{3s}$ 245
Table A3.8: Static Bending Test Data of M_1, $[\pm 45°]_{3s}$ 245
Table A3.9: Static Bending Test Data of M_2, $[0,90°]_{3s}$ 245
Table A3.10: Static Bending Test Data of M_2, $[\pm 45°]_{3s}$ 245
Table A3.11: Static Torsion Test Data of M_1, $[0,90°]_{3s}$ 245
Table A3.12: Static Torsion Test Data of M_1, $[\pm 45°]_{3s}$ 246
Table A3.13: Static Torsion Test Data of M_2, $[0,90°]_{3s}$ 246
Table A3.14: Static Torsion Test Data of M_2, $[\pm 45°]_{3s}$ 246
Table A3.15: Static Pressure Test Data of Closed Cylinder, M_1, $[0,90°]_{3s}$ 247
Table A3.16: Stress –Strain Data of Closed Cylinder, M_1, $[0,90°]_{3s}$ 247
Table A3.17: Static Pressure Test Data of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ 247
Table A3.18: Stress –Strain Data of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ 247
Table A3.19: Static Pressure Test Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ 247
Table A3.20: Stress –Strain Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ 248
Table A3.21: Interface Pressures Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ 248
Table A3.22: Static Pressure Test Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ 248
Table A3.23: Stress –Strain Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ 248
Table A3.24: Interface Pressures Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ 248
Table A3.25: Static Pressure Test Data of Open Cylinder, M_1, $[0,90°]_{3s}$ 249
Table A3.26: Stress –Strain Data of Open Cylinder, M_1, $[0,90°]_{3s}$ 249
Table A3.27: Static Pressure Test Data of Open Cylinder, M_1, $[\pm 45°]_{3s}$ 249
Table A3.28: Stress –Strain Data of Open Cylinder, M_1, $[\pm 45°]_{3s}$ 249
Table A3.29: Static Pressure Test Data of Open Cylinder, M_2, $[0,90°]_{3s}$ 249
Table A3.30: Stress –Strain Data of Open Cylinder, M_2, $[0,90°]_{3s}$ 250
Table A3.31: Interface Pressures Data of Open Cylinder, M_2, $[0,90°]_{3s}$ 250

openkanan.com

Table A3.32: Static Pressure Test Data of Open Cylinder, M_2, $[\pm 45°]_{3s}$ 250
Table A3.33: Stress –Strain Data of Open Cylinder, M_2, $[\pm 45°]_{3s}$ 250
Table A3.34: Interface Pressures Data of Open Cylinder, M_2, $[\pm 45°]_{3s}$ 250
Table A3.35: Completely Reversed Pure Bending specimens Data of M_1, $[0,90°]_{3s}$ Under $P_r = 0$ 251
Table A3.36: Completely Reversed Pure Bending specimens Data of M_1, $[\pm 45°]_{3s}$ Under $P_r = 0$ 251
Table A3.37: Completely Reversed Pure Bending specimens specification of M_2, $[0,90°]_{3s}$ Under $P_r = 0$ 251
Table A3.38: Completely Reversed Pure Bending specimens Data of M_2, $[\pm 45°]_{3s}$ Under $P_r = 0$ 252
Table A3.39: Completely Reversed Pure Torsion specimens Data of M_1, $[0,90°]_{3s}$ 253
Table A3.40: Completely Reversed Pure Torsion specimens Data of M_1, $[\pm 45°]_{3s}$ 253
Table A3.41: Completely Reversed Pure Torsion specimens Data of M_2, $[0,90°]_{3s}$ 253
Table A3.42: Completely Reversed Pure Torsion specimens Data of M_2, $[\pm 45°]_{3s}$ 254
Table A3.43: Data of Closed Cylinder, M_1, $[0,90°]_{3s}$ Under $P_r = 0.25$ 255
Table A3.44: Data of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ Under $P_r = 0.25$ 255
Table A3.45: Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ Under $P_r = 0.25$ 255
Table A3.46: Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ Under $P_r = 0.25$ 256
Table A3.47: Data of Closed Cylinder, M_1, $[0,90°]_{3s}$ Under $P_r = 0.5$ 256
Table A3.48: Data of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ Under $P_r = 0.5$ 256
Table A3.49: Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ Under $P_r = 0.5$ 257
Table A3.50: Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ Under $P_r = 0.5$ 257
Table A3.51: Data of Closed Cylinder, M_1, $[0,90°]_{3s}$ Under $P_r = 0.75$ 257
Table A3.52: Data of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ Under $P_r = 0.75$ 258
Table A3.53: Data of Closed Cylinder, M_2, $[0,90°]_{3s}$ Under $P_r = 0.75$ 258
Table A3.54: Data of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ Under $P_r = 0.75$ 258
Table A3.55: Fatigue Constants (a) and (b) for of Closed Cylinder, M_1, $[0,90°]_{3s}$ 258
Table A3.56: Fatigue Constants (a) and (b) for of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ 259
Table A3.57: Fatigue Constants (a) and (b) for of Closed Cylinder, M_2, $[0,90°]_{3s}$ 259

Obeikandl.com

Table A3.58: Fatigue Constants (a) and (b) for of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ 259
Table A3.59: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure bending R=-1 (Data adapted from Elmidany A. A. **[83]**) 260
Table A3.60: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure bending R=-1 (Data adapted from Elmidany A. A. **[83]**) 260
Table A3.61: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure torsion R=-1 (Data adapted from Elmidany A. A. **[83]**) 260
Table A3.62: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure torsion R=-1 (Data adapted from Elmidany A. A. **[83]**) 261
Table A3.63: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure bending R=-1 (Data adapted from Nasr M. A. **[84]**) 261
Table A3.64: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure torsion R=-1 (Data adapted from Nasr M. A. **[84]**) 261
Table A3.65: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Elhadary M. M **[87]**) 262
Table A3.66: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Elhadary M. M **[87]**) 262
Table A3.67: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Elhadary M. M **[87]**) 262
Table A3.68: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Elhadary M. M **[87]**) 263
Table A3.69: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y **[88]**) 263
Table A3.70: Data of $[0,90°]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Mohamed S. Y **[88]**) 263
Table A3.71: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y **[88]**) 264
Table A3.72: Data of $[\pm 45°]_{2s}$ specimen tested under completely reversed pure

obeikandi.com

torsion (Data adapted from Mohamed S. Y **[88]**) 264

Table A3.73: Data of $[30°,-60°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y **[88]**) 264

Table A3.74: Data of $[30°,-60°]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Mohamed S. Y **[88]**) 265

Table A3.75: Data of $[60°,-30°]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y **[88]**) 265

Table A3.76: Data of $[60°,-30°]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Mohamed S. Y **[88]**) 265

Table A3.77: Data adapted from Amijima S. et al. **[72]** 266

Table A3.78: Data adapted from Ahmed M.E. et al. **[75]** 266

Table A3.79: Data adapted from Atcholi KE. et al. **[151]** 266

Table A3.80: Data adapted from Kawakami H. et al. **[152]** 267

Table A3.81: Data adapted from Önder A. **[8]** (static pressure test) 267

Table A3.82: Data adapted from Tolga L. **[52]** (static pressure test) 267

Table A3.83: Data adapted from Tolga L. **[52]** (static pressure test) 267

Table A3.84: Data adapted from Erkal S. **[163]** (static pressure test) 268

Table A3.85: Failure criteria / Theories of failure **[83]** 268

obeikandl.com

LIST OF FIGURES

Figure 1.1 Types of composites based on reinforcement shape 2

Figure1.2 Formation of a composite material using fibers and resin 3

Figure 1.3.Types of matrix materials (a) Classification of matrix materials, (b) Some kinds of thermosets and (c) Some kinds of thermoplastics. 5

Figure 1.4 Various types of fiber-reinforced composite lamina 6

Figure 1.5 The mechanical behavior of composite materials 8

Figure 1.6 A laminate made up of lamina with different fiber orientations **[6]** 9

Figure 1.7 Different Modes of Failure 10

Figure 1.8 Crack tip showing local failure events 11

Figure 1.9 Hand lay-up process technique 13

Figure 1.10 Spray lay-up process technique 14

Figure 1.11 Filament Winding process technique 15

Figure 1.12 Vacuum Bag process technique 15

Figure 1.13 Injection Molding process technique 16

Figure 1.14 Pultrusion process technique 17

Figure 2.1 Fatigue life diagram for unidirectional composites for axial tension–tension loading **[60]** 33

Figure 2.2 Tensile strength of Thornel-50 / epoxy unidirectional composite **[82]** 40

Figure 3.1 The Global Stress State 59

Figure 3.2 the global (*x*-*y*) and local (*1*-*2*) coordinate system for specimen 61

Figure 3.3 Geometrical model and the stress distribution in a thick-walled tube subjected to internal pressure 66

Figure 3.4.A three-layer tube mould with the first method of manufacturing M_1 67

Figure 3.5.A three-layer tube made of three bonded layers 68

Figure 4.1 Dimensions of used specimens. 71

Figure 4.2 Schematic of Specimen closure system details 74

Figure 4.3 General layout of mechanical testing machine 78

Figure 4.4 Schematic arrangement of mechanical testing machine 79

obeikandl.com

Figure 4.5 General layout of hydraulic testing machine 80
Figure 4.6 Mechanical Testing machine 81
Figure 4.7 Bending and twisting Coupling 82
Figure 5.1.Completely Reversed Pure Bending of M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0$ 86
Figure 5.2.Completely Reversed Pure Bending of M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0$ 87
Figure 5.3.Completely Reversed Pure Bending of M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0$ 87
Figure 5.4.Completely Reversed Pure Bending of M_2, $[\pm45°]_{3s}$ specimens Under $P_r = 0$ 88
Figure 5.5.Completely Reversed Pure Torsion of M_1, $[0,90°]_{3s}$ specimens 89
Figure 5.6.Completely Reversed Pure Torsion of M_1, $[\pm45°]_{3s}$ specimens 89
Figure 5.7.Completely Reversed Pure Torsion of M_2, $[0,90°]_{3s}$ specimens 90
Figure 5.8.Completely Reversed Pure Torsion of M_2, $[\pm45°]_{3s}$ specimens 90
Figure 5.9.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.25$ 92
Figure 5.10.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0.25$ 92
Figure 5.11.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.25$ 93
Figure 5.12.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[\pm45°]_{3s}$ specimens Under $P_r = 0.25$ 93
Figure 5.13.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.5$ 94
Figure 5.14.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1, $[\pm45°]_{3s}$ specimens Under $P_r = 0.5$ 94
Figure 5.15.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.5$ 95
Figure 5.16.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[\pm45°]_{3s}$ specimens Under $P_r = 0.5$ 95
Figure 5.17.Completely Reversed Bending plus Internal Pressure of Closed Cylinder,

oseikandi.com

M_1, $[0,90°]_{3s}$ specimens Under $P_r = 0.75$ 96
Figure 5.18.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1, $[\pm 45°]_{3s}$ specimens Under $P_r = 0.75$ 96
Figure 5.19.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[0,90°]_{3s}$ specimens Under $P_r = 0.75$ 97
Figure 5.20.Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2, $[\pm 45°]_{3s}$ specimens Under $P_r = 0.75$ 97
Figure 6.1 Ultimate strength for both fiber orientations and both methods of Manufacturing 100
Figure 6.2 Burst Static Pressure for both fiber orientations and both methods of manufacturing 101
Figure 6.3 The optimum fiber orientation under bending 101
Figure 6.4 The optimum fiber orientation under torsion 102
Figure 6.5 The optimum fiber orientation under static pressure 103
Figure 6.6 The failure modes of specimens under static tests 108
Figure 6.7 The S-N curves for both fiber orientations and both methods of manufacturing under completely reversed pure bending 109
Figure 6.8 The S-N curves for both fiber orientations and both methods of manufacturing under completely reversed pure torsion 109
Figure 6.9 The Constant (a) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0$ 110
Figure 6.10 The Constant (b) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0$ 110
Figure 6.11 The Constant (c) as a function of fiber orientation and Methods of Manufacturing 111
Figure 6.12 The Constant (d) as a function of fiber orientation and Methods of Manufacturing 111
Figure 6.13 The S-N curves for both fiber orientations and method of manufacturing M_1 under completely reversed pure bending and torsion 113
Figure 6.14 The S-N curves for both fiber orientations and method of manufacturing M_2 under completely reversed pure bending and torsion 114

open-kanal.com

Figure 6.15 The Dispersed Whitened Areas under Completely Reversed Pure Bending for Both Fiber Orientations 115
Figure 6.16 The Dispersed Whitened Areas under Completely Reversed Pure Torsion for Both Fiber Orientations 116
Figure 6.17.S-N Curve of M_1, $[0,90°]_{3s}$ specimens Tested 117
Figure 6.18.S-N Curve of M_1, $[\pm45°]_{3s}$ specimens Tested 117
Figure 6.19.S-N Curve of M_2, $[0,90°]_{3s}$ specimens Tested 118
Figure 6.20.S-N Curve of M2, [±45°]3s specimens Tested 118
Figure 6.21 The Constant (a) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.25$ 119
Figure 6.22 The Constant (b) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.25$ 119
Figure 6.23 The Constant (a) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.5$ 120
Figure 6.24 The Constant (b) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.5$ 120
Figure 6.25 The Constant (a) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.75$ 121
Figure 6.26 The Constant (b) as a function of fiber orientation and Methods of Manufacturing Under $P_r = 0.75$ 121
Figure 6.27 The S-N curves for both fiber orientations and both methods of manufacturing under combined completely reversed bending plus internal pressure with $P_r = 0.25$ 124
Figure 6.28 The S-N curves for both fiber orientations and both methods of manufacturing under combined completely reversed bending plus internal pressure with $P_r = 0.5$ 125
Figure 6.29 The S-N curves for both fiber orientations and both methods of manufacturing under combined completely reversed bending plus internal pressure with $P_r = 0.75$ 125
Figure 6.30 Effect of Pressure ratios (P_r) on the fatigue constant (a) for both fiber orientations and both methods of manufacturing 126

Oğuzkanal.com

Figure 6.31 The Damage Mechanism Under internal hydrostatic pressure and completely reversed bending 127
Figure 6.32 Tension-Compression local (σ_1) and global (σ_x) stress components of M_1, $[0,90°]_{3s}$ specimens Under all Pressure ratio (P_r) 129
Figure 6.33 Tension-Compression local (σ_1) and global (σ_x) stress components of M_2, $[0,90°]_{3s}$ specimens Under all Pressure ratio (P_r) 129
Figure 6.34 (a) Tension-Compression local stress (σ_1 & σ_2) components of M_1, $[\pm45°]_{3s}$ specimens Under all Pressure ratio (P_r) 130
Figure 6.34 (b) Tension-Compression global stress (σ_{max}) components of M_1, $[\pm45°]_{3s}$ specimens Under all Pressure ratio (P_r) 130
Figure 6.35 (a) Tension-Compression local stress (σ_1 & σ_2) components of M_2, $[\pm45°]_{3s}$ specimens Under all Pressure ratio (P_r) 131
Figure 6.35(b) Tension-Compression global stress (σ_{max}) components of M_2, $[\pm45°]_{3s}$ specimens Under all Pressure ratio (P_r) 131
Figure 6.36.Hoop-amplitude relation for M_1, $[0,90°]_{3s}$ specimens 133
Figure 6.37.Hoop-amplitude relation for M_1, $[\pm45°]_{3s}$ specimens 133
Figure 6.38.Hoop-amplitude relation for M_2, $[0,90°]_{3s}$ specimens 134
Figure 6.39.Hoop-amplitude relation for M_2, $[\pm45°]_{3s}$ specimens 134
Figure 6.40 The G.R.D. for both manufacturing method M_1 and M_2 for all fiber orientations and all pressure ratios 136
Figure 6.41 The SWT parameter for M_1, $[0,90°]_{3s}$ specimens 140
Figure 6.42 The SWT parameter for M_1, $[\pm45°]_{3s}$ specimens 141
Figure 6.43 The SWT parameter for M_2, $[0,90°]_{3s}$ specimens 141
Figure 6.44 The SWT parameter for M_2, $[\pm45°]_{3s}$ specimens 142
Figure 6.45 The SWT^* parameter for M_1, $[0,90°]_{3s}$ specimens 142
Figure 6.46 The SWT^* parameter for M_1, $[\pm45°]_{3s}$ specimens 143
Figure 6.47 The SWT^* parameter for M_2, $[0,90°]_{3s}$ specimens 143
Figure 6.48 The SWT^* parameter for M_2, $[\pm45°]_{3s}$ specimens 144
Figure 6.49 The modified SWT parameter for both fiber orientation and both methods of manufacturing 144
Figure 6.50.The Modified Fatigue Strength Ratio (Ψ) for M_1, $[0,90°]_{3s}$ specimens 146
Figure 6.51.The Modified Fatigue Strength Ratio (Ψ) for M_1, $[\pm45°]_{3s}$ specimens 147

openkanal.com

Figure 6.52.The Modified Fatigue Strength Ratio (Ψ) for M_2, $[0,90°]_{3s}$ specimens 147
Figure 6.53.The Modified Fatigue Strength Ratio (Ψ) for M_2, $[\pm45°]_{3s}$ specimens 148

Figure 6.54.Relative damage (R.D.) applying Hill failure criterion for the M_1, $[0,90°]_{3s}$ specimens 150
Figure 6.55.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_1, $[0,90°]_{3s}$ specimens 151
Figure 6.56.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_1, $[0,90°]_{3s}$ specimens 151
Figure 6.57.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_1, $[0,90°]_{3s}$ specimens 152
Figure 6.58.Relative damage (R.D.) applying Hill failure criterion for the M_2, $[0,90°]_{3s}$ specimens 152
Figure 6.59.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_2, $[0,90°]_{3s}$ specimens 153
Figure 6.60.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_2, $[0,90°]_{3s}$ specimens 153
Figure 6.61.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_2, $[0,90°]_{3s}$ specimens 154
Figure 6.62.Relative damage (R.D.) applying Hill failure criterion for the M_1, $[\pm45°]_{3s}$ specimens 154
Figure 6.63.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_1, $[\pm45°]_{3s}$ specimens 155
Figure 6.64.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_1, $[\pm45°]_{3s}$ specimens 155
Figure 6.65.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_1, $[\pm45°]_{3s}$ specimens 156
Figure 6.66.Relative damage (R.D.) applying Hill failure criterion for the M_2, $[\pm45°]_{3s}$ specimens 156
Figure 6.67.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_2, $[\pm45°]_{3s}$ specimens 157

obeikandi.com

Figure 6.68.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_2, $[\pm 45°]_{3s}$ specimens 157
Figure 6.69.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_2, $[\pm 45°]_{3s}$ specimens 158
Figure 6.70.Relative damage (R.D.) applying El-Midany **[83]** failure criterion for both manufacturing method M1 and M2 for all fiber orientations and all pressure ratios 160
Figure 6.71.Relative damage (R.D.) applying El Mohamed **[88]** failure criterion for both manufacturing method M1 and M2 for all fiber orientations and all pressure ratios 162
Figure 6.72.Relative damage (R.D.) applying present failure criterion for both manufacturing method M_1 and M_2 for all fiber orientations and all pressure ratios 164
Figure 6.73.Relative damage (R.D.) applying the old failure criterion for data adapted from El-midany **[83]** Under R = -1 and $P_r = 0$ 166
Figure 6.74.Relative damage (R.D.) applying the new failure criterion for data adapted from El-midany **[83]** Under R = -1 and $P_r = 0$ 167
Figure 6.75.Relative damage (R.D.) applying the old failure criterion for data adapted from El-hadary **[86-87]** Under R = -1 and Pr = 0 167
Figure 6.76.Relative damage (R.D.) applying the new failure criterion for data adapted from El-hadary **[86-87]** Under R = -1 and Pr = 0 168
Figure 6.77.Relative damage (R.D.) applying the old failure criterion for fiber orientations $[0,90°]_{2s}$ and $[\pm 45°]_{2s}$ of data adapted from Mohamed **[88]** Under R = -1 and Pr = 0 168
Figure 6.78.Relative damage (R.D.) applying the new failure criterion for fiber orientations $[0,90°]_{2s}$ and $[\pm 45°]_{2s}$ of data adapted from Mohamed **[88]** Under R = -1 and Pr = 0 169
Figure 6.79.Relative damage (R.D.) applying the old failure criterion for fiber orientations $[30°,-60°]_{2s}$, $[60°,-30°]_{2s}$ of data adapted from Mohamed **[88]** Under R = -1 and Pr = 0 169
Figure 6.80.Relative damage (R.D.) applying the new failure criterion for fiber orientations $[30°,-60°]_{2s}$, $[60°,-30°]_{2s}$ of data adapted from Mohamed **[88]** Under R = -1 and Pr = 0 170
Figure 6.81.Relative damage (R.D.) applying the new failure criterion for data adapted from Amijima et al. **[72]** Under R = -1 and Pr = 0 170

obeikandi.com

Figure 6.82.Relative damage (R.D.) applying the new failure criterion for data adapted from Atcholi et al. **[151]** Under R = -1 and Pr = 0 171
Figure 6.83.Relative damage (R.D.) applying the new failure criterion for data adapted from Kawakami et al. **[152]** Under R = -1 and Pr = 0 171
Figure 6.84.Relative damage (R.D.) applying the new failure criterion for data adapted from Ahmed M.E. et al. **[75]** Under R = -1 and Pr = 0 172
Figure 7.1.Schematic illustration of ANN project cycle 173
Figure 7.2.Schematic representation of Artificial Neural networks ANN 174
Figure 7.3.Schematic Illustration of Single Layer of Neurons 176
Figure 7.4.Schematic Illustration of Multi Layer of Neurons 177
Figure 7.4 training performance of suggested feed-forward NN 181
Figure 7.5 Comparison between the experimental data and the feed forward neural network FFNN predicted data for M_1, $[0,90°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 182
Figure 7.6 Comparison between the experimental data and the feed forward neural network FFNN predicted data for M_1, $[\pm 45°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 182
Figure 7.7 Comparison between the experimental data and the feed forward neural network FFNN predicted data for M_2, $[0,90°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 183
Figure 7.8 Comparison between the experimental data and the feed forward neural network FFNN predicted data for M_2, $[\pm 45°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 183
Figure 7.9 Comparison between the experimental data and the feed forward neural network FFNN Expected data for M_1, $[0,90°]_{3s}$ specimens with$P_r = 0.75$ 184
Figure 7.10 Comparison between the experimental data and the feed forward neural network FFNN Expected data for M_1, $[\pm 45°]_{3s}$ specimens with$P_r = 0.75$ 184
Figure 7.11 Comparison between the experimental data and the feed forward neural network FFNN Expected data for M_2, $[0,90°]_{3s}$ specimens with$P_r = 0.75$ 185
Figure 7.12 Comparison between the experimental data and the feed forward neural network FFNN Expected data for M_2, $[\pm 45°]_{3s}$ specimens with$P_r = 0.75$ 185
Figure 7.13 Schematic Illustration of GRNN design for present study with input data σ_{max} P_r , θ and N **[154]** 186
Figure 7.14 Comparison between the experimental data and the generalized regression neural network GRNN predicted data for M_1, $[0,90°]_{3s}$ specimens with $P_r = 0, 0.25, 0.5$ 187

Figure 7.15 Comparison between the experimental data and the generalized regression neural network GRNN predicted data for M_1, $[\pm 45°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 187
Figure 7.16 Comparison between the experimental data and the generalized regression neural network GRNN predicted data for M_2, $[0,90°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 188
Figure 7.17 Comparison between the experimental data and the generalized regression neural network GRNN predicted data for M_2, $[\pm 45°]_{3s}$ specimens with$P_r = 0, 0.25, 0.5$ 188
Figure 7.18 Comparison between the experimental data and the generalized regression neural network GRNN Expected data for M_1, $[0,90°]_{3s}$ specimens with$P_r = 0.75$ 189
Figure 7.19 Comparison between the experimental data and the generalized regression neural network GRNN Expected data for M_1, $[\pm 45°]_{3s}$ specimens with$P_r = 0.75$ 189
Figure 7.20 Comparison between the experimental data and the generalized regression neural network GRNN Expected data for M_2, $[0,90°]_{3s}$ specimens with$P_r = 0.75$ 190
Figure 7.21 Comparison between the experimental data and the generalized regression neural network GRNN Expected data for M_2, $[\pm 45°]_{3s}$ specimens with$P_r = 0.75$ 190
Figure 7.22 Comparison between the experimental data and the Radial basis neural network RBNN predicted data for M_1, $[0,90°]_{3s}$ specimens with $P_r = 0, 0.5, 0.75$ 191
Figure 7.23 Comparison between the experimental data and the Radial basis neural network RBNN predicted data for M_1, $[\pm 45°]_{3s}$ specimens with $P_r = 0, 0.5, 0.75$ 192
Figure 7.24 Comparison between the experimental data and the Radial basis neural network RBNN predicted data for M_2, $[0,90°]_{3s}$ specimens with $P_r = 0, 0.5, 0.75$ 192
Figure 7.25 Comparison between the experimental data and the g Radial basis neural network RBNN predicted data for M_2, $[\pm 45°]_{3s}$ specimens with $P_r = 0, 0.5, 0.75$ 193
Figure 7.26 Comparison between the experimental data and the Radial basis neural network RBNN Expected data for M_1, $[0,90°]_{3s}$ specimens with $P_r = 0.25$ 193

obeikandi.com

Figure 7.27 Comparison between the experimental data and the Radial basis neural network RBNN Expected data for M_1, $[\pm 45°]_{3s}$ specimens with $P_r = 0.25$ 194
Figure 7.28 Comparison between the experimental data and the Radial basis neural network RBNN Expected data for M_2, $[0,90°]_{3s}$ specimens with $P_r = 0.25$ 194
Figure 7.29 Comparison between the experimental data and the Radial basis neural network RBNN Expected data for M_2, $[\pm 45°]_{3s}$ specimens with $P_r = 0.25$ 195
Figure 7.30 Expected Data for M_1, $[0,90°]_{3s}$ specimens 197
Figure 7.31 Expected Data for M_1, $[\pm 45°]_{3s}$ specimens 198
Figure 7.32 Expected Data for M_2, $[0,90°]_{3s}$ specimens 198
Figure 7.33 Expected Data for M_2, $[\pm 45°]_{3s}$ specimens 199
Figure 7.34 The G.R.D. of both manufacturing method M_1 and M_2 for all fiber orientations and all pressure ratios for expected data 201
Figure 6.35. Relative damage (R.D.) applying present failure criterion of both manufacturing method M_1 and M_2 for all fiber orientations and all pressure ratios for expected data 202
Figure A3.1.Calibration of Bending Arm (Gain Factor 2 and Volts/ Div 10.5 [(m volts]) 243
Figure A3.4.Calibration of Torsion Arm (Gain Factor 0.31 and Volts/ Div 10.5[(m volts]) 244
Figure A4.1.Thick-walled cylinder, the solid line is unstrained cylinder and the dash line is strained cylinder 273
Figure A4.2 Thick-walled cylinder element 274
Figure A4.3 Three-layer thick-walled pipes 278

obeikandi.com