

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

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_{2t}	Local tension component in directions (2)
F_{2c}	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

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

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 V_f	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

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 $[0,90^\circ]_{3s}$ specimens	62
3.3.2 The $[\pm 45^\circ]_{3s}$ 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

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

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 $[0,90^\circ]_{3s}$ specimens	149
6.6.4	The relative damage for $[\pm 45^\circ]_{3s}$ 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

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

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 , $[0,90^\circ]_{3s}$ specimens	132
Table 6.4: The Hoop-amplitude relation for M_1 , $[\pm 45^\circ]_{3s}$ specimens	132
Table 6.5: The Hoop-amplitude relation for M_2 , $[0,90^\circ]_{3s}$ specimens	132
Table 6.6: The Hoop-amplitude relation for M_2 , $[\pm 45^\circ]_{3s}$ specimens	132
Table 6.7: Values of constants (a_1) and (b_1) for the (SWT) parameter	138
Table 6.8: The ratio between the constant (a_1) to the static ultimate strength (S_u)	139
Table 6.9: Values of constants (a_2) and (b_2) for Modified Fatigue Strength Ratio (Ψ)	145

Table 6.10: Selected Failure criteria for $[0, 90^\circ]_{3s}$ and $[\pm 45^\circ]_{3s}$ 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 $M_1, [0,90^\circ]_{3s}$ specimens tested	199
Table 7.4: Fatigue Constant (a) and (b) for $M_1, [\pm 45^\circ]_{3s}$ specimens tested	200
Table 7.5: Fatigue Constant (a) and (b) for $M_2, [0,90^\circ]_{3s}$ specimens tested	200
Table 7.6: Fatigue Constant (a) and (b) for $M_2, [\pm 45^\circ]_{3s}$ specimens tested	200
Table A2.1: The failure modes of $M_1, [0,90^\circ]_{3s}$ specimens under completely reversed pure bending	222
Table A2.2: The failure modes of $M_2, [0,90^\circ]_{3s}$ specimens under completely reversed pure bending	223
Table A2.3: The failure modes of $M_1, [\pm 45^\circ]_{3s}$ specimens under completely reversed pure bending	224
Table A2.4: The failure modes of $M_2, [\pm 45^\circ]_{3s}$ specimens under completely reversed pure bending	225
Table A2.5: The failure modes of $M_1, [0,90^\circ]_{3s}$ specimens under completely reversed pure torsion	226
Table A2.6: The failure modes of $M_2, [0,90^\circ]_{3s}$ specimens under completely reversed pure torsion	227
Table A2.7: The failure modes of $M_1, [\pm 45^\circ]_{3s}$ specimens under completely reversed pure torsion	228
Table A2.8: The failure modes of $M_2, [\pm 45^\circ]_{3s}$ specimens under completely reversed pure torsion	229
Table A2.9: The failure modes of $M_1, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.25$	230
Table A2.10: The failure modes of $M_2, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.25$	231
Table A2.11: The failure modes of $M_1, [\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.25$	232
Table A2.12: The failure modes of $M_2, [\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.25$	233
Table A2.13: The failure modes of $M_1, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.5$	234
Table A2.14: The failure modes of $M_2, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.5$	235
Table A2.15: The failure modes of $M_1, [\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.5$	236
Table A2.16: The failure modes of $M_2, [\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.5$	237
Table A2.17: The failure modes of $M_1, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.75$	238
Table A2.18: The failure modes of $M_2, [0,90^\circ]_{3s}$ specimens Under $P_r = 0.75$	239
Table A2.19: The failure modes of $M_1, [\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.75$	240

Table A2.20: The failure modes of M_2 , $[\pm 45^\circ]_{3s}$ 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 , $[0, 90^\circ]_{3s}$	245
Table A3.8: Static Bending Test Data of M_1 , $[\pm 45^\circ]_{3s}$	245
Table A3.9: Static Bending Test Data of M_2 , $[0, 90^\circ]_{3s}$	245
Table A3.10: Static Bending Test Data of M_2 , $[\pm 45^\circ]_{3s}$	245
Table A3.11: Static Torsion Test Data of M_1 , $[0, 90^\circ]_{3s}$	245
Table A3.12: Static Torsion Test Data of M_1 , $[\pm 45^\circ]_{3s}$	246
Table A3.13: Static Torsion Test Data of M_2 , $[0, 90^\circ]_{3s}$	246
Table A3.14: Static Torsion Test Data of M_2 , $[\pm 45^\circ]_{3s}$	246
Table A3.15: Static Pressure Test Data of Closed Cylinder, M_1 , $[0, 90^\circ]_{3s}$	247
Table A3.16: Stress –Strain Data of Closed Cylinder, M_1 , $[0, 90^\circ]_{3s}$	247
Table A3.17: Static Pressure Test Data of Closed Cylinder, M_1 , $[\pm 45^\circ]_{3s}$	247
Table A3.18: Stress –Strain Data of Closed Cylinder, M_1 , $[\pm 45^\circ]_{3s}$	247
Table A3.19: Static Pressure Test Data of Closed Cylinder, M_2 , $[0, 90^\circ]_{3s}$	247
Table A3.20: Stress –Strain Data of Closed Cylinder, M_2 , $[0, 90^\circ]_{3s}$	248
Table A3.21: Interface Pressures Data of Closed Cylinder, M_2 , $[0, 90^\circ]_{3s}$	248
Table A3.22: Static Pressure Test Data of Closed Cylinder, M_2 , $[\pm 45^\circ]_{3s}$	248
Table A3.23: Stress –Strain Data of Closed Cylinder, M_2 , $[\pm 45^\circ]_{3s}$	248
Table A3.24: Interface Pressures Data of Closed Cylinder, M_2 , $[\pm 45^\circ]_{3s}$	248
Table A3.25: Static Pressure Test Data of Open Cylinder, M_1 , $[0, 90^\circ]_{3s}$	249
Table A3.26: Stress –Strain Data of Open Cylinder, M_1 , $[0, 90^\circ]_{3s}$	249
Table A3.27: Static Pressure Test Data of Open Cylinder, M_1 , $[\pm 45^\circ]_{3s}$	249
Table A3.28: Stress –Strain Data of Open Cylinder, M_1 , $[\pm 45^\circ]_{3s}$	249
Table A3.29: Static Pressure Test Data of Open Cylinder, M_2 , $[0, 90^\circ]_{3s}$	249
Table A3.30: Stress –Strain Data of Open Cylinder, M_2 , $[0, 90^\circ]_{3s}$	250
Table A3.31: Interface Pressures Data of Open Cylinder, M_2 , $[0, 90^\circ]_{3s}$	250

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

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

torsion (Data adapted from Mohamed S. Y [88])	264
Table A3.73: Data of $[30^\circ, -60^\circ]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y [88])	264
Table A3.74: Data of $[30^\circ, -60^\circ]_{2s}$ specimen tested under completely reversed pure torsion (Data adapted from Mohamed S. Y [88])	265
Table A3.75: Data of $[60^\circ, -30^\circ]_{2s}$ specimen tested under completely reversed pure bending (Data adapted from Mohamed S. Y [88])	265
Table A3.76: Data of $[60^\circ, -30^\circ]_{2s}$ 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

LIST OF FIGURES

Figure 1.1 Types of composites based on reinforcement shape	2
Figure 1.2 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

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 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0$	86
Figure 5.2. Completely Reversed Pure Bending of M_1 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0$	87
Figure 5.3. Completely Reversed Pure Bending of M_2 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0$	87
Figure 5.4. Completely Reversed Pure Bending of M_2 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0$	88
Figure 5.5. Completely Reversed Pure Torsion of M_1 , $[0,90^\circ]_{3s}$ specimens	89
Figure 5.6. Completely Reversed Pure Torsion of M_1 , $[\pm 45^\circ]_{3s}$ specimens	89
Figure 5.7. Completely Reversed Pure Torsion of M_2 , $[0,90^\circ]_{3s}$ specimens	90
Figure 5.8. Completely Reversed Pure Torsion of M_2 , $[\pm 45^\circ]_{3s}$ specimens	90
Figure 5.9. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0.25$	92
Figure 5.10. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.25$	92
Figure 5.11. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0.25$	93
Figure 5.12. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.25$	93
Figure 5.13. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0.5$	94
Figure 5.14. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_1 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.5$	94
Figure 5.15. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2 , $[0,90^\circ]_{3s}$ specimens Under $P_r = 0.5$	95
Figure 5.16. Completely Reversed Bending plus Internal Pressure of Closed Cylinder, M_2 , $[\pm 45^\circ]_{3s}$ specimens Under $P_r = 0.5$	95
Figure 5.17. Completely Reversed Bending plus Internal Pressure of Closed Cylinder,	

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 , [±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 , [±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

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 , $[0,90^\circ]_{3s}$ specimens Tested	117
Figure 6.18.S-N Curve of M_1 , $[\pm 45^\circ]_{3s}$ specimens Tested	117
Figure 6.19.S-N Curve of M_2 , $[0,90^\circ]_{3s}$ specimens Tested	118
Figure 6.20.S-N Curve of M_2 , $[\pm 45^\circ]_{3s}$ 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

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 , $[0,90^\circ]_{3s}$ 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 , $[0,90^\circ]_{3s}$ specimens Under all Pressure ratio (P_r)	129
Figure 6.34 (a) Tension-Compression local stress (σ_1 & σ_2) components of M_1 , $[\pm 45^\circ]_{3s}$ specimens Under all Pressure ratio (P_r)	130
Figure 6.34 (b) Tension-Compression global stress (σ_{max}) components of M_1 , $[\pm 45^\circ]_{3s}$ specimens Under all Pressure ratio (P_r)	130
Figure 6.35 (a) Tension-Compression local stress (σ_1 & σ_2) components of M_2 , $[\pm 45^\circ]_{3s}$ specimens Under all Pressure ratio (P_r)	131
Figure 6.35(b) Tension-Compression global stress (σ_{max}) components of M_2 , $[\pm 45^\circ]_{3s}$ specimens Under all Pressure ratio (P_r)	131
Figure 6.36.Hoop-amplitude relation for M_1 , $[0,90^\circ]_{3s}$ specimens	133
Figure 6.37.Hoop-amplitude relation for M_1 , $[\pm 45^\circ]_{3s}$ specimens	133
Figure 6.38.Hoop-amplitude relation for M_2 , $[0,90^\circ]_{3s}$ specimens	134
Figure 6.39.Hoop-amplitude relation for M_2 , $[\pm 45^\circ]_{3s}$ 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 , $[0,90^\circ]_{3s}$ specimens	140
Figure 6.42 The SWT parameter for M_1 , $[\pm 45^\circ]_{3s}$ specimens	141
Figure 6.43 The SWT parameter for M_2 , $[0,90^\circ]_{3s}$ specimens	141
Figure 6.44 The SWT parameter for M_2 , $[\pm 45^\circ]_{3s}$ specimens	142
Figure 6.45 The SWT* parameter for M_1 , $[0,90^\circ]_{3s}$ specimens	142
Figure 6.46 The SWT* parameter for M_1 , $[\pm 45^\circ]_{3s}$ specimens	143
Figure 6.47 The SWT* parameter for M_2 , $[0,90^\circ]_{3s}$ specimens	143
Figure 6.48 The SWT* parameter for M_2 , $[\pm 45^\circ]_{3s}$ 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 , $[0,90^\circ]_{3s}$ specimens	146
Figure 6.51.The Modified Fatigue Strength Ratio (Ψ) for M_1 , $[\pm 45^\circ]_{3s}$ specimens	147

Figure 6.52.The Modified Fatigue Strength Ratio (Ψ) for M_2 , $[0,90^\circ]_{3s}$ specimens	147
Figure 6.53.The Modified Fatigue Strength Ratio (Ψ) for M_2 , $[\pm 45^\circ]_{3s}$ specimens	148
Figure 6.54.Relative damage (R.D.) applying Hill failure criterion for the M_1 , $[0,90^\circ]_{3s}$ specimens	150
Figure 6.55.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_1 , $[0,90^\circ]_{3s}$ specimens	151
Figure 6.56.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_1 , $[0,90^\circ]_{3s}$ specimens	151
Figure 6.57.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_1 , $[0,90^\circ]_{3s}$ specimens	152
Figure 6.58.Relative damage (R.D.) applying Hill failure criterion for the M_2 , $[0,90^\circ]_{3s}$ specimens	152
Figure 6.59.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_2 , $[0,90^\circ]_{3s}$ specimens	153
Figure 6.60.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_2 , $[0,90^\circ]_{3s}$ specimens	153
Figure 6.61.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_2 , $[0,90^\circ]_{3s}$ specimens	154
Figure 6.62.Relative damage (R.D.) applying Hill failure criterion for the M_1 , $[\pm 45^\circ]_{3s}$ specimens	154
Figure 6.63.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_1 , $[\pm 45^\circ]_{3s}$ specimens	155
Figure 6.64.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_1 , $[\pm 45^\circ]_{3s}$ specimens	155
Figure 6.65.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_1 , $[\pm 45^\circ]_{3s}$ specimens	156
Figure 6.66.Relative damage (R.D.) applying Hill failure criterion for the M_2 , $[\pm 45^\circ]_{3s}$ specimens	156
Figure 6.67.Relative damage (R.D.) applying Tsai-Hahn failure criterion for the M_2 , $[\pm 45^\circ]_{3s}$ specimens	157

Figure 6.68.Relative damage (R.D.) applying Tsai-Wu failure criterion for the M_2 , $[\pm 45^\circ]_{3s}$ specimens	157
Figure 6.69.Relative damage (R.D.) applying Norris & Mckinnon failure criterion for the M_2 , $[\pm 45^\circ]_{3s}$ 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 $[0,90^\circ]_{2s}$ and $[\pm 45^\circ]_{2s}$ 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 $[0,90^\circ]_{2s}$ and $[\pm 45^\circ]_{2s}$ 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 $[30^\circ, -60^\circ]_{2s}$, $[60^\circ, -30^\circ]_{2s}$ 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 $[30^\circ, -60^\circ]_{2s}$, $[60^\circ, -30^\circ]_{2s}$ 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

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 $M_1, [0,90^\circ]_{3s}$ 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 $M_1, [\pm 45^\circ]_{3s}$ 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 $M_2, [0,90^\circ]_{3s}$ 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 $M_2, [\pm 45^\circ]_{3s}$ 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 $M_1, [0,90^\circ]_{3s}$ 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 $M_1, [\pm 45^\circ]_{3s}$ 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 $M_2, [0,90^\circ]_{3s}$ 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 $M_2, [\pm 45^\circ]_{3s}$ 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 $M_1, [0,90^\circ]_{3s}$ 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 $M_1, [\pm 45^\circ]_{3s}$ 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 $M_2, [0, 90^\circ]_{3s}$ 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 $M_2, [\pm 45^\circ]_{3s}$ 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 $M_1, [0, 90^\circ]_{3s}$ 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 $M_1, [\pm 45^\circ]_{3s}$ 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 $M_2, [0, 90^\circ]_{3s}$ 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 $M_2, [\pm 45^\circ]_{3s}$ 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 $M_1, [0, 90^\circ]_{3s}$ 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 $M_1, [\pm 45^\circ]_{3s}$ 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 $M_2, [0, 90^\circ]_{3s}$ 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 $M_2, [\pm 45^\circ]_{3s}$ 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 $M_1, [0, 90^\circ]_{3s}$ specimens with $P_r = 0.25$	193

Figure 7.27 Comparison between the experimental data and the Radial basis neural network RBNN Expected data for M_1 , $[\pm 45^\circ]_{3s}$ 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 , $[0, 90^\circ]_{3s}$ 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 , $[\pm 45^\circ]_{3s}$ specimens with $P_r = 0.25$	195
Figure 7.30 Expected Data for M_1 , $[0, 90^\circ]_{3s}$ specimens	197
Figure 7.31 Expected Data for M_1 , $[\pm 45^\circ]_{3s}$ specimens	198
Figure 7.32 Expected Data for M_2 , $[0, 90^\circ]_{3s}$ specimens	198
Figure 7.33 Expected Data for M_2 , $[\pm 45^\circ]_{3s}$ 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