

LIST OF FIGURES

SR. NO	FIGURE NO.	FIGURE DESCRIPTION	PAGE NO.
1	Figure 2.1	Schematic illustration of the carbon fibre production process out of polyacrylonitrile	16
2	Figure 2.2	Structure of Carbon fibre	17
3	Figure 2.3	A single rod- like fibre structure of Kevlar	18
4	Figure 2.4	Structure of HDPE	19
5	Figure 2.5	Pictorial representation of hybrid and homogenous laminates	24
6	Figure 2.6	Different laminates sequence lay-up with varied angle ply	25
7	Figure 2.7	Schematic representation of hand lay-up technique.	29
8	Figure 2.8	Charpy test set-up	42
9	Figure 2.9	Izod test set-up	43
10	Figure 2.10	Impact load on Charpy and Izod test	44
11	Figure 2.11	Static Indentation data superimposed over impact data for 16-ply simply supported specimens over a 12-inch opening	45
12	Figure 2.12	Comparison of JKR curves generated from the results of Displacement method I analysis and Displacement method II analysis for quasi static and dynamic	45
13	Figure 2.13	Schematic and test set up of the quasi-static indentation test	47
14	Figure 2.14	Schematic Diagram of Scanning Electron Microscope	48
15	Figure 2.15	Schematic diagram for micro-level failure mechanism in unidirectional composite	50
16	Figure 2.16	Applications of composites	51
17	Figure 2.17	Schematic diagram of plain weave	57
18	Figure 2.18	Longitudinal cross section oriented along the weft yarn.	58

19	Figure 2.19	Geometry of a RUC of the reinforcing yarn of a flexible woven composite	58
20	Figure 2.20	Schematics of woven composites	59
21	Figure 2.21	Schematic diagram of composite types by yarn orientation.	59
22	Figure 2.22	Schematics for steps involved in manufacturing and analysis of textile reinforced composites	60
23	Figure 2.23	Geometric models for fabric's Unit Cell using variable section yarns	60
24	Figure 2.24	Steps in Finite element method	66
25	Figure 3.1	Kevlar, Carbon, and HDPE yarn package	71
26	Figure 3.2	Sample handloom	72
27	Figure 3.3	Typical image of initial samples prepared on handloom samples	72
28	Figure 3.4	(a) CCI Rigid rapier loom and (b) CCI single end warping machine	74
29	Figure 3.5	Arrangement on package for side withdrawal on CCI single end warping machine	75
30	Figure 3.6	Path of the warp at the back of the loom	76
31	Figure 3.7	Damage to Carbon yarn during preliminary weaving	76
32	Figure 3.8	a) Original heald wire b) Modified heald wire c) Original heald eye and d) Modified heald eye	78
33	Figure 3.9	a) Original reed (reed count=25); Modified reed (reed count=6)	78
34	Figure 3.10	Schematic diagram of newly developed modified reed with dimensions	79
35	Figure 3.11	Schematic diagram modified arrangement for take-up on CCI loom	79
36	Figure 3.12	Initial matrix sheet preparation a) Preparation stage of matrix sheet b) Cured matrix sheet	81
37	Figure 3.13	Initial preparation of matrix specimen. [a: polymer matrix cured in round shape; b: polymer matrix cut to dumbbell shape	81

38	Figure 3.14	Single layer fabric composite sample	81
39	Figure 3.15	Three layered fabric composite sample	82
40	Figure 3.16a	Schematic diagram for skew angle ($\pm 45^\circ$) with respect to warp (0°)	83
41	Figure 3.16b	Marking and labelling on fabric for cutting.	83
42	Figure 3.17	Resin preparation steps	85
43	Figure 3.18	Sequence of polymer textile composite laminate.	88
44	Figure 3.19	Image showing air bubble squeezed out of composite	89
45	Figure 3.20	The hand lay-up set up	90
46	Figure 3.21a	Schematic diagram of fabric prepared	92
47	Figure 3.21b	Schematic diagram of layering sequence of Carbon-Carbon TPCL	93
48	Figure 3.21c	Schematic diagram of layering sequence of Carbon-HDPE TPCL	93
49	Figure 3.21d	Schematic diagram of layering sequence of Kevlar-Carbon-HDPE TPCL	94
50	Figure 3.22	Arrangement for cutting of composite samples	94
51	Figure 3.23a	Typical graph of stress v/s strain of 12K Carbon tow	96
52	Figure 3.23b	Typical graph of stress v/s strain of 6K Carbon tow	96
53	Figure 3.23c	Typical graph of stress v/s strain of Kevlar yarn	97
54	Figure 3.23d	Typical graph of stress v/s strain of HDPE yarn	97
55	Figure 3.24	Dimension measurement of specimen	98
56	Figure 3.25	Density measurement	101
57	Figure 3.26a	Universal Testing Machine by TINIUS OLSEN/L-Series H50KL (Left); Sample fixture (Right)	105
58	Figure 3.26b	Schematic diagram of tensile test	106
59	Figure 3.27 a	Typical graphs Load v/s Extension (Elongation) for carbon-carbon composite in longitudinal direction for tensile property	107

60	Figure 3.27 b	Typical graphs Load v/s Extension (Elongation) for carbon-carbon composite in Transverse direction for tensile property	107
61	Figure 3.28	Schematic diagram of flexural test	109
62	Figure 3.29	Typical graphs Load v/s Cross head travel composite for flexural property	109
63	Figure 3.30	FSA Model M-30 (FG-13/1) UTM (Left); Sample Fixture (Right).	110
64	Figure 3.31	Dialog box of flexural test	110
65	Figure 3.32	a) XJUD-5.5 IZOD Impact Tester. b) JJANM-21 Notching machine.	111
66	Figure 3.33	Schematic diagram of Izod impact test	112
67	Figure 3.34	Quasi static indentation test set-up	115
68	Figure 3.35	Schematic diagram of Quasi static indentation test set-up	116
69	Figure 3.36	Schematic diagram of Quasi static indentation test apparatus	117
70	Figure 3.37	Scanning Electronic Microscope	118
71	Figure 4.1	Polymer textile composite laminates with different layup sequence	123
72	Figure 4.2	Effect of skew angle of fabric orientation on tensile behaviour of TPCL (a) longitudinal (b) transverse	131
73	Figure 4.3	Effect of skew angle of fabric orientation on breaking strength of TPCL	132
74	Figure 4.4	Schematic diagram of effect of skew angle on tensile properties of TPCL	133
75	Figure 4.5	Effect of skew angle on tensile modulus of carbon-carbon composite	134
76	Figure 4.6	Effect of weave effect on breaking strength of composites	136
77	Figure 4.7	Effect of weave structure on longitudinal direction of composites	136
78	Figure 4.8	Effect of weave structure on transverse direction of composites	137

79	Figure 4.9	Effect of weave effect on Modulus of elasticity of composites	137
80	Figure 4.10	Effect of yarn type on Modulus of elasticity of composites	138
81	Figure 4.11	Fractured tensile sample CC1 from four different sides	139
82	Figure 4.12	SEM images of the fracture surface of composites after tensile test: a) CC1 b) CC1 c) CC1 d) CC1 from side 1	140
83	Figure 4.13	SEM images of the fracture surface of composites after tensile test: a) CC1 b) CC1 from side 2	141
84	Figure 4.14	SEM images of the fracture surface of composites after tensile test: a) CC1 b) CC1 from side 3	142
85	Figure 4.15	Effect of skew angle of fabric orientation on flexural properties of TPCL	144
86	Figure 4.16	Effect of weave structure on flexural properties of composite (a) longitudinal direction (b) transverse direction	144
87	Figure 4.17	Effect of type of reinforced yarn on flexural properties of TPCL (a)longitudinal direction (b) transverse direction	146
88	Figure 4.18	Comparison of flexural modulus of differently oriented TPCL	147
89	Figure 4.19	SEM images of the fracture surface of composites after flexural test: (a) CC1 (b) CC2 (c) CC2/T (d)CC3/T (e) CC4/T (f) CC4/T	149
90	Figure 4.20	Optical images of the fracture surface of composites after flexural test: (a) CC1(b) CH1/T (c) CC2/T (d)CH1(e) CC3/T (f)CK (g)CC4 (h)KH1(i)CH2	151
91	Figure 4.21	SEM images of the fracture surface of composites after flexural test: (a) CH1 (b) (b) CH1 (c) CH1/T (d) CH1/T	152
92	Figure 4.22	SEM images of the fracture surface of composites: (a) CH2/T (b) CH2/T (c) CH3 (d) CH3	153
93	Figure 4.23	Effect of skew angle on Impact properties of carbon composite	154

94	Figure 4.24	SEM image of fracture of sample CC2	155
95	Figure 4.25	Effect of weave structure on Impact properties of TPCL	157
96	Figure 4.26	Effect of type of reinforced yarn on Impact properties of TPCL	158
97	Figure 4.27	SEM images of the fracture surface of composites: a) CC1 b) CC1 c) CK d) CK e) KH1 f) KH1	159
98	Figure 4.28	Force-displacement curves of Carbon-Carbon composites for damage resistance properties	162
99	Figure 4.29	Comparison of damage resistance strength of TPCL	163
100	Figure 4.30	Optical image of specimen after damage resistance test for TPCL having differently oriented angles (skew angle)	164
101	Figure 4.31	Force-displacement curves of Carbon-HDPE composites	165
102	Figure 4.32	Optical image of specimen after damage resistance test of TPCL with different weave structure: a) CH1 b) CH2 c) CH3	166
103	Figure 4.33	Force-displacement curves of composites with different type of reinforced yarn	167
104	Figure 4.34	Optical image of specimen after damage resistance test of TPCL having different type of reinforced yarn: a) CC1 b) CH1 c) KH1 d) CK	169
105	Figure 5.1	Detail of schematic diagram showing detail of CC1	172
106	Figure 5.2	Diagram representing different fabric layers and resin layers	173
107	Figure 5.3	Diagram representing different fabric layers and resin layers with mesh formation. (a-expanded view of Composite; b- composite with rectangular mesh)	174
108	Figure 5.4	Dialog box representing the number of nodes and elements.	174
109	Figure 5.5a	Deformation of CC1 in longitudinal direction	177
110	Figure 5.5b	Stress of CC1 in longitudinal direction	177

111	Figure 5.6a	Strain distribution of CC2 in longitudinal direction	178
112	Figure 5.6b	Stress distribution of CC2 in longitudinal direction	178
113	Figure 5.6c	Stress distribution of CC2 in longitudinal direction on the first layer	179
114	Figure 5.6d	Stress distribution of CC2 in longitudinal direction on the second layer0	179
115	Figure 5.6e	Stress distribution of CC2 in longitudinal direction on the third layer	180
116	Figure 5.6f	Stress distribution of CC2 in longitudinal direction on the fourth layer	180
117	Figure 5.7a	Strain distribution of CC3 in longitudinal direction	181
118	Figure 5.7b	Stress distribution of CC3 in longitudinal direction	181
119	Figure 5.7c	Stress distribution of CC3 in longitudinal direction on the first layer	182
120	Figure 5.7d	Stress distribution of CC3 in longitudinal direction on the second layer	182
121	Figure 5.7e	Stress distribution of CC3 in longitudinal direction on the third layer	183
122	Figure 5.7f	Stress distribution of CC3 in longitudinal direction on the fourth layer	183
123	Figure 5.8a	Strain distribution of CC4 in longitudinal direction	184
124	Figure 5.8b	Stress distribution of CC4 in longitudinal direction	184
125	Figure 5.8c	Stress distribution of CC4 in longitudinal direction on the first layer	185
126	Figure 5.8d	Stress distribution of CC4 in longitudinal direction on the second layer	185
127	Figure 5.8e	Stress distribution of CC4 in longitudinal direction on the third layer	186
128	Figure 5.8f	Stress distribution of CC4 in longitudinal direction on the fourth layer	186

129	Figure 5.9a	Strain distribution of CC5 in longitudinal direction	187
130	Figure 5.9b	Stress distribution of CC5 in longitudinal direction	187
131	Figure 5.9c	Stress distribution of CC5 in longitudinal direction on the first layer	188
132	Figure 5.9d	Stress distribution of CC5 in longitudinal direction on the second layer	188
133	Figure 5.9e	Stress distribution of CC5 in longitudinal direction on the third layer	189
134	Figure 5.9f	Stress distribution of CC5 in longitudinal direction on the fourth layer	189
135	Figure 5.10a	Strain distribution of CC1 in transverse direction	190
136	Figure 5.10b	Stress distribution of CC1 in transverse direction	190
137	Figure 5.11a	Strain distribution of CC2 in transverse direction	191
138	Figure 5.11b	Stress distribution of CC2 in transverse direction	191
139	Figure 5.11c	Stress distribution of CC2 in transverse direction on the first layer	192
140	Figure 5.11d	Stress distribution of CC2 in transverse direction on the second layer	192
141	Figure 5.11e	Stress distribution of CC2 in transverse direction on the third layer	193
142	Figure 5.11f	Stress distribution of CC2 in transverse direction on the fourth layer	193
143	Figure 5.12a	Strain distribution of CC3 in transverse direction	194
144	Figure 5.12b	Stress distribution of CC3 in transverse direction	194
145	Figure 5.12c	Stress distribution of CC3 in transverse direction on the first layer	195
146	Figure 5.12d	Stress distribution of CC3 in transverse direction on the second layer	195
147	Figure 5.12e	Stress distribution of CC3 in transverse direction on the second layer	196
148	Figure 5.12f	Stress distribution of CC3 in transverse direction on the fourth layer	196
149	Figure 5.13a	Strain distribution of CC4 in transverse direction	197

150	Figure 5.13b	Stress distribution of CC4 in transverse direction	197
151	Figure 5.13c	Stress distribution of CC4 in transverse direction on the first layer	198
152	Figure 5.13d	Stress distribution of CC4 in transverse direction on the second layer	198
153	Figure 5.13e	Stress distribution of CC4 in transverse direction on the third layer	199
154	Figure 5.13f	Stress distribution of CC4 in transverse direction on the fourth layer	199
155	Figure 5.14a:	Strain distribution of CC5 in transverse direction	200
156	Figure 5.14b	Stress distribution of CC5 in transverse direction	200
157	Figure 5.14c	Stress distribution of CC5 in transverse direction on the first layer	201
158	Figure 5.14d	Stress distribution of CC5 in transverse direction on the second layer	201
159	Figure 5.14e	Stress distribution of CC5 in transverse direction on the third layer	202
160	Figure 5.14f	Stress distribution of CC5 in transverse direction on the fourth layer	202
161	Figure 5.15	Comparison of Modelling Values and Experimental values for longitudinal case if the fabric orientation is 0/0/0/0	205
162	Figure 5.16	Comparison of Modelling Values and Experimental values for Transverse case if the fabric orientation is 0/0/0/0	205
163	Figure 5.17	Comparison of Modelling Values and Experimental values for longitudinal case if the fabric orientation is 0/30/30/0	206
164	Figure 5.18	Comparison of Modelling Values and Experimental values for Transverse case if the fabric orientation is 0/30/30/0	206
165	Figure 5.19	Comparison of Modelling Values and Experimental values for longitudinal case if the fabric orientation is 0/45/45/0	207
166	Figure 5.20	Comparison of Modelling Values and Experimental values for Transverse case if the fabric orientation is 0/45/45/0	207

167	Figure 5.21	Comparison of Modelling Values and Experimental values for longitudinal case if the fabric orientation is 0/60/60/0	208
168	Figure 5.22	Comparison of Modelling Values and Experimental values for Transverse case if the fabric orientation is 0/60/60/0	208
169	Figure 5.23	Comparison of Modelling Values and Experimental values for longitudinal case if the fabric orientation is 0/90/90/0	209
170	Figure 5.24	Comparison of Modelling Values and Experimental values for Transverse case if the fabric orientation is 0/90/90/0	209
171	Figure 6.1	Suggested applications of the TPCL prepared	220