

Table of Contents

Acknowledgements	i
Abstract	iii
Table of contents	vi
List of figures	x
List of tables	xiv
Nomenclature	xv
Abbreviations	xvii
1. Introduction	1
1.1 Overview of composites	1
1.1.1 Particle-reinforced composites	2
1.1.1.1 Dispersion-strengthened composites	2
1.1.1.2 Large-particle reinforced composites	2
1.1.2 Structural composites	2
1.1.2.1 Laminates structures	2
1.1.2.2 Sandwich structures	3
1.1.3 Fiber-reinforced composite	3
1.2 Introduction to fiber reinforced polymer	4
1.2.1 Hand layup method	5
1.2.2 Pultrusion technique	6
1.2.2.1 Historical development	6
1.2.2.2 Manufacturing process	6
1.3 Materials used in fabrication of FRP beams	7
1.3.1 Reinforcement	7
1.3.1.1 Glass fibers	7
1.3.1.2 Carbon fibers	7
1.3.1.3 Aramid fibers	8
1.3.1.4 Veil	8
1.3.2 Matrix	8
1.3.2.1 Polyester resin	8
1.3.2.2 Vinylester resin	8
1.3.2.3 Epoxy resin	9
1.4 FRP I-beams	9
1.5 The problem in broad-sense	10
1.6 Need of this research	11
1.7 Objectives of the present study	12
1.8 Methodology	12
1.9 Outline of thesis	13
1.10 Scope of the present investigation	14
2. Literature Review	16
2.1 Introduction	16
2.2 Fibers	17
2.2.1 Carbon fibers	17
2.2.2 Glass fibers	18
2.3 Material characterization of beams	19

2.3.1 Experimental methods	19
2.3.2 Analytical methods	24
2.4 Flexural response of the pultruded I-beams	25
2.4.1 Lateral-torsional buckling	26
2.4.2 Web-flange junction failure	29
2.5 Beams with stiffening elements	34
2.6 Castellated beams	35
2.7 Gaps in present research	38
3. Material Characterization	39
3.1 Introduction	39
3.2 Description of beams	39
3.3 Analytical method	41
3.3.1 Fiber volume fraction and stiffness of lamina	41
3.3.2 Stiffness of beam	43
3.3.2.1 Approximate classical lamination theory	43
3.3.2.2 Mechanics of laminated beam theory	44
3.4 Experimental investigation	46
3.4.1 Physical and mechanical properties of specimens	47
3.4.1.1 Fiber content	47
3.4.1.2 Tensile characteristics	48
3.4.1.3 Compressive characteristics	50
3.4.1.4 Flexural modulus from 3-point bending test of FRP coupon	51
3.4.1.5 Interlaminar shear strength	53
3.4.1.6 Mechanical properties using bending test of beams	54
3.5 Results and discussion	59
3.6 Conclusions	61
4. Flexural Study of Beams: Experimental Investigation	63
4.1 Introduction	63
4.2 Description of specimens	64
4.3 Experimental setup	66
4.4 Behavior of FRP I-beam under flexural loading	66
4.5 Effect of different stiffening elements	68
4.5.1 Beam with bearing stiffeners	69
4.5.2 Addition of cover plate	75
4.5.3 Increasing the thickness of web	76
4.5.4 Installation of cover angles under the loading	77
4.6 Effect of stiffening elements for different length-to-depth ratios (L/d)	79
4.6.1 Beams having L/d ratio 5	79
4.6.2 Beams having L/d ratio 3	81
4.7 Discussion	83
4.8 FRP castellated Beams	85
4.8.1 Fabrication	85
4.8.2 Flexural response of castellated beams	87
4.9 Conclusions	88
5. Flexural Study of Beams: Analytical Modelling	89
5.1 Introduction	89
5.2 Analytical approach	89
5.3 Kinematic formulation	90

5.3.1 Beam with bearing plate	94
5.3.2 Beam with bearing plate and stiffening element	95
5.3.3 Beam with bearing stiffeners	97
5.3.4 Beam with longitudinal stiffening elements	98
5.4 Failure load	99
5.4.1 Buckling of beams	99
5.4.1.1 European code	99
5.4.1.2 Italian code (CNR DT-205, 2007)	101
5.4.1.3 Pultex design manual	104
5.4.1.4 ASCE code	104
5.4.2 Failure load based on strength	105
5.4.2.1 European code	105
5.4.2.2 ASCE code	105
5.5 Delamination failure criteria	106
6. Flexural Study of Beams: Numerical Investigation	108
6.1 Introduction	108
6.2 Modelling of FRP beams	109
6.2.1 Part module	109
6.2.2 Material properties	110
6.2.3 Assembly module	110
6.2.4 Meshing properties	110
6.2.5 Loading	111
6.2.6 Interaction	112
6.2.7 Analysis procedure	112
6.3 Comparison of experimental, analytical and numerical responses	113
6.3.1 Beam with bearing plate	113
6.3.2 Beam with bearing plate and bearing stiffeners	116
6.3.3 Beam with bearing plate and stiffening elements	120
6.3.3.1 Cover angle	120
6.3.3.2 Carbon fiber layer	121
6.3.3.3 Web plate	122
6.3.3.4 Cover plate	123
6.4 Parametric study on different sizes of beams and stiffeners	124
6.4.1 Influence of length of bearing plate	125
6.4.2 Influence of transverse and shear modulus	127
6.4.3 Influence of length of bearing plate on T-shaped bearing stiffener	131
6.4.4 Influence of length of cover angle	133
6.4.5 Influence of length of carbon fiber layers	134
6.4.6 Influence of length of cover plate	138
6.4.7 Influence of spacing of bolts and sizes of web plate	139
6.5 Flexural behavior of castellated beams	141
6.5.1 Validation of numerical models	141
6.5.2 Parametric study of castellated beams	142
6.5.3 Results and discussion	142
6.6 Conclusions	144
7. Summary and Conclusions	146
7.1 Summary	146
7.2 Conclusions	147
7.3 Limitations and scope of future work	149

References	150
List of Publications	160
Biographical notes	163