

COMPOSITES FOR CONSTRUCTION:

Structural Design with FRP Materials

Lawrence C. Bank

inventarisiert unter:

B26-7



WILEY

JOHN WILEY & SONS, INC.

TECHNISCHE UNIVERSITÄT DARMSTADT

Fachgebiet Konstruktiver Leichtbau und Bauweisen

Prof. Dr.-Ing. Helmut Schürmann

64289 Darmstadt, Petersenstraße 20

CONTENTS

Preface

xiii

1 Introduction

1

- 1.1 Overview, 1
- 1.2 Historical Background, 2
- 1.3 FRP Reinforcements for New Concrete Structural Members, 3
 - 1.3.1 FRP Bars or Grids for Reinforced Concrete Members, 4
 - 1.3.2 FRP Tendons for Prestressed Concrete Members, 6
 - 1.3.3 Stay-in-Place FRP Formwork for Reinforced Concrete Members, 8
- 1.4 FRP Strengthening of Existing Structural Members, 10
- 1.5 FRP Profiles for New Structures, 18
- 1.6 Other Emerging Applications of Interest to Structural Engineers, 23
- 1.7 Properties of FRP Products for Structural Engineering Design, 25
- 1.8 Published Design Guides, Codes, and Specifications for FRP Composites in Structural Engineering, 34
 - 1.8.1 FRP Reinforcing Bars and Tendons, 34
 - 1.8.2 FRP Strengthening Systems, 34
 - 1.8.3 FRP Pultruded Profiles, 35
 - 1.8.4 Manufacturers' Design Manuals, 35
 - 1.8.5 Key Conferences Series, 36
 - 1.8.6 Archival Journals, 37

2 Materials and Manufacturing

40

- 2.1 Overview, 40
- 2.2 Raw Materials, 41
 - 2.2.1 Reinforcing Fibers, 41
 - 2.2.2 Polymer Resins, 45

TECHNISCHE UNIVERSITÄT DARMSTADT
Fachgebiet Konstruktiver Leichtbau und Bauweisen
Prof. Dr.-Ing. Helmut Schürmann
64287 Darmstadt, Petersenstraße 30

- 2.3 Manufacturing Methods, 51
 - 2.3.1 Pultrusion, 52
 - 2.3.2 Hand Layup, 68
 - 2.3.3 Other Manufacturing Processes, 75

3 Properties of FRP Composites 78

- 3.1 Overview, 78
- 3.2 Theoretical Determination of Properties, 78
 - 3.2.1 Fiber Level, 78
 - 3.2.2 Lamina Level, 83
 - 3.2.3 Laminate Level, 89
 - 3.2.4 Full-Section Level, 103
- 3.3 Experimental Determination of Properties, 104
 - 3.3.1 Fiber Level, 105
 - 3.3.2 Lamina Level, 106
 - 3.3.3 Laminate Level, 107
 - 3.3.4 Full-Section Level, 110
- 3.4 Relevant Standard Test Methods for FRP Composites for Structural Engineers, 118
 - 3.4.1 American Society of Testing and Materials Test Methods, 118
 - 3.4.2 Full-Section Test Methods for FRP Bars and Laminates, 120

4 Design Basis for FRP Reinforcements 128

- 4.1 Overview, 128
- 4.2 Introduction, 129
- 4.3 Properties of FRP Reinforcing Bars, 129
- 4.4 Design Basis for FRP-Reinforced Concrete, 133
 - 4.4.1 Resistance Factors, 134
 - 4.4.2 Minimum Reinforcement Requirements, 135
 - 4.4.3 Determination of Guaranteed Properties of FRP Rebars, 135
 - 4.4.4 Design for Environmental Effects on FRP Rebars, 136
 - 4.4.5 Special Considerations Regarding FRP Rebars, 137
 - 4.4.6 Design for Serviceability, 139
 - 4.4.7 Temperature and Shrinkage Reinforcement in Slabs, 140

5	FRP Flexural Reinforcement	143
5.1	Overview, 143	
5.2	Introduction, 143	
5.3	Flexural Strength of an FRP-Reinforced Section, 145	
5.3.1	Overreinforced Section, 147	
5.3.2	Underreinforced Section, 148	
5.3.3	Minimum Flexural Reinforcement, 151	
5.4	Design Procedure for an FRP-Reinforced Flexural Member, 151	
5.4.1	Design of FRP-Reinforced Bridge Deck Slabs, 160	
5.5	Serviceability Design of FRP-Reinforced Beams, 166	
5.5.1	Deflections Under Service Loads, 166	
5.5.2	Flexural Cracking, 169	
5.5.3	Creep and Fatigue at Service Loads, 170	
5.6	Design Procedure for Serviceability, 170	
6	FRP Shear Reinforcement	182
6.1	Overview, 182	
6.2	Introduction, 182	
6.3	Shear Design of an FRP-Reinforced Concrete Section, 185	
6.3.1	Concrete Contribution to Shear Capacity, 185	
6.3.2	Shear Capacity of FRP Stirrups, 187	
6.3.3	Punching Shear Capacity in Slabs, 189	
6.4	Limits on Shear Reinforcement and Shear Strengths for Shear Design, 189	
6.5	Design Procedure for FRP Shear Reinforcement, 190	
7	FRP Reinforcement Detailing	198
7.1	Overview, 198	
7.2	Introduction, 198	
7.3	Geometric Details, 200	
7.3.1	Calculation of Bar Spacing, 202	
7.4	Bond Strength of FRP Bars, 204	
7.5	Development of Straight FRP Bars, 205	
7.6	Development of Hooked FRP Bars, 206	
7.7	Lap Splices for FRP Bars, 207	
7.8	Design Procedure to Detail FRP Bars in a Beam, 207	

8	Design Basis for FRP Strengthening	214
8.1	Overview,	214
8.2	Introduction,	215
8.3	Properties of FRP Strengthening Systems,	217
8.4	Design Basis for FRP Strengthening Systems,	219
8.4.1	Resistance Factors,	219
8.4.2	Guaranteed Properties,	220
8.4.3	Environmental Effects,	220
8.4.4	Limits on Strengthening,	221
8.4.5	Limits on Stresses in FRP Strengthening Systems at Service Loads,	223
8.4.6	Compression Strengthening in Flexural Members,	223
8.5	Deflections in FRP-Strengthened Structures,	223
8.6	FRP Strengthening System Area Calculations,	223
9	FRP Flexural Strengthening	227
9.1	Overview,	227
9.2	Introduction,	227
9.3	Flexural Capacity of an FRP-Strengthened Member,	230
9.3.1	Stress in the FRP Strengthening System,	233
9.3.2	Strain in the Internal Reinforcing Steel,	234
9.3.3	Neutral-Axis Depth,	234
9.3.4	Existing Substrate Strain,	235
9.4	Determination of Failure Modes and Flexural Capacity,	236
9.4.1	Mode 1a: Concrete Crushing After Steel Yields,	237
9.4.2	Mode 1b: Concrete Crushing Before Steel Yields,	238
9.4.3	Mode 2a: FRP Failure After Steel Yields,	239
9.4.4	Mode 2b: FRP Failure Before Steel Yields,	241
9.5	Balanced Condition,	243
9.6	Detailing for Flexural Strengthening,	244
9.7	Design Procedure for a Flexurally Strengthened Concrete Member,	245
9.8	Serviceability of FRP-Strengthened Flexural Members,	266

9.8.1	Cracked FRP Strengthened Section, 266	
9.8.2	Service-Level Stress in the Internal Steel Reinforcing Bars, 268	
9.8.3	Service-Level Stress in the FRP Strengthening System, 270	
9.9	Load-Deflection Response of FRP-Strengthened Flexural Members, 271	
10	FRP Shear Strengthening	288
10.1	Overview, 288	
10.2	Introduction, 289	
10.3	Shear Capacity of an FRP-Strengthened Member, 293	
10.4	Effective Strain in the FRP for Shear Strengthening, 296	
10.5	Design Procedure for Shear Strengthening, 298	
10.6	Shear Strengthening of Fully Wrapped Axially Loaded Columns, 308	
11	FRP Confining	316
11.1	Overview, 316	
11.2	Introduction, 316	
11.3	FRP Confining for Axial Strengthening, 324	
11.3.1	Serviceability for FRP-Strengthened Axial Members, 326	
11.4	Design Procedure for FRP Axial Strengthening of RC Circular Columns, 327	
11.5	FRP-Strengthened Eccentrically Loaded Columns, 333	
11.6	FRP Confining for Increased Ductility, 346	
11.6.1	Lateral Displacement Ductility, 347	
11.6.2	Flexural Hinge Confinement, 348	
11.7	Design Procedure for Flexural Hinge Confinement, 350	
11.8	Lap Splice Region Confinement, 351	
11.9	Plastic Shear Overstrength Demand, 352	
12	Design Basis for FRP Profiles	359
12.1	Overview, 359	
12.2	Introduction, 360	
12.3	Properties of Pultruded Profiles, 363	
12.4	Design Basis for FRP Pultruded Structures, 369	

12.4.1	Allowable Stress Design,	370
12.4.2	Load and Resistance Factor Design,	373
12.5	Performance-Based Design,	380
13	Pultruded Flexural Members	384
13.1	Overview,	384
13.2	Introduction,	384
13.3	Stresses in Flexural Members,	385
13.4	Deformations in Flexural Members,	388
13.5	Determination of Deflections and Stresses for Serviceability and Ultimate Limit States,	392
13.6	Serviceability Limits States,	393
13.6.1	Deformation Limit State: Transverse Deflection,	393
13.6.2	Long-Term Deflection in Pultruded Beams,	397
13.7	Ultimate Limit States,	401
13.7.1	Lateral-Torsional Buckling,	401
13.7.2	Local Buckling of Walls Due to In-Plane Compression,	403
13.7.3	Local Buckling of Walls Due to In-Plane Shear,	413
13.7.4	Web Crushing and Web Buckling in the Transverse Direction,	414
13.7.5	Additional Factors Affecting Local Buckling in Pultruded Profiles,	415
13.7.6	Flange and Web Longitudinal Material Failure,	417
13.7.7	Flange and Web Material Shear Failure,	418
13.8	Design Procedure for Flexural Members,	419
14	Pultruded Axial Members	436
14.1	Overview,	436
14.2	Introduction,	436
14.3	Concentrically Loaded Compression Members,	437
14.4	Deformations in Concentrically Loaded Compression Members,	439
14.5	Determination of Deflections and Stresses for Serviceability and Ultimate Limit States,	439
14.6	Serviceability Limit States: Axial Shortening,	439
14.7	Ultimate Limit States,	440

- 14.7.1 Global Flexural Buckling, 440
- 14.7.2 Global Torsional Buckling, 442
- 14.7.3 Local Buckling Due to Axial Loads, 443
- 14.7.4 Interaction Between Local and Global Buckling Modes in Intermediate-Length Compression Members, 450
- 14.7.5 Flange and Web Longitudinal Material Failure, 453
- 14.8 Design Procedure for Concentrically Loaded Compression Members, 453
- 14.9 Concentrically Loaded Tension Members, 467
 - 14.9.1 Deformations in Concentrically Loaded Tension Members, 468
- 14.10 Determination of Deflections and Stresses for Serviceability and Ultimate Limit States: Axial Elongation, 468
- 14.11 Ultimate Limit States, 469
 - 14.11.1 Longitudinal Material Failure on the Gross Area, 469
 - 14.11.2 Longitudinal Material Failure on the Net Area, 469
- 14.12 Design Procedure for Concentrically Loaded Tension Members, 470
- 14.13 Combined Load Members, 471
 - 14.13.1 Members Subjected to Combined Flexure and Compression (Beam-Columns), 471
 - 14.13.2 Members Subjected to Combined Flexure and Tension, 477

15 Pultruded Connections

484

- 15.1 Overview, 484
- 15.2 Introduction, 485
 - 15.2.1 Conventional Pultruded Connections, 485
 - 15.2.2 Custom Pultruded Connections, 488
- 15.3 Mechanical Fasteners and Connection Parts, 490
 - 15.3.1 FRP Nuts and Bolts, 492
- 15.4 Research on Heavy Beam-to-Column Pultruded Connections, 492
- 15.5 Bolted Pultruded Connections, 496
- 15.6 Light-Truss Pultruded Connections, 498
 - 15.6.1 Lap Joint Connections, 499

15.7	Heavy-Frame Pultruded Connections,	503
15.8	Design of Bolted Pultruded Connections,	504
15.9	Determination of Stresses in In-Plane Lap Joints,	505
15.9.1	Bearing Stress in the Base Pultruded Material,	505
15.9.2	Net-Tension Stress in the Base Pultruded Material,	506
15.9.3	Shear-Out Stress in the Base Pultruded Material,	506
15.9.4	Shear Stress on a Bolt,	507
15.10	Stresses in Out-of-Plane Shear Connections,	507
15.10.1	Longitudinal Shear Stress at the Heel of an Angle,	507
15.10.2	Flexural Stress in the Leg of an Angle Bolted to a Column Member,	508
15.10.3	Transverse Tensile Stress in a Web-Flange Junction of a Column,	509
15.10.4	Block Shear in a Beam Web,	509
15.10.5	Flexural and Shear Stresses in Flexible Seated Connections,	510
15.11	Critical Connection Limit States,	510
15.12	Design Procedure for a Pultruded Connection,	512

References

527

Index

545