

CONSTRUCTION TECHNOLOGY FOR INTEGRAL BRIDGES WITH BASALT FIBER-REINFORCED POLYMER PRESTRESSING TENDONS

ALI ALRAIE



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2022**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2022

CONSTRUCTION TECHNOLOGY FOR INTEGRAL BRIDGES WITH BASALT FIBER-REINFORCED POLYMER PRESTRESSING TENDONS

by

ALI ALRAIE

Department of Civil Engineering

Submitted

in fulfillment of the requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2022

*Dedicated to my family members
for their love, support, and inspiration*

CERTIFICATE

This is to certify that the PhD thesis titled, “**CONSTRUCTION TECHNOLOGY FOR INTEGRAL BRIDGES WITH BASALT FIBER-REINFORCED POLYMER PRESTRESSING TENDONS**” being submitted by **ALI ALRAIE** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. He worked under my supervision for the submission of this PhD thesis, which to my knowledge has reached the requisite standard as demonstrated by excellent publications in national and international journals.

Further, the contents of his research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of my knowledge and belief.

New Delhi

Prof. Dr Vasant A. Matsagar

(Dogra Chair Professor)

Department of Civil Engineering,
Indian Institute of Technology (IIT) Delhi,
Hauz Khas, New Delhi – 110 016, India.

ACKNOWLEDGEMENT

Throughout my stay in India, and particularly at the Indian Institute of Technology (IIT) Delhi, I have come across many people whose love, encouragement, and inspiration have helped me a lot on this achievement. I would like to convey my gratitude to all those people who directly or indirectly helped me during my stay in my second home (India).

I would like to express my deep sense of gratitude from the core of my heart to my supervisor Prof. Dr Vasant A. Matsagar (Dogra Chair Professor) for his constant guidance and support. I greatly appreciate his crucial contribution towards the completion of my doctoral research work. My words can never express his endless dedication in teaching and guiding me with utmost patience and generosity. Thank you very much, Sir, for everything. I truly know how difficult it was to raise me up to the standard of IIT Delhi and your standard with your big name in academia and research field.

I would like to thank my Student Research Committee (SRC) members, Prof. Dr J. T. Shahu, Prof. Dr K. N. Jha, and Prof. Dr Amit Rawal, for being a part of my research journey. I would like to convey a special thanks to Prof. Dr Dipti Ranjan Sahoo for acting as my caretaking supervisor and checking my journal papers with his invaluable comments. I would like to further thank my international coauthors from Germany and UK; Prof. Mike Schlaich, Prof. Arndt Goldack, Prof. Bohumil Kasal, and Prof. Saverio Spadea, for the valuable discussions and contribution in my international journal publications. My gratitude is also conveyed to the senior laboratory assistants who helped me in performing my experimental work, Mr Biri Singh, Mr Anil Kumar, and Mr Roshan Lal. I extend my deepest gratitude to the Department of Civil Engineering, IIT Delhi for providing excellent academic environment, and to all faculty and staff members.

This is the right occasion to thank all the people attached to the Multi-Hazard Protective Structures (MHPS) Laboratory who were really like family members. I specially thank Dr Pravin Jagtap, Dr Said Elias, Dr Ankit Bhardwaj, Mr Naseef Umeer, Mr Anil Kumar, Dr Tathagata Roy, Mr Daniel Habtamu Zelleke, Mrs Harshada Sharma, Mr Sharang Totekar, Mr Akshay Baheti, Ms Kusum Saini, Mrs SreeNitya Singamsetty, Mr Yash Chordiya, Ms Namrata Singh, Mr Sarranya Banerjee, Mr Gaurav Swami, Ms Bushra Rehman, Mr M. Farhan Khan, Mr Divyarth Dikshit, Mr Devesh Dubey, Mr Jitendra Prajapati, and Ms Simran Kaur.

Last but not the least, I would also like to thank my parents and family members whose blessings have helped me in achieving this milestone; my dear wife, the beat of my

heart, who was standing by me all the time and giving me the power; and the pupil of my eye, Karam, who spent the first two years of his life staying with me in India before moving to Syria due to COVID-19. Love you all!

New Delhi.

Ali Alraie

ABSTRACT

Attention has recently been shifted from the conventional structural materials to advanced composite materials owing to their superior mechanical properties. Basalt fiber-reinforced polymer (BFRP) has been the newest fiber-reinforced polymer (FRP) composite material introduced as reinforcement and prestressing tendons for reinforced concrete (RC) and prestressed concrete (PSC) structures. On the other hand, with the increasing demand on flyovers and bridges in city spaces, planning and design must address faster constructions of aesthetically appealing slender bridges. Hence, joint-less, integral bridges are becoming popular. Therefore, beginning from designing the components required for the use of BFRP in prestressing operations to design procedure of the BFRP-PSC members of integral bridges are required to be developed. Measuring the mechanical properties of BFRP rods/tendons is challenging using the existing mechanical testing methods due to their relatively lower transverse direction strength. This creates issues not only in characterization of the BFRP in laboratory conditions but also on-field prestressing application in integral bridges. Hence, development of a proper anchor with optimum size for the BFRP rods is crucial for further studies. For this purpose, expansive cement grout-based anchor is developed, tested, and assessed, and the parameters affecting the gripping behavior are studied for optimizing the anchor design based on the finite element (FE) analysis. The proposed anchor is found to have achieved 49% saving as compared to the existing anchor developed by previous researchers. On the other hand, understanding of the thermo-mechanical behavior of the BFRP composites is needed for practical and cost-effective applications in integral bridges, which experience thermal stresses throughout their service lives. Characterization and assessment of performance of the BFRP rods at elevated temperatures is investigated through extensive experimental and analytical studies. Owing to high thermal properties, the BFRP rod could retain 57% tensile strength at 400°C. Consequently, a semi-empirical constitutive law for predicting the thermo-mechanical behavior of FRP composites is proposed and validated with experimental results of research studies from the literature. The proposed model is original, generic, and flexible, and is based on general characteristics of the composite eliminating hence the requirement for conducting the tension test at elevated temperatures.

For addressing the arguable design philosophy of the BFRP-reinforced/ prestressed concrete members, extensive experimental investigations are carried out to assess the flexural performance of the BFRP-prestressed concrete (PSC) beams designed as over-

reinforced, under-reinforced, and significantly under-reinforced, as well as the non-prestressed concrete beams. The assessment is made based on the flexural strength, serviceability satisfaction, safety factor against failure, and deformability/ ductility. The efficacy of the partial prestressing of the beams in a multi-layered system of tendons is investigated, and an alternative source of ductility is introduced by allowing the tendons to rupture sequentially in a kind of progressive failure. Furthermore, the flexural analysis of the tested beams is carried out based on the available codal provisions and referred studies from the literature for complimenting the experimental findings. Further investigations are carried out on ductility evaluation of concrete beams prestressed with FRP tendons, wherein the effect of the partial prestressing, layering of the tendons, addition of sacrificial rebars, and functionally-graded concrete (FGC) is elaborated. The finite element analysis (FEA) is also employed for further testifying on the efficacy of the introduced techniques in improving the ductility of FRP-prestressed members. The investigations show that the ductile behavior can be achieved in multi-layered systems with energy ratio as high as 82.5%, and in partially prestressed beams with energy ratio above 75%. Apart from that, the natural fiber composites, being cost effective and environmentally friendly, are investigated for possible use in post-tensioning of reinforced concrete beams. The successful utilization of such natural fibers in structural applications may result in more sustainability in construction industry. Finally, to investigate on the efficacy of using BFRP prestressing tendons in integral bridges, BFRP tendons are used for the design of conventional and integral bridges, and a comparative assessment is carried out with steel-prestressed conventional bridges. The integral bridge with BFRP tendons is found to have 71.4% dead weight as compared to the conventional bridge with steel tendons. It is concluded that employing both the techniques of using the non-corroding BFRP tendons and the proposed integral form of bridges is a promising technology in bridge construction.

हाल ही में पारंपरिक संरचनात्मक सामग्रियों से उन्नत मिश्रित सामग्रियों पर उनके बेहतर यांत्रिक गुणों के कारण ध्यान स्थानांतरित कर दिया गया है। बेसाल्ट फाइबर-प्रबलित बहुलक (BFRP) नवीनतम फाइबर-प्रबलित बहुलक (FRP) मिश्रित सामग्री है जिसे प्रबलित कंक्रीट (RC) और प्रेस्ट्रेसड कंक्रीट (PSC) संरचनाओं के लिए सुदृढीकरण और प्रेस्ट्रेसिंग पट्टा के रूप में पेश किया गया है। दूसरी ओर, शहर के स्थानों में फ्लाईओवर और पुलों की बढ़ती मांग के साथ, योजना और डिजाइन को सौंदर्य की दृष्टि से आकर्षक पतले पुलों के तेजी से निर्माण को संबोधित करना चाहिए। इसलिए, संयुक्त-विहीन, अभिन्न पुल लोकप्रिय हो रहे हैं। इसलिए, प्रीस्ट्रेसिंग संचालन में BFRP के उपयोग के लिए आवश्यक घटकों को डिजाइन करने से लेकर अभिन्न पुल के BFRP-PSC सदस्यों की डिजाइन प्रक्रिया विकसित करने की आवश्यकता है। BFRP छड़ी / पट्टा के यांत्रिक गुणों को मापना उनके अपेक्षाकृत कम अनुप्रस्थ दिशा शक्ति के कारण मौजूदा यांत्रिक परीक्षण विधियों का उपयोग करना चुनौतीपूर्ण है। यह न केवल प्रयोगशाला स्थितियों में BFRP के लक्षण वर्णन में बल्कि अभिन्न पुलों में साइट पर प्रीस्ट्रेसिंग एप्लिकेशन में भी समस्याएं पैदा करता है। इसलिए, आगे के अध्ययन के लिए BFRP रॉड के लिए इष्टतम आकार के साथ एक उचित धारक का विकास महत्वपूर्ण है। इस प्रयोजन के लिए, विस्तृत सीमेंट ग्राउट-आधारित एंकर विकसित, परीक्षण और मूल्यांकन किया गया है, और परिमित तत्व (FE) विश्लेषण के आधार पर एंकर डिजाइन को अनुकूलित करने के लिए पकड़ बर्ताव को प्रभावित करने वाले मापदंडों का अध्ययन किया गया है। दूसरी ओर, अभिन्न पुलों में व्यावहारिक और लागत प्रभावी अनुप्रयोगों के लिए BFRP संमिश्रित के थर्मो-यांत्रिक व्यवहार की समझ की आवश्यकता होती है, जो अपने पूरे सेवा जीवन में थर्मल तनाव का अनुभव करते हैं। व्यापक प्रयोगात्मक और विश्लेषणात्मक अध्ययनों के माध्यम से ऊंचे तापमान पर BFRP छड़ी के प्रदर्शन की विशेषता और मूल्यांकन की जांच की गई है। नतीजतन, FRP कंपोजिट के थर्मो-यांत्रिक व्यवहार की अनुमान के लिए एक अर्ध-अनुभवजन्य संवैधानिक कानून प्रस्तावित किया गया है और साहित्य से शोध अध्ययन के प्रयोगात्मक परिणामों के साथ सत्यापित किया गया है। प्रस्तावित मॉडल मूल, सामान्य और लचीला है, और समग्र के सामान्य गुणों पर आधारित है, जो ऊंचे तापमान पर तनाव परीक्षण करने की आवश्यकता को समाप्त करता है।

बीएफआरपी-प्रबलित/प्रेस्ट्रेसड कंक्रीट सदस्यों के तर्कपूर्ण डिजाइन दर्शन को संबोधित करने के लिए, BFRP-अत्यधिक प्रबलित कंक्रीट बीम तथा BFRP-प्रेस्ट्रेस कंक्रीट (PSC) बीम के फ्लेक्सुरल प्रदर्शन का आकलन करने के लिए व्यापक प्रयोगात्मक जांच की गई, जिसे अत्यधिक प्रबलित, कम-प्रबलित, और अत्यधिक कम-प्रबलित के रूप में डिजाइन किया गया था। यह मूल्यांकन फ्लेक्सुरल ताकत, सेवाक्षमता संतुष्टि, विफलता के खिलाफ सुरक्षा कारक, और विकृति / लचीलापन के आधार पर

किया गया है। टेंडन की एक बहु-स्तरीय प्रणाली में बीम के आंशिक प्रेस्ट्रेस की प्रभावशीलता की जांच की गई है, और एक प्रकार की प्रगतिशील विफलता में टेंडन को क्रमिक रूप से टूटने की अनुमति देकर लचीलापन का एक वैकल्पिक स्रोत पेश किया गया है। इसके अलावा, प्रायोगिक निष्कर्षों का समर्थन करने के लिए उपलब्ध कोडल प्रावधानों और साहित्य से अध्ययन के आधार पर फ्लेक्सुरल विश्लेषण किया गया है। FRP टेंडन के साथ प्रेस्ट्रेस कंक्रीट बीम के लचीलापन मूल्यांकन पर आगे की जांच की गई है, जिसमें आंशिक प्रेस्ट्रेसिंग, टेंडन के लेयरिंग, बलि सरिया के अतिरिक्त कार्यात्मक रूप से वर्गीकृत कंक्रीट (FGC) के प्रभाव को विस्तृत किया गया है। परिमित तत्व विश्लेषण (FEA) को FRP-प्रेस्ट्रेस्ड सदस्यों की लचीलापन बढ़ाने में शुरू की गई तकनीकों की प्रभावकारिता का समर्थन करने के लिए भी नियोजित किया गया है। इसके अलावा, प्राकृतिक फाइबर कंपोजिट, लागत प्रभावी और पर्यावरण के अनुकूल होने के कारण, प्रबलित कंक्रीट बीम के पोस्ट-टेंशनिंग में संभावित उपयोग के लिए जांच की गई है। संरचनात्मक अनुप्रयोगों में ऐसे प्राकृतिक रेशों के सफल उपयोग से निर्माण उद्योग में अधिक स्थिरता आ सकती है। अंत में, अभिन्न पुलों में BFRP प्रेस्ट्रेसिंग टेंडन के उपयोग की प्रभावकारिता की जांच करने के लिए, BFRP टेंडन का उपयोग पारंपरिक और अभिन्न पुलों के डिजाइन के लिए किया गया है, और इस्पात-प्रेस्ट्रेस्ड पारंपरिक पुलों के साथ एक तुलनात्मक मूल्यांकन किया गया है। यह निष्कर्ष निकाला गया है कि गैर-संक्षारक BFRP टेंडन और पुलों के प्रस्तावित अभिन्न रूप का उपयोग करने की दोनों तकनीकों का उपयोग पुल निर्माण में एक आशाजनक तकनीक है।

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE NO.
	Abstract	v
	संक्षेप	vii
	Table of Contents	ix
	List of Figures	xxi
	List of Tables	xxix
	Mathematical Notations	xxxiii
	Abbreviations	xli
CHAPTER-1	Introduction and Literature Review	1-38
1.1	General	1
1.2	Integral Bridges	2
1.2.1	Beam and frame bridges	4
1.2.2	Concept of integral bridge	5
1.2.3	Contraction of bridge deck	7
1.2.4	Analysis of integral bridges	8
1.3	Prestressed Concrete	9
1.3.1	Pre-tensioning and post-tensioning systems	10
1.3.2	External versus internal post-tensioning systems	10
1.3.3	Development of prestressed concrete bridges	11
1.4	Basalt Fiber-Reinforced Polymer (BFRP)	12
1.4.1	Source of basalt fiber	13
1.4.2	Matrix of the composite	14
1.4.3	Characteristics of BFRP composites	14
1.4.4	Applications of BFRP composites	16
1.4.5	Development of FRP-reinforced bridges	17
1.5	Anchoring of Fiber-Reinforced Polymer (FRP) Rebars/ Tendons	19
1.6	Thermo-Mechanical Behavior of FRP Composites	23

CHAPTER	TITLE	PAGE NO.
	1.7 FRP-Reinforced/ Prestressed Structural Members	25
	1.8 Ductility and Deformability of FRP-Reinforced/ Prestressed Members	28
	1.9 Natural Fibers in Structural Applications	31
	1.10 Need and Relevance of the Present Study	34
	1.11 Objectives of the Present Study	35
	1.12 Organization of the Thesis	36
CHAPTER-2	Application of Technology and Optimization of Anchor Design for Basalt Fiber-Reinforced Polymer Rods	39-63
	2.1 General	39
	2.2 Analytical Study on Expansive Cement-Based Anchor	40
	2.3 Experimental Investigation	45
	2.3.1 Preparation of samples	47
	2.3.2 Results and discussion on expansion stage	48
	2.3.3 Pull-out test	49
	2.3.4 Results and discussion on the pull-out test	51
	2.4 Finite Element (FE)-Based Simulation	54
	2.4.1 Validation of developed FE model	56
	2.4.2 Optimal anchor design	61
	2.4.3 Experimental testing of introduced anchor	62
	2.5 Closure	63
CHAPTER-3	Characterization and Performance of Basalt Fiber-Reinforced Polymer Rods at Elevated Temperatures	65-86
	3.1 General	65
	3.2 Experimental Investigations	66
	3.2.1 Prerequisite tests	66
	3.2.1.1 <i>Determination of fiber content</i>	66
	3.2.1.2 <i>Dynamic mechanical thermal analysis (DMTA) test</i>	67
	3.2.1.3 <i>Thermo-gravimetric analysis (TGA) test</i>	69

CHAPTER	TITLE	PAGE NO.
	3.2.1.4 <i>Tension test on BFRP rod at ambient temperature</i>	70
	3.2.2 Tension test on BFRP rod at elevated temperatures	71
	3.2.2.1 <i>Observations and results</i>	73
	3.2.2.2 <i>Degradation in mechanical properties with elevated temperatures</i>	76
	3.2.3 Assessment of performance of the BFRP rod at elevated temperatures	78
	3.2.4 Scanning electron microscopy (SEM) investigation	79
3.3	Development of Constitutive Law	80
	3.3.1 Investigations on existing approaches	80
	3.3.2 Proposed model for thermo-mechanical behavior of FRP composites	81
3.4	Closure	86
CHAPTER-4	Experimental Investigations on Basalt Fiber-Reinforced Polymer (BFRP)-Reinforced/Prestressed Concrete Beams with Different Design Philosophies	87-113
4.1	General	87
4.2	Design Details	87
4.3	Experimental Investigation	90
	4.3.1 Pre-tensioning of tendons	90
	4.3.2 Construction of beam specimens	91
	4.3.3 Instrumentation and test procedure	93
	4.3.4 Experimental observations and results	94
	4.3.4.1 <i>Load-deflection response and modes of failure</i>	95
	4.3.4.2 <i>Strain response</i>	97
	4.3.4.3 <i>Serviceability</i>	98
	4.3.4.4 <i>Deformability and ductility</i>	104
4.4	Comparative Assessment of the Different Design Categories	112
4.5	Closure	112

CHAPTER	TITLE	PAGE NO.
CHAPTER-5	Flexural Analysis of Basalt Fiber-Reinforced Polymer (BFRP)-Reinforced/ Prestressed Concrete Beams	115-140
5.1	General	115
5.2	Assumptions	116
5.3	Analytical Procedure	116
5.3.1	Prestress losses	116
5.3.2	Checking for stresses under permanent loads	117
5.3.3	Balanced ratio	117
5.3.4	Reinforcement ratio	118
5.3.5	Cracking moment	119
5.3.6	Depth of neutral axis	119
5.3.7	Strains in concrete and tendons	121
5.3.8	Compressive force in concrete and tensile forces in tendons	121
5.3.9	Moment of resistance	122
5.3.10	Computation of deflection	122
5.4	Analytical Results	127
5.4.1	Flexural analysis results	127
5.4.2	Results of deflection	129
5.4.3	Shear capacity calculations and results	131
5.5	Finite Element (FE) Analysis	133
5.5.1	Finite element modeling	133
5.5.2	Finite element analysis results	137
5.6	Closure	142
CHAPTER-6	Analytical and Numerical Investigations on Ductility of Fiber-Reinforced Polymer (FRP)-Prestressed Beams	143-177
6.1	General	143
6.2	Analytical Approach	144
6.3	Validation of the Analytical Approach	148
6.4	Finite Element (FE) Analysis	149

CHAPTER	TITLE	PAGE NO.
6.5	Comparison of the Different Approaches	154
6.6	Proposed Model for Ductility Assessment	159
6.7	Results and Discussion	160
6.7.1	Effect of prestressing force on pseudo-ductility in single-layered system	160
6.7.2	Layering of tendons	161
6.7.2.1	<i>Proposed solution for compromised economy</i>	166
6.7.2.2	<i>Comparative assessment on the different cases of the parametric study</i>	169
6.7.2.3	<i>Quantitative comparison between over- and under-reinforced designs</i>	171
6.7.3	Partial prestress	172
6.8	Closure	177
CHAPTER-7	Investigations on Possible Use of Natural Jute Fiber (NJF) Ropes for Post-Tensioning of Reinforced Concrete Beams	179-196
7.1	General	179
7.2	Characterization of Natural Jute Fiber (NJF) Rope	180
7.3	Design Details	180
7.4	Analytical Investigation	181
7.5	Finite Element (FE) Analysis	184
7.5.1	Concrete damaged plasticity (CDP)	185
7.5.2	Validation of finite element (FE) model	187
7.5.3	Effect of post-tensioning on flexural behavior	188
7.5.3.1	<i>Effect of varying post-tensioning force on flexural performance</i>	189
7.5.4	NJF rope versus steel strand for post-tensioning	192
7.5.5	Basalt fiber-reinforced polymer (BFRP) versus steel in NJF-post-tensioned beam	193
7.6	Experimental Work and Observations	194
7.7	Closure	196

CHAPTER	TITLE	PAGE NO.
CHAPTER-8	Use of Basalt Fiber-Reinforced Polymer Prestressing Tendons in Integral Bridges	197-216
8.1	General	197
8.2	Design and Analysis of Integral Bridges	198
8.2.1	Form optimization of integral abutment bridges	199
8.3	Design Guidelines for FRP-Reinforced Structures	199
8.4	Description of Investigated Bridge	200
8.5	Design of the Proposed Bridges	201
8.5.1	Design methodology and analysis	201
8.5.2	Applied loads on the bridges	202
8.5.2.1	<i>Dead load and superimposed loads</i>	202
8.5.2.2	<i>Live loads on the bridges</i>	203
8.5.2.3	<i>Braking and traction loads</i>	204
8.5.2.4	<i>Wind load on the bridges</i>	204
8.5.2.5	<i>Overall temperature rise and fall</i>	204
8.5.2.6	<i>Temperature gradient rise and fall</i>	205
8.5.2.7	<i>Seismic loads on the bridges</i>	205
8.5.2.8	<i>Snow load on the bridges</i>	206
8.5.3	Load combinations for design and analysis of the bridges	207
8.5.4	Design and analysis results	207
8.5.4.1	<i>Dead weight of superstructure</i>	212
8.5.4.2	<i>Vertical deflection of bridge girders under live load</i>	213
8.5.4.3	<i>Bending moment diagram in girders</i>	214
8.5.4.4	<i>Stress diagram at top fiber</i>	214
8.5.4.5	<i>Aesthetical comparison</i>	215
8.6	Closure	216
CHAPTER-9	Summary, Conclusions, and Future Scope of Research Work	217-223
9.1	Summary	217

CHAPTER	TITLE	PAGE NO.
9.2	Conclusions	218
9.3	Future Scope of Research Work	222
	References	225-238
APPENDIX-1	Numerical Study on Pre-Tensioned Bridge Girder	239-250
A1.1	Description of Problem	239
A1.2	Analysis of Girder	239
A1.2.1	Determination of properties and applied moments	239
A1.2.2	Determination of stresses at top and bottom fibers	239
A1.2.3	Computation of losses of stress in pre-tensioned girder	242
A1.2.4	Computation of deflection at mid-span	243
A1.3	Comparison between Cases with and without Prestress	244
A1.4	Analysis of Girder in Commercially Available Software SAP2000®	245
A1.5	Comparison of Hand Calculations and Numerical Simulation Results	250
A1.6	Closure	250
APPENDIX-2	Analysis of Post-Tensioned Bridge Beam with Unbonded Tendons	251-273
A2.1	General	251
A2.2	Strain Compatibility Method	251
A2.3	Indian Code Method	255
A2.4	British Code Provisions	257
A2.5	American Code Recommendations	259
A2.6	Numerical Problem	261
A2.6.1	Analysis using strain compatibility method	261
A2.6.2	Analysis as per Indian Code	264
A2.6.3	Analysis as per British Code	265
A2.6.4	Analysis as per American Code	265
A2.6.5	Analysis of post-tensioned beam in SAP2000®	266

CHAPTER	TITLE	PAGE NO.
	A2.6.6 Comparison of analysis results of the different approaches	272
	A2.7 Closure	273
APPENDIX-3	Analysis of Reinforced Concrete (RC) Beam and Post-Tensioned Beam with Unbonded Natural Jute Fiber (NJF) Ropes	275-278
	A3.1 Design Details	275
	A3.2 Reinforced Concrete (Control) Beam	275
	A3.3 Reinforced Concrete (RC) Beam Post-Tensioned with Unbonded NJF Rope	276
APPENDIX-4	Development of MATLAB Code for Analysis of Beam and Portal Frame Using Finite Element Method (FEM)	279-325
	A4.1 Development of Beam Equations	279
	A4.1.1 General	279
	A4.1.2 Derivation of beam stiffness matrix using direct equilibrium approach	279
	A4.1.3 Derivation of beam element equations using potential energy approach	286
	A4.1.4 Derivation of beam element equations using Galerkin approach	289
	A4.1.5 Equations of arbitrarily oriented beam element	291
	A4.2 Development of Frame Equations	292
	A4.2.1 General	292
	A4.2.2 Derivation of stiffness matrix of linear bar element	293
	A4.2.3 Derivation of stiffness matrix and equations of frame element	295
	A4.3 Numerical Problem on Beam Analysis	297
	A4.3.1 Development of MATLAB code for beam analysis	298
	A4.3.2 Beam analysis in commercially available software SAP2000®	304
	A4.3.3 Beam analysis by hand calculation	305
	A4.3.4 Comparison of the different approaches	308
	A4.4 Numerical Problem on Portal Frame Analysis	309
	A4.4.1 Frame analysis using finite element method (FEM)	309
	A4.4.2 Frame analysis in commercially available software SAP2000®	315

CHAPTER	TITLE	PAGE NO.
	A4.4.3 Frame analysis using MATLAB code	316
	A4.4.4 Comparison of the different approaches for portal frame analysis	318
	A4.5 Closure	319
	A4.6 MATLAB Code Developed Based on FEM for Beam Analysis	320
	A4.7 MATLAB Code Developed Based on FEM for Portal Frame Analysis	322
APPENDIX-5	MATLAB Code for Flexural Analysis of Under-Reinforced Partially Prestressed Concrete Beams with Fiber-Reinforced Polymer (FRP) Tendons	327-333
APPENDIX-6	Finite Element (FE)-Based Numerical Modeling of Bridge and Structural Elements with Fiber-Reinforced Polymer (FRP) Reinforcements	335-345
	A6.1 General	335
	A6.2 Problem Statement	335
	A6.3 Finite Element-Based Simulation in ABAQUS®	337
	A6.3.1 Concrete models in ABAQUS®	337
	A6.3.2 Material properties of concrete and CFRP tendons	338
	A6.3.3 Establishment of FE model of AASHTO beam	340
	A6.3.4 Results and discussion on FE analysis	342
	A6.4 Closure	345
APPENDIX-7	Structural Design Basis for Integral Abutment Bridges	347-391
	A7.1 Purpose	347
	A7.2 Scope	347
	A7.3 General Overview	347
	A7.4 Sustainability	347
	A7.4.1 Design life	347
	A7.4.2 Clearances	348
	A7.4.3 Durability	348
	A7.4.3.1 Exposure classes for concrete	348
	A7.4.3.2 Concrete cover	348
	A7.4.3.3 Design crack width	349

CHAPTER	TITLE	PAGE NO.
A7.4.4	Material	350
A7.4.4.1	<i>Concrete</i>	350
A7.4.4.2	<i>Steel reinforcement</i>	350
A7.4.4.3	<i>Prestressing steel</i>	350
A7.4.4.4	<i>Partial factor for materials</i>	351
A7.5	Design Parameters	352
A7.5.1	Dead load	352
A7.5.2	Superimposed dead load	352
A7.5.3	Highway live load	352
A7.5.4	Pedestrian live load	353
A7.5.5	Braking and traction	354
A7.5.6	Centrifugal force	354
A7.5.7	Wind load	355
A7.5.7.1	<i>Wind load on live load (WL)</i>	355
A7.5.7.2	<i>Wind load on structure (WS)</i>	355
A7.5.7.3	<i>Wind load on the superstructure</i>	356
A7.5.7.4	<i>Wind load on the substructure</i>	356
A7.5.8	Temperature	357
A7.5.9	Earthquake	357
A7.5.9.1	<i>Design response spectra-horizontal motion</i>	359
A7.5.9.2	<i>Design response spectra-vertical motion</i>	359
A7.5.9.3	<i>Rayleigh damping method for time history analysis</i>	360
A7.5.9.4	<i>Seismic analysis</i>	360
A7.5.10	Accidental load from road traffic	361
A7.5.11	Differential settlement	362
A7.5.12	Time-dependent effects – creep, shrinkage, and relaxation	362
A7.5.13	Fatigue load	363
A7.5.14	Dynamic effect	364

CHAPTER	TITLE	PAGE NO.
	A7.5.15 Construction tolerance and buckling effect	364
A7.6	Load Combination and Design Checks	364
	A7.6.1 Load combinations	365
	A7.6.1.1 <i>Serviceability limit state (SLS)</i>	365
	A7.6.1.2 <i>Ultimate limit state (ULS)</i>	377
A7.7	Prestressed Concrete Elements	377
	A7.7.1 Stresses in tendons	377
	A7.7.2 Temporary stresses in concrete before losses	378
	A7.7.3 Stresses in concrete at service limit state after losses	380
A7.8	Reinforced Concrete Elements	383
	A7.8.1 Stresses in concrete at service limit state	383
	A7.8.2 Summary of service limits to be considered	383
	A7.8.3 Resistance factors	385
	A7.8.3.1 <i>Service limit state resistance factor</i>	385
	A7.8.3.2 <i>Strength limit state resistance factor</i>	385
	A7.8.3.3 <i>Extreme event limit state resistance factor</i>	386
A7.9	Deformations	386
	A7.9.1 Vertical deformation of deck	386
	A7.9.2 Transverse deformation of deck	387
	A7.9.3 Transverse vibration of deck	387
A7.10	Design Methodology	387
	A7.10.1 Superstructure	387
	A7.10.2 Substructure and foundation	388
A7.11	Design Codes/ Standards	389
	List of Publications	393
	Brief Bio-Data	395

LIST OF FIGURES

FIGURE	CAPTION	PAGE NO.
1.1	Real examples of integral bridges	3
1.2	Schemes of (a) discontinuous bridge, (b) continuous bridge, (c) quasi-integral bridge, and (d) integral bridge	6
1.3	External (a) and (b), and internal (c) post-tensioning	12
1.4	Basalt fiber-reinforced polymer (BFRP) products	13
1.5	Stress-strain curves of steel and different FRP composites	15
1.6	Applications of fiber-reinforced polymers (FRPs) in construction industry	17
1.7	Various types of anchorages used in practice; (a) split-wedge anchorage, (b) clamp anchorage, (c) metal overlay anchorage, (d) sleeve resin anchorage, and (e) clamped sleeve resin anchorage	21
1.8	(a) Conventional wedge grip and (b) expansive grout-based grip	23
2.1	Detailed geometry of the considered anchor	43
2.2	Flowchart showing the steps followed to determine optimal anchor for BFRP in this study	46
2.3	Schematic drawing of the anchor	47
2.4	Anchors and samples for pull-out test	48
2.5	Variation in hoop strain with time	49
2.6	Load-relative displacement curves of tested samples in pull-out test	50
2.7	Pull-out test of BFRP rod samples	51
2.8	Relationship between gripping pressure and T/UL	53
2.9	3-D view of finite element model of the anchor in ABAQUS®	56
2.10	Finite element analysis results of S 2: (a) hoop strain and (b) expansive pressure	57
2.11	Validation of the finite element model in terms of load-relative displacement response	58
2.12	(a) Variation in gripping pressure with cement grout thickness and (b) variation in optimal grout thickness with rod diameter	59
2.13	Variation in (a) gripping pressure and gripping length, and (b) anchor volume with rod diameter	60
2.14	Anchor length for different commercially available rod diameters	61
2.15	(a) Specimen for tension test; specimen in the material testing system, (b) before testing; (c) after testing	62
2.16	Load-deflection curves of the tension tests: experimental and FE analysis	63

FIGURE	CAPTION	PAGE NO.
3.1	Raw and analyzed SEM images of the BFRP at a scale bar of 100-micron (a and c) and 50-micron (b and d), respectively	67
3.2	Dynamic mechanical thermal analysis (DMTA) test results against temperature for (a) complex modulus and loss factor, and (b) storage and loss moduli	69
3.3	Thermo-gravimetric analysis (TGA) test results of two BFRP samples	70
3.4	Reliability assessment of the total elongation-based approach for measurement of the elastic modulus from the stress-strain curves of nine tested BFRP rod specimens	71
3.5	Experimental setup of the tension test on the BFRP rods at elevated temperatures	73
3.6	(a) Ruptured BFRP rod sample inside the furnace and (b) smoke rising out from the furnace at 350°C onwards	74
3.7	Number of BFRP rod samples tested at different temperatures	75
3.8	Load-deflection curves of the tested BFRP rod samples at ambient and elevated temperatures	76
3.9	Degradation in (a) tensile strength and (b) elastic modulus of the BFRP rod at elevated temperatures	78
3.10	Comparative assessment of performance of the BFRP rod tested in the current study with selected past studies for (a) tensile strength and (b) elastic modulus	79
3.11	SEM micrographs of three BFRP rod samples tested at different temperatures	79
3.12	Proposed versus existing models for variation in tensile strength of the BFRP rod, tested in the present study, with temperature	83
3.13	Implementation of the proposed constitutive law on different FRP rods	85
3.14	Variation of strength retention of the BFRP rods with the parameter C (for $A = 1.5$)	86
4.1	Geometry, reinforcement, and cross-section details of the beams in four series	89
4.2	Pre-tensioning of BFRP tendons of the PSC beams	91
4.3	Construction of the BFRP-reinforced and/or prestressed concrete beams	92
4.4	Experimental setup of the four-point bending test on the BFRP-beam specimens	94
4.5	Load-deflection response of the twelve BFRP-beam specimens tested in flexure	97
4.6	Strain response of the BFRP-beams tested in the four series	98
4.7	Deflection assessment of the beams tested in the four series	100
4.8	Load-crack width response of the beams tested in three series	101
4.9	Elevational view with crack patterns for the beams tested in Series 1, 2, and 3 (loads are in kN)	103

FIGURE	CAPTION	PAGE NO.
4.10	Elevational view with crack patterns for the beams tested in Series 4	104
4.11	Variation in deformability index and cracking load to ultimate load ratio (P_{cr} / P_u) with reinforcement ratio to balanced ratio (ρ_f / ρ_b)	105
4.12	(a) Energy-based approach (Grace et al., 1998); (b) calculation of factor γ ; and (c) resultant energies evaluated	107
4.13	(a) Varying unloading slope in load-deflection curve of B 5; and (b) variation in unloading slope with load	107
4.14	Energy ratio evaluation for four different beams tested from the series	108
4.15	Comparative assessment of results for all the beams tested in the four series	112
5.1	Strain, stress, and force diagrams in the cross-section	122
5.2	Transformed cross-section for the cracked section analysis	123
5.3	Proposed approach by Abdelrahman and Rizkalla (1999) for load-deflection relationship under repeated loading	125
5.4	Flowchart showing the steps followed in flexural analysis of under-reinforced design of BFRP-reinforced/ prestressed concrete beams	126
5.5	Analytically obtained load-deflection response of beams in Series 1 and 2, compared to the experimental results	130
5.6	Analytically obtained load-deflection response of beams in Series 3 and 4, compared to the experimental results	131
5.7	Finite element (FE) model of the BFRP beam of Series 1, 2, and 3 in ABAQUS® environment	134
5.8	Finite element (FE) analysis results for stress and strain of Series 1 and 2	137
5.9	Finite element (FE) analysis results for stress and strain of Series 3 and 4	138
5.10	Finite element (FE) analysis results of Series 1 and 2 for load-deflection and stress-deflection response	139
5.11	Finite element (FE) analysis results of Series 3 and 4 for load-deflection and stress-deflection response	140
5.12	Comparison of finite element (FE) analysis and experimental results for load-deflection response of the four series of the beams	142
6.1	Flowchart showing steps involved in ductility evaluation of FRP-prestressed under-reinforced beams following the analytical approach presented in Chapter 5	146
6.2	Constitutive model of concrete damaged plasticity (CDP) in ABAQUS® environment	150
6.3	Finite element (FE) model of the beam, B-2, developed in ABAQUS® environment	153
6.4	Finite element (FE) analysis results of the three beams considered for validation	156
6.5	Validation of the analytical approach and the finite element analysis with the experimental results reported in the literature	157

FIGURE	CAPTION	PAGE NO.
6.6	Strain diagrams over the height of the cross-sections of the three beams obtained from the finite element (FE) analysis	158
6.7	Energy ratios and load-deflection curves of the beam reinforced with a single layer of CFRP reinforcements and prestressed at (a) 30%, (b) 40%, (c) 50%, and (d) 60%	161
6.8	Energy ratios and load-deflection curves of the beam reinforced with two layers of CFRP reinforcements and prestressed at (a) 30%, (b) 40%, (c) 50%, and (d) 60%	163
6.9	Energy ratios and load-deflection curves of the beam reinforced with three layers of CFRP reinforcements and prestressed at (a) 30%, (b) 40%, (c) 50%, and (d) 60%	164
6.10	Finite element (FE) analysis comparison between beams prestressed at 30% with (a) single layer, (b) two layers, and (c) three layers of CFRP tendons	165
6.11	Variation in ductility/ deformability and load-carrying capacity with number of reinforcement layers	166
6.12	Comparison between (a) single-layered system with uniform cross-section and multi-layered systems with functionally-graded cross-sections: without warning rebar (b and d) and with warning rebar (c)	169
6.13	Comparison between all the cases: (a), (b), and (c) for uniform cross-section with single-layered, two-layered, and three-layered systems, respectively; (d), (e), and (f) for functionally-graded cross-section with two-layered, two-layered with warning rebar, and three-layered systems, respectively	170
6.14	Ductility evaluation results of the beams partially prestressed with BFRP tendons at (a) 30%, (b) 40%, (c) 50%, and (d) 60%, with two prestressing magnitudes	175
6.15	Variation in ductility/ deformability and load-carrying capacity with prestressing ratio	175
6.16	Ductility results of fully prestressed beam (a) and partially prestressed beams with two, three, and four numbers of prestressing magnitudes (b, c, and d), respectively	176
6.17	Variation in ductility/ deformability and load-carrying capacity with number of prestressing magnitudes	177
7.1	Natural jute fiber (NJF) rope and stress-strain curves of the tested samples	181
7.2	Design details of the considered beam	181
7.3	Finite element model of the post-tensioned beam in ABAQUS® environment	187
7.4	Validation of the finite element model with the experimental results	188
7.5	Load-deflection response of the reinforced concrete (control) beam and post-tensioned beam with four unbonded NJF ropes in finite element analysis	189

FIGURE	CAPTION	PAGE NO.
7.6	Variation in (a) load-deflection response, (b) load-compressive stress in concrete, (c) load-tensile stress in reinforcement, and (d) load-tensile stress in NJF rope with varying post-tensioning force	191
7.7	Variation in load-carrying capacity and deflection of the beam at service load with varying post-tensioning force	191
7.8	Load-deflection response of the control, NJF rope-post-tensioned, and high-strength steel-post-tensioned beams	192
7.9	Load-deflection response for all the studied cases	193
7.10	Experimental setup for bending test on jute-post-tensioned beam	195
7.11	Average load-deflection response of the jute-post-tensioned beam compared to the non-post-tensioned beam (control beam)	195
7.12	Elevational view of the tested jute-post-tensioned beam, B-1, with cracks (the load values adjacent to cracks are in kN)	196
8.1	(a) Plan and (b) elevation of the investigated bridge	201
8.2	Live load model 1 on the bridge and notional lanes	203
8.3	(a) Temperature gradient rise and (b) temperature gradient fall on the bridges	205
8.4	3-D view and cross-sections of the four types of conventional and integral bridges	208
8.5	Longitudinal sections of all the four designed bridges	212
8.6	Dead weight of girders of the four types of bridge considered in this study	213
8.7	Vertical deflection of girders of the four types of bridge considered in this study under live load	213
8.8	Bending moment diagram of central girder of all the bridges	214
8.9	Stress diagram at top fiber of central girder of all the bridges	215
8.10	Three-dimensional view of girders of all the four bridges considered in the study	216
A1.1	Stresses due to prestress (P) and dead load (DL)	241
A1.2	Stresses due to prestress (P), dead load (DL), and live load (LL)	242
A1.3	Comparison of stress distribution with and without prestress	244
A1.4	Stress in girder due to dead load (MPa)	246
A1.5	Stress in girder due to live load (MPa)	246
A1.6	Stress in girder due to prestressing force (MPa)	246
A1.7	Stress in girder due to combination of dead load and live load (MPa)	247
A1.8	Stress in girder due to combination of dead load and prestressing force (MPa)	247

FIGURE	CAPTION	PAGE NO.
A1.9	Stress in girder due to combination of dead load, live load, and prestressing force (MPa)	247
A1.10	Deflection of girder due to dead load (mm)	248
A1.11	Deflection of girder due to live load (mm)	248
A1.12	Deflection of girder due to prestressing force (mm)	248
A1.13	Deflection of girder due to combination of dead load and live load (mm)	249
A1.14	Deflection of girder due to combination of dead load and prestressing force (mm)	249
A1.15	Deflection of girder due to combination of dead load, live load, and prestressing force (mm)	249
A2.1	Stress-strain distribution at failure for rectangular cross-section	252
A2.2	Characteristics of Hognestad stress block	253
A2.3	Short-term design stress-strain curve for normal concrete	253
A2.4	Short-term design stress-strain curve for prestressing tendons	254
A2.5	Moment of resistance of rectangular section	255
A2.6	Moment of resistance of flanged sections ($x_u > D_f$)	256
A2.7	Moment of resistance of rectangular sections (BS: 8110, 1985)	258
A2.8	Moment of resistance of flanged sections ($x > D_f$) (BS: 8110, 1985)	259
A2.9	Prestressed box section and the equivalent I-section (dimensions are in mm)	261
A2.10	Short-term design stress-strain curve for prestressing tendons of the considered beam (BS: 8110, 1985)	262
A2.11	Solution procedure using strain compatibility method	264
A2.12	Three-dimensional view of the prestressed beam	267
A2.13	Bending moment diagrams of the post-tensioned concrete beam in SAP2000® under (a) dead load, (b) live load, and (c) post-tensioning load (N·mm)	268
A2.14	Bending moment diagrams of the post-tensioned concrete beam in SAP2000® under (a) dead load and live load, (b) dead load and post-tensioning load, and (c) dead load, live load, and post-tensioning load (N·mm)	269
A2.15	Deformed shape of the post-tensioned concrete beam in SAP2000® under (a) dead load, (b) live load, and (c) post-tensioning load	270
A2.16	Deformed shape of the post-tensioned concrete beam in SAP2000® under (a) dead load and live load, (b) dead load and post-tensioning load, and (c) dead load, live load, and post-tensioning load	271

FIGURE	CAPTION	PAGE NO.
A2.17	Design moment and moment of resistance of the post-tensioned concrete beam in SAP2000®	272
A3.1	Cross-section of the beam with balanced conditions corresponding to the reinforcement materials	277
A4.1	Beam element with all degrees of freedom	279
A4.2	Beam segments (a) before deformation and (b) after deformation; (c) angle of rotation of cross-section ABCD	282
A4.3	Beam with uniformly distributed loading: (a) applied load, (b) beam reactions, and (c) equivalent nodal force system	284
A4.4	Structural beam of two elements and six degrees of freedom	285
A4.5	Beam element subjected to surface loading and concentrated nodal forces	287
A4.6	Beam element with shear forces, moments, and distributed load	291
A4.7	Arbitrarily oriented beam element	292
A4.8	Linear bar element subjected to tensile forces	294
A4.9	Local forces and displacements acting on a beam element arbitrarily oriented	297
A4.10	Beam geometry and cross-section (dimensions are in mm)	298
A4.11	Beam elements and nodes labels	298
A4.12	Beam geometry and deformed shape in SAP2000®	304
A4.13	Companion beam method for solving the redundant beam	306
A4.14	Computation of beam forces and displacements	307
A4.15	Plane frame geometry and loads	309
A4.16	Numbers of nodes, elements, and degrees of freedom	310
A4.17	Geometry and deformed shape with displacement values of the portal frame	315
A6.1	Cross-section of the AASHTO bridge beam considered in the FE-based numerical modeling	336
A6.2	Longitudinal section of the AASHTO bridge beam	336
A6.3	Reinforcement layout of the AASHTO bridge beam considered in the FE-based numerical simulation	341
A6.4	FE model of the AASHTO bridge beam in ABAQUS® environment	342
A6.5	Finite element (FE) results for deflection of the bridge beam at failure	343
A6.6	Load-deflection response of the bridge girder	343
A6.7	Load-compressive strain response of the bridge girder	344
A6.8	Load-tensile strain response of the CFRP tendons/ rebars	345

FIGURE	CAPTION	PAGE NO.
A7.1	AASHTO HL-93 design truck for bridges	352
A7.2	Overload live load on bridges	353
A7.3	Design wind pressure on the superstructure for a given level	357
A7.4	Normalized seismic design response spectra	360
A7.5	Variation of ϕ with net tensile strain ε_t and d/c for Grade 420 reinforcement and for prestressing steel	385
A7.6	Relationship between bridge span (L) and span to depth ratio (L/d) for different speeds for deformation limit	386

LIST OF TABLES

TABLE	CAPTION	PAGE NO.
1.1	Material properties and commercial viability of FRPs and steel	16
1.2	Life-cycle cost comparison between RC and FRP bridges	19
2.1	Properties of the BFRP rods used in the experiments	45
2.2	Properties of expansive cement grout used for the anchors	46
2.3	Recorded and resultant properties of anchors	49
2.4	Validation of the developed anchor with experimental and analytical data	52
2.5	Comparison between the introduced anchor and the reference one	62
3.1	Results of the tension test on the BFRP rod samples at ambient and elevated temperatures	77
3.2	Curve fitting results obtained from existing models in the literature and from the proposed model on tensile strength degradation of the BFRP rod tested in the present study	82
3.3	Characteristics and parameters of the referred studies	84
4.1	Properties of BFRP rebars/ tendons and steel used for the beams	90
4.2	Mix design proportion of concrete used for construction of the beams	92
4.3	Parameters and bending test results of the BFRP-beam specimens	94
4.4	Comparison of slopes obtained based on the proposed reinforcement factor and the reference factor with respect to the actual slopes obtained from individual beams	110
4.5	Ductility parameters of the tested beams based on the calculated and the reference reinforcement material factors	111
5.1	Analytical results of the BFRP-reinforced/ prestressed concrete beams compared to the experimental findings	128
5.2	Shear capacity calculations for the different series of the beams	132
5.3	Details of materials properties for the finite element analysis in ABAQUS®	135
5.4	Parameters of tensile behavior of the concrete in ABAQUS®	135
5.5	Parameters of compressive behavior of the concrete in ABAQUS®	136
6.1	Stirrup material and reinforcing material factors for ductility evaluation (Grace et al., 1998)	147
6.2	Failure mode factor for ductility evaluation (Grace et al., 1998)	148
6.3	Details of research studies considered from the literature for the validation	149
6.4	Details of materials properties of the validated beams for FEA in ABAQUS®	151

TABLE	CAPTION	PAGE NO.
6.5	Parameters of compressive behavior of the concrete in ABAQUS® for the validated beams	152
6.6	Parameters of tensile behavior of the concrete in ABAQUS® for the validated beams	153
6.7	Comparison of the results obtained from the different approaches	158
6.8	Details of the different cases considered with the CFRP tendons	160
6.9	Comparison between all the cases of the parametric study with the CFRP tendons	171
6.10	Quantitative comparison between over- and under-reinforced sections	172
6.11	Details of the considered cases for the partially prestressed beams with BFRP tendons	173
7.1	Compressive parameters of concrete in concrete damaged plasticity (CDP) model for the NJF-post-tensioned beam	185
7.2	Tensile parameters of concrete in concrete damaged plasticity (CDP) model for the NJF-post-tensioned beam	186
7.3	Load-carrying capacity of the NJF-post-tensioned beam with different post-tensioning ratios	190
8.1	Material and dimensional properties of all the four bridges	209
8.2	Sample calculation for integral abutment bridge prestressed with BFRP tendons	210
8.3	Sample calculation for integral abutment bridge prestressed with steel tendons	211
A1.1	Comparison between stress and deflection of cases with and without prestress	245
A1.2	Comparison of analysis results of hand calculation and SAP2000®	250
A2.1	Conditions at the ultimate limit state for post-tensioned rectangular beams having unbonded tendons (IS: 1343, 1980)	257
A2.2	Comparison of moment of resistance of the post-tensioned beam following the different approaches	273
A4.1	Nodal displacements and rotation of the beam in SAP2000®	305
A4.2	Shear forces and bending moments of the beam in SAP2000®	305
A4.3	Comparison of analysis results of MATLAB, SAP2000®, and hand calculations for beam element	308
A4.4	Nodal displacements and rotation of the portal frame in SAP2000®	316
A4.5	Shear forces and bending moments of the portal frame in SAP2000®	316
A4.6	Comparison of the different approaches for element forces of the portal frame	319
A4.7	Comparison of the different approaches for nodal displacements of the portal frame	319
A6.1	Properties of CFRP tendons and steel stirrups	337

TABLE	CAPTION	PAGE NO.
A6.2	Parameters of concrete-53 grade for FE-based numerical simulation	339
A6.3	Constitutive model of concrete in compression	340
A6.4	Constitutive model of concrete in tension	340
A7.1	Minimum design life of bridges	348
A7.2	Concrete cover as per AASHTO specifications	349
A7.3	Material partial factors	351
A7.4	Axle loading on bridges	352
A7.5	Uniform lane loading on bridges	352
A7.6	Multiple presence factors (AASHTO LRFD, 2007)	353
A7.7	Time period versus soil profile	359
A7.8	Accidental forces on abutments from road traffic	362
A7.9	Fraction of truck traffic in a single lane, p (AASHTO LRFD, 2007)	363
A7.10a	Summary of live load combinations (a)	366
A7.10b	Summary of live load combinations (b)	366
A7.10c	Summary of live load combinations (c)	367
A7.10d	Summary of live load combinations (d)	368
A7.10e	Summary of live load combinations (e)	369
A7.10f	Summary of live load combinations (f)	370
A7.10g	Summary of live load combinations (g)	371
A7.10h	Summary of live load combinations (h)	372
A7.11a	Load combinations (a)	375
A7.11b	Load combinations (b)	376
A7.12	Stress limits for prestressing tendons as per AASHTO LRFD (2007)	378
A7.13	Temporary tensile stress limits in prestressed concrete before losses as per AASHTO LRFD (2007)	379
A7.14	Compressive stress limits in prestressed concrete at service limit state after losses as per AASHTO LRFD (2007)	380
A7.15a	Tensile stress limits in prestressed concrete at service limit state after losses as per AASHTO LRFD (2007) [a]	381
A7.15b	Tensile stress limits in prestressed concrete at service limit state after losses as per AASHTO LRFD (2007) [b]	382

TABLE	CAPTION	PAGE NO.
A7.16	Stress limits in service	384

MATHEMATICAL NOTATIONS

μ_ψ	Curvature-based ductility index
ψ_u	Curvature at the ultimate moment
ψ_y	Curvature at the yielding moment
μ_d	Displacement-based ductility index
Δ_u	Displacement at the ultimate load
Δ_y	Displacement at the yielding load
E_{in}	Initial inelastic energy absorbed before reaching the ultimate capacity
$E_{in(addy)}$	Additional inelastic energy absorbed after reaching the ultimate load-carrying capacity
E_{esc}	Elastic energy
T	Pull-out load
U	Circumference of the tendon
L	Length of the anchor
τ_0	Bond stress
μ	Friction coefficient
P	Gripping pressure
σ_r	Radial stress
σ_θ	Hoop stress
σ_z	Longitudinal axial stress
P_i	Internal pressure
P_o	External pressure
r_i	Inner radius of the steel sleeve
r_o	Outer radius of the steel sleeve
r	The radius where the stresses are obtained
$\varepsilon_\theta(r)$	Hoop strain
$u_r(r)$	Radial displacement
$u_{r,s}(b)$	Radial displacement of the steel sleeve at the grout-sleeve interface
$u_{r,o,g}(b)$	Radial displacement of the grout shell at the grout-sleeve interface
$u_{r,i,g}(a)$	Radial displacement of the grout shell at the rod-grout interface
$u_{r,o,f}(a)$	Radial displacement of the fiber rod at the rod-grout interface

p_{sg}	Internal pressure at the sleeve-grout interface
p_{gf}	Internal pressure at the grout-fiber rod interface
E_f	Transverse elastic modulus of the fiber rod
ν_f	Transverse Poisson's ratio of the fiber rod
P_{grip}	Gripping pressure acting inward on the outer surface of the fiber rod
P_{exp}	Expansive pressure acting outward on the inner surface of the steel sleeve
t_c	Cement grout thickness
$t_{c(opt)}$	Optimal cement grout thickness
L_{grip}	Gripping length
A_v	Volume of anchor
A_l	Length of anchor
f_f	Tensile strength of the fiber rod
d_b	BFRP rod diameter
T_g	Glass transition temperature
σ_A	Stress amplitude
ε_A	Strain amplitude
E^*	Complex modulus
E'	Storage modulus
E''	Loss modulus
δ	Phase angle
T_d	Resin decomposition temperature
f_{uT}	Tensile strength of the BFRP rod at a particular temperature
E_{uT}	Tensile modulus of elasticity of the BFRP rod at a particular temperature
T_0	Room temperature
T_{ref}	Ultimate temperature at which the mechanical properties vanish
$P(T)$	Mechanical properties of the composite at any temperature T
P_0	Mechanical properties of the composite at room temperature
P_r	Mechanical properties of the composite in the decomposed state
ν_f	Fiber volume fraction
R^2	Coefficient of determination

f_c'	Compressive strength of concrete
f_t	Tensile strength of concrete
ρ_f	Actual reinforcement ratio
ρ_b	Balanced reinforcement ratio
P_{cr}	Cracking load of the beam
P_u	Load-carrying capacity of the beam
Δ_u	Deflection of the beam at failure
α	Stirrup material factor
β	Failure mode factor
γ	Reinforcement material factor
E_s	Elastic modulus of the steel
f_y	Steel yield strength
f_{ds}	Fiber-reinforced polymer (FRP) design strength
Δf_{es}	Loss due to elastic shortening of concrete
m	Modular ratio
f_{cp}	Compressive stress in the concrete at the tendon level
E_{ci}	Elastic modulus of the concrete at the prestress transfer stage
F_{pi}	Initial prestressing force
e	Eccentricity of the prestressing force
S_b	Section modulus corresponding to the extreme bottom fiber
A	Area of the beam cross-section
M_d	Moment due to dead load
Δf_s	Loss of stress due to shrinkage of concrete
Δf_{cr}	Loss of stress due to creep of the BFRP tendons
f_{pi}	Initial prestress
Δf_r	Loss of stress due to relaxation of the BFRP tendons
f_{ci}'	Compressive strength of the concrete at the prestress transfer
S_t	Section modulus corresponding to the extreme top fiber
β_1	Ratio of depth of the equivalent rectangular stress block to the depth of the neutral axis
f_{fu}	Tensile strength of the BFRP prestressing tendons

ε_{cu}	Ultimate compressive strain in the extreme concrete fiber
ε_{fu}	Ultimate tensile strain of the BFRP
ε_{pmi}	Initial prestressing strain in the lowest prestressing tendon (m^{th} row) farthest from the neutral axis
A_{fi}	Cross-sectional area of the tendon
α_i	Ratio of stress in a tendon at balanced condition to the ultimate tensile strength of the tendon
f_{bi}	Stress in the tendon at the balanced condition
d_m	Distance of the bottommost prestressing tendon (m^{th} row) from the extreme compression fiber
M_{cr}	Cracking moment
f_r	Modulus of rupture of concrete
$\sum \sigma_{bp}$	Resultant compressive stress at the extreme bottom fiber due to prestressing forces
F_{pe}	Magnitude of the total effective prestressing force
e_e	Eccentricity of the total effective prestressing force
n	Depth of neutral axis
f_{pmi}	Initial effective prestress in the bottommost prestressing tendon (m^{th} row)
E_c	Elastic modulus of concrete
A_f	Cross-sectional area of the BFRP tendons
ε_f	Difference between the ultimate rupture strain and the initial prestressing strain of the lowest prestressing tendons
h_i	Distance of the tendons in each individual layer from the extreme compression fiber
ε_{pji}	Initial prestress in a tendon in an individual layer j
q	Number of the tendons' layers
d_j	Depth of a prestressing tendon in an individual layer j from the extreme compression fiber
h_j	Depth of a non-prestressing tendon in an individual layer j from the extreme compression fiber
ε_{pj}	Strain in the prestressing tendons of a layer j
ε_{nj}	Strain in the non-prestressing tendons of a layer j
ε_c	Strain in the extreme compression fiber of the concrete
C_c	Compressive force resultant in the concrete
F_{pj}	Tensile force in the prestressing tendons placed in a layer j
F_{nj}	Tensile force in the non-prestressing tendons placed in a layer j
A_{fpi}	Cross-sectional area of prestressing tendons of a layer j

A_{fnj}	Cross-sectional area of non-prestressing tendons of a layer j
M_u	Moment of resistance
$\bar{d}$	Depth of the centroid of the rectangular stress block of concrete from the top fiber
I_g	Gross moment of inertia of the beam cross-section
I_e	Effective moment of inertia of the beam cross-section
I_{cr}	Moment of inertia of the cracked transformed beam section
M_a	Service load moment at the stage for which the deflection is being considered
β_d	Reduction coefficient related to the reduced tension stiffening exhibited by FRP-reinforced members
M_{dc}	Decompression moment corresponding to zero stress at the extreme bottom fiber
y_g	Uncracked centroidal distance
D	Overall depth of the beam cross-section
y_{cr}	Cracked centroidal distance
G_c	Shear modulus of concrete
F_p	Prestressing force applied at a constant eccentricity
Δ	Beam deflection at the mid-span
x	Shear arm
I_{rep}	Moment of inertia for repeated loading
Δ_r	Residual deflection
d_c	Compressive damage parameter of concrete
d_t	Tensile damage parameter of concrete
σ_{c0}	Yield stress of concrete
ε_{in}	Inelastic strain of concrete
σ_{t0}	Tensile stress of concrete
ε_{cr}	Cracking strain of concrete
ρ_{bs}	Balanced reinforcement ratio corresponding to steel's limit state
ε_y	Yield strain of steel
ρ_{bj}	Balanced reinforcement ratio corresponding to jute's limit state
f_{ju}	Ultimate tensile strength of the jute rope
ε_{ju}	Strain at failure of the jute rope

ε_s	Strain in steel reinforcement
ε_j	Strain in jute rope
d_s	Effective depth of the steel reinforcement
d_j	Effective depth of the natural jute fiber (NJF) rope
ε_{ji}	Initial stress in the NJF rope due to post-tensioning
Ω_u	Ultimate bond reduction coefficient
L_u	Distance between the ends of the post-tensioning rope
T_s	Tensile force in the steel reinforcement
A_s	Area of steel reinforcement
T_j	Tensile force in the natural jute fiber (NJF) rope
E_j	Elastic modulus of the natural jute fiber (NJF) rope
A_j	Cross-sectional area of the natural jute fiber (NJF) rope
k	Wobble coefficient
γ_c	Material partial factor for concrete
γ_s	Material partial factor for steel
φ	Dynamic amplification factor
v	Vehicle speed
R	Radius of curvature of traffic lane
g	Gravity acceleration
P_D	Design wind pressure
P_B	Base wind pressure
V_{DZ}	Design wind velocity at a design elevation Z
V_{10}	Wind velocity at 10 m above water level
V_B	Base wind velocity at 10 m above ground level
Z_0	Friction length of upstream meteorological wind characteristic
Z	Height of structure at which load is being calculated
M_{Ed}	Maximum seismic design moment
M_{Rd}	Section capacity in flexure
C_{sm}	Elastic seismic response coefficient
T	Structural period

A	Acceleration coefficient for the relevant limit state
γ_i	Load factor
ϕ	Resistance factor
R_n	Nominal resistance
R_r	Factored resistance
η	Factor related to ductility, redundancy, and operational importance
η_D	Ductility factor
η_R	Redundancy factor
η_I	Factor related to operational importance
f_{cd}	Design compressive strength of concrete
α_{cc}	Coefficient taking account of long term effects on the compressive strength and of unfavorable effects resulting from the way the load is applied
f_{py}	Yield strength of the prestressing tendon
f_{pu}	Ultimate tensile strength of the prestressing tendon
f_{ss}	Maximum tensile stress in steel reinforcement at service limit state for complying to the crack width maximum value
γ_e	Exposure factor
f_{pu}	Specified tensile strength of prestressed reinforcement (psi)
A_{ps}	Area of prestressed longitudinal tension reinforcement (in. ²)
f_{se}	Effective stress in prestressed reinforcement (psi)
f_{yt}	Specified yield strength of transverse reinforcement (psi)
A_v	Area of shear reinforcement within spacing s (in. ²)
s	Center-to-center spacing of transverse reinforcement (in.)
A_s	Area of non-prestressed longitudinal tension reinforcement (in. ²)
f_y	Specified yield strength of non-prestressed reinforcement (psi)
$A_{v,min}$	Minimum area of shear reinforcement within spacing s (in. ²)
λ	Modification factor for lightweight concrete
P_u	Failure load of the beam (lb)
M_{max}	Maximum moment due to failure load (lb-in.)
V_i	Maximum shear force at failure (lb)
V_d	Shear force due to dead load (lb)
f_d	Stress due to dead load, at extreme fiber of section (psi)

f_{pe}	Compressive stress in concrete, due to effective prestressing force, at extreme fiber of section (psi)
f_{pc}	Compressive stress in concrete, due to effective prestressing force, at centroid of cross-section (psi)
M_{cre}	Moment causing flexural cracking due to applied loads (lb·in.)
V_{ci}	Nominal shear strength provided by concrete where diagonal cracking results from combined shear and moment (lb)
V_{cw}	Nominal shear strength provided by concrete where diagonal cracking results from high principal tensile stress in web (lb)
V_c	Nominal shear strength provided by concrete (lb)
V_s	Nominal shear strength provided by shear reinforcement (lb)
V_n	Nominal shear capacity of beam section (lb)

ABBREVIATIONS

RC	Reinforced Concrete
PSC	Prestressed Concrete
FRP	Fiber-Reinforced Polymer
BFRP	Basalt Fiber-Reinforced Polymer
GFRP	Glass Fiber-Reinforced Polymer
CFRP	Carbon Fiber-Reinforced Polymer
TBM	Tunnel Boring Machine
CFCC	Carbon Fiber Composite Cables
ACI	American Concrete Institute
AFRP	Aramid Fiber-Reinforced Polymer
AASHTO	American Association of State Highway and Transportation Officials
FRC	Fiber-Reinforced Concrete
NSC	Normal Strength Concrete
HSC	High-Strength Concrete
CFRC	Coconut Fiber-Reinforced Concrete
JFRCC	Jute Fiber-Reinforced Cementitious Composite
FFRP	Flax Fabric-Reinforced Polymer
SCM	Supplementary Cementitious Material
FEA	Finite Element Analysis
FGC	Functionally-Graded Concrete
JSCE	Japan Society of Civil Engineers
ASCE	American Society of Civil Engineers
CDP	Concrete Damaged Plasticity
UTM	Universal Testing Machine
SEM	Scanning Electron Microscopy
DMTA	Dynamic Mechanical Thermal Analysis
TGA	Thermo-Gravimetric Analysis
RRC	Remaining Resin Content
IS	Indian Standard

OPC	Ordinary Portland Cement
SSD	Saturated-Surface-Dry
LVDT	Linear Variable Differential Transformer
NJF	Natural Jute Fiber
SSB	Simply-Supported Bridge
IAB	Integral Abutment Bridge
SV	Special Vehicle
CQC	Complete Quadratic Combination
BS	British Standards
SIDL	Superimposed Dead Load
SRSS	Square Root of the Sum of Squares
ADTT	Average Daily Truck Traffic
ADTTSL	Average Daily Truck Traffic for Single-Lane
ULS	Ultimate Limit State
SLS	Serviceability Limit State
DL	Dead Load
LL	Live Load
WL	Wind Load
EQ	Earthquake
RCC	Reinforced Cementitious Concrete