Prestressed Concrete Bridges

Second Edition

(IRC: 6-2014; IRC: 112-2011; IS: 1343-2012)

follows the principle of limit state design incorporated in the revised Indian Roads Congress Codes—IRC: 6-2014 and IRC: 112-2011, for the design of different types of prestressed concrete bridges. An integrated design approach involving limit states of strength and serviceability has been followed for the design of various types of bridges covering the slab, tee beam and slab, continuous span, box girder, rigid frame and cable stayed bridges commonly used for national highway crossings. This monograph lays special emphasis on conceptual clarity through theory, design, construction, inspection, maintenance, repairs and rehabilitation of bridges, fortified with numerous design examples and illustrations.

Salient features

- Conforms to the latest codes of practice IRC: 6–2014; IRC: 112–2011 and IS: 1343–2012
- Detailed theory, design, construction, inspection, maintenance, repairs and rehabilitation of bridges, well supported by numerous design examples and illustrations
- Practice examples supplemented with exhaustive number of references, review and objective questions with detailed illustration for better understanding
- Assignments to enhance problem-solving skills/practice

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Dr Raju has published over 60 research papers in reputed journals and is the author of several engineering books like *Design of Concrete Mixes, Prestressed Concrete, Design of Reinforced Concrete Structures, Advanced Reinforced Concrete Design, Design of Bridges, Design and Drawing of Reinforced Concrete and Steel Structures, Numerical Methods for Engineering Problems, Structural Design and Drawing, Prestressed Concrete (Problems & Solutions), Reinforced Concrete Structural Elements,* and *Advanced Mechanics of Solids and Structures*.

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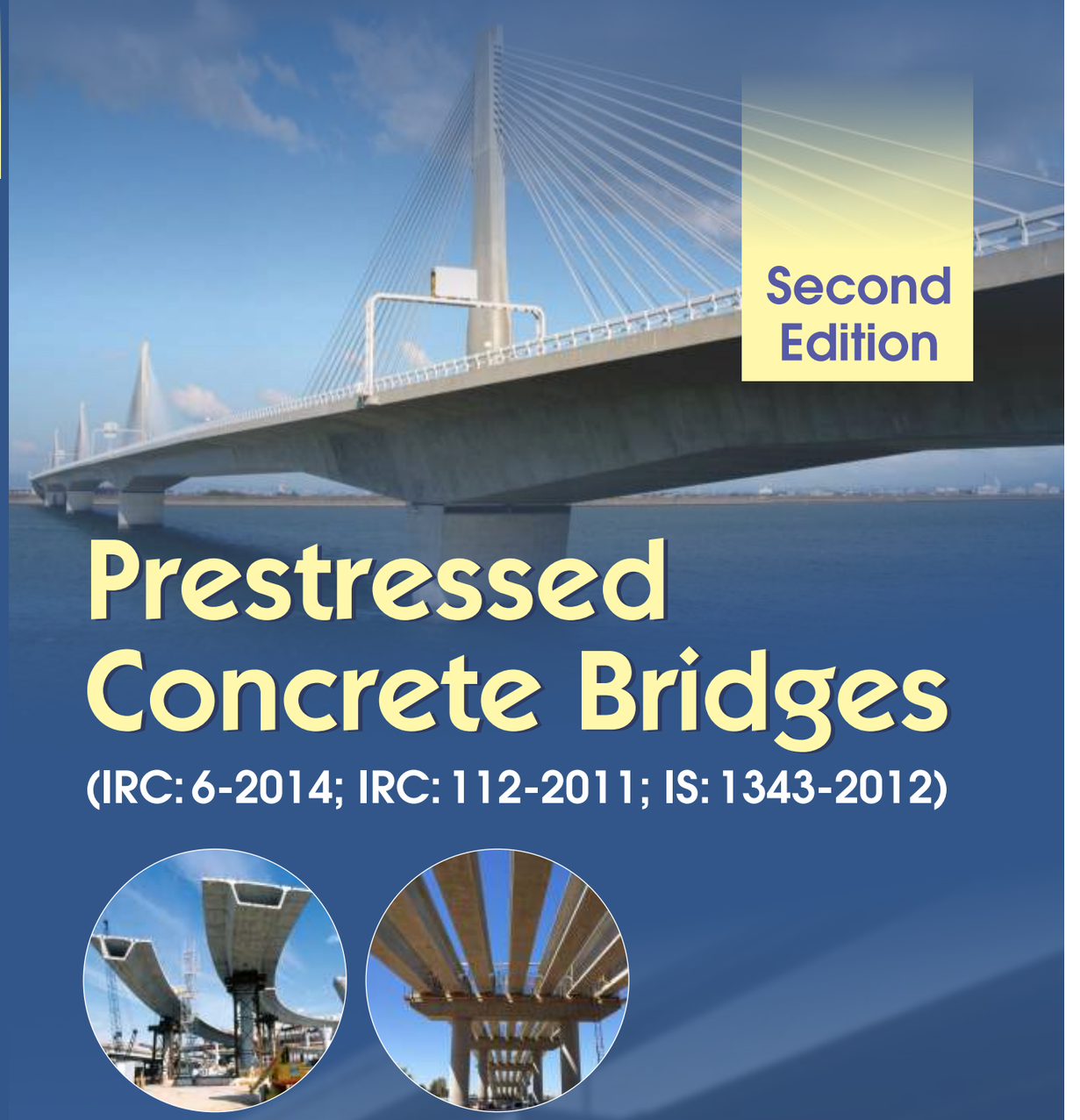

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to

Eugene Freyssinet

(Father of Prestressing)

and

the pioneers and research workers

Yves Guyon, Gustav Magnel, Paul W Abeles, M Birkenmaier, F Dischinger,
Finisterwalder, TY Lin, Fritz Leonhardt, Ben C Gerwick Jr, RH Evans,
EW Bennett, RE Rowe, OC Zienkiewicz, W Rockenhouser,
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PE Regan, JJ Mc Namee, DJ Dowrick, TN Subba Rao
and a host of others who toiled incessantly for the
development and widespread use of
prestressed concrete bridges

Preface to the Second Edition

The first edition of the book published in 2009 was reprinted four times indicating the ever increasing popularity of the book among the engineering students, teaching faculty and practicing bridge designers and consultants. The monograph has also served as a useful reference guide for research workers. The purpose of this edition is to update the contents conforming to the latest developments in the field of design of bridges and the national codes governing the design principles of bridges. The Ministry of Surface Transport, Government of India, has launched the golden quadrilateral scheme connecting the capital cities of various states with modern highways. Bridges being the basic components of highway systems, have witnessed rapid progress and innovations during the last decade.

The design philosophy of prestressed concrete bridges has been revised by the Indian Roads Congress (IRC), while introducing an integrated and comprehensive code (IRC:112-2011) for the design of concrete bridges based on the limit state philosophy. The revised edition of IRC:6-2014 (Section II) dealing with loads and stresses incorporates the partial safety factors for verification of structural strength and serviceability limit states. The new code lays emphasis on both strength and serviceability aspects of bridge decks and specifies the method of computation of ultimate strength, width of cracks and deflections at service loads. This new code supersedes the earlier codes IRC:21-2000 and IRC:18-2000. However, the earlier codes IRC:21 and IRC:18 based on working stress method of design are retained in the code with its use being limited to those grades of concrete and steel specified in Annexure (A4) of the code.

The present edition incorporates several improvements in each of the chapters by the introduction of limit state philosophy in all the design computations according to the revised Indian Roads Congress codes. Review and objective type questions have been included at the end of each chapter to help students to concentrate on the salient aspects of the subject matter and also to prepare for competitive examinations and professional interviews. Some of the chapters have been updated with additional designs of bridges in keeping with the latest developments in the field of prestressed concrete.

The chapterwise revisions incorporated in this edition are as follows.

Chapter 1 has been updated with the data regarding the longest span prestressed concrete bridges built in China and the use of longest precast prestressed concrete beams in Zudihorn, the Netherlands.

New codes introduced by the Indian Roads Congress, have replaced the old codes earlier used in **Chapter 2** with the addition of review and objective questions at the end of the chapter.

Chapter 3 is thoroughly revised by updating the grades of concrete and the new clauses in the codes relating to shrinkage and creep of concrete. Also the representative and bilinear stress–strain curves recommended in the IRC codes for high tensile steel required for limit state design are incorporated in the text alongwith the review and objective questions.

Chapter 4 has been completely revised to cover the principles of limit state design involving the comprehensive treatment of criteria of limit states, safety factors, characteristic and design loads and strength with global factor of safety alongwith review and objective questions.

The newly introduced **Chapter 5** deals with the various limit states of ultimate strength of prestressed concrete bridge decks under flexure, shear, torsion and their combinations in the light of specifications in the revised IRC codes. Numerous examples are included to illustrate the use of code specifications. Additional examples for practice by students alongwith review and objective questions are also included at the end of chapter.

Chapter 6 is newly introduced to present the use of IRC code specifications regarding the limit state of serviceability such as deflections and cracking in prestressed concrete members. The computations of deflections and cracking in members are illustrated with examples alongwith the assignment for practice, review and objective questions.

The design of prestressed concrete slab bridge decks are presented in **Chapter 7** illustrating the use of design aids in numerical examples together with the computations of strength and serviceability of bridge decks. Also the practice, review and objective questions are included at the end of the chapter.

Chapter 8 deals with the design of prestressed concrete tee beam and slab bridge decks conforming to the limit states of strength and serviceability. Practice examples, review and objective questions are included at the end of the chapter.

Chapter 9 deals with the theory and design aspects of prestressed concrete continuous bridge decks involving the arrangement of cables in continuous spans and the design of anchorages at the end of beams together with the list of references, practice examples, review and objective questions.

In **Chapter 10,** the complete design of prestressed concrete cellular box girder decks is illustrated together with an exhaustive list of references, practice examples, review and objective questions at the end of text.

Chapter 11 deals with the design of prestressed concrete rigid frame bridge used in national highway intersections. Detailed design computations alongwith practice examples, review and objective questions are presented at the end of the chapter.

Chapter 12 deals with the entire gamut of cable stayed bridges used for long spans. The theory and design are treated in detail alongwith a practical example together with practice examples, review and objective questions.

Chapters 13 and 14 deal exclusively on the planning and economical aspects and construction of prestressed concrete bridge decks. Cost considerations in relation to the type of bridge deck are examined. Examples of flyovers used in metropolitan cities are presented alongwith review and objective examples.

Chapter 15 is devoted to a detailed study of the maintenance and rehabilitation aspects of prestressed concrete bridge decks. Numerous examples of repairs and rehabilitation of damaged bridge decks are compiled alongwith an exhaustive list of references followed by review and objective questions.

Chapter 16 presents a comprehensive survey of the world's prominent prestressed concrete bridges with illustrations from different countries. A list of longest span prestressed concrete bridges in the world is compiled with their location and span length.

Each chapter is provided with relevant references to help students for further reading. The assignment at the end of chapters prepares students to face all types of examinations with confidence. Numerous figures have been included in keeping with the spirit of *'drawing is the language of the engineer'*.

N Krishna Raju

Preface to the First Edition

During the last fifty years, rapid advances in the development and widespread use of new materials like high strength concrete, high tensile steel, epoxy resins, polymeric materials in conjunction with phenomenal developments in computer and constructional technology have facilitated creative bridge engineers to design and build structurally sound, aesthetically superior bridge structures which are economical and also durable using the revolutionary building material **'Prestressed Concrete'**.

The prophetic words of Yves Guyon **"there is probably no structural problem to which prestressed concrete cannot provide a solution and often a revolutionary one"** have been amply justified if one scans through the tremendous progress achieved in the field of analysis, design and construction of prestressed concrete bridges throughout the world.

At present, India has embarked on a gigantic highway project involving the golden quadrilateral connecting the north-south and east-west corridors connecting the capital cities of various states. Naturally this massive highway project necessarily involves the design and construction of innumerable number of bridges to cross the east and west flowing rivers.

The purpose of this book is to present under one cover the whole gamut of theory and design of prestressed concrete bridges of different types to the extent required by undergraduate and postgraduate students of civil, structural and highway engineering streams. The subject matter in this book should also serve as useful reference material for practicing highway and structural engineers dealing with the design, construction and maintenance of prestressed concrete bridges.

The book presents a concise and lucid exposition of the various types of prestressed concrete bridges, illustrated by examples relevant to design practice. The designs presented conform to the various National Codes such as IS:1343-1980 (2000), IS:456-2000 and the Indian Roads Congress codes IRC:6-2000, IRC:18-2000 and IRC:21-2000.

The book traces the historical evolution of bridges together with the advantages of pretensioned and post-tensioned prestressed concrete bridges in Chapter 1. Chapter 2 deals with the highway bridge loading standards followed in various countries together with their comparative analysis. A concise description of the materials used in prestressed concrete bridges is presented in Chapter 3 while Chapter 4 deals with the

limit state design concepts of reinforced and prestressed concrete bridge decks alongwith numerous design examples. Chapter 5 presents the analysis and design of prestressed concrete slab bridge decks followed by the load distribution methods of tee beam and slab bridge decks in Chapter 6. Chapter 7 is devoted to the design of prestressed concrete continuous girder bridge decks while Chapter 8 presents the analysis and design of rigid frame bridges generally used in urban flyover crossings. The design of prestressed concrete cellular box girder bridges is presented in Chapter 9 while prestressed cable stayed bridges are treated exhaustively in Chapter 10. The planning, economical aspects and cost considerations of different types of prestressed concrete bridges are detailed in Chapter 11. Chapter 12 presents the constructional aspects dealing with concrete, assembly of prestressing steel, expansion joints together with the various techniques developed for the construction of long span post-tensioned bridges. The maintenance, repairs and rehabilitation of prestressed concrete bridge components together with practical examples of restoration and case studies are included in Chapter 13. Illustrations of prominent prestressed concrete bridges built in India and various other countries are presented alongwith their structural details in Chapter 14.

Most of the chapters contain design examples together with exercises for practice by students and list of references are included in each of the chapters. Appendix 1, 2, 3 & 4 contain the properties of commonly used prestressing steels, constants for beam sections and data regarding the prominent proprietary posttensioning anchorage systems and grouting of posttensioned ducts. The data compiled is useful in the design of various types of prestressed concrete bridge decks.

Numerous figures have been included in keeping with the spirit of **'drawing is the language of the engineer'**. Finally the author welcome constructive criticisms and useful suggestions which will immensely help in updating the text material.

N Krishna Raju

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Indian Roads Congress; Indian Standards Institution; American Concrete Institute; American Association of State Highway Organization; Prestressed Concrete Institute; Federation Internationale de la Precontrainte; European Concrete Committee; Institution of Engineers (India); International Association for Bridge and Structural Engineering; Structural Engineering Research Centre, Roorkee; Japan Prestressed Concrete Industry; Bridge Loading Standards, UK, Germany, France, and various other European countries. The complete details of the sources are listed in the form of references at the end of each chapter.

I deeply indebted to Dr EW Bennett, Prof RH Evans and Prof AM Neville, for inspiring and initiating me to the field of prestressed concrete during my doctoral research work under the Commonwealth Fellowship Programme at the University of Leeds (UK), during 1965–68. I want to put on records the gratitude of Prof Fritz Leonhardt; Prof Ben C Gerwick Jr; Dr VK Raina, and various other authors whose innumerable publications served as an invaluable source material and inspired me in the preparation of this book.

The text material in the book has been compiled from the lecture notes prepared for teaching the masters degree courses in structural engineering at Karnataka Regional Engineering College, Surathkal; University of Basrah, Iraq; MS Ramaiah Institute of Technology, Bangalore, and the material prepared by me to deliver expert lectures during the short term courses at various technical institutions in India during my active career spanning over four decades. I have benefited immensely by the feedback, comments of students, research workers, fellow teachers and participants in various short term courses.

I gratefully acknowledge the help rendered by my wife Pramila Raju and many of my colleagues and practicing structural and highway engineers in updating the contents of this edition. Thanks are also due to CBS Publishers & Distributors, New Delhi, for their excellent co-operation in the publication of this monograph.

N Krishna Raju

Contents

List of Symbols

1. Latin Upper Case Letters

A	Cross-sectional area of member
A_{br}	Bearing area
A_c	Area of concrete section
A_{ct}	Area of concrete in tension zone
A_i	Area of the *in situ* concrete section
A_{pf}	Area of prestressing steel for flange
A_{pw}	Area of prestressing steel for web
A_{ps}	Area of prestressing tendons
A_{pun}	Punching area
A_s	Area of nonprestressed tension reinforcement
A'_s	Area of compression reinforcement
A_{sl}	Area of longitudinal reinforcement for torsion
A_{st}	Area of transverse reinforcement for torsion
A_{sv}	Area of transverse reinforcement for shear
A_{tot}	Area of total reinforcement
C	Torsional moment of inertia
C_{min}	Minimum cover to tensile steel
C_x	Torsional rigidity in the x-direction
C_y	Torsional rigidity in the y-direction
D_c	Density of concrete
D_f	Thickness of flange
D_x	Flexural rigidity in the x-direction
D_y	Flexural rigidity in the y-direction
E_c	Modulus of elasticity of concrete
E_{ce}, $E_{c,eff}$	Effective (long term) modulus of elasticity of concrete
EI	Flexural rigidity
E_s	Modulus of elasticity of steel
F_{bst}	Bursting tension
F_d	Design load
F_k	Characteristic load
G_k	Characteristic dead load
I	Second moment of area of section
I_c	Second moment of area of uncracked concrete section
I_e	Effective second moment of area for computation of deflection
I_r	Second moment of area of cracked concrete section
K	Friction coefficient for wave effect

K_1, K_2, K_3	Constants
L	Effective span
L_t	Transmission length
M	Bending moment
M_{cr}	Cracking moment
M_d	Design service moment
M_g	Bending moment due to dead loads
M_0	Moment necessary to produce zero stress in concrete at depth 'd'
M_q	Bending moment due to live loads
M_u	Design ultimate moment
N	Force normal to a section
N_{adm}	Safe allowable axial load on column
N_{cr}	Cracking load
N_d	Design tensile load
N_{min}	Minimum tensile load
N_u	Ultimate load capacity of axially loaded short column
N_{ub}	Ultimate load capacity of a short column subjected to axial load and bending moment
P	Prestressing force
P_k	Characteristic load in tendon
P_o	Prestressing force in the tendon at the jacking end
P_i	Initial prestresing force
P_t	Prestressing force after time 't'
P_x	Prestressing force at a distance 'x' from the jack
Q_k	Characteristic variable load
R	Radius of the shell structure
RH	Relative humidity of the ambient environment in percent
S	Statical moment or first moment of area of concrete section
T	Torsional moment due to ultimate load
T_{tp}	Torsional resistance moment of the prestressed concrete section
T_{ts}	Torsional resistance due to nonprestressed reinforcement
T_u	Ultimate torsional resistance
V	Shear force at a section
V_c	Ultimate shear resistance of concrete
V_{cw}	Ultimate shear resistance of concrete section uncracked in flexure (web cracks)
V_{cf}	Ultimate shear resistance of concrete section cracked in flexure
V_u	Ultimate shear force
W_k	Characteristic concentrated wind load
Z	Section modulus
Z_t	Section modulus of top fibre of beam section
Z_b	Section modulus of bottom fibre of beam section

2. Latin Lower Case Letters

a	Deflection
b	Breadth of section or compression face
b_w	Breadth of web
c	Cover to steel reinforcement
d	Effective depth of tension reinforcement
d'	Cover to compression reinforcement
d_{ps}	Depth from compression face to tensioned steel
d_{us}	Depth from compression face to untensioned steel
e	Eccentricity of prestressing force with respect to the centroid of section
f_c	Compressive stress in concrete

f_c', f_{cy}	Characteristic cylinder compressive strength of concrete
f_{ck}, f_{cu}	Characteristic cube strength of concrete
f_{ci}	Compressive strength of concrete at initial transfer of prestress
f_{cp}	Compressive stress at centroidal axis due to prestress
f_{cr}	Flexural tensile strength of concrete
f_{ct}	Allowable compressive stress in concrete at initial transfer of prestress
$f_{ct,eff}$	Tensile strength of concrete at the time of cracking
f_{cw}	Allowable compressive stress in concrete under service loads
f_{ctd}	Design value of concrete tensile strength (f_{ct} / γ_m)
f_{ctm}	Mean value of axial tensile strength of concrete
$f_{ctm, fl}$	Mean flexural tensile strength of reinforced concrete
f_d	Design strength of material
f_h	Direct stress
f_{inf}	Prestress in concrete at bottom of section (inferior)
f_k	Characteristic strength of material
f_{max}, f_{min}	Maximum and minimum principal stresses
f_p	Characteristic strength of prestressing steel
f_{pb}	Tensile stress in tendons at failure
f_{pe}	Effective stress in tendons after losses
f_{pi}	Initial stress in tendons
f_{pu}, f_p	Characteristic strength of prestressing tendons
f_s	Stress in reinforcement
f_{sc}	Compressive stress in reinforcement
f_{st}	Tensile stress in reinforcement
f_{sup}	Prestress in concrete at top of section (superior)
f_t	Characteristic tensile strength of concrete
f_{tt}	Allowable tensile stress in concrete at initial transfer of prestress
f_{tw}	Allowable tensile stress in concrete under service loads
f_v	Transverse tensile stress
f_y, f_{yk}	Characteristic tensile strength of reinforcement
f_{yl}	Characteristic strength of stirrups for torsion
f_{yv}	Characteristic strength of stirrups for shear
g	Distributed dead load or acceleration due to gravity
h	Overall depth of the member
h_f	Thickness of compression flange
h_{max}	The larger dimension of the section
h_{min}	The smaller dimension of the section
k	Constant
m	Modular ratio
m_1 and m_2	Moment coefficients
n	Neutral axis depth factor
q	Distributed load
s	Spacing of stirrups or links
t	Time
u	Perimeter
w_c	Density of concrete
w_{cr}	Design surface crack width
w_k	Characteristic crack width
w_{min}	Minimum uniformly distributed load
w_{ud}	Ultimate design load

w	Crack width
x	Linear coordinate of depth of neutral axis
x_1	Smaller dimension of transverse reinforcement
x_u	Neutral axis depth
y	Vertical distance of a point from centroid of concrete section
y_b	Distance of lower point (inferior) from centroid of concrete section
y_1	Larger dimension of transverse reinforcement
y_o	Half depth of bearing area anchorage zone
y_{po}	Half depth of punching area of anchorage zone
y_t	Distance of highest (superior) point from centroid of cross-section
z	Lever arm between the compressive force in concrete and the tensile force in steel

3. Greek lower case letters

α	Angle, ratio or dimensionless coefficient
α_e	Modular ratio
β	Dimensionless coefficient
γ_f	Partial safety factor for loads
γ_m	Partial safety factor for material strength
ε	Strain
ε_c	Strain in concrete
ε_{ce}	Ultimate creep strain in concrete
ε_{cs}	Total shrinkage strain
ε_{cd}	Drying shrinkage strain
ε_{ca}	Autogeneous shrinkage strain
ε_{cm}	Mean strain in concrete between cracks
ε_{cu}	Ultimate compressive strain in concrete
ε_m	Average strain at the level where the cracking is considered
ε_s	Strain in steel
ε_{se}	Effective strain in tendons after all losses
ε_{sm}	Mean strain in the reinforcement
ρ	Reinforcement ratio
$\rho_{\rho, eff}$	Effective reinforcement ratio based on an effective concrete tension area
η	Reduction factor for loss of prestress or loss ratio
θ	Rotation of the beam at supports
μ	Coefficient of friction
τ	Shear stress
τ_b	Bond stress (generally)
τ_c	Shear stress in concrete
τ_{bp}	Bond stress between concrete and prestressing steel
τ_t	Shear stress due to torsion
τ_u	Ultimate shear stress
τ_v	Shear stress due to transverse shear
$Ø$	Creep coefficient or capacity reduction factor
$Ø_I$	Initial curvature
$Ø_{mt}$	Change of curvature caused by transverse loads
$Ø_{pt}$	Change of curvature caused by prestress
ν_c	Poisson's ratio for concrete
ν_s	Poisson's ratio for steel
Δ	Difference in increment
ψ	Dimensionless coefficient
ϕ	Diameter of the reinforcing bar
β_1	A factor depending upon the compressive strength of concrete
λ	A factor depending upon the density of concrete
ξ_c	Design shear strength of concrete
Σ	Summation