Chapter 9

PRESTRESSED CONCRETE STRUCTURES

Part A - Design

9.1 Scope

9.1.1 Provisions of this chapter shall apply to members prestressed with wires, strands, or bars conforming to the specifications of prestressing tendons given in Article 9.5.1.3.

9.1.2 All provisions of this code not specifically excluded, and not in conflict with provisions of this Chapter 9, shall apply to prestressed concrete.

9.2 Definitions

ACTION: Mechanical force or environmental effect to which the structure (or structural component) is subjected.

AERODYNAMIC SHAPE FACTOR: Factor to account for the effect of geometry of structure on the surface pressure due to wind.

ANALYSIS (ASSESSMENT): Acceptable methods of evaluating the performance indices or verifying the compliance of specific criteria.

ANCHORAGE: In post-tensioning, a mechanical device used to anchor the tendon to the concrete; in pretensioning, a device used to anchor the tendon until the concrete has reached a pre-determined strength, and the prestressing force has been transferred to the concrete; for reinforcing bars, a length of reinforcement, or a mechanical anchor or hook, or combination thereof at the end of a bar needed to transfer the force carried by the bar into the concrete.

ANCHORAGE BLISTER: A build-up area on the web, flange, or flange-web junction for the incorporation of tendon anchorage fittings.

ANCHORAGE ZONE: The portion of the structure in which the prestressing force is transferred from the anchorage device on to the local zone of the concrete, and then distributed more widely in the general zone of the structure.

AT JACKING: At the time of tensioning the prestressing tendons.

AT LOADING: The maturity of the concrete when loads are applied. Such loads include prestressing forces and permanent loads but generally not live loads.

AT TRANSFER: Immediately after the transfer of prestressing force to the concrete.

AUTOGENEOUS SHRINKAGE: Volume decrease due to loss of water in the hydration process causing negative pore pressure in concrete.

BIOLOGICAL DEGRADATION: The physical or chemical degradation of concrete due to the effect of organic matters such as bacteria, lichens, fungi, moss, etc.

BLEEDING: Segregation between water and the other ingredients in concrete causing water to rise up to the surface of the freshly placed concrete.

BONDED MEMBER: A prestressed concrete member in which tendons are bonded to the concrete either directly or through grouting.

BONDED POST-TENSIONING: Post-tensioned construction in which the annular space around the tendons is grouted after stressing, thereby bonding the tendon to the concrete section.

BONDED TENDON: Prestressing tendon that is bonded to concrete either directly or through grouting.

BURSTING FORCE: Tensile forces in the concrete in the vicinity of the transfer or anchorage of prestressing forces.

CARBONATION: Action caused by chemical reaction between calcium hydroxide in concrete and carbon dioxide in the environment, resulting in a denser surface for the carbonated concrete and reduction of alkalinity in the carbonated portion.

CAST-IN-PLACE CONCRETE: Concrete placed in its final position in the structure while still in a plastic state.

CHARACTERISTIC STRENGTH: Unless otherwise stated in this code, the characteristic strength of material refers to the value of the strength below which none of the test results should fall below by more than 15% or 3.5 MPa for ≤35 MPa concrete, and 10% or 3.5 MPa for ≥35 Mpa concrete, whichever is larger.

CHEMICAL ADMIXTUREs: Admixtures which are usually used in small quantities typically in the form of liquid and can be added to the concrete both at the time of mixing and before placing to improve various concrete properties such as workability, air content and durability, etc.

CLOSELY SPACED ANCHORAGES: Anchorage devices are defined as closely spaced if their centre to centre spacing does not exceed 1.5 times the width of the anchorage devices in the direction considered.

CLOSURE: A placement of cast-in-place concrete used to connect two or more previously cast portions of a structure.

COMPOSITE CONSTRUCTION: Concrete components or concrete and steel components interconnected to respond to force effects as a unit.

COMPRESSION-CONTROLLED SECTION: A cross-section in which the net tensile strain in the extreme tension steel at nominal resistance is less than or equal to the compression-controlled strain limit.

COMPRESSION-CONTROLLED STRAIN LIMIT: The net tensile strain in the extreme tension steel at balanced strain conditions.

CONCRETE COVER: The specified minimum distance between the surface of the reinforcing bars, strands, post-tensioning ducts, anchorages, or other embedded items, and the surface of the concrete.

CONFINEMENT: A condition where the disintegration of the concrete under compression is prevented by the development of lateral and/or circumferential forces such as may be provided by appropriate reinforcing steel or composite tubes, or similar devices.

CONFINEMENT ANCHORAGE: Anchorage for a post-tensioning tendon that functions on the basis of containment of the concrete in the anchorage zone by special reinforcement.

CREEP: Time dependent deformation of concrete under permanent load.

CREEP COEFFICIENT: The ratio of creep strain to elastic strain in concrete.

CREEP IN CONCRETE: Increase in strain with time in concrete subjected to sustained stress.

CURVATURE FRICTION: Friction resulting from bends or curves in the specified prestressing tend stage at which the compressive stresses on profile.

DAMAGE CONTROL: A means to ensure that the limit state requirement is met for restorability or repairability of a structure.

DECOMPRESSION: The stage at which the compressive stresses, induced prestress, are overcome by the tensile stresses.

DEEP COMPONENT: components in which the distance from the point of 0.0 shear to the face of the support is less than 2d or components in which a load causing more than one-third of the shear at a support is closer than 2d from the face of the support.

DEFORMABILITY: A term expressing the ability of concrete to deform.

DEGREE OF DETERIORATION: The extent to which the performance of a structure is degraded or the extent to which the deterioration has progressed from the time of construction, as a result of its exposure to the environment.

DESIGN LIFE: Assumed period for which the structure is to be used satisfactorily for its intended purpose or function with anticipated maintenance but without substantial repair being necessary.

DETERIRATION FACTOR: The factor affecting the deterioration process.

DETERIRATION INDEX: An index selected for estimating and evaluating the extent of the deterioration process.

DETERIORATION PREDICTION: Prediction of the future rate of deterioration of a structure based on results of inspection and relevant records made during the design and construction stages.

DEVIATION SADDLE: A concrete block build-out in web, flange, or web-flange junction used to control the geometry of or to provide a means for changing direction of, external tendons.

DRYING SHRINKAGE: Volume decrease due to loss of moisture from concrete in the hardened state which is usually serious in hot and dry environment.

DURABILITY DESIGN: Design to ensure that the structure can maintain its required functions during service life under environmental actions.

DURABILITY GRADE: The extent of durability to which the structure shall be maintained in order to satisfy the required performance during its design life. This affects the degree and frequency of the remedial actions to be carried out during that life.

DURABILITY LIMIT STATE: The maximum degree of deterioration allowed for the structure during its design life.

DURABILITY PREDICTION: Prediction of the future degree of deterioration of the structure based on data used in its design.

DYNAMIC APPROACH: An approach based on dynamic analysis to assess the overall forces on a structure liable to have a resonant response to wind action.

DYNAMIC RESPONSE FACTOR: Factor to account for the effects of correlation and resonant response.

EARLY AGE STATE: The state of concrete from final setting until the achievement of the required characteristic strength.

EFFECTIVE PRESTRESS : Stress remaining in prestressing tendons after all losses have occurred, excluding effects of dead load and superimposed load.

ENVIRONMENTAL ACTIONS: An assembly of physical, chemical or biological influences which may cause deterioration to the materials making up the structure, which in turn may adversely affect its serviceability, restorability and safety.

FATIGUE LOADS: Repetitive loads causing fatigue in the material which reduces its strength, stiffness and deformability.

FINAL PRESTRESS : Stress which exists after substantially all losses have occurred.

FINAL TENSION : The tension in the steel corresponding to the state of the final prestress.

FORMWORK: Total system of support for freshly placed concrete including the mould or sheathing, all supporting members, hardware and necessary bracings.

FRESH STATE OF CONCRETE: The state of concrete after mixing until the completion of placing.

FUNCTION: The task which a structure is required to perform.

GENERAL ZONE: Region adjacent to a post-tensioned anchorage within which the prestressing force spreads out to an essentially linear stress distribution over the cross section of the component.

GROUT: A mixture of cementitious material and water with or without admixtures.

HARDENED STATE OF CONCRETE: The state of concrete after achieving the required strength.

IMPORTANCE: rank assigned to a structure according to the likely overall impact caused by its failure, due to deterioration, to satisfactorily perform its functions as determined at the time of design.

INITIAL PRESTRESS : The prestress in the concrete at transfer.

INITIAL TENSION : The maximum stress induced in the prestressing tendon at the time of stressing operation.

IRREGULAR STRUCTURES: Structures having unusual shapes such as open structures, structures with large overhangs or other projections, and any building with a complex shape.

JACKING FORCE : Temporary force exerted by device that introduces tension into prestressing tendons.

LIMIT STATE: A critical state specified using a performance index, beyond which the structure no longer satisfies the design performance requirements.

LIMITS OF DISPLACEMENT: Allowable deformation of structure in terms of such parameters as inter-storey drift and relative horizontal displacement, to control excessive deflection, cracking and vibration.

Long-term performance index: Index defining the remaining capacity of a structure in performing its design functions during the design life.

LOCAL ZONE: The volume of concrete that surrounds and is immediately ahead of the anchorage device and that is subjected to high compressive stresses.

MAINTENANCE: A set of activities taken to ensure that the structure continues to perform its functions satisfactorily during the design life.

MECHANICAL FORCES: An assembly of concentrated or distributed forces acting on a structure, or deformations imposed on it.

MODEL: Mathematical description or experimental setup simulating the actions, material properties and behavior of a structure.

MONITORING: Continuous recording of data pertaining to deterioration and/or performance of structure using appropriate equipment.

NOMINAL STRENGTH OF MATERIAL: The characteristic values of the strength of materials used for calculation, in absence of the available statistical data.

NORMAL CONCRETE: Concrete which is commonly used in construction; it does not include special constituent materials other than Portland cement, water, fine aggregate, coarse aggregate and common mineral and chemical admixtures; it does not require any special practice for its manufacturing and handling.

OVERALL PERFORMANCE INDEX: Index indicating the overall performance of the structure.

special practice for its manufacturing and handling.

PARTIAL PERFORMANCE INDEX: Index indicating a partial performance of the structure.

PARTIAL SAFETY FACTOR FOR MATERIAL: For analysis purposes, the design strength of a material is determined as the characteristic strength divided by a partial safety factor.

PERFORMANCE: Ability (or efficiency) of a structure to perform its design functions.

PERFORMANCE INDEX: Index indicating structural performance quantitatively.

PERMANENT ACTIONS: Self-weights of structures inclusive of permanent attachments, fixtures and fittings.

PLASTIC SHRINKAGE: Shrinkage arising from loss of water from the exposed surface of concrete during the plastic state, leading to cracking at the exposed surface.

PLSTIC STATE: The state of concrete from just after placing until the final setting of concrete.

POST-TENSIONING : Method of prestressing in which tendons are tensioned after concrete has hardened.

PRESTRESSED CONCRETE : Reinforced concrete in which internal stresses have been introduced to reduce potential tensile stresses in concrete resulting from loads.

PRETENSIONING : Method of prestressing in which tendons are tensioned before concrete is placed.

SHRINKAGE LOSS : The loss of stress in the prestressing steel resulting from the shrinkage of concrete.

RELIABILITY: Ability of a structure to fulfill specified requirements during its designlife.

REMAINING SERVICE LIFE: Period from the point of inspection to the time when the structure is no longer useable, or does not satisfactorily perform the functions determined at the time of design.

REMEDIAL ACTION: Maintenance action carried out with the objective of arresting or slowing down the deterioration process, restoring or improving the performance of a structure, or reducing the danger of damage or injury to the users or any third party.

REPAIR: Remedial action taken with the objective of arresting or slowing down the deterioration of a structure, or reducing the possibility of damage to the users or third party.

RESTORABILTY (OR REPAIRABILIY): Ability of a structure to be repaired physically and economically when damaged under the effects of considered actions.

ROBUSTNESS (OR STRUCTURAL INSENSITIVITY): Ability of a structure to withstand damage by events like fire, explosion, impact, instability or consequences of human errors.

SAFETY: Ability of a structure to ensure that no harm would come to the users and to people in the vicinity of the structure under any action.

SEGREGATION: Separation of one or more constituent materials from the rest of the concrete, such as bleeding, aggregate blocking, etc.

SERVICE LIFE: The length of time from the completion of a structure until the time when it is no longer usable because of its failure to adequately perform its design functions.

SERVICEABILITY: Ability of a structure to provide adequate services or functionality in use under the effects of considered actions.

SETTLEMENT OF CONCRETE: Sinking of the concrete surface after placing due to bleeding and/or escaping of the entrapped and entrained air in the concrete.

SPECIAL CONCRETE: Concrete other than normal concrete including light weight concrete, roller compacted concrete, self-compacting concrete, fiber-reinforced concrete, anti-washout under water concrete, etc.

STIFF AND FLEXIBLE STRUCURES: Stiff structures refer to those that are not sensitive to dynamic effects of wind, while flexible ones are those that are sensitive to such effects.

STRENGTHENING: Remedial action applied to a structure with the objective of restoring or improving its load bearing capacity to a level which is equal to, or higher than, the original design level.

STRESS AT TRANSFER : The stress in both the prestressing tendon and the concrete at the stage when the prestressing tendon is released from the prestressing mechanism.

SURFACE FINISHING: Action, such as troweling, applied to the exposed portion of concrete to obtain a neat surface.

TEMPERATURE CRACKING: Cracking caused by thermal stress which arises from differential temperatures in the concrete mass.

TENDON : Steel element such as wire, cable, bar, rod, or strand, or a bundle of such elements, used to impart prestress to concrete.

THRESHOLD LEVEL OF PERFORMANCE: Minimum acceptable level of performance of a structure.

TRANSFER: Act of transferring stress in prestressing tendons from jacks or pretensioning bed to concrete member.

TRIBUTARY AREA: Area of building surface contributing to the force being considered, due to wind actions, and projected on a vertical plane normal to the wind direction.

TRANSMISSION LENGTH : The distance required at the end of a pretensioned tendon for developing the maximum tendon stress by bond.

ULTIMATE LIMIT STATE: Limit state for safety.

VARIABLE ACTION: Action due to a moving object on the structure as well as any load whose intensity is variable, including traffic load, wave load, water pressure, and load induced by temperature variation.

WOBBLE FRICTION: Friction caused by unintended deviation of prestressing sheath or duct from its specified profile.

WORKABILITY: The term expressing the ease with which concrete can be placed, compacted and filled.

9.3 Notations

a	=	depth of equivalent rectangular stress block, mm
A	=	area of the part of cross-section between flexural tension face and centre of gravity of gross section, mm^2
Aps	=	area of prestressed reinforcement in tension zone, mm^2
As	=	area of nonprestressed tension reinforcement, mm^2
$A's$	=	area of compression reinforcement, mm^2
b	=	width of compression face of member, mm
d	=	distance from extreme compression fiber to centroid of nonprestressed tension reinforcement, mm
d'	=	distance from extreme compression fiber to centroid of compression reinforcement, mm

d_b	=	nominal diameter of bar, wire, or prestressing strand, mm
d_p	=	distance from extreme compression fiber to centroid of prestressed reinforcement, mm
D	=	dead loads, or related internal moments and forces
e	=	base of Napierian logarithm
f'_c	=	specified compressive strength of concrete, N/mm^2
f'_{ci}	=	compressive strength of concrete at transfer of prestress, N/mm^2
f_d	=	stress due to unfactored dead load, at extreme fiber of section where tensile stress is caused by externally applied loads, N/mm2
f_{pe}	=	compressive stress in concrete due to effective prestress forces only (after allowance for all prestress losses) at extreme fiber of section where tensile stress is caused by externally applied loads, N/mm^2
fpc	=	average compressive stress in concrete due to effective prestress force only (after allowance for all prestress losses), N/mm^2
f_{ps}	=	stress in prestressed reinforcement at nominal strength, N/mm2
f_{pu}	=	specified tensile strength of prestressing tendons, N/mm2
f_{py}	=	specified yield strength of prestressing tendons, N/mm2
f_r	=	modulus of rupture of concrete, N/mm2
f_{se}	=	effective stress in prestressed reinforcement (after allowance for all prestress
f_y	=	specified yield strength of nonprestressed reinforcement, N/mm2
h	=	overall thickness of member, mm
h_f	=	overall thickness of flange of flanged section, mm
I	=	moment of inertia of cross-section resisting externally applied factored loads, mm^4
k	=	wobble friction coefficient per meter of prestressing tendon
ℓ	=	length of span of two-way flat plates in direction parallel to that of the reinforcement being determined, mm
ℓx	=	length of prestressing tendon element from jacking end to any point x, metre
L	=	live loads, or related internal moments and forces
M_{cr}	=	moment causing flexural cracking at section due to externally applied loads, kNm
M_{max}	=	maximum factored moment at section due to externally applied loads, kNm
M_u	=	factored moment at section, kNm
N_c	=	tensile force in concrete due to unfactored dead load plus live load (D + L), kN
P_j	=	prestressing tendon force at jacking end, kN

PI_P	=	Inherent or possessed performance index
PI_R	=	Inherent or possessed performance index
P_x	=	prestressing tendon force at any point x
s	=	spacing of shear or torsion reinforcement in direction parallel to longitudinal reinforcement, mm
V_c	=	nominal shear strength provided by concrete, kN
V_{ci}	=	nominal shear strength provided by concrete when diagonal cracking results from combined shear and moment, kN
V_{cw}	=	nominal shear strength provided by concrete when diagonal cracking results from excessive principal tensile stress in web, kN
V_d	=	shear force at section due to unfactored dead load, kN
V_i	=	factored shear force at section due to externally applied loads occurring simultaneously with Mmax, kN
V_n	=	nominal shear strength, kN
V_p	=	vertical component of effective prestress force at section, kN
V_s	=	nominal shear strength provided by shear reinforcement, kN
V_u	=	factored shear force at section,kN
x	=	shorter overall dimension of rectangular part of cross-section
α	=	total angular change of prestressing tendon profile in radians from tendon jacking end to any point x
y	=	longer overall dimension of rectangular part of cross-section
y_t	=	distance from centroidal axis of gross section, neglecting reinforcement, to extreme fibre in tension
β_1	=	factor defined in Sec 9.5.5(c)
γ_p	=	factor for type of prestressing tendon
	=	0.55 for f_{py}/f_{pu} not less than 0.80
	=	0.40 for f_{py}/f_{pu} not less than 0.85
	=	0.28 for f_{py}/f_{pu} not less than 0.90
μ	=	curvature friction coefficient
ρ	=	ratio of nonprestressed tension reinforcement = A_s/bd
ρ'	=	ratio of compression reinforcement = A_s'/bd
ρ_p	=	ratio of prestressed reinforcement = A_{ps}/bd_p
ϕ	=	strength reduction factor
ω	=	$\rho f_y/f_c'$
ω'	=	$\rho' f_y/f_c'$
ω_p	=	$\rho_p\, f_{ps}/f_c'$

$\omega_w, \omega_{pw}, \omega'_w =$ reinforcement indices for flanged sections computed for w, w_p, and w' except that b shall be the web width, and reinforcement area shall be that required to develop compressive strength of web only.

For other symbols and units of quantities, reference shall be made to Chapter 6.

9.4 Analysis and design

9.4.1 Requirement

9.4.1.1 General

(a) Prestressed members shall be designed for adequate strength in accordance with the provisions of this chapter.

(b) Unless specifically excluded or superseded by the provisions of this chapter, all other relevant provisions of this code shall apply to prestressed concrete.

(c) Design of prestressed members shall be based on strength and on the behavior at service conditions at all critical load stages during the life of the structure from the time of prestress is first applied.

(d) Stress concentrations due to prestressing shall be considered in design.

(e) Provisions shall be made for effects on adjoining construction of elastic and plastic deformations, deflections, changes in length and rotations due to prestressing. Effects of temperature and shrinkage shall also be considered.

(f) The possibility of buckling in a member between points where there is intermittent contact between prestressing steel and an oversized duct and buckling in thin webs and flanges shall be considered.

(g) In computing section properties before bonding of prestressing steel, effect of loss of area due to open ducts shall be considered.

(h) Thermal gradient and differential shrinkage shall be considered in composite construction using prestressed concrete members.

(i) In evaluating the slenderness effects during lifting of slender beams, consideration shall be given to beam geometry, location of lifting points, method of lifting and tolerances in construction. All beams which are lifted on vertical or inclined slings shall be checked for lateral stability and lateral moment on account of tilting of beam. Reference may be made to specialist literature in this regard.

9.4.1.2 Design Assumptions

(a) Strength design of prestressed members for flexure and axial loads shall be based on assumptions given in Sec 9.4.1.2 b. to g. and shall satisfy the applicable conditions of equilibrium and compatibility of strains.

(b) Strains in steel and concrete shall be assumed to be directly proportional to the distance from the neutral axis except for Deep Beams.

(c) Stress in nonprestressed reinforcement (if used) below f_y, shall be taken as Es times steel strain. For strains greater than that corresponding to f_y, stress in reinforcement shall be considered independent of strain and equal to f_y.

(d) Maximum usable strain at extreme concrete compression fiber shall be assumed to be 0.003.

(e) The relationship between concrete compressive stress distribution and concrete strain shall be assumed to be rectangular, trapezoidal, parabolic, or any other shape that results in prediction of strength in substantial agreement with results of comprehensive tests

(f) Requirements of 9.4.1.2e. are satisfied by an equivalent rectangular concrete stress distribution defined by the following:

i) Concrete stress of $0.85f_c'$ shall be assumed uniformly distributed over an equivalent compression zone bounded by edges of the cross section and a straight line located parallel to the neutral axis at a distance $a = \beta_1 c$ from the fiber of maximum compressive strain.

ii) Distance from the fiber of maximum strain to the neutral axis, c, measured in a direction perpendicular to the neutral axis.

iii) For fc' between 17.5 and 28 MPa, β_1 shall be taken as 0.85. For fc' above 28 MPa, β_1 shall be reduced linearly at a rate of 0.05 for each 7 MPa of strength in excess of 28 MPa, but β_1 shall not be taken less than 0.65.

(g) For investigation of stresses at transfer of prestress, at service loads, and at cracking loads, elastic theory shall be used with the following assumptions:

i) Strains vary linearly with depth through the entire load range.

ii) At cracked sections, concrete resists no tension.

9.4.1.3 **Classification of prestressed concrete members**

Prestressed concrete flexural members shall be classified as Class U (uncracked), Class T (transition) and Class C (cracked) based on extreme fiber stress in tension in the pre-compressed tensile zone as follows:

(a) Class U: Permissible flexural tensile stresses $f_t \leq 0.62\sqrt{f_c'}$

(b) Class T: $0.62\sqrt{f_c'} \leq f_t \leq 1.0\sqrt{f_c'}$

(c) Class C: $f_t > 1.0\sqrt{f_c'}$

(d) d. Prestressed two-way slab systems shall be designed as $f_t \leq 0.50\sqrt{f_c'}$

9.4.1.4 **Shapes of beams and girders**

For prestressed concrete non-composite beams/girders, the frequently used shapes are:

(a) Symmetrical I-section, (b) Unsymmetrical I-section, (c) T-section,

(d) Inverted T-section, (e) Box section, (f) solid rectangular section.

Commentary:

The suitability of selecting a particular shape will depend on the specific design requirement and economy of construction. In general, to achieve economy in steel and concrete, it is best to put the concrete near the extreme fibers of the compression flange. To suit this condition, I-section is the most natural choice. The inverted T-section may only be selected for composite construction when tension flange is precast and the compression flange is poured in place.

In choosing beam/girder shapes, due consideration should be given to the simplicity of formwork. When formwork is to be used once, it may constitute the major cost of beam/girder. Any irregular shape of beam/girder is generally unjustifiable on this ground. Rectangular solid sections are an obvious choice for flat slabs for floor and roof. Precast Tee or double Tee sections with a light concrete tapping may be more economical choice for floor construction of multi-storied residential, commercial and factory buildings with moderate column spacing.

9.4.2 Material properties for design

9.4.2.1 **Concrete**

(a) **Class**

The Class of concrete is defined by the characteristic strength of concrete in cylinder at 28 days, f'c. For example, Class 10 concrete indicates concrete with f_c' = 10 N/mm^2. The classes of concrete commonly used are: Class 10, 15, 20, 25, 30, 35, 40, 45 and 50, although concrete in between these classes may also be used.

(b) **Modulus of elasticity, Ec**

Modulus of elasticity, Ec for concrete shall be permitted to be taken as $w_c^{1.5}0.043(f_c')^{0.5}$ (in N/mm^2) for values of w_c between 1440 and 2560 kg/m^3. For normal weight concrete, Ec may be permitted to be taken as 4700 $(f_c')^{0.5}$.

9.4.2.2 **Reinforcing steel**

a. **Modulus of elasticity, Es**

Where it is not possible to ascertain the modulus of elasticity of reinforcing steel by test and from the manufacturer of steel, the modulus of elasticity of reinforcing steel may be permitted to be taken as Es = 200,000 N/mm^2.

9.4.2.3 **Prestressing steel**

(a) Modulus of elasticity, Es

Where it is not possible to ascertain the modulus of elasticity of reinforcing and prestressing steel by test and from the manufacturer of steel, the values of Es given in Table 9.4.1 may be used:

Table 9.4.1 Modulus of elasticity of prestressing steel and cold drawn wire

Type of steel	Modulus of elasticity, Es (kN/mm^2)
Plain/indented cold-drawn wire	200
High tensile steel bars rolled or heat-treated	205
Strands	195

9.4.3 Nominal strengths of bonded reinforcement and of concrete at transfer

9.4.3.1 Bonded reinforcement

(a) Tensile stress at nominal strength of bonded reinforcement is limited to fy for nonprestressed reinforcement and to f_{py} for prestressed reinforcement. Tensile stress at nominal strength of unbonded prestressed reinforcement for resisting tensile forces in the anchorage zone shall be limited to $f_{ps} = f_{se} + 70$.

(b) Except for concrete confined within spirals or hoops providing confinement equivalent to that corresponding to Eq. (9.4.3-1), compressive strength in concrete in the general zone shall be limited to $0.7\lambda f_{ci}'$.

Commentary:

Eq. (9.4.3-1) is given below.

$$\rho_s = 0.45(\frac{A_g}{A_{ch}} - 1)\frac{f_c'}{f_{yt}} \tag{9.4.3-1}$$

where the value of f_{yt} used in Eq. (9.4.3-1) shall not exceed 700 N/mm^2. For f_{yt} greater than 420 N/mm^2 normal lap splices as shown in Chapter 6 shall not be applied.

9.4.3.2 **Concrete strength at transfer**

Compressive strength of concrete at time of post-tensioning shall be specified in the contract documents. Unless oversize anchorage devices are sized to compensate for the lower compressive strength or the prestressing steel is stressed to no more than 50 percent of the final prestressing force, prestressing steel shall not be stressed until compressive strength of concrete as indicated by tests consistent with the curing of the member, is at least 28 N/mm^2 for multi-strand tendons or at least 17 N/mm^2 for single-strand or bar tendons.

9.4.4 Serviceability Requirements – Flexural Members

9.4.4.1 **Stresses in concrete immediately after prestress transfer**

Stresses in concrete immediately after prestress transfer (before time-dependent prestress losses occur) are as follows:

(a) Extreme fiber stress in compression except as permitted in (b) shall not exceed .... $0.60f'_{ci}$

(b) Extreme fiber stress in compression at ends of simply support members shall not exceed... $0.70f'_{ci}$

(c) Where computed concrete tensile strength, f_t , exceeds $0.5\sqrt{f_c'}$ at ends of simply supported members, or $0.25\sqrt{f_c'}$ at other locations, additional bonded reinforcement shall be provided in the tensile zone to resist the total tensile force in concrete computed with the assumption of an uncracked section.

9.4.4.1.1 Stresses in concrete at service loads and reinforcement spacing

9.4.4.1.2 Allowable stresses in concrete

For Class U and Class T prestressed flexural members, stresses in concrete at service loads (based on uncracked section properties and after allowance for all prestress losses) shall not exceed the following:

(a) Extreme fiber stress in compression due to prestress plus sustained load .... $0.45f_c'$

(b) Extreme fiber stress in compression due to prestress plus total load............................ $0.60f_c'$

(c) Permissible stresses in 9.4.3.2 and 9.4.4.1 shall be permitted to be exceeded if shown by test or analysis that performance will not be impaired.

9.4.4.1.3 Reinforcement spacing

(a) For Class C prestressed flexural members not subject to fatigue or to aggressive exposure, the spacing of bonded reinforcement nearest the extreme tension face shall not exceed that for normal Reinforced Concrete, as given below:

$$s = 380\,(280/fs) - 2.5\,c_c \qquad (9.4.4\text{-}1)$$

but not greater than 300 ($280/f_s$), where c_c is the least distance from the surface of reinforcement or prestressing steel to the tension face. If there is only one bar or wire nearest to the extreme tension face, s used in the above equation is the width of the extreme tension face.

(b) Calculated stress fs in reinforcement closest to the tension face at service loads shall be computed based on the unfactored moment. It shall be permitted to take fs as $2/3f_y$.

(c) For structures subject to fatigue or exposed to corrosive environments, investigations, judgment and precautions are required.

(d) The spacing requirements shall be met by nonprestressed reinforcement and bonded tendons. The spacing of bonded tendons shall not exceed 2/3rd of the maximum spacing permitted for nonprestressed reinforcement.

(e) Where both reinforcement and bonded tendons are used to meet the spacing requirement, the spacing between a bar and a tendon shall not exceed 5/6 of that permitted by 9.4.3.2.2 a., b. and c.

(f) In applying Eq. 9.4.4-1 to prestressing tendons, Δf_{ps} shall be substituted for f_s, where Δf_{ps} shall be taken as the calculated stress in the prestressing steel at service loads based on a cracked section analysis minus the decompression stress f_{dc} . It shall be permitted to take f_{dc} equal to the effective stress in the prestressing steel f_{se}. See also 9.4.4.2.2g. below.

(g) In applying Eq. (9.4.4-1) to prestressing tendons, the magnitude of Δf_{ps} shall not exceed 250 N/mm^2. When Δf_{ps} is less than or equal to 140 N/mm^2, the spacing requirements of 9.4.4.2.2 a. and b. shall not apply.

(h) Where h of a beam exceeds 900 mm, the area of longitudinal skin reinforcement consisting of untensioned reinforcing steel or bonded tendons shall be uniformly distributed along both side faces of the member. Skin reinforcement shall extend for a distance of h/2 from the tension face. The spacing s shall be as provided in 9.4.4.2.2, where c_c is the least distance from the surface of the skin reinforcement or prestressing steel to the side face. It shall be permitted to include such reinforcement or prestressing steel to the side face. It shall be permitted to include such reinforcement in strength computations if a strain compatibility analysis is made to determine stress in the individual bars or wires.

9.4.5 Permissible stresses in prestressing steel

Tensile stress in prestressing tendons shall not exceed the following:

(a) Due to prestressing steel jacking force ...... $0.94f_{py}$

but not greater than the lesser of $0.80f_{pu}$ and the maximum value recommended by the manufacturer of prestressing steel or anchorage devices.

(b) Immediately after prestress transfer........ $0.82f_{py}$

but not greater than $0.74f_{pu}$.

(c) Post-tensioning tendons, at anchorage devices and couplers, immediately after force transfer.......$0.70f_{pu}$

9.4.6 Losses of prestress

To determine effective stress in the prestressing steel, f_{se}, allowance for the following sources of loss of prestress shall be considered:

9.4.6.1 Immediate losses

(a) Loss due to elastic shortening of concrete;

(b) Loss due to prestressing steel seating at transfer (Anchorage slip);

(c) Loss due to friction (for post-tensioned concrete only).

9.4.6.2 Long-term losses

(a) Loss due to relaxation of prestressing steel stress;

(b) Loss due to creep of concrete;

(c) Loss due to shrinkage of concrete.

Unless otherwise determined by actual tests, allowance for these losses shall be made in accordance with the provisions of Sec 9.4.6.3 through 9.4.6.8.

9.4.6.3 Loss due to elastic shortening of concrete

(a) The loss of prestress due to immediate elastic shortening of adjacent concrete upon transfer of initial prestress shall be calculated as specified in this section. For pretensioning, the loss of prestress in the tendons at transfer shall be calculated on a modular ratio basis using the stress in the adjacent concrete.

(b) For members with post-tensioned tendons which are not stressed simultaneously, there is a progressive loss of prestress during transfer due to the gradual application of the prestressing forces. This loss of prestress shall be calculated on the basis of half the product of the stress in the concrete adjacent to the tendons averaged along their lengths and the modular ratio. Alternatively, the loss of prestress may be exactly computed based on the sequence of tensioning.

9.4.6.4 Loss Due to prestressing steel seating at transfer (Anchorage slip)

a. Any loss of prestress which may occur due to slip of wire or strand during anchoring or due to straining of the anchorage shall be allowed for in the design. Necessary additional elongation may be provided for at the time of tensioning to compensate for this loss.

9.4.6.5 Loss due to friction (for post-tensioned tendons only)

(a) The design shall take into consideration all losses in prestress that may occur during tensioning due to friction between the post-tensioning tendons and the surrounding concrete or any fixture attached to the steel or concrete.

(b) The value of prestressing force P_X at a distance ℓ_x metres from the jacking end and acting in the direction of the tangent to the curve of the cable, shall be calculated from the relation:

$$P_x = P_j e^{-(K\ell_x + \mu\alpha)} \tag{9.4.5-1}$$

When ($klx + \mu\alpha$) is greater than 0.3, P_x may be computed from

$$P_x = \frac{P_j}{1 + Kl_x + \mu\alpha} \tag{9.4.5-2}$$

For use in Eq. (9.4.5-1) and Eq. (9.4.5-2), the values of wobble friction coefficient K and curvature friction coefficient μ shall be experimentally determined or obtained from the tendon manufacturer, and verified during tendon stressing operations.

(c) In absence of test results or manufacturer's recommendation, the following values of μ and K shown in Table 9.4.2 may be taken as a guide:

Table 9.4.2 Friction Coefficients (K & μ) for post-tensioned tendons

			coefficient, K per meter	**Curvature coefficient,μ per radian**
Grouted	**Tendons in metal sheathing**	Wire tendons	0.0033-0.0049	0.15-0.25
		High-strength bars	0.0003-0.0020	0.08-0.30
		7-wire strand	0.0016-0.0066	0.15-0.25
Unbonded tendons	**Mastic coated**	Wire tendons	0.0033-0.0066	0.05-0.15
		7-wire strand	0.0033-0.0066	0.05-0.15
	Pre-greased	Wire tendons	0.001-0.0066	0.05-0.15
		7-wire strand	0.001-0.0066	0.05-0.15

Values of wobble and curvature friction coefficients used in design shall be shown on design drawings.

(e) The effect of reverse friction shall be taken into consideration in such cases where the initial tension applied to a prestressing tendon is partially released and action of friction in the reverse direction causes significant alteration in the distribution of stress along the length of the tendon.

(f) Where loss of prestress in a member occurs due to connection of member to adjoining construction, such loss of prestress shall be allowed for in design.

9.4.6.6 Loss due to relaxation of pretressing steel stress

(a) The relaxation losses in prestressing steel shall be determined from experiments. When experimental values are not available, the relaxation losses, considering normal relaxation steel, may be assumed as given in Table 9.4.3.

Table 9.4.3 Relaxation Losses for prestressing steel at 1000 hours at 27^{o}C

Initial Stress	Relaxation Loss N/mm2
0.5 fpu	0
0.6 fpu	35
0.7 fpu	70
0.8 fpu	90

For tendons at higher temperature or subject to large lateral loads, greater relaxation losses may be allowed, subject to the advice of the metallurgy specialist.

(b) No reduction in the value of the relaxation losses should be made for a tendon with a load equal to or greater than the relevant jacking force that has been applied for a short duration prior to the anchoring of the tendon.

9.4.6.7 Loss due to creep of concrete

(a) Creep occurs due to superimposed permanent dead load added to the member after it has been prestressed. Creep of concrete may be assumed to be proportional to the stress provided the stress in concrete does not exceed 40 per cent of its compressive strength.

(b) In the absence of test data, the ultimate creep strain may be estimated from the following values of creep coefficient, which is the ratio of the ultimate creep strain to the elastic strain at the age of loading. Table 9.4.4 shows the values at different days.

Table 9.4.4 Creep coefficient of concrete

Age at Loading	Creep coefficient
7 days	2.2
28 days	1.6
1 year	1.1

(c) The ultimate creep strain estimated as above does not include the elastic strain. For the calculation of deformation at some stage before the total creep is reached, it may be assumed that 50 per cent of the total creep takes place in the first month after loading and about 75 per cent of the total creep takes place in the first six months after loading. For post-tensioning the creep coefficients shall be taken as 80% of those given here.

(d) The loss of prestress due to creep of concrete shall be determined for all the permanently applied loads including the prestress. Loss due to stresses of short duration including live load and erection stresses may be ignored.

(e) The loss of prestress due to creep of concrete shall be obtained as the product of the modulus of elasticity of the prestressing steel and the ultimate creep strain of the concrete fiber integrated along the centre-line of the prestressing steel over its entire length.

(f) The total creep strain during any specific period shall be assumed to be the creep strain due to sustained stress equal to the average of the stresses at the beginning and end of the period.

9.4.6.8 Loss due to shrinkage of concrete

(a) In the absence of test data, the approximate value of shrinkage strain in concrete for design purposes shall be assumed as follows:

For pretensioning : 0.0003

For post-tensioning : $\dfrac{0.0002}{\log_{10}(t+2)}$

where, t = age of concrete at transfer in days.

(b) For the calculation of deformation of concrete at some stage before the maximum shrinkage occurs it may be assumed that 50 per cent of the shrinkage takes place during the first month and about 75 per cent of the shrinkage takes place in the first six months after drying of concrete starts.

(c) The loss of prestress due to shrinkage of concrete shall be obtained as the product of the modulus of elasticity of steel and the shrinkage strain of concrete.

9.4.7 Control of Deflection

9.4.7.1 For prestressed concrete flexural members, designed in accordance with the provisions of this chapter, immediate deflection shall be computed by usual methods or formulas for elastic deflections, and the moment of inertia of gross concrete section, Ig, shall be permitted to be used for Class U flexural members.

9.4.7.2 For Class C and Class T flexural members, deflection calculations shall be based on cracked transformed section analysis. It shall be permitted to base calculations on an effective moment of inertia, Ie as given in Eq. 9.4.7-1.

$$Ie = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \qquad (9.4.7\text{-}1)$$

Where, $M_{cr} = \frac{f_r I_g}{y_t}$ and $f_r = 0.62\lambda\sqrt{f_c'}$

Deflection computed in accordance with 9.4.7.1 shall not exceed the limits stipulated in 6.5.9.4.

9.4.7.3 Additional long-term deflection of prestressed concrete members shall be computed taking into account stresses in concrete and steel under sustained load and including effects of creep and shrinkage of concrete and relaxation of steel.

9.4.8 Flexural Strength

9.4.8.1 Design moment strength of flexural members shall be computed by the strength methods of the Code. For prestressing steel, f_{ps} shall be substituted for f_y in strength computations.

9.4.8.2 As an alternative to a more accurate determination of $\boldsymbol{f_{ps}}$ based on strain compatibility, the following approximate values of fps shall be permitted to be used if $\boldsymbol{f_{se}}$ is not less than $0.5f_{pu}$.

(a) For members with bonded tendons

$$f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}(\omega - \omega')\right]\right\} \qquad (9.4.8\text{-}1)$$

where ω is $\rho f_y / f_c'$, ω′ is $\rho' f_y / f_c'$, and γ_p is 0.55 for f_{py} / f_{pu} not less than 0.80; 0.40 for f_{py} / f_{pu} not less than 0.85; and 0.28 for f_{py} / f_{pu} not less than 0.90.

If any compression reinforcement is taken into account when calculating f_{ps} by Eq. (9.4.8-1), the term shall be taken not less than 0.17 and d' shall be no greater than d_p.

$$\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}(\omega - \omega')\right]$$

(b) For members with unbonded tendons and with a span-to-depth ratio of 35 or less:

$$f_{ps} = f_{se} + 70 + \frac{f_c'}{100\rho_p} \qquad (9.4.7\text{-}2)$$

but $\boldsymbol{f_{ps}}$ in Eq. (9.4.7.2) shall not be taken greater than the lesser of f_{py} and $(f_{se} + 420)$.

c. For members with unbonded tendons and with a span-to-depth ratio greater than 35:

$$f_{ps} = f_{se} + 70 + \frac{f_c^{'}}{300\rho_p} \tag{9.4.7-3}$$

but f_{ps} in Eq. (9.4.7.3) shall not be taken greater than the lesser of f_{py} and $(f_{se} + 210)$

9.4.8.3 Nonprestressed reinforcement conforming to 9.4.4.2.2, if used with prestressing steel, shall be permitted to be considered to contribute to the tensile force and to be included in moment strength computations at a stress equal to f_y. Other nonprestressed reinforcement shall be permitted to be included in strength computations only if a strain compatibility analysis is performed to determine stresses in such reinforcement.

9.4.9 Limits for flexural reinforcement

9.4.9.1 Prestressed concrete sections shall be classified as either tension-controlled, transition, or compression-controlled sections, in accordance with a. and b. below.

(a) Sections are compression-controlled if the net tensile strain in the extreme tension fiber ε_t, is equal to or less than the compression-controlled strain limit when the concrete in compression reaches its assumed strain limit of 0.003. The compression-controlled strain limit is the net tensile strain in the reinforcement at balanced strain conditions. For Grade 420 reinforcement, and for all prestressed reinforcement, it shall be permitted to set the compression-controlled strain limit to 0.002.

(b) Sections are tension-controlled if the net tensile strain in the extreme tension steel, ε_t, is equal to or greater than 0.005 when the concrete in compression reaches its assumed strain limit of 0.003. Sections with ε_t between the compression-controlled strain limit and 0.005 constitute a tension region between the compression-controlled and tension-controlled sections. Appropriate strength reduction factor, □, from 9.4.9.2 shall apply.

9.4.9.2 The appropriate strength reduction factor, ϕ, shall apply as given in a. to f. below.

(a) Tension-controlled sections 0.90

(b) For compression-controlled sections

i. Members with spiral reinforcement as defined in 9.4.9.4 0.75

ii. Other reinforced members 0.65

(c) Shear and torsion 0.75

(d) Post-tensioned anchorage zones 0.85

(e) Strut and tie models 0.75

(f) Flexural sections in pre-tensioned members where strand embedment length is less than the development length

i. From the end of the member to the end of the transfer length 0.75

ii. From the end of the transfer length to the end of the development length, ϕ shall be taken as 0.75 to 0.90

Where bonding of the strand does not extend to the end of the member, strand embedment shall be assumed to begin at the end of the debonded length.

9.4.9.3 Total amount of prestressed and nonprestressed reinforcement in members with bonded prestressed reinforcement shall be adequate to develop a factored load at least 1.2 times the cracking load computed on the basis of the modulus of rupture f_r, as given in 9.4.6.2. This provision shall be permitted to be waived for flexural members with shear and flexural strength at least twice that required by 9.4.8.

9.4.9.4 Volumetric spiral reinforcement ratio, ρ_s, shall be not less than the value given by

$$\rho_s = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c'}{f_{yt}} \qquad (9.4.9\text{-}1)$$

where the value of f_{yt} in Eq. (9.4.9-1) shall not exceed 700 N/mm^2. For f_{yt} greater than 420 N/mm^2 where lap splices shall not exceed in accordance with 9.4.9.4 a. this shall not be used.

(a) Spiral reinforcement shall be spliced, if needed, by any one of the following methods:
Lap splices not less than the larger of 300 mm and the length indicated in one of (1) through (5) below:

i) deformed uncoated bar or wire $48d_b$

ii) plain uncoated bar or wire $72d_b$

iii) epoxy-coated deformed bar or wire $72d_b$

iv) plain uncoated bar or wire with a standard stirrup or tie hook in accordance with 9.4.8.5 c. at ends of lapped spiral reinforcement.

(b) The term “standard hook” as used in this code shall mean one of the following:

i) 180-degree bend plus $4d_b$ extension, but not less than 65 mm at free end of bar.

ii) 90-degree bend plus $12d_b$ extension at free end of bar.

(c) For stirrup and tie hooks

i) No. 16 bar and smaller, 90-degree bend plus $6d_b$ extension at free end of bar; or

ii) No. 19, No. 22 bar and No. 25 bar, 90-degree bend plus $12d_b$ extension at free end of bar; or

iii) No. 25 bar and smaller, 135-degree bend plus $6d_b$ extension at free end of bar.

9.4.9.5 Part or all of the bonded reinforcement consisting of bars or tendons shall be provided as close as practicable to the tension face in prestressed flexural members. In members prestressed with unbonded tendons, the minimum bonded reinforcement consisting of bars or tendons shall be as required by 9.4.10.

9.4.10 Minimum bonded reinforcement

9.4.10.1 A minimum area of bonded reinforcement shall be provided in all flexural members with unbonded tendons as required by 9.4.10.2 and 9.4.10.3.

9.4.10.2 Except as provided in 9.4.10.1, minimum area of bonded reinforcement shall be computed by

$$A_s = 0.004A_{ct} \qquad (9.4.10\text{-}1)$$

where A_{ct} is area of that part of cross section between the flexural tension face and center of gravity of gross section.

(a) Bonded reinforcement required by Eq. (9.4.10-1) shall be uniformly distributed over pre-compressed tensile zone as close as practicable to extreme tension fiber.

(b) Bonded reinforcement shall be required regardless of service load stress conditions.

9.4.10.3 For two-way flat slab systems, minimum area and distribution of bonded reinforcement shall be as required in a., b., and c below.

(a) Bonded reinforcement shall not be required in positive moment areas where ft , the extreme fibre stress in tension in the precompressed tensile zone at service loads (after allowance for all prestress losses), does not exceed $0.17\sqrt{f'_c}$.

(b) In positive moment areas where computed tensile stress in concrete at service load exceeds $0.17\sqrt{f'_c}$ minimum area of bonded reinforcement shall be computed by

$$A_s = N_c / 0.5 f_y \qquad (9.4.10\text{-}2)$$

where the value of $\boldsymbol{f_y}$ used in Eq. (9.4.10-2) shall not exceed 420 MPa. Bonded reinforcement shall be uniformly distributed over precompressed tensile zone as close as practicable to the extreme tension fiber.

(c) In negative moment areas at column supports, the minimum area of bonded reinforcement A_s in the top of the slab in each direction shall be computed by

$$A_s = 0.00075 A_{cf} \qquad (9.4.10\text{-}3)$$

where, A_{cf} is the larger gross cross-sectional area of the slab-beam strips in two orthogonal equivalent frames intersecting at a column in a two-way slab.

9.4.10.4 Bonded reinforcement required by Eq. (9.4.10-3) shall be distributed between lines that are outside opposite faces of the column support. At least four bars or wires shall be provided in each direction. Spacing of bonded reinforcement shall not exceed 300 mm.

9.4.10.5 Minimum length of bonded reinforcement required by 9.4.10.2 and 9.4.10.3 shall be as required in 9.4.10.5 a., b., and c.

(a) In positive moment areas, minimum length of bonded reinforcement shall be one-third the clear span length, l_n , and centered in positive moment area.

(b) In negative moment areas, bonded reinforcement shall extend one-sixth the clear span, l_n , on each side of support.

(c) Where bonded reinforcement is provided for ϕM_n in accordance with 9.4.7.8, or for tensile stress conditions in accordance with 9.4.9.3 b., minimum length also shall conform to provisions of Chapter 6.

9.4.11 Statically indeterminate structures

9.4.11.1 Frames and continuous construction of prestressed concrete shall be designed for satisfactory performance at service load conditions and for adequate strength.

9.4.11.2 Performance at service load conditions shall be determined by elastic analysis, considering reactions, moments, shears, and axial forces induced by prestressing, creep, shrinkage, temperature change, axial deformation, restraint of attached structural elements, and foundation settlement.

9.4.11.3 Moments used to compute required strength shall be the sum of the moments due to reactions induced by prestressing (with a load factor of 1.0) and the moments due to factored loads. Adjustment of the sum of these moments shall be permitted as allowed in 9.4.11.4.

9.4.11.4 Redistribution of moments in continuous prestressed flexural members shall be as follows:

(a) Where bonded reinforcement is provided at supports in accordance with 9.4.11, it shall be permitted to decrease negative or positive moments calculated by elastic theory for any assumed loading, in accordance with 9.4.11.4 b., c. and d. below.

(b) Except where approximate values for moments are used, it shall be permitted to decrease factored moments calculated by elastic theory at sections of maximum negative or maximum positive moment in any span of continuous flexural members for any assumed loading arrangement by not more than $1000\varepsilon_t$ percent, with a maximum of 20 percent.

(c) Redistribution of moment shall be made only when ε_t is equal to or greater than 0.0075 at the section at which moment is reduced.

(d) The reduced moment shall be used for calculating redistributed moments at all other sections within the spans. Static equilibrium shall be maintained after redistribution of moments for each loading arrangement.

9.4.12 Compression members — Combined flexure and axial load

9.4.12.1 Prestressed concrete members subject to combined flexure and axial load, with or without non-prestressed reinforcement, shall be proportioned by the strength design methods of this Code. Effects of prestress, creep, shrinkage, and temperature change shall be included.

9.4.12.2 Limits for reinforcement of prestressed compression members shall be as follows:

(a) Members with average compressive stress in concrete less than 1.6 N/mm^2, due to effective prestress force only, shall have minimum reinforcement in accordance with Chapter 6.

(b) Except for walls, members with average compressive stress in concrete due to effective prestress force only, equal to or greater than 1.6 N/mm^2 shall have all tendons enclosed by spirals or lateral ties in accordance with c. through g.

(c) Spirals shall conform to Chapter 6.

(d) Lateral ties shall be at least No. 10 in size or welded wire reinforcement of equivalent area, and shall be spaced vertically not to exceed 48 tie bar or wire diameters, or the least dimension of the compression member.

(e) Ties shall be located vertically not more than half a tie spacing above top of footing or slab in any story, and not more than half a tie spacing below the lowest horizontal reinforcement in members supported above.

(f) Where beams or brackets frame into all sides of a column, ties shall be terminated not more than 75 mm below lowest reinforcement in such beams or brackets.

(g) For walls with average compressive stress in concrete due to effective prestress force only equal to or greater than 1.6 N/mm^2, minimum reinforcement required by Chapter 6 shall not apply where structural analysis shows adequate strength and stability.

9.4.13 Slab systems

9.4.13.1 Factored moments and shears in prestressed slab systems reinforced for flexure in more than one direction shall be determined in accordance with provisions of 6.5 or by more detailed design procedures.

9.4.13.2 ϕM_n of prestressed slabs with loads and load combinations required by Chapter 2 and 6 at every section shall be greater than or equal to M_u considering 9.4.11.3 and 9.4.11.4. ϕV_n of prestressed slabs at columns required by Chapter 6 shall be greater than or equal to Vu.

9.4.13.3 At service load conditions, all serviceability limitations, including limits on deflections, shall be met, with appropriate consideration of the factors listed in 9.4.11.2~~.~~

9.4.13.4 For uniformly distributed loads, spacing of tendons or groups of tendons in at least one direction shall not exceed the smaller of eight times the slab thickness and 1.5 m. Spacing of tendons also shall provide a minimum average effective prestress of 0.9 N/mm^2 on the slab section tributary to the tendon or tendon group. For slabs with varying cross section along the slab span, either parallel or perpendicular to the tendon or tendon group, the minimum average effective prestress of 0.9 N/mm^2 ~~MPa~~ is required at every cross section tributary to the tendon or tendon group along the span. Concentrated loads and opening in slabs shall be considered when determining tendon spacing.

9.4.13.5 In slabs with unbonded tendons, bonded reinforcement shall be provided in accordance with 9.4.9.3 and 9.4.9.5.

Except as permitted in 9.4.13.6, in slabs with unbonded tendons, a minimum of two 12.7 mm diameter or larger, seven-wire post-tensioned strands shall be provided in each direction at columns, either passing through or anchored within the region bounded by the longitudinal reinforcement of the column. Outside column and shear cap faces, these two structural integrity tendons shall pass under any orthogonal tendons in adjacent spans. Where the two structural integrity tendons are anchored within the region bounded by the longitudinal reinforcement of the column, the anchorage shall be located beyond the column centroid and away from the anchored span.

9.4.13.6 Prestressed slabs not satisfying 9.4.13.5 shall be permitted provided they contain bottom reinforcement in each direction passing within the region bounded by the longitudinal reinforcement of the column and anchored at exterior supports as required by bar detailing requirement of slabs given in Chapter 6. The area of bottom reinforcement in each direction shall be not less than 1.5 times that required by Eq. (9.4.13-1) as given below.

$$As,\min = \frac{0.25\sqrt{f_c'}}{f_y} b_w d \qquad (9.4.13\text{-}1)$$

and not less than $2.1 b_w d/f_y$, where b_w is the width of the column face through which the reinforcement passes. Minimum extension of these bars beyond the column or shear cap face shall be equal to or greater than the bar development length required by Chapter 6.

9.4.13.7 In lift slabs, bonded bottom reinforcement shall be detailed in accordance with 9.4.13.8.

9.4.13.8 In slabs with shear heads and in lift slab construction where it is not practical to pass to pass the bottom bars, required by bar detailing requirement of Chapter 6, at least two bonded bars or wires in each direction shall pass through the shear head or lifting collar as close to the column as practicable and be continuous or spliced with a Class A splice. At the exterior columns, the reinforcement shall be anchored the spear head or lifting collar.

9.4.14 Post-tensioned tendon anchorage zones

9.4.14.1 **Division into zones**

The anchorage zone shall be considered as composed of two zones as described below and shown in Fig. 9.4.14-1.

(a) The local zone is the rectangular prism (or equivalent rectangular prism for circular or oval anchorages) of concrete immediately surrounding the anchorage device and any confining reinforcement;

(b) The general zone is the anchorage zone beyond the local zone.

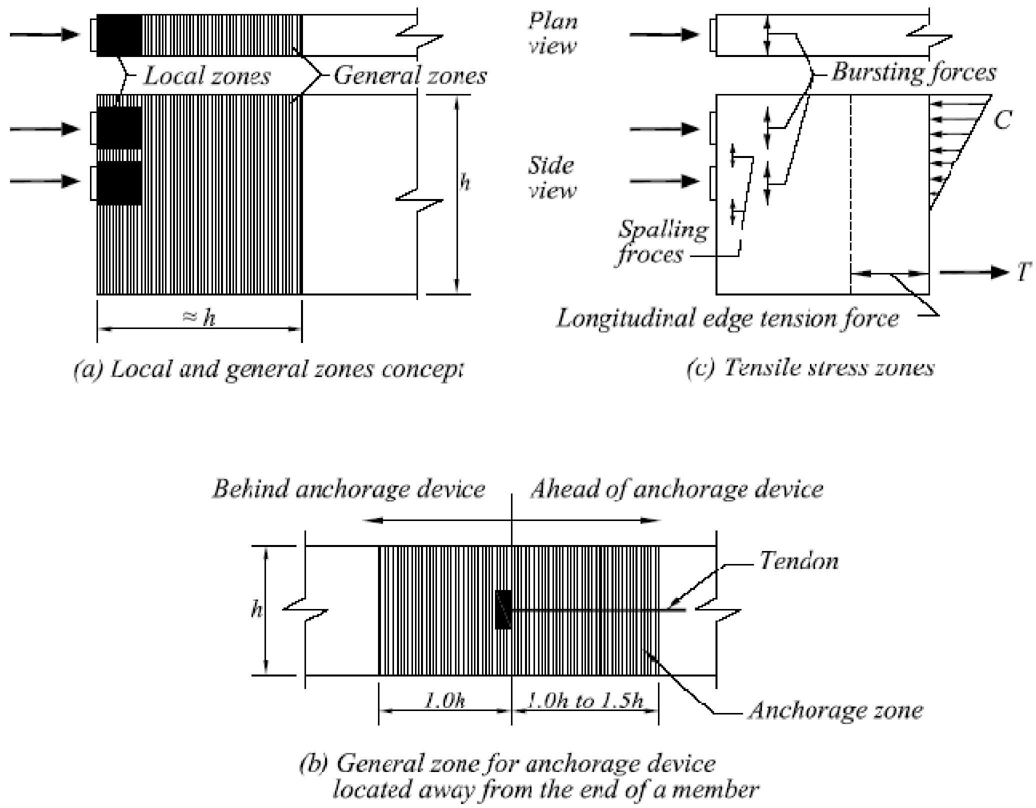

Fig.9.4.14-1 Anchorage zones

9.4.14.2 **Local zone**

(a) Design of local zones shall be based upon the factored prestressing force, Ppu, and the requirements of 9.4.14.2 b. and c. below.

(b) For post-tensioned anchorage zone design, a load factor of 1.2 shall be applied to the maximum steel jacking force.

(c) While design strength provided by a member, its connections to other members, and its cross sections in terms of flexure, axial load, shear and torsion, shall be taken as the nominal strength calculated in accordance with requirements and assumptions of this code, multiplied by the strength reduction factor, □, for post- tensioned anchorage zone this shall be taken as 0.85.

(d) Local-zone reinforcement shall be provided where required for proper functioning of the anchorage device.

9.4.14.3 **General zone**

(a) Design of general zones shall be based upon the factored prestressing force, P_{pu}, and the requirements of 9.4.14.3 b. and c.

(b) General-zone reinforcement shall be provided where required to resist bursting, spalling, and longitudinal edge tension forces induced by anchorage devices. Effects of abrupt change in section shall be considered.

(c) The general zone requirements of 9.4.14.3b. are satisfied by 9.4.3, 9.4.14.4, and 9.4.14.5 and whichever one of 9.4.15.2 or 9.4.15.3 or 9.4.16.3 is applicable.

9.4.14.4 **Design methods**

The following methods shall be permitted for the design of the general zones of the prestressed components provided that the specific procedures used result in prediction of strength in substantial agreement with results of comprehensive tests:

a. Equilibrium-based plasticity models (strut-and-tie models);

b. Linear stress analysis (including finite element analysis or equivalent); or

c. Simplified equations where applicable.

d. Simplified equations shall not be used where member cross sections are nonrectangular, where discontinuities in or near the general zone cause deviations in the force flow path, where minimum edge distance is less than 1-1/2 times the anchorage device lateral dimension in that direction, or where multiple anchorage devices are used in other than one closely spaced group.

e. The stressing sequence shall be considered in the design and specified on the design drawings.

f. Three-dimensional effects shall be considered in design and analyzed using three-dimensional procedures or approximated by considering the summation of effects for two orthogonal planes.

g. For anchorage devices located away from the end of the member, bonded reinforcement shall be provided to transfer at least $0.35A_{ps}f_{pu}$ into the concrete section behind the anchor. Such reinforcement shall be placed symmetrically around the anchorage devices and shall be fully developed both behind and ahead of the anchorage devices.

h. Where tendons are curved in the general zone, except for mono-strand tendons in slabs or where analysis shows reinforcement is not required, bonded reinforcement shall be provided to resist radial and splitting forces.

i. Except for mono-strand tendons in slabs or where analysis shows reinforcement is not required, minimum reinforcement with a nominal tensile strength equal to 2 percent of each factored prestressing force shall be provided in orthogonal directions parallel to the back face of all anchorage zones to limit spalling.

j. Tensile strength of concrete shall be neglected in calculations of reinforcement requirements.

9.4.14.5 **Detailing requirements**

Selection of reinforcement sizes, spacing, cover, and other details for anchorage zones shall make allowances for tolerances on the bending, fabrication, and placement of reinforcement, for the size of aggregate, and for adequate placement and consolidation of the concrete.

9.4.15 Design of anchorage zones for monostrand or single ϕ16 mm bar tendons

9.4.15.1 **Local zone design**

Monostrand or single φ16 mm or smaller diameter bar anchorage devices and local zone reinforcement shall meet the requirements of ACI 423.7 or the special anchorage device requirements of 9.4.16.2.

9.4.15.2 **General zone design for slab tendons**

(a) For anchorage devices of 12.7 mm or smaller diameter strands in normal weight concrete slabs, minimum reinforcement meeting the requirements of 9.4.15.2 b. and c. shall be provided unless a detailed analysis satisfying 9.4.14.4 shows such reinforcement is not required.

(b) Two horizontal bars at least No. 13 in size shall be provided parallel to the slab edge. They shall be permitted to be in contact with the front face of the anchorage device and shall be within a distance of h/2 ahead of each device. Those bars shall extend at least 150 mm either side of the outer edges of each device.

(c) If the center-to-center spacing of anchorage devices is 300 mm or less, the anchorage devices shall be considered as a group. For each group of six or more anchorage devices, n + 1 hairpin bars or closed stirrups at least No. 10 in size shall be provided, where n is the number of anchorage devices. One hairpin bar or stirrup shall be placed between each anchorage device and one on each side of the group. The hairpin bars or stirrups shall be placed with the legs extending into the slab perpendicular to the edge. The center portion of the hairpin bars or stirrups shall be placed perpendicular to the plane of the slab from 3h/8 to h/2 ahead of the anchorage devices.

(d) For anchorage devices not conforming to 9.4.15.1, minimum reinforcement shall be based upon a detailed analysis satisfying 9.4.14.4.

9.4.15.3 **General zone design for groups of monostrand tendons in beams and girders**

Design of general zones for groups of monostrand tendons in beams and girders shall meet the requirements of 9.4.13.3, 9.4.14.2 or 9.4.14.3 or 9.4.15.3.

9.4.16 Design of anchorage zones for multi-strand tendons

9.4.16.1 **Local and general zone design**

Basic multistrand anchorage devices and the related local and general zone reinforcement shall meet the requirements of AASHTO "LRFD Bridge Design Specifications (SI), 2007", Articles 5.10.9.6, Approximate Stress Analysis and Design, and 5.10.9.7, Design of Local Zones.

9.4.16.2 **Special anchorage devices**

(a) AASHTO "LRFD Bridge Design Specifications (SI), 2007", Articles 5.10.9.7.3, Special Anchorage Devices requires that special anchorage devices that do not satisfy the requirements specified in 9.4.16.1, they have been tested by an independent testing agency acceptable to the Engineer and have met the acceptance criteria specified in Articles 10.3.2 and 10.3.2.3.10 of AASHTO LRFD Bridge Construction Specifications.

(b) Where special anchorage devices are to be used, supplemental skin reinforcement shall be furnished in the corresponding regions of the anchorage zone, in addition to the confining reinforcement specified for the anchorage device. This supplemental reinforcement shall be similar in configuration and at least equivalent in volumetric ratio to any supplementary skin reinforcement used in the qualifying acceptance tests of the anchorage device.

9.4.17 Cold Drawn Low Carbon Wire Prestressed Concrete (CWPC)

CWPC (Cold drawn wire prestressed concrete) is termed as prestressed concrete technology of chinese pattern. This technology is a modification of conventional prestressed concrete. In the conventional prestressed concrete high strength wire is used as reinforcement while in Chinese pattern cold drawn low carbon mild steel wire is used as such this technology is named as cold drawn wire prestressed concrete. In short it is termed as CWPC. CWPC technology is a process whereby cold drawn low carbon steel wire has been adopted as reinforcement for pre-fabricated prestressed concrete members of medium and small size as produced by pre tensioning method. In the other hand large sizes structural members are produced by conventional prestressed concrete.

The main features and advantages of CWPC technology can be summarised as follows:

(a) **Availability (Availability of materials):** The raw material of cold drawn wire is made from low carbon mild steel which can be supplied by the local mills. The tensioning process of cold-drawn wire and production of pre-cast members are also simple and very easy to handle.

(b) **Simplicity (Simplicity of equipment and devices for production):** The cold process of low carbon mild steel and prefabrication process of members are done using simple equipments and devices. The precise and large sized equipments are not necessary. The production techniques of manufacturing members are rather simple.

(c) **Quality (Good in quality):** The members so manufactured have high crack resistance and stiffness. After pre-tensioning no crack would occur under the service load, thus the wires within the concrete members are well protected. In Contrast to conventional reinforced concrete members under the same service conditions, they have comparatively high durability to ensure long term quality.

(d) **Economy (Low cost):** The cold drawn low carbon steel wire used for prestressing is made of ordinary hot-rolled carbon steel coil rod. This is processed at room temperature through a special wire drawing die. The low carbon coil rods are manufactured by the steel mills; the wires are processed at the construction site or in a prefabrication plant; or are supplied by the cold drown wire plants as ready made products. By cold drawing the low carbon rod into wires the strength is enhanced about twice as much as that of the coil rod. This reduces the amount of steel required in prefabricating prestressed concrete members.

(e) Therefore, in comparison with conventional reinforced concrete reinforced with common carbon steel, a prestressed concrete member reinforced with cold drawn wire would have saving of steel consumption by 30-50%. Furthermore, since prestressed concrete members have high stiffness a reduction of cross section of members is possible. A considerable amount of concrete can also be saved and hence work including transportation, handling and erection can be reduced.

(f) **Light weightedness (Light in weight):** As already mentioned that the stiffness of prestressed concrete members may be enhanced, the dimension of it's cross-section can be reduced crosspondingly. These result not only reduction of concrete volume but also its dead weight which is estimated as 10-30%.

9.4.17.1 **Materials**

Basically the materials used in CWPC technology are steel and concrete.

(a) **Steel:** steel used for CWPC is obtained by cold drawing. Cold drawing as already mentioned is a process of reducing the diameter of the coil rod by forcing it to pass through a conical die. By this process, the steel can be strengthened by 100%.

(b) **Concrete:** The requirement of concrete in CWPC is same as that of ordinary reinforced concrete.

9.4.17.2 **Design**

Similar to other reinforced concrete structures, CWPC structures have a complete set of design specification and computational approaches by which various members of the CWPC can be designed. In the design of prestressed members the function of pre-stressing force and pre-stressing losses should be calculated. CWPC members should be checked for its strength, stability and cracking resistance respectively at different stages including service, manufacturing, erection and construction. In designing members conformity to local specifications should be considered.

Cold drawn low carbon wire conforming to ASTM A615 or equivalent may be permitted for prestressing provided the mechanical requirements shown in Table 9.4.5 are satisfied.

Table 9.4.5 Tensile Strength and Elongation of Cold Drawn Wire

Diameter of wire (mm)	Minimum tensile strength (N/mm^2)	Minimum elongation (per cent)
3	650	2.0
4	600	2.5
5	550	3.0

9.4.18 External post-tensioning

9.4.18.1 Post-tensioning tendons shall be permitted to be external to any concrete section of a member. The strength and serviceability design methods of this Code shall be used in evaluating the effects of external tendon forces on the concrete structure.

9.4.18.2 External tendons shall be considered as unbonded tendons when computing flexural strength unless provisions are made to effectively bond the external tendons to the concrete section along its entire length.

9.4.18.3 External tendons shall be attached to the concrete member in a manner that maintains the desired eccentricity between the tendons and the concrete centroid throughout the full range of anticipated member deflection.

9.4.18.4 External tendons and tendon anchorage regions shall be protected against corrosion, and the details of the protection method shall be indicated on the drawings or in the project specifications.

9.4.19 Performance requirement of prestressed concrete design

9.4.19.1 Classification of performance requirement

After the outline of the member dimensions are determined and the most suitable kind and type of prestressing options are selected at the structural planning stage, the prestressed concrete noncomposite and composite structures and members shall satisfy all of the required performances such as safety, serviceability, restorability, durability, reparability, societal and environmental compatibility, etc. at every stage of design, construction and maintenance throughout the design life of the structure.

Table 9.4.8 gives the performance requirement of prestressed concrete structures and components and related performance items.

9.4.19.2 Performance verification method

(a) Performance verification shall be based on the partial factor method on the basis of reliability theory and as a standard design procedure, it shall be based on the limit state method.

(b) In general verification shall be based on design responses to design actions, design limits as determined by design material strengths, and individual partial factors. The performance of the structure shall, in general, be verified using Equations 9.4.19-1 and 9.4.19-2:

Table 9.4.8 Classification of performance requirement for prestressed concrete structures

Performance requirements	Performance item	**Examples of check items**	**Example of verification index**
Safety	Structural safety	Resistance of whole structure, components, stability, deformation performance	Stress resultant, stress
	Public safety	Injury to users and third parties	-
Serviceability	Live load operating performance	Soundness and rigidity of structures/members under usual conditions	Floor flatness, deformation of main girder
	User comfort	User-comfort under walking-induced vibrations	Natural frequency of main girders
Restorability	Restorability after earthquake, cyclone, tidal bore, fire, etc.	Level of damage (ease of restoration)	Response value (damage level)/ limit value of performance (damage level)
Durability	Fatigue resistance	Fatigue durability against variable actions	Equivalent stress range/allowable stress range
	Corrosion resistance	Rust prevention and corrosion protection performance of steel material	Corrosion environment and surface finish, paint specification
	Resistance to material deterioration	Concrete deterioration	Water- cement ratio, cover of concrete
	Maintainability	Ease of maintenance (inspection, ease of repair, etc.) and ease of restoration	-
Social and	Social compatibilty	Appropriateness of partial factor	Partial factor, structural factor,

Performance requirements	Performance item	**Examples of check items**	**Example of verification index**
environmental compatibility		(consideration of social importance of structure)	etc.
	Economic rationality	Social utility during life cycle of structure	Life cycle cost (LCC), life cycle utility (LTU)
	Environmental compatibility	Noise, vibration, environmental impact, aesthetics, etc.	Noise and vibration levels for surrounding residents, aesthetic reaction to structural shape and color, monumental aspect, etc.
Constructability / workability	Safety during construction	Safety during construction	Stress resultant, stress, deformation
	Initial soundness	Material quality, welding quality, etc.	Material properties, workmanship
	Ease of construction	Ease of fabrication and construction work	User-friendly construction methodology conceived at design stage

$$\gamma_i \frac{S_d}{R_d} \leq 1.0 \qquad (9.14.19\text{-}1)$$

$$\gamma_i \frac{\sum \gamma_a . S(\gamma_f . F_k)}{R(f_k / \gamma_m)} \leq 1.0 \qquad (9.14.19\text{-}2)$$

where, R_d : design resistance

f_k : characteristic value of material strength

γ_m : material factor

γ_b : structural member factor

R(…) : function for calculating limit value of structure from material strength

S_d : design response

F_k : individual characteristic value of action

γ_a : structural analysis factor

γ_f : action factor corresponding to each action (load factor)

S(…) : function for calculating response value of structure from action

γ_i : structural factor

(a) During design, a verification shall be carried out for every limit state that can be considered.

(b) The flow chart explaining the concept of verification of safety is given in Fig.9.4.19.

Design resistance R

Characteristic value of material strength: f_k

γ_m ↓

Design value of material strength: $f_d = f_k / \gamma_m$

↓

Design action effect

Characteristic value of action: F_k

↓ γ_f

Design value of action: $F_d = \gamma_f F_k$

↓

Resistance: $R(f_d)$ Action effect: $S(F_d)$

γ_b γ_a

Design resistance: $R_d = R(f_d)/\gamma_b$ Design action effect: $S_d = \square\ \gamma_a S(F_d)$

γ_i

Verification: $\gamma_i \dfrac{Sd}{Rd} \leq 1.0$

9.4.19.3 Partial factors

(a) Partial factors shall be determined on the concept given i. and ii. below.

i) The material factor, structural member factor, structural analysis factor, and action factor shall be determined in consideration of (i) unfavorabledeviations from characteristic values, (ii) uncertainties in computational accuracy, and (iii) discrepancies between design and practice with respect to actions or structures and materials.

Table 9.4.9 shows the standard values of partial factors.

ii) The structural factor γ_i shall be determined according to structural importance and also the social and economical impact of the structure reaching its limit state.

Table 9.4.10 shows the standard values of structural factor γ_i for different performance items.

Table 9.4.9 Standard values of partial factors

Performance item	**Action factor γ_f**	**Structural analysis factor γ_a**	**Material factor γ_m**	**Structural member Factor γ_b**
Structural safety	1.0 ~ 1.6	1.0 ~ 1.1	1.0 ~ 1.05	1.0 ~ 1.3
Serviceability (user comfort)	1.0	1.0	1.0 ~ 1.05	1.0
Durability (fatigue resistance)	1.0 ~ 1.1	1.0	1.0	1.0 ~ 1.1

Table 9.4.10 Standard values of structural factors

Performance item	**Structural factor γ_i**
Structural safety	1.0 ~ 1.2
Serviceability (User comfort)	1.0
Durability (fatigue resistance)	1.0

Part B-Material and Construction

9.5 Material and Construction

9.5.1 Materials

9.5.1.1 Concrete ingredients and applicable ASTM standards

Table 9.5.1 shows the list of commonly applicable standards for cement, coarse and fine aggregates, admixtures and mixing water.

Table 9.5.1 Cement, coarse and fine aggregates, admixtures, water and applicable standards

Material	Designation of the Standard	Title of the Standard
Concrete	ASTM C39	Compression testing of cylindrical concrete specimens
Cement	BDS EN 197-1, issued April 2003	Part 1: Composition, specifications and conformity criteria for common cements
Fine & coarse aggregates	ASTM C136-06	Standard test method for sieve analysis of fine and coarse aggregates
	ASTM C40-04	Standard test method for organic impurities in fine aggregates for concrete
		Clay lumps and friable particles
	ASTM C142	Specific gravity and absorption of coarse aggregate
	ASTM C127	Specific gravity and absorption of fine aggregate
	ASTM C128	Degradation of small-size coarse aggregate by L.A. abrasion test
	ASTM C131	Unit weights and voids in aggregates
	ASTM C29	Surface moisture in fine aggregate Soundness of aggregates by use of sodium sulfate or magnesium sulfate
	ASTM C70	Soundness of aggregates by use of sodium sulfate or magnesium sulfate
		Alkali reactivity, potential of cement aggregate combinations
		Potential alkali reactivity of aggregates (Mortar-bar method)
	ASTM C88	Sand equivalent value of soils and fine aggregate
	ASTM C227	
	ASTM C1260	
	ASTM D2419	
Admixtures	ASTM C494	Type A – Water reducing
		Type B – Retarding
		Type C – Accelerating
		Type D – Water reducing and retarding
		Type E – Water reducing and accelerating
		Type F – Water reducing, high range
		Type G – Water reducing, high range and retarding
		Type S – Specific performance admixture

Material	Designation of the Standard	Title of the Standard
Mixing Water	ASTM C 1602/ C1602M-06	Standard specification for mixing water used in the production of hydraulic cement concrete T

9.5.1.2 **Reinforcing steel and applicable standards**

Table 9.5.2 shows the types of reinforcing steel with the ASTM and BDS Designation standard specifications.

Table 9.5.2 List of Standards for the reinforcing steel

Material	Designation of the Standard	Title of the Standard
Reinforcing Steel	ASTM A615/ A615M-04a	Standard specifications for deformed and plain carbon steel bars for concrete reinforcement
	ASTM A706/ A706M-04a	Standard specifications for low-alloy steel deformed and plain carbon steel bars for concrete reinforcement
	BDS ISO 6935-2: 2009/ ISO 6935-2: 2007	Bangladesh standard, Steel for the reinforcement of concrete, Part 2: Ribbed bars (1st revision)

9.5.1.3 **Prestressing steel and applicable ASTM standards**

Table 9.5.3 shows the types of high tensile prestressing steel and cold drawn wires used for prestressing, with the ASTM Designation standard specifications.

Table 9.5.3 List of Standards for the pretressing steel

Material	Designation of the Standard	Title of the Standard
Prestressing Steel	ASTM A416-416M-02	Standard specification for steel, wire, hard drawn for prestressing concrete pipe
	ASTM A648-04a	Standard specification for uncoated high strength steel bars for prestressing concrete

9.5.2 Construction of prestressed concrete structures

9.5.2.1 Post-tensioning ducts

9.5.2.1.1 Corrosion protection for unbonded tendons

(a) Unbonded prestressing steel shall be encased with sheathing. The prestressing steel shall be completely coated and the sheathing around the prestressing steel filled with suitable material to inhibit corrosion.

(b) Sheathing shall be watertight and continuous over entire length to be unbonded.

(c) For applications in corrosive environments, the sheathing shall be connected to all stressing, inter- mediate and fixed anchorages in a watertight fashion.

(d) Unbonded single-strand tendons shall be protected against corrosion in accordance with ACI 423.7.

9.5.2.2 **Post-tensioning ducts**

(a) Ducts for grouted tendons shall be mortar- tight and nonreactive with concrete, prestressing steel, grout, and corrosion inhibitor.

(b) Ducts for grouted single-wire, single-strand, or single-bar tendons shall have an inside diameter at least 6 mm larger than the prestressing steel diameter.

(c) Ducts for grouted multiple wire, multiple strand, or multiple bar tendons shall have an inside cross-sectional area at least two times the cross-sectional area of the prestressing steel.

(d) Ducts shall be maintained free of ponded water if members to be grouted are exposed to temperatures below freezing prior to grouting.

9.5.2.3 **Grout for bonded tendons**

9.5.2.3.1 Materials for grouts

(a) Grout shall consist of Portland cement and water; or Portland cement, sand, and water.

(b) Materials for grout shall conform to 9.5.2.2.1c., d., e. and f. below.

(c) Portland cement shall conform to 9.5.1.1.

(d) Water shall conform to 9.5.1.1.

(e) Sand, if used, shall conform to 9.5.1.1 except that gradation shall be permitted to be modified as necessary to obtain satisfactory workability.

(f) Admixtures conforming to 9.5.1.1 and known to have no injurious effects on grout, steel, or concrete shall be permitted. Calcium chloride shall not be used.

9.5.2.3.2 Selection of grout proportions

Proportions of materials for grout shall be based on either a. or b. below.

(a) Results of tests on fresh and hardened grout prior to beginning grouting operations; or

(b) Prior documented experience with similar materials and equipment and under comparable field conditions.

(c) Cement used in the Work shall correspond to that on which selection of grout proportions was based.

(d) Water content shall be minimum necessary for proper pumping of grout; however, water-cement ratio shall not exceed 0.45 by weight.

(e) Water shall not be added to increase grout flowability that has been decreased by delayed use of the grout.

9.5.2.3.3 Mixing and pumping of grout

(a) Grout shall be mixed in equipment capable of continuous mechanical mixing and agitation that will produce uniform distribution of materials, passed through screens, and pumped in a manner that will completely fill the ducts.

(b) Temperature of members at time of grouting shall be above 2°C and shall be maintained above 2°C until field-cured 50 mm cubes of grout reach a minimum compressive strength of 5.5 N/mm^2.

(c) Grout temperatures shall not be above 32°C during mixing and pumping.

9.5.2.4 **Protection for prestressing steel during welding**

Burning or welding operations in the vicinity of prestressing steel shall be performed so that prestressing steel is not subject to excessive temperatures, welding sparks, or ground currents.

9.5.2.5 **Application and measurement of prestressing force**

9.5.2.5.1 Prestressing force shall be determined by both of (a) and (b):

(a) Measurement of steel elongation. Required elongation shall be determined from average load-elongation curves for the prestressing steel used;

(b) Observation of jacking force on a calibrated gage or load cell or by use of a calibrated dynamometer.

9.5.2.5.2 Cause of any difference in force determination between 9.5.2.4.1 (a) and (b) that exceeds 5 percent for pretensioned elements or 7 percent for post-tensioned construction shall be ascertained and corrected.

9.5.2.5.3 Where the transfer of force from the bulk- heads of pretensioning bed to the concrete is accomplished by flame cutting prestressing steel, cutting points and cutting sequence shall be predetermined to avoid undesired temporary stresses.

9.5.2.5.4 Long lengths of exposed pretensioned strand shall be cut near the member to minimize shock to concrete.

9.5.2.5.5 Total loss of prestress due to unreplaced broken prestressing steel shall not exceed 2 percent of total prestress.

9.5.2.6 **Post-tensioning anchorages and couplers**

9.5.2.6.1 Anchorages and couplers for bonded and unbonded tendons shall develop at least 95 percent of the f_{pu} when tested in an unbonded condition, without exceeding anticipated set. For bonded tendons, anchorages and couplers shall be located so that 100 percent of f_{pu} shall be developed at critical sections after the prestressing steel is bonded in the member.

9.5.2.6.2 Couplers shall be placed in areas approved by the licensed design professional and enclosed in housing long enough to permit necessary movements.

9.5.2.6.3 In unbonded construction subject to repetitive loads, attention shall be given to the possibility of fatigue in anchorages and couplers.

9.5.2.6.4 Anchorages, couplers, and end fittings shall be permanently protected against corrosion.

9.5.3 Performance requirement of material

9.5.3.1 **Performance requirement of material**

(a) The fundamental performance requirement of materials forming the structure is that they should be able to resist actions such as the various loadings to which the structure is exposed.

(b) Materials forming the structure should not reach unexpected limit states as a result of deterioration phenomena during the working life of the structure.

(c) Materials-related energy consumption and CO_2 discharges should be minimized, while recyclability should be high.

(d) Any materials that escape into the surrounding environment during construction and service should not have a strong impact on human beings, animals and plants.

Commentary:

Corresponding to design requirements, the materials should be evaluated to ensure that their properties are suitable with respect to strength (tensile, compressive and shear), deformation (e.g. elastic modulus), heat resistance and water tightness.

The characteristic values obtained from the tests, complying appropriate BDS, ASTM, BS, or equivalent standards, on such specimens should be converted to suit the design calculation models using appropriate conversion factors or functions.

The characteristic value of material strength f_k is calculated from test results using Eq. 9.5.3-1.

$$f_k = f_m - k\sigma \qquad (9.5.3\text{-}1)$$

where f_m : mean of test values, σ : standard deviation of test values, and k: coefficient of variance. The coefficient k is determined from the probability of obtaining a test value less than the characteristic value and the probability distribution of test results. The 5% fractile value is often taken as the characteristic value. In this case, the value of k is 1.64 if the normal distribution is assumed for the test values.

At the structural design stage, verification shall be performed so that response value is less than or equal to the limit value of performance throughout both construction period and working life. At the end of construction stage, just completed structure shall fulfill the all required performances considered in its design.

Part C-Maintenance

9.6 Maintenance

9.6.1 General

If the prestressed concrete structure is designed and constructed in accordance with the appropriate concepts described in Part I and II of this Chapter, based on which the durability is checked by verifying the performance requirements of the concrete and its constituent materials, it is not likely that structural deterioration would become so significant as to degrade the performance of the structure. On the other hand it is not easy to estimate the performance degradation process of the structure during its service life accurately. Also, it is difficult to completely avoid construction defects at all construction stages. Therefore, the new structure should be appropriately maintained by routine and regular inspections, based on an adequate maintenance plan formulated at the design stage.

For existing structures, deterioration may be evident in some cases, with the performance having been degraded. The defects of such structures should be accurately assessed and identified as initial defects, damage, or deteriorations. Major causes for such defects should be identified subsequently so that appropriate remedial actions can be selected. The initial defects and damage should be treated promptly and appropriately including emergency treatments. When the deterioration that would degrade the performance is evident, the deterioration mechanisms should be identified and appropriate maintenance, carried out based on the results of deterioration prediction and performance degradation evaluation.

9.6.2 Classification of Maintenance Action

Maintenance actions shall be classified into different categories depending on such factors as the importance of the structure, design life, impact on a third party, environmental conditions, ease of maintenance, and cost.

In the view of the above, four categories are recommended for the classifications of the maintenance actions:

Category A – Preventive maintenance

Maintenance to prevent deterioration which would otherwise lead to unsatisfactory structural performance.

Category A structures are those

- for which remedial actions are difficult to take after deterioration becomes apparent;
- of which deterioration must not be apparent;
- having a long design life.

Structures in this category generally have a high degree of importance which in many cases require monitoring.

Category B – Corrective maintenance

Maintenance to restore the performance level and/or to reduce the rate of deterioration so as to maintain satisfactory structural performance.

Category B structures are those for which

- remedial measures can be taken after deterioration becomes apparent;
- apparent deterioration causes no appreciable inconvenience.

Category C – Observational maintenance

Maintenance in which visual inspection is necessary without any remedial action regardless of the deterioration level.

Category C structures are those

- for use as long as they are usable;
- for which ensuring safety from threats posed to third parties is the only requirement.

Category D – Indirect maintenance

Maintenance in which no direct inspection is necessary or possible.

Category D structures are those for which direct inspection is extremely difficult. For these reasons, non-inspection maintenance after the initial inspection is carried out not as routine or regular inspection, but as extraordinary inspection following natural disasters, accidents, etc.

9.6.3 Maintenance Record

Records, drawings and related documents prepared during the time of planning, design and construction shall be referred to and made use of while developing an appropriate methodology for maintenance covering inspection and repairs.

Commentary:

A thorough study of the planning, design and construction related documents often provide insights into the inherent weaknesses of the structure which in turn often serve as pointers for further detailed inspection and/or repairs.

Furthermore, a clear record should be kept of the difficulties encountered, remedial actions taken and any deviation from the design drawings. These record also serve as a valuable reference in the design and construction of similar structures and their subsequent inspections.

9.6.4 Inspection

9.6.4.1 General

On the basis of the methods used in the frequency and timing, inspection shall be classified as initial inspection, routine inspection, regular inspection, detailed inspection, extraordinary inspection, and monitoring.

9.6.4.2 Initial inspection

Initial inspection is intended to examine whether the structure is adequately constructed. It also allows the collection of basic data for initiating a maintenance program. Initial inspection shall also be carried out just after the completion of remedial actions.

Initial inspection should cover the external appearance of the structure, variation of concrete quality, existence of construction defects, construction errors on reinforcing and pretsressing bar arrangement, and so on.

9.6.4.3 Routine inspections

It shall be carried out on a routine basis at certain intervals without making any specific effort to identify signs of deterioration, if any, and the time of their first appearance. The exact tools to be used and the frequency of such inspections may be decided on the basis of such factors as the likely mechanisms of such deterioration, environmental conditions, importance of the structure, and the maintenance action classification.

A routine inspection should cover the external appearance of the structure including cracks, spalling, delamination, color changes, rust stain from reinforcement, and isolation of free lime from concrete.

9.6.4.4 Regular inspection

It shall be carried out at regular intervals using appropriate tools to identify signs of deterioration and the time of their first appearance. Efforts shall be made during a regular inspection to observe the structure closely to obtain details which will be difficult to gather during a routine inspection.

Visual inspection and/or hammering inspection are carried out mainly to obtain more details on the items inspected in a routine inspection. In addition, inspections by using appropriate non-destructive tests or taking concrete cores etc. can be effectively combined with the visual inspection.

9.6.4.5 Detailed inspection

Detailed inspection shall be done when

(a) some signs of deterioration or a change in the performance level are observed during a routine and/or regular inspection;

(b) it is difficult to obtain reliable and accurate information during a routine and/or regular inspection;

(c) it is found that the structural integrity of the structure has been adversely affected by the extent of the deterioration;

(d) more detailed information is required before deciding on the necessity and scope for undertaking a major repair, rehabilitation or strengthening work.

9.6.4.6 Extraordinary inspection

It shall be carried out after a structure has been subjected to an accidental load to assess the extent of the damage and the need for remedial actions. Such accidental loads may include those caused by an earthquake, storm, flood, fire, explosion, etc.

9.6.5 Monitoring

The deterioration and/or performance of the concerned structure as determined in 9.6.2, shall be monitored, through continuous recording of the appropriate data, together with routine and regular inspections, so that the appropriate remedial actions can be taken before the deterioration becomes detrimental to the appearance and other performance of the structure.

9.6.6 Deterioration Mechanism and Prediction

9.6.6.1 General

The prevailing state of the concerned structure shall be evaluated as properly as possible according to the inspection results, design and construction records, environmental conditions, and any other relevant information. Then when any deterioration is found, the possible causes of the deterioration and the corresponding mechanism can be appropriately estimated.

9.6.6.2 Identification of deterioration mechanisms

Deterioration of a structure is caused by the environmental actions and loading conditions. Environment-oriented deterioration includes carbonation-induced deterioration, chloride-induced deterioration, chemical attack, alkali-aggregate reaction, etc. On the other hand external force-oriented deterioration includes fatigue, excessive loading, and differential settlement of the support.

9.6.6.3 Deterioration factors

Deterioration factors may be classified into those

(a) external to structures such as temperature, humidity and any other environmental characteristics; and

(b) internal to the structure such as design parameters and quality control during construction.

Commentary:

Design factors include the geometry of the members/ segments, crack width specifications, concrete cover to reinforcing bar and pretressing steel/ducts, and design strength. Construction factors include material selection, mix proportions, transportation, placement, and curing methods.

9.6.6.4 Determination of deterioration levels and rates

The level of deterioration and/or performance shall be determined based on the results of inspections and simulations using appropriate models for the mechanisms of deterioration.

The following features appearing on the surface of the structure may be used for evaluating the degree of deterioration and the level of performance:

(a) crack pattern, length and width;

(b) the extent of delamination, peeling and spalling of concrete cover, and scaling and degradation areas;

(c) abnormal hammer tapping sound and the extent of abnormality;

(d) presence and degree of exudation of rust and efflorescence and water leakage.

9.6.7 Evaluation and Decision Making

9.6.7.1 General

In general, the deterioration and performance degradation of a structure progress monotonically. The decision, therefore, should be made based on the evaluation outcome of the performance of the structure at the time of inspection and at the end of its design life.

9.6.7.2 Threshold level

The threshold level of the structure's degraded performance shall be specified in accordance with the requirements of safety, functionality, appearance, societal friendliness and such other factors, taking into consideration the type, importance and maintenance level of the structure and the environmental conditions.

9.6.7.3 Evaluation of inspection results

The results from routine and regular inspections shall be evaluated and a decision shall be made whether a detailed inspection is required or otherwise.

The results from the detailed and/or extraordinary inspections shall be evaluated and a decision shall be made whether a remedial action is required or otherwise.

Immediate remedial actions shall be taken in cases where deterioration, damage and/or initial defects are found to be hazardous to third parties.

9.6.8 Remedial Action

9.6.8.1 General

A remedial action on a deteriorated structure shall be taken on the basis of the inspection results, importance of the structure, maintenance classification, and the threshold level of deterioration and/or performance.

Commentary:

Repair and strengthening are the main techniques of remedial actions of which details are described in 9.6.8.3 and 9.6.8.4 respectively. The following measures are also included in the remedial actions.

Intensified inspection: inspection may be carried out by suitably increasing one or more of the following: frequency of inspection, number of inspection items, and the locations for inspection.

Usage restriction: suitable restriction shall be imposed on the maximum live load that the structure may carry, depending on the level of deterioration observed.

Functional improvement or restoration: this may include an appearance improvement that beautifies a structure with suitably painting or placing additional concrete, and so on.

Dismantling and removal: in a case when the deterioration of a structure is too severe for its structural performance to be sufficiently restored, and dismantling or the removal is one of the choices as the remedial measures.

Special care for emergency: when a deteriorated structure poses an immediate threat to the environment, its users, or third parties, suitable emergency action shall be taken immediately.

9.6.8.2 Selection of remedial action

Selection of methods and materials suitable for the relevant deterioration mechanism and degree of performance degradation is particularly important for measures for which wide varieties of methods and materials are available. Care should be taken as the method of restoring the performance may vary depending on the deterioration mechanism, ven if the level of performance is the same.

9.6.8.3 Repair

9.6.8.3.1 General

Repair of a structure refers to the remedial action taken to prevent or slow down its further deterioration and reduce the possibility of damage to its users or third parties.

Types of repair include (i) repair of defects such as cracking and peeling; (ii) removal of concrete damaged by deterioration due to carbonation and such like; (iii) surface coating to prevent re-intrusion of hazardous substances.

9.6.8.3.2 Preparation and execution

A complete plan for the repair work including methods of repair, materials to be used, and tests to ensure the quality of work, shall be developed before the repair work commences.

Repair works shall be carried out with minimum disturbances to the surrounding environment. Necessary tests to ensure the quality of the repair work shall be carried out. Detailed record of the repair work shall be maintained for future reference.

9.6.8.3.3 Methods and materials

Some current repair methods and associated materials are

- crack repair by injecting epoxy;
- section repair including patching using polymer cement mortar;
- surface protection by resin or mortar;
- cathodic protection;
- re-alkalization;
- desalination wherever required.

Commentary:

Development of a repair plan comprises the selection of a repair method suitable for the deterioration mechanism, establishment of the required repair level, and decisions on the repair policy, specifications for the repair materials, sectional dimensions after repair, and execution methods.

9.6.8.4 **Strengthening**

9.6.8.4.1 General

Strengthening of a structure refers to the remedial action taken to restore or improve its structural properties including load carrying capacity and stiffness, to a level which is equal to or higher than that of the original design.

Commentary:

Strengthening methods include (i) replacement of members; (ii) an increase in the cross-sectional area of concrete; (iii) addition of members; (iv) an increase of the support points; (v) addition of strengthening members; (vi) external prestressing, etc.

9.6.8.4.2 Preparation and execution

Strengthening of a structure shall be preceded by a thorough investigation of its deterioration considering such factors as the remaining design life, deterioration mechanism, possible causes and extent of deterioration, the remaining and desired load-carrying capacity or stiffness, importance of the structure, maintenance classification, and any remedial actions taken previously.

A complete plan for the strengthening work including design calculations, methods of strengthening, materials to be used, and tests to ensure quality of the work, shall be developed before work commences.

Strengthening work shall be carried out with minimum disturbance to the surrounding environment and the service condition of the structure.

9.6.8.4.3 Methods and materials

Some current methods and associated materials for strengthening are

- external bonding viz plate or sheet bonding and over or under-laying using steel or carbon sheets;

- external prestressing using additional tension cables;
- addition of girders, braces and/or supports;
- replacement of members;
- seismic isolation.

Commentary:

When selecting a strengthening method, it is necessary to consider effects of strengthening, constructability, cost-effectiveness, and impact on the community/environment during execution. It is also important to consider the ease of maintenance after strengthening and any influence on the landscape.

9.6.8.5 **Record**

9.6.8.5.1 General

Records shall be kept and preserved for future reference. Such records shall include details concerning the design, inspection and evaluation procedures, plans and execution of any repair and/or strengthening work undertaken, and other such information.

9.6.8.5.2 Preservation

The maintenance records of a structure shall be preserved while the structure remains in service. It is also desirable that such records be preserved for an indefinite period as a useful reference for the construction and maintenance of other similar structures.

Commentary:

It is important to devise a format that makes it easy to understand the history of a structure by simply referring to records. The records should be made accessible at all times.

9.6.8.5.3 Method and item of recording

Records shall be kept in an easy-to-understand format.

The items to be recorded shall include references to concerned agencies, drawings, immediate and nearby environment, classification of structure, results of deterioration rate estimation, results of any inspections carried out, evaluation of the structure, and details of the plan and actual execution of remedial and other actions.