CHAPTER 11: PRESTRESSED CONCRETE

11.1 GENERAL

(1) This chapter gives general guidelines required for the design of prestressed concrete structures or members with CFRM tendons or CFRM tendons in conjunction with steel tendons.

(2) Prestress levels shall be determined to ensure that the structure or member can fulfill its purpose safely and economically and give the desired performance.

[COMMENTS]:

Prestressed concrete structures make possible improvement of the crack characteristics at the serviceability limit state as well as reduction of the cross sectional area of a member, thus offering an extended range of options for many types of structure.

Design calculations of prestress force in concrete members are generally handled by regarding prestress forces in the serviceability limit state as loads, considering only the statically indeterminate forces in loads when the effects of prestress forces are included in calculation of cross-sectional bearing capacity at ultimate limit state. In this case, the ultimate strain of CFRM has to be checked.

Where member forces are calculated other than by linear analysis, prestress forces must be handled in the appropriate manner for the analysis method used.

(1) The provisions of this chapter shall be applied to general prestressed concrete structures or members with CFRM tendons or CFRM tendons in conjunction with steel tendons. These provisions shall not be applied to the following types of structures or members:

[1] Structures or members where the prestress force is transferred by a method other than prestressing tendons; for example methods to use a jack to give prestress to arch members or concrete pavement, methods using expanding agent to introduce prestressing, or methods whereby concrete is cast on the tension side of a steel girder to which flexural moment has previously been applied, subsequently releasing the moment to induce prestressing after the concrete has hardened.

[2] Prestressed steel reinforced concrete structures or members; prestressed composite structures or members consisting of steel and concrete.

[3] Prestressed concrete members or structures constantly exposed to abnormal temperatures, where "normal temperature" is taken to signify a temperature within the range 0°C~40°C.

[4] Factory products such as prestressed concrete piles, prestressed concrete pipes, etc.

For structures or members having unbonded prestressing tendons ("unbonded CFRM") and structures or members wherein which CFRM is used as external cables, considerations other than those given here must be allowed for; these will include the increase in flexural cracking widths due to the lack of bond with the concrete members, the reduction of flexural capacity, the minimum reinforcement quantity, fatigue resistance of the anchoring devices etc. In structures with external cables which are exposed to a fire risk, fireproofing measures will be required.

(2) Prestressing may generally be determined for limit states at the tensile edge, according to the function of the structure (cf. 11.2)

11.2 CATEGORIZATION OF PRESTRESSED CONCRETE

It shall be in accordance with JSCE Standard Specification (Design), 10.2.

11.3 PRESTRESS FORCE

(1) Prestress force shall be calculated according to Eq. (11.3.1).

$$P(x) = P_i - \left[\Delta P_i(x) + \Delta P_t(x)\right] + \Delta P_T(x) \qquad (11.3.1)$$

where

$P(x)$ = prestress force in design section under consideration

P_i = prestress force during prestressing due to tension applied to tendon ends

$\Delta P_i(x)$ = loss of prestressing force during and immediately after prestressing, to be calculated allowing for the following effects:

[1] elastic deformation of concrete
[2] friction between tendon and duct
[3] set loss on anchoring of tendon
[4] other considerations

$\Delta P_t(x)$ = time-dependent loss of prestressing force, to be calculated allowing for the following effects:

[5] relaxation of tendon
[6] creep of concrete
[7] shrinkage of concrete

$\Delta P_T(x)$ = variation of prestress force due to temperature change

(2) In calculating the indeterminate forces at the serviceability limit state or the fatigue limit state, the prestress force given by Eq. (11.2.1) may be considered to be the characteristic value for the prestress forces.

[COMMENTS]:

(1) The effects to be considered in calculating prestress losses $\Delta P_i(x)$ and $\Delta P_t(x)$ in relation to calculation of prestress force.

[1] Effects of elastic deformation of concrete: Prestress loss due to elastic deformation of concrete shall always be considered when the pretensioning system is used (c.f. Eq. (C 11.3.1)). When post-tensioning tendons are tensioned consecutively, the prestress loss due to elastic deformation of concrete shall be calculated. In such cases, the average prestress loss may be calculated in accordance with Eq. (C 11.3.2).

(pretensioning) $\Delta\sigma_p = n\sigma'_{cpg}$ (C 11.3.1) (post-tensioning) $\Delta\sigma_p = \frac{1}{2} n\sigma'_{cpg} \frac{N-1}{N}$ (C 11.3.2)

where

$\Delta\sigma_p$ = prestress loss in tendon
n = Young's modulus ratio E_p/E_c
σ'_{cpg} = compressive stress of concrete at tendon centroid due to tensioning
N = number of tendon tensionings (i.e. number of tendon groups)
E_c = Young's modulus of concrete
E_p = Young's modulus of tendons; for CFRM $E_p = E_f$

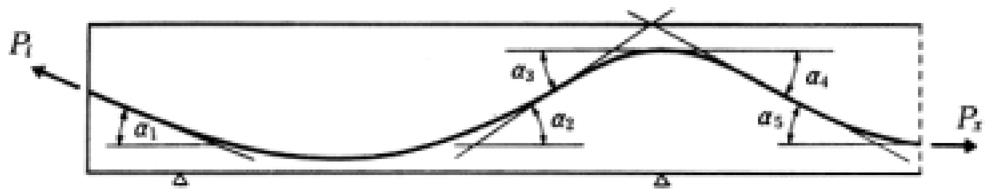
[2] Effects of friction between tendon and duct: prestress loss in prestressing tendons due to friction depends on the condition of the inner surface of the duct, the type of prestressing tendon, and the positioning of tendons.

Loss of prestressing tendon force due to friction can generally be divided into two terms, one related to the angular change of the centroid line of the prestressing tendons, and the other related to the length of the prestressing tendons. The tensile force in the prestressing tendon at the design section may be expressed by Eq. (C 11.3.3).

$P_x = P_i e^{-(\mu\alpha+\lambda x)}$ (C 11.3.3)

where

P_x = tensile force of tendon at design section
P_i = tensile force at position of prestressing jack
μ = coefficient of friction per radian of angular change
α = angular change (radians) (c.f. **Fig. C 11.3.1**)
λ = coefficient of friction per unit length of tendon
x = distance from tensioned edge of tendon to design section



$$\alpha = \sum_1^n \alpha_i = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \cdots\cdots\cdots \alpha_n$$

Fig. C 11.3.1: Angular change of tendon centroid line

The values of μ and λ will vary depending on the tendon and sheath material, and must therefore be determined by testing, but where sheaths are used with CFRM, the tensile force in the tendon may generally be calculated with μ = 0.3, λ = 0.004.

[3] Effects of set loss on anchoring of tendon: Where there is set loss during anchoring of tendons, the resultant prestress loss must be allowed for. Set loss is especially significant with wedge-type anchorage systems, therefore the prestress loss and the length affected by it must be examined prior to tensioning by applying the assumed set loss based on available data. "Set loss" refers to the pulling of a tendon into

the anchoring device during anchoring. The amount of set loss varies depending on the type of anchoring device, and must therefore be studied separately for each type.

Where there is no friction between the prestressing tendons and the duct, loss of prestressing force due to set loss is calculated according to Eq. (C 11.3.4).

$$\Delta P = \frac{\Delta l}{l} \times A_p E_p \qquad \text{(C 11.3.4)}$$

where

ΔP = loss of prestressing force due to set loss
Δl = set loss
l = length of tendon
A_p = cross-sectional area of tendon

Where there is friction between the prestressing tendons and the duct, loss of prestressing force in the tendons may be calculated as follows. Assuming identical frictional force during tensioning and releasing, the distribution of tendon force is as shown in **Fig. C 11.3.2**. When a tendon is tensioned from end a, the prestressing force in the tendon is a'b'co' immediately prior to anchoring, and the prestressing force at the tensioning end immediately after to anchoring decreases to P_t. In this case, lines a'b'c and a"b"c are symmetrical with respect to the horizontal axis ce, and the amount of set is equal to the area A_{ep} enclosed by a'b'cb"a", divided by A_pE_p.

$$\Delta l = \frac{A_{ep}}{A_p E_p} \qquad \text{(C 11.3.5)}$$

Thus, the line cb"a" may be obtained by determining the point c where A_{ep} is equal to $\Delta l A_p E_p$.

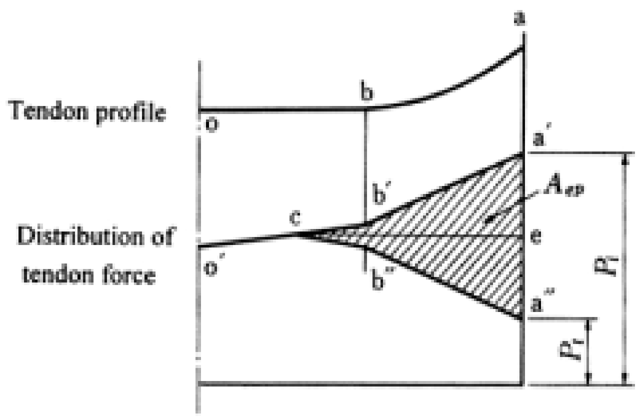


Fig. C 11.3.2: Distribution of tendon force

[4] Other effects: these will include e.g. deformation of joints used in precast block construction

[5] Effects of relaxation of tendon: loss of prestressing force in tendons due to tendon relaxation may be obtained from Eq. (C 11.3.6).

$$\Delta\sigma_{pr} = \gamma\sigma_{pt} \qquad \text{(C 11.3.6)}$$

where

$\Delta\sigma_{pr}$ = loss of prestressing force in tendons due to tendon relaxation
γ = apparent relaxation rate in tendon

[6] Creep of concrete, [7] Shrinkage of concrete: loss of prestressing force in tendons due to creep and shrinkage of concrete are determined on the basis of appropriate creep analysis; in general **COMMENTS** (1) (ii) to section **11.4** below may be applied.

Owing to the difference between the thermal expansion coefficients and the Young's modulus of concrete and CFRM, the prestressing of CFRM varies with temperature; for example a prestress loss of around 2% is found for a temperature rise of 20°C in the case of carbon fiber CFRM. This effect must therefore be allowed for where major temperature variations are expected. Prestress loss due to temperature change may be obtained from Eq. (C 11.3.7).

$$\Delta\sigma_{pT} = \Delta T(\alpha_f - \alpha_{CON})E_f \qquad \text{(C 11.3.7)}$$

where

$\Delta\sigma_{pt}$ = prestressing force loss in CFRM due to temperature change
ΔT = temperature change
α_{CON} = thermal expansion coefficient of concrete
α_f = thermal expansion coefficient of CFRM
E_f = Young's modulus of CFRM

(2) For indeterminate structures, it is possible to prevent indeterminate forces due to prestressing by selecting the appropriate tendon arrangement. Generally, though, indeterminate forces occur when member deflection due to prestress force is restricted, and these indeterminate forces must be allowed for when calculating stresses acting on the cross sections.

It should be noted that the level of indeterminate forces due to prestress forces are significantly affected by changes in the cross-sectional area of the member.

11.4 SERVICEABILITY LIMIT STATE

11.4.1 Flexural moments and axial forces

(1) Stress calculation

(i) Stress calculation
Stress in concrete, CFRM and steel shall be calculated according to **7.2**, based on the following assumptions etc.:

[1] In prestressed concrete structures, the entire concrete section is effective
[2] In prestressed reinforced concrete structures, the tensile stress of concrete shall generally be ignored
[3] Strain increase in bonding tendons is identical to that at the same position in concrete
[4] Axial ducts in members are not considered part of the effective cross-section
[5] The section constant of the integrated tendons and concrete shall be determined allowing for the

Young's modulus ratio of the tendons and the concrete.

(ii) Stresses in concrete, CFRM and steel subjected to permanent load shall be determined allowing for the effects of tendon relaxation, creep and shrinkage of concrete, and the constraining effect of steel.

(iii) Stresses in concrete, CFRM and steel subjected to variable loads shall be determined based on the stress under permanent loads calculated in (ii) above.

(2) Limiting values of stress

Limiting values for compressive stress in concrete due to flexural moment and axial forces shall be according to section **7.3** above. Limiting values for tensile stress in tendons shall be determined based on testing, according to the type of tendon sued. Limiting values for prestressing steel shall be according to JSCE Standard Specification(Design), 10.4.

(3) Examination for prestressed concrete structures

(i) Limiting values for edge tensile stress in concrete shall be the design tensile strength, allowing for the effects of member dimensions.

(ii) Where edge tensile stress of concrete acts as tensile stress, in general a quantity of tensile steel in excess of the cross-sectional area calculated according to Eq. (11.4.1) shall be arranged. Deformed bars shall generally be used for steel reinforcement.

$$A_s = T_c / \sigma_{st} \qquad (11.4.1)$$

where

A_s = cross-sectional area of tensile steel

T_c = total tensile force acting on concrete

σ_{st} = limiting value for tensile stress of tensile steel, may be set at 200 N/mm^2 for deformed bars. Bonding prestressing steel arranged in concrete where tensile stresses occur may be regarded as tensile steel. In this case, the limiting value for tensile stress of prestressing steel used in pretensioning may be set at 200 N/mm^2, and at 100 N/mm^2 for prestressing steel used in post-tensioning.

(4) Examination for prestressed reinforced concrete structures
Verification of flexural cracking shall be according to section **7.4** above.

(5) Verification of deflection shall be according to section **7.5** above, allowing for the effects of prestressing.

[COMMENTS]:
(1)(i): [3] In calculating strain increase in external cable tendons and unbonded tendons (i.e. unbonded CFRM or unbonded prestressing steel), the assumption of "plane remains plane" cannot be applied, therefore separate study is required. In this case, concrete stress may be calculated ignoring stress increase in tendons, regarding the structure as a reinforced concrete structure subject to eccentric axial force due to the effective prestress force.

[4] Grouting in ducts is not subject to prestress, therefore ducts in the axial direction of the member should not be included in the effective section, even when grouted.

(1) (ii) Where there is bond between the concrete and the tendons, stresses in the concrete, tendons and steel under permanent load shall be calculated as follows.

[1] Prestressed concrete structures:
The constraining effect of steel may be ignored in prestressed concrete structures. The reduction in tensile stress of tendons may in this case be calculated according to Eq. (C 11.4.1):

$$\Delta\sigma_{pcs} = \frac{n_p \cdot \varphi(\sigma'_{cpt} + \sigma'_{cdp}) + E_p \cdot \varepsilon'_{cs}}{1 + n_p \cdot \dfrac{\sigma'_{cpt}}{\sigma_{pt}} \cdot \left(1 + \dfrac{\varphi}{2}\right)} \qquad \text{(C 11.4.1)}$$

where

$\Delta\sigma_{pcs}$ = tensile stress reduction in tendons due to concrete creep and shrinkage

φ = creep factor

ε'_{cs} = shrinkage strain of concrete
n_p = ratio of Young's modulus of tendons to that of concrete
σ_{pt} = tensile stress of tendons immediately after tensioning
σ'_{cpt} = compressive stress of concrete at tendons due to prestressing immediately after tensioning
σ'_{cdp} = compressive stress of concrete at tendons due to permanent load

[2] Prestressed reinforced concrete structures
In prestressed reinforced concrete structures, the constraining effect of steel is generally considered in calculations. In this case, the reduction of tensile stress in tendons and the stress change in tensile reinforcement may be calculated according to Eqq. (C 11.4.2) and (C 11.4.3). Stress in concrete where cracking does not occur under permanent loads shall be calculated allowing for the effects of the reaction force of the compressive forces acting on tensile reinforcement.

$$\{1 + \alpha_{pp} \cdot (1 + \varphi / 2)\} \cdot \Delta\sigma_{pcs} + \alpha_{sp} \cdot (1 + \varphi / 2) \cdot \Delta\sigma_{scs}$$

$$= n_p \cdot \{\varphi \cdot (\sigma'_{cpt} + \sigma'_{cdp}) + E_c \cdot \varepsilon'_{cs}\} \qquad \text{(C 11.4.2)}$$

$$\alpha_{ps} \cdot (1 + \varphi / 2) \cdot \Delta\sigma_{pcs} + \{1 + \alpha_{ss} \cdot (1 + \varphi / 2)\} \cdot \Delta\sigma_{scs}$$

$$= n_s \cdot \{\varphi \cdot (\sigma'_{cps} + \sigma'_{cds}) + E_c \cdot \varepsilon'_{cs}\} \qquad \text{(C 11.4.3)}$$

given that

$$\alpha_{pp} = n_p \cdot A_p \cdot (1 / A_c + e_p^{\ 2} / I_c)$$

$$\alpha_{ps} = n_s \cdot A_p \cdot (1 / A_c + e_p \cdot e_s / I_c)$$

$$\alpha_{sp} = n_p \cdot A_s \cdot (1 / A_c + e_p \cdot e_s / I_c)$$

$$\alpha_{ss} = n_s \cdot A_s \cdot (1 / A_c + e_s{}^2 / I_c)$$

where

$\Delta\sigma_{pcs}$ = tensile stress reduction in tendons due to concrete creep and shrinkage

$\Delta\sigma_{scs}$ = variation in tensile reinforcement stress due to concrete creep and shrinkage

φ = creep factor

ε'_{cs} = shrinkage strain of concrete

n_p, n_s = ratio of Young's modulus of tendons and steel to that of concrete

$n_p = E_p/E_c$; for CFRM $n_p = E_f/E_c$, $n_s = E_s/E_c$

σ'_{cpt} = compressive stress of concrete at tendons due to prestressing immediately after tensioning

σ'_{cps} = compressive stress of concrete at steel reinforcement due to prestressing immediately after tensioning

σ'_{cdp} = compressive stress of concrete at tendons due to permanent load

σ'_{cds} = compressive stress of concrete at steel reinforcement due to permanent load

A_p = cross-sectional area of tendons

A_s = cross-sectional area of steel reinforcement

e_p = distance from centroid axis of member section to centroid of tendon

e_s = distance from centroid axis of member section to centroid of steel reinforcement

A_c = total cross-sectional area of concrete

I_c = moment of inertia of total concrete section

The effective prestress of unbonded tendons and tendons used in external cabling can in theory be calculated by first determining the stress changes along the entire tendon length at the centroid of the tendon due to deformation of concrete members, then calculating stress changes in the tendon from the average strain. As this calculation would be enormously complex, while member deformation at the serviceability limit state is minimal and the effects of strain changes at the tendon positions are slight, Eq. (C 11.4.1) may also be applied to external cabling.

(2) If concrete cracking, prestressing steel fatigue etc. are studied, there is no particular need to limit tensile stress in concrete and prestressing steel, but once tensile stresses exceed the elastic limit, the assumptions made in structural analysis and stress calculation fail to hold good, and prestress force can no longer be treated as an external force. For this reason, tensile stress must be kept below the elastic limit stress. Consistency has also been allowed for in long-term relaxation testing of prestressing steel, where the initial load was set at 70% of the characteristic value of the tensile strength of prestressing steel.

Unlike reinforcing or prestressing steel, CFRM is liable to fail below their static strength (creep failure) when subjected for long periods to significant, sustained stress for long periods. When using CFRM tendons, therefore, the tension must be set allowing for the creep failure strength. Creep failure strength is calculated on the basis of JSCE-E 533 "Testing Method for Creep Failure of Continuous Fiber Reinforcing Materials", testing up to 1000 hours and extrapolating creep failure strength at 1 million hours. The limit value for tensile stress of tendons may generally be taken as the creep failure strength characteristic value f_{fck}, multiplied by a reduction factor of 0.8. The limit value shall be not more than 70% of tensile strength (c.f. 7.3).

(3)

(i) Limiting values for edge tensile stress in concrete for prestressed concrete structures is taken as being the design tensile strength, allowing for the effects of member dimensions according to Eq. (C 7.4.1) in the JSCE Standard Specification (Design).

Table C 11.4.1 gives limiting values for edge tensile stress.

Table C 11.4.1: Limiting values for edge tensile stress in concrete for prestressed concrete structures

Loading status	Section depth (m)	Design strength f'_{ck} (N/mm^2)					
		30	40	50	60	70	80
Subject to variable load	0.25	2.1	2.6	3.0	3.4	3.8	4.1
	0.5	1.7	2.1	2.4	2.7	3.0	3.3
	1.0	1.3	1.6	1.9	2.2	2.4	2.6
	2.0	1.1	1.3	1.5	1.7	1.9	2.0
	3.0 ~	0.9	1.1	1.3	1.5	1.7	1.8

(ii) Provision is made for calculation of the tensile steel quantity to be placed where the concrete is subject to tensile stress, minimizing the difference between section stress calculated assuming the entire concrete section to be effective and section stress calculated assuming cracking to be present.

The quantity of tensile steel may be calculated either by the method given here, or by a method ignoring the tensile stress of concrete. For tensile stresses up to the level of the design strength, the method given here has been adopted as it is simpler and also more conservative.

If CFRM tendons are considered as being equivalent to tensile reinforcement, the strain limit value may be substituted for the limiting value for stress in prestressing steel, and this strain limit value applied to CFRM.

A distinction is drawn between pre- and post-tensioning tendons, to allow for the different bond strengths to the concrete in the two systems.

When unbonded tendons are used, the required quantity of tensile steel may be calculated multiplying the value by 1.35 with regard to variable loads. Unbonded tendons are not regarded as tensile reinforcement, as in prestressed concrete with small quantities of steel reinforcement may be liable to significant crack concentrations with attendant steel corrosion.

Concrete members used in external cabling systems are to be arranged with the minimum quantity of steel for reinforced concrete members subject to flexure. No additional variable loads are to be factored into the calculation of tensile steel quantities. Tendons placed as external cables are not regarded as tensile reinforcement.

(4) For prestressed reinforced concrete structures, a limit value for crack width shall be determined based on environmental conditions, the function and purpose of the structure or member, etc., and flexural cracking studied according to **7.4**. In this case, the increase in tensile reinforcement stress may be calculated according to (1)(iii), and flexural crack widths calculated with regard to durability according to Eq. (7.4.1).

In prestressed reinforced concrete structures, unbonded tendons, external cabling tendons etc. are used in conjunction with deformed steel bars. Corrosion-proofing for prestressing steel is considered separately, while CFRM is not liable to corrosion. As flexural crack widths are normally studied with regard to the outermost layer of deformed steel bars, the standard method of calculation of flexural crack widths may be adhered to.

11.4.2 Shear and torsion

It shall be in accordance with JSCE Standard Specification (Design), 10.4.2.

11.5 ULTIMATE LIMIT STATE

Verification of ultimate limit state for sectional failure shall be done in accordance with Chapter 6.

[COMMENTS]:
When unbonded tendons are used, flexural capacity is generally lower than when bonding tendons are used. For this reason, flexural capacity shall be reduced by 30% except in special cases where allowance is made for tensile stress of tendons, tendon layout, flexural moment distribution, coefficient of friction between tendons and concrete etc.

When ducts etc. are provided perpendicular to the member axis for transverse reinforcement etc., the duct sections need not be deducted from the concrete section. Duct sections shall be deducted from the concrete section in the following cases:
[1] When ducts etc. are not grouted
[2] When the diameter of the ducts etc. exceeds 30% of the member thickness

11.6 FATIGUE LIMIT STATE

It shall be in accordance with JSCE Standard Specification (Design), 10.6, where "steel" shall be taken to signify "steel or CFRM".

11.7 SAFETY DURING CONSTRUCTION

The following studies shall generally be made in relation to construction:

(1) Tensile stress in tendons during or immediately following prestressing shall be determined by testing, allowing for variations in material strengths.

(2) In verifying the safety of flexural moments and axial loads, the tensile stress of the concrete shall be not greater than the design tensile strength of the concrete, allowing for scale effect in the members. The design tensile strength of the concrete may be determined using the characteristic value for the compressive strength of the concrete at the time of calculation, taking g_c as equal to 1.0.

In concrete regions subject to tensile stress, tensile reinforcement having a cross-sectional area of not less than 3/4 of that calculated according to **11.4.1(3)** shall be arranged.

(3) Flexural compressive stress and axial compressive stress in concrete due to flexural moment and axial forces immediately following prestressing shall be respectively not more than 1/1.7 and 1/2 of the characteristic values for compressive strength of the concrete.

(4) Deflection shall be verified in accordance with Section **7.5** above, allowing for the effects of prestressing.

(5) The effects of shear and torsion shall be verified in accordance with Section **11.4.2** above. The design tensile strength of the concrete may be determined using the characteristic value for the compressive strength of the concrete, taking γ_c as equal to 1.0.

(6) Verification of the ultimate limit state may be done if necessary in accordance with Chapter 6.

[COMMENTS]:

The expression "during construction" shall generally be taken to signify the period during prestressing, immediately after prestressing, and subsequent stages until the structure goes into service.

(1) The limiting values for tensile stresses during and immediately after prestressing (respectively prestress forces P_i and (P_i-$\Delta P_i(x)$ in Eq. (11.3.1)) are to be determined by testing, given that they vary for different materials, and that tensile strength is subject to significant fluctuations. When carbon fiber CFRM is used, these values will generally be 0.7 f_{puk} and 0.65 f_{puk} respectively.

(2) Cracking during construction is generally not permitted, for the following reasons:
[1] Difficulty in controlling the width of cracks occurring during construction
[2] Difficulty in controlling deformation after loss of rigidity due to cracking
[3] Lack of data concerning shrinkage and creep behavior in the compressive zone of cracked concrete at the serviceability limit state

When all of the above issues have been adequately resolved, cracking during construction may be permitted. The limit value for flexural tensile stress has been determined based on considerations such as load combinations during construction, magnitude of flexural tensile stress, timing of the onset of flexural tensile stress etc. With regard to short-term tensile stresses, given that the section affected changes to compressive stress in service state, and also that the quantity of tensile steel in the service state is calculated separately, the quantity of tensile reinforcement may be reduced by 1/4, as provided for in this section. This reduction, however, is not recommended for tensile reinforcement subject to long-term tensile stresses, as the crack widths may grow due to creep of concrete.

11.8 STRUCTURAL DETAILS

11.8.1 Prestressing Tendons

(1) Clear distance

(i) The clear distance between sheaths for post-tensioning tendons shall satisfy the following

requirements:
[1] Horizontal and vertical spacing between sheaths shall be not less than 4/3 times the maximum size of the coarse aggregate;
[2] In areas where an internal vibrator is inserted, the horizontal spacing of sheaths or groups of sheaths shall be not less than 6cm, and the necessary spacing for the internal vibrator shall be maintained;
[3] Small size sheaths may be arranged in contact with each other if this is unavoidable. In such cases, the maximum number of sheaths shall be two, in the vertical direction;
[4] The vertical spacing between sheaths or groups of sheaths should be not less than the vertical section of the sheath

(ii) In pre-tensioning systems, the horizontal and vertical spacing of tendons at member ends shall be not less than 3 times the diameter of the tendon, and the horizontal spacing shall be not less than 4/3 times the maximum size of the coarse aggregate. When tendons are bundled in regions other than member ends, the numbers of layers ad tendons in a group shall be not more than 2 layers and 4 tendons respectively, and the spacing between each group shall be not less than 4/3 times the maximum size of the coarse aggregate.

(2) Concrete cover
Cover for a tendon, sheath or group of sheaths, and anchoring device shall be not less than the values given in Section **10.2**.

(3) Arrangement
(i) Tendons shall be so arranged that the prestress loss due to friction is low, and that there is no abrupt change in the cross-sectional area of the tendons throughout the member length.

(ii) Prestressing tendons shall be extended straight with the required length from the bearing face of the anchoring device.

(iii) When straight CFRM is arranged in a curve, the minimum curve radius to which the material may be bent by elastic deformation without causing damage shall first be determined by testing. Measures must be taken to eliminate any discrepancy between design and construction regarding the bending radius, allowing for the effects of secondary stresses on the strength of the reinforcement. The radius shall be determined such that excessive bearing pressure is not exerted on the concrete.

(iv) In the vicinity of section where moment reversal occurs due to the combination of loads, tendons should be dispersed between the upper and lower edges of the member section, avoiding concentrations of tendons near the centroid of the section.

(v) At an end support of a girder, some of the tendons should be extended along the lower face and anchored near the lower edge of the girder end.

(4) Arrangement of anchoring devices and couplers
(i) Anchoring devices shall be arranged so that each design section is subjected effectively to the necessary prestress, and that the tendons are securely fastened. Couplers shall be so arranged that the tendons can be securely coupled.
(ii) When multiple anchoring devices are arranged in the same section, the section configuration and

dimensions of the concrete in the anchorage region shall be determined allowing for the number of anchorage devices, the tendon forces and the required minimum spacing of the devices.

(5) Reinforcement for concrete adjacent to anchorage regions
Concrete adjacent to anchorage regions shall be reinforced with steel or CFRM, to prevent development of harmful cracks due to tensile stress.

(6) Protection of anchorages
Anchorages of tendons shall free from damage or corrosion for the duration of the design service life of the structure.

[COMMENTS]:
(1) (i) Spacing between sheaths shall generally be determined based on the following considerations.

Sheaths should be arranged as described in clauses [1] and [2], and group arrangements should if possible be avoided, in order to ensure that the concrete fully encloses the sheaths and that the entire cross section is filled with concrete.

Where group arrangement of sheaths is unavoidable due to limited member thickness and requirements for insertion of internal vibrators etc., vertical arrangements of up to two sheaths in the vertical direction as described in clause [3] may be used, provided that the sheaths are small and that special considerations are applied. A "small" sheath shall be one with a diameter of not more than approximately 70mm. "Special considerations" refers to sectional properties used in stress calculations, spacing of sheath bend-up locations, concrete casting method, concrete quality etc.

When a sheath is bent, the concrete between sheaths must be capable of withstanding the bearing stress of the tendons acting on the sheath walls. Where sheaths in the direction of the bearing stress at a bend are ungrouted as shown in **Fig. C 11.8.1(a)**, damage may occur if the clear distance is too small. Generally the clearance should be not less than one diameter of the sheath, as described in clause [4] (c.f. **Fig. C 11.8.1(b)**).

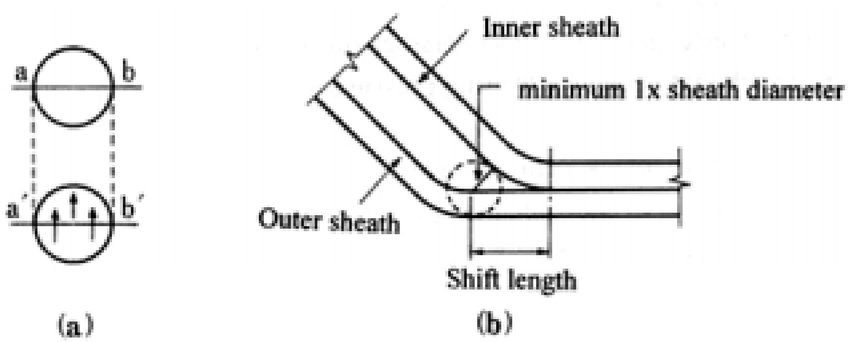


Fig. C 11.8.1: Arrangement of curved sheaths

(ii) In pre-tensioning systems, significant bond stress acts between the concrete and the tendons especially at the member ends. The clear spacing required here is given to ensure the development of adequate bond resistance, and adequate compaction of the concrete.

(3)
(i) Prestress loss due to friction is proportional to the angle change in the tendons and to tendon length, For bend-up or bend-down of tendons such as those in continuous girders, therefore, the effects of friction loss are considerable.

(iv) In continuous girders etc., in zones where loading causes reversal of bending moments, concentration of tendons around the center of the member section will reduce the quantity of reinforcement at the member edges, making cracking more likely. This should be prevented by distributing tendons in the zones close to the upper and lower edges (c.f. **Fig. C 11.8.2**).

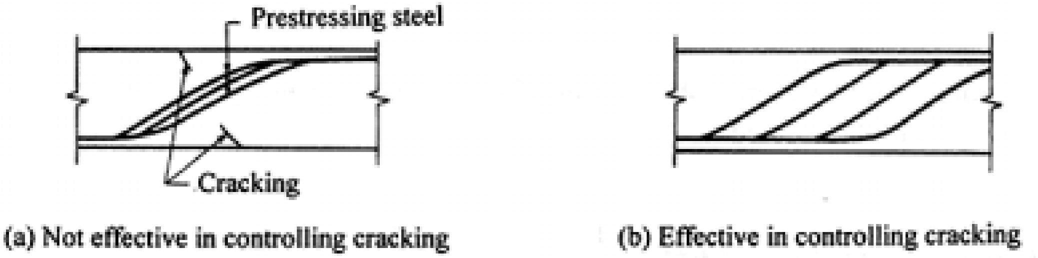


Fig. C 11.8.2: Arrangement of tendons in zones subject to moment reversal due to loading

(v) Where tendons cannot be arranged as described in this clause, the tendons must be replaced by axial reinforcement.

(4)
(i) In sections around anchorages, propagation of prestress and other effects cause stress disturbance, therefore the section cannot be treated as a normal section subject to eccentric axial loads for the purposes of stress calculation. When the design section is in the vicinity of an anchorage, the calculated prestress is not exerted, therefore the design section and the anchorage must be sufficiently separated to ensure prestressing is exerted effectively.

When an anchorage is placed in the central part of a member, it should generally be in the compression zone of the member.

The fatigue strength of an anchorage due to repeated loads is generally lower than the fatigue strength of tendons, therefore when an anchoring device is placed in the center of a member, it should located in a position where stress variation is at a minimum, and sufficiently removed from positions subject to large stress variation.

Couplers should be placed either in the vicinity of the centroid of the section, or in positions where bending moment variation is low.

For coupling in bent regions, tendons should be kept straight for a certain distance on either side of the coupler, and the coupling must be kept in a straight line.

(ii) The required minimum spacing of anchorages and the minimum concrete cover shall be determined by testing. Where the anchoring technique adopted is conventional and known to be sufficiently safe, the conventional practices may be adopted in determining the section configuration and dimensions of the concrete in the anchoring region.

(5) Regarding to reinforcing methods for concrete in the vicinity of anchorages in post-tensioning techniques, see JSCE "Recommendations for Design and Construction of Prestressed Concrete (1991 edition), Chapter 3 "Anchorage Design".

In pre-tensioning, harmful cracking may occur at the anchorages due to the arrangement and section configuration of tendons, therefore reinforcement must be provided to eliminate adverse effects on member performance.

(6) See present recommendation Part 2, "Construction".

When anchoring devices are embedded in a member after prestressing, the minimum concrete cover for these devices must be ensured.

11.8.2 Minimum reinforcement

(1) The minimum quantity of reinforcement in prestressed concrete shall be 0.1% of the concrete section, where "reinforcement" shall be taken as referring to deformed bars and pre-tensioning tendons.

(2) Reinforcing steel, prestressing steel or CFRM placed in accordance with **11.4.1(3)** above shall have a minimum diameter of 9mm, and shall be spaced not more than 30cm apart.

[COMMENTS]:

(1) Cracking due to shrinkage or temperature gradients may occur in prestressed concrete members prior to prestressing. In order to keep such cracking below harmful levels, all member sections shall include a minimum of 0.1% of the total section area of reinforcing steel, prestressing steel or CFRM. As CFRM has a lower Young’s modulus than steel, placing of an equivalent quantity of CFRM will increase crack widths, but CFRM is also not liable to corrosion, therefore the minimum required quantity of reinforcement has been kept the same both for steel and for CFRM.

For prestressed concrete members in post-tensioning, and for prestressed concrete girders in pre-tensioning, the total quantity of steel and the total quantity of CFRM, including bonding tendons, should be not less than 0.15% of the cross-sectional area of the concrete (c.f. **6.2.2**).

(2) "Prestressing steel or CFRM" refers here to pre-tensioning tendons and grouted post-tensioning tendons.

11.8.3 Joints

It shall be in accordance with JSCE Standard Specification (Design), 10.8.4.