

**Comprehensive Research and Development Projects
Research and Development on the Application
of New Materials to Construction Industries**

**Design and Construction Guidelines
for
Prestressed Concrete Highway Bridges
Using FRP Tendons
(Draft)**

March 1994

**Public Works Research Institute, Ministry of Construction
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by

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Synopsis:

The utilization of non-corrodable materials is raised instead of using conventional steel to prevent deterioration due to the salt attack for concrete structures. FRP (Fiber Reinforced Plastics) has strength equal to or better than conventional steel tendons, and is lightweight and non-corrodable; such qualities are shortcomings of steel.

This Cooperative Research has been conducted from the fiscal 1989 to 1992 in order to develop the technology using FRP tendons for prestressed concrete highway bridges along with Comprehensive Research and Development Projects, "Research and Development on the Application of New Materials to Construction Industries".

This report compiles the guidelines (draft) for prestressed concrete highway bridges to use new materials as tendons.

Keywords: Guidelines, FRP, Prestressed concrete highway bridge, Tendon, Steel, Corrosion, Salt attack

PREFACE

Recent advance in material technology has resulted in successive development of new materials with superb quality and function previously unknown. Some of these materials have already found practical use in the fields of electronics, automotive engineering, leisure, space exploration, etc. In the construction industry, new materials have emerged and are beginning to be utilized alongside conventional materials such as steel, concrete and timber which have remained unchanged. It is envisaged that such new materials will contribute to the fulfillment of the diverse needs of the modern society, by rationalizing material usage and by providing future amenities constructed with materials of high durability.

The Ministry of Construction, amongst others, has embarked on a program of technology development to promote the concept of reducing costs on maintenance, administration and renewal as a means to consolidate social capital. In a comprehensive project called "Development of Technology for Utilization of New Base Materials in Construction Projects", carried out between 1989 to 1992, FRP (Fiber Reinforced Plastic) was focused as the new base material.

In the above program, as a joint government and public sector research collaboration (referred hereinafter as the Collaboration Research), a project entitled "Research on Utilization of New Base Materials for Tendons in Prestressed Concrete Bridges" was carried out by the Ministry of Construction Public Works Research Institute and ten private companies. The objective was to utilize materials such as CFRP (Carbon Fiber Reinforced Plastic) and AFRP (Aramid Fiber Reinforced Plastic) in prestressed concrete highway bridges subject to hostile environmental exposure conditions such as chloride attack, by taking advantage of the excellent properties of such materials in terms of strength, chemical stability and so on.

Based on results of the collaboration Research, the present "Design and Construction Guidelines (Draft)" have been compiled to provide guidance for specific construction projects utilizing FRP as a new base material. However, these guidelines are not final recommendations and, in order to indicate the viewpoints in arriving at individual provisions, commentaries are provided for further reference. It is hoped that these guidelines will promote early accumulation of records on performance and will help to contribute to practical application of FRP materials, particularly in bridges, leading to a new era of construction with high degree of safety and durability.

August 1993

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CHAPTER 1 GENERAL

1.1 Scope of Application

These Guidelines (Draft) concern prestressed concrete highway bridges using FRP reinforcing materials as tendons.

Commentary:

These Guidelines (Draft) cover matters concerning the design and construction of pre- or post-tensioned concrete highway bridges using FRP (Fiber Reinforced Plastic) materials as prestressing tendons.

New base materials such as carbon fiber are being used in aerospace and automotive engineering, etc., and have begun to find use as chopped fibers in reinforced concrete with an increasing scope for further applications. A more recent development in applying new materials to construction is the use of FRP as reinforcement to concrete. FRP, made by resin-bonding long filaments of new base materials such as carbon fiber, aramid fiber, or glass fiber, has strength equal to or better than conventional steel tendons. It is lightweight and non-corrodable; such qualities are, unfortunately, the shortcomings of steel.

In coastal areas or on concrete surfaces where anti-freeze chemicals are spread during winter, there will be concern for deterioration of the reinforced concrete caused by salt damage. Under such conditions, structures reinforced with FRP are found to have excellent performance in terms of durability.

In general, FRP can be used in concrete structures both as prestressing reinforcement (FRP tendons) or as a substitute for normal non-prestressed steel reinforcement (FRP bars). It is more effective to use FRP tendons in prestressing as their excellent strength can be better utilized in this manner. Hence the present Guidelines (Draft) mainly consider the use of FRP tendons in such type of construction. Whilst it is conceivable to use FRP tendons unbonded or as external cables, there are unresolved aspects regarding their fatigue characteristics, performance of the anchorages and the cable deflecting devices, design methods, etc. These unknown areas are to be investigated in order that further guidelines can be developed.

Since research concerning new base materials is at an developing stage, these Guidelines (Draft) cover fundamental matters based on research findings to-date. Therefore, revisions will have to be made regarding necessary changes based upon future development of new technology or upon accumulation of further research results. For matters not already covered, readers are advised to refer to the document "Highway Bridge Specifications, with Commentary, Japan Road Association, February 1990".

1.2 Definition of Terms

Meaning of the terms used in these Guidelines (Draft) shall be as follows:

- (1) FRP reinforcement FRP (Fiber Reinforced Plastics) in rod form made of continuous filaments of new materials such as carbon fiber, aramid or glass fiber, bonded together by resin to be used as reinforcement in concrete.
- (2) FRP tendon FRP reinforcing materials used for prestressing concrete.
- (3) FRP bar FRP reinforcing materials used as an alternative to non-prestressed steel reinforcement in concrete.
- (4) Anchoring device A device for locking prestressed FRP tendons to hardened concrete.
- (5) Anchorage zone A general term for the part of a prestressed concrete member affected by the anchoring device.
- (6) Connector A device to connect an FRP tendon to another tendon or an anchoring device to a corresponding unit.
- (7) Sheath A steel or plastic tube for duct forming.
- (8) Standard tensile load of FRP material The tensile load guaranteed by the FRP manufacturer.
- (9) Pure relaxation ratio A value expressing the percentage of reduction in tensile force in the FRP tendon in relation to the tensile force first applied, considering the phenomenon of reduction in stress with time when a given strain is maintained.
- (10) Apparent relaxation ratio A value expressing the percentage of reduction in tensile force in the FRP tendon in relation to the tensile force first applied, considering the phenomenon of reduction in stress with time when a given strain is maintained, taking into consideration of the influence of drying shrinkage, creep, etc. of the concrete in the prestressed member.
- (11) FRP anchoring coefficient The coefficient applied to the specified tensile strength of an FRP tendon during or immediately after prestressing according to the type of anchoring device used.

(12) Clearance The clear space between adjacent reinforcing steel bars, FRP bars, FRP tendons or sheaths.

(13) Cover The shortest distance from the surface of a reinforcing steel bar, FRP bar, FRP tendon or sheath to the surface of concrete.

(14) CFRP Fiber reinforced plastic in rod form for reinforcing concrete, made by bonding long filaments of carbon fiber with resin. In the present Guidelines (Draft), strands of PAN carbon fiber are called CFRP (I) and rods using pitch carbon fiber are called CFRP (II).

(15) AFRP Fiber reinforced plastic in rod form for reinforcing concrete, made by bonding long filaments of aramid fiber with resin. In the present Guidelines (Draft), braided rods using Kevlar aramid fiber are called AFRP (I) and rods using para aramid fiber are called AFRP (II).

Commentary:

Meaning of the terms given above are the same as defined in "Highway Bridge Specifications, with Commentary" published by the Japan Road Association, February 1990. In particular, the terms "prestress, effective prestress, effective tensile force, effective coefficient, amount of set at the anchoring device, duct, pre-tensioning system, post-tensioning system", defined or not defined here, shall have the same meaning as the corresponding terms listed in Section 1.2, III, Concrete Bridge Volume, Highway Bridge Specifications, by replacing the term "prestressing steel" with FRP tendons".

1.3 Notations and Units

Notations and units used in these Guidelines (Draft) are as follows:

- (1) A_p : cross-sectional area of FRP reinforcement (cm^2)
- (2) E_p : Young's modulus of FRP reinforcement (kgf/cm^2)
- (3) P_u : standard tensile load of FRP reinforcement (kgf)
- (4) σ_{pu} : standard tensile strength of FRP reinforcement (kgf/cm^2)
- (5) R : anchoring coefficient for FRP reinforcement of standard tensile strength
- (6) μ : coefficient of friction per radian of angular variation of FRP tendon (/RAD)
- (7) λ : coefficient of friction per meter length of FRP tendon (/m)

Commentary :

In common with definition of the terms, the notations used in the present Guidelines are generally those used in the document "Highway Bridge Specifications" referred to earlier. Therefore, only special notations adopted are indicated here.

CHAPTER 2 MATERIALS

2.1 FRP Tendons

2.1.1 Configurations and Dimensions

Standard configurations and dimensions of FRP tendons are given in Table 1 as below.

Table 2.1 -- Configurations and Dimensions of FRP Tendons

Fiber	FRP Type	Configuration	Nomenclature	Nominal Dia. (mm)	Effective Cross Sectional (mm ²)	Unit Weight (kgf/m)
Carbon	CFRP (I)	Strand	12.5 mm 7-strand	12.5	76.0	0.151
	CFRP (II)	Round rod	Round 8 mm	8	49.0	0.080
		Deformed rod	Deformed 8 mm	8	44.0	0.070
Aramid	AFRP (I)	Braided rod	10.4 mm braid	10.4	85.0	0.108
	AFRP (II)	Deformed rod	Deformed 6 mm	6	28.3	0.041

Commentary:

The FRP tendons listed in Table 2.1 are items used in general and their performance have been confirmed by tests in the Collaboration Research. Accordingly, FRP tendons other than those listed but of identical material and with performance adequately satisfying requirements such as tensile strength shown in this table may also be used.

For further reference, additional details of FRP tendons for pretensioning and post-tensioning are given in Tables Comm. 2.1 and Comm. 2.3 respectively.

Table Comm. 2.1 -- Configurations and Dimensions of FRP Tendons for Pretensioning

Fiber	FRP Type	Configuration	Nomenclature	Nominal Dia. (mm)	Effective Cross-sectional Area (mm²)	Unit Weight (kgf/m)
Carbon	CFRP (I)	Strand	7.5 mm 7-strand	7.5	30.4	0.064
			10.5 mm 7-strand	10.5	55.7	0.114
			12.5 mm 7-strand	12.5	76.0	0.151
			15.2 mm 7-strand	15.2	113.6	0.226
			17.8 mm 7-strand	17.8	154.9	0.31
	CFRP (II)	Deformed rod	8 mm deformed	8	44.0	0.07
		Indented rod bundle	2 ϕ 8 mm indented	16	92.9	0.154
			3 ϕ 8 mm indented	20	138.3	0.231
			5 ϕ 8 mm indented	25	230.5	0.385

Table Comm. 2.1 -- Continued

Fiber	FRP Type	Configuration	Nomenclature	Nominal Dia.	Effective Cross-sectional Area (mm ²)	Unit Weight (kgf/m)
Aramid	AFRP (I)	Braided rod	10.4 mm braid	10.4	85	0.108
			12.7 mm braid	12.7	127	0.162
			14.7 mm braid	14.7	170	0.216
			18.0 mm braid	18.0	254	0.324
	AFRP (II)	Deformed rod	$\phi 6$	6.0	28.3	0.041
			$\phi 7.4$	7.4	42.4	0.062
		Deformed rod bundle	3 $\phi 6$	16.0	84.9	0.123
			4 $\phi 6$	20.0	113.2	0.164
			7 $\phi 6$	30.0	197.4	0.287
			2 $\phi 7.4$	20.0	84.8	0.124
			3 $\phi 7.4$	25.0	127.2	0.186

2.1.2 Standard Design Values of FRP Tendons

Standard values of tensile strength, Young's Modulus, relaxation ratio, linear coefficient of expansion of FRP tendons for design calculations are given in Table 2.2 as below.

Table 2.2 -- Standard Design Values of FRP Tendons

Fiber	FRP Type	Standard Tensile Strength (kgf/mm ²)	Young's Modulus (kgf/mm ²)	Pure Relaxation Ratio* (%)	Linear Coefficient of Expansion (x10 ⁻⁶ /° C)
Carbon	CFRP (I)	191	14000	5.0	0.6
	CFRP (II)	157	15000	5.8	0.7
Aramid	AFRP (I)	141	7000	8.1	-5.2
	AFRP (II)	180	5400	11.4	-3.0

* Pure relaxation ratios values for 2000 hours.

Commentary:

Values given in Table 2.2 have been determined with due consideration paid to safety and the scatter in values obtained during tests. As the specified tensile strength of the FRP tendons may differ from the standard values given in this table depending on their configuration or diameter, further data are given in Table Comm. 2.2 which may be used in design calculations.

Table Comm. 2.2 -- Standard Tensile Capacity of FRP Tendons for Pretensioning

Fiber	FRP Type	Configuration	Nomenclature	Effective Cross-sectional Area (mm ²)	Standard Tensile Capacity (tf)	Tensile Strength (kgf/mm ²)
Carbon	CFRP (I)	Strand	7.5 mm 7-strand	30.4	5.80	191
			10.5 mm 7-strand	55/7	10.64	191
			12.5 mm 7-strand	76.0	14.52	191
			15.2 mm 7-strand	113.6	20.30	179
			17.8 mm 7-strand	154.9	27.70	179
	CFRP (II)	Deformed rod	8 mm deformed	44.0	6.91	157
		Indented rod bundle	2 ϕ 8 mm indented	92.9	20.0	217
			3 ϕ 8 mm indented	138.3	30.0	217
			5 ϕ 8 mm indented	230.5	50.0	217
Aramid	AFRP (I)	Braided rod	10.4 mm braid	85	12.0	141
			12.7 mm braid	127	18.0	141
			14.7 mm braid	170	24.0	141

Table Comm.2.2 -- continued

Fiber	FRP Type	Configuration	Nomenclature	Effective Cross-sectional Area (mm ²)	Standard Tensile Capacity (tf)	Tensile Strength (kgf/mm ²)
Aramid	AFRP (I)	Braided rod	18.0 mm braid	254	35.0	138
	AFRP (II)	Braided rod	$\phi 6$	28.3	5.10	180
			$\phi 7.4$	42.4	7.60	180
		Braided rod bundle	3 $\phi 6$	84.9	15.30	180
			4 $\phi 6$	113.2	20.40	180
			7 $\phi 6$	197.4	35.60	180
			2 $\phi 7.4$	84.8	15.20	180
			3 $\phi 7.4$	127.2	22.80	280

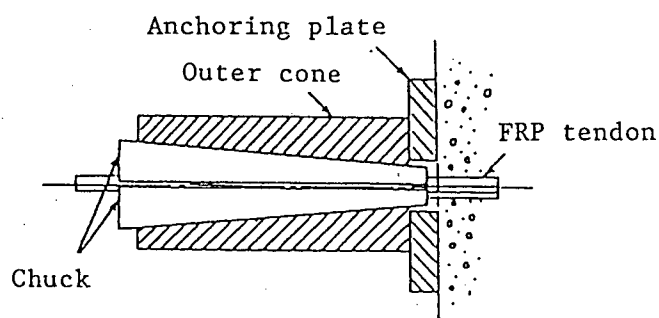
2.2 Anchoring Devices and Connectors

2.2.1 Anchoring and Connecting Methods

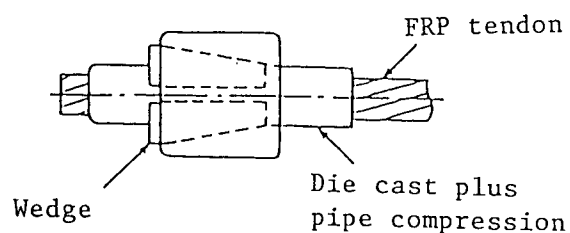
Only suitable types of anchoring device and connector should be selected for design and construction.

Commentary:

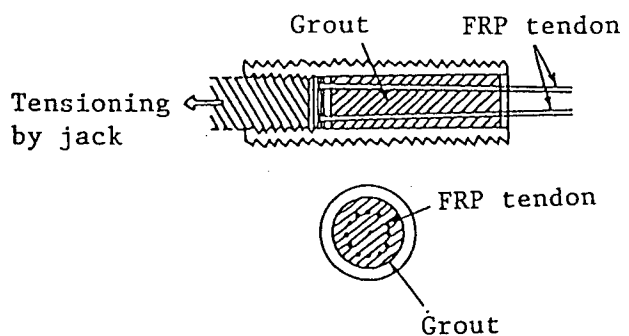
Examples of anchoring methods for FRP tendons are shown in Fig. Comm. 2.1. The anchoring devices shown are those generally used. In Fig. Comm. 2.2, two typical connections are shown using anchorages with externally threaded sleeves and a coupler.



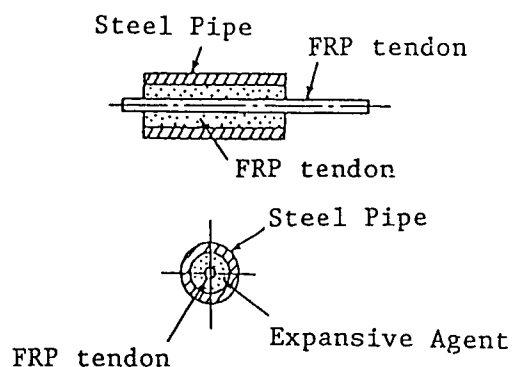
(1) Wedge Method



(2) Wedge + Die Casting +
Pipe Compression Method

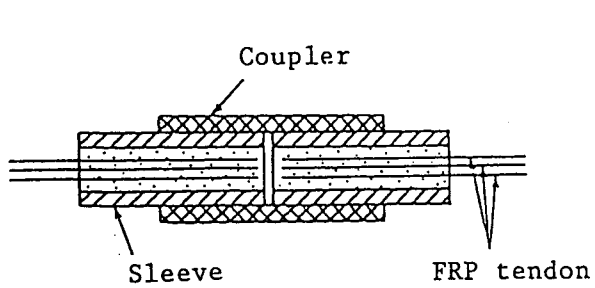


(3) Resin or Cement Mortar
Grouting Method

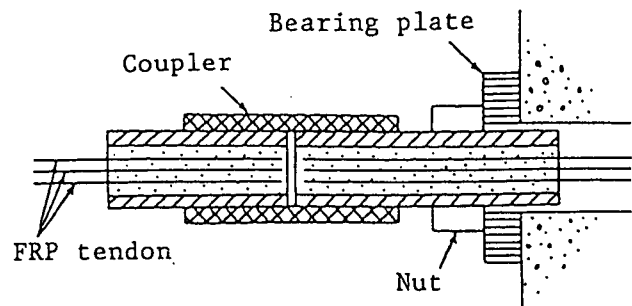


(4) Expansive Agent
Injection Method

Fig. Comm.2.1 -- Anchoring Methods



(1) Ordinary Connecting Method



(2) Anchorage Connecting Method

Fig. Comm.2.2 -- Connecting Method

2.2.2 Standard Design Values of Anchoring Devices

- (1) An anchoring device should have such a construction and strength that failure or excessive deformation of the anchored FRP tendon will not occur prior to the product of the standard tensile load of the tendon and the FRP anchoring coefficient reaching 95% of the tensile force during or after prestressing.
- (2) The Engineer should determine the FRP anchoring coefficient of the anchoring device by tests.

Commentary:

- (1) When a FRP tendon is anchored by an anchoring device, the tensile capacity of the tendon is determined by the performance of the anchoring device. Accordingly, the tensile force in the tendon during and immediately after prestressing, P_{tu} is governed by:

$$P_{tu} = R \cdot N \cdot A_p \cdot \sigma_{pu} \quad \text{.....(Comm. 2.2.1)}$$

Some typical values of anchoring coefficient with the associated FRP tendon and anchoring device are given in Table Comm. 2.3. As these anchoring coefficients were obtained by tests, they can be used directly without further testing. Where the performance of the anchoring device has been improved and the tensile capacity of the anchored tendon confirmed by tests, the value of the FRP anchoring coefficient may be increased. Table Comm. 2.4 is an example of an improved FRP anchoring coefficient obtained after the Collaboration Research. Additional data of the FRP tendons used in tests during the Collaboration Research and some other FRP tendons not listed in Table Comm. 2.3 are given in Table A for further reference (see data section).

- (2) Tests for determining FRP anchoring Coefficient are specified in the Japan Society of Civil Engineers Standard called "Method of Testing Performance of Anchoring Device and Connectors for Prestressed Concrete (Draft)" and this should be followed.

Table Comm.2.3 -- FRP Anchoring Coefficients for Post-tensioning

Fiber	FRP Type	Configuration	FRP Tendon Nomenclature	Nominal Dia. (mm)	System	FRP Tendon Composition	Anchor-age Type	FRP Anchoring Coefficient R	Tensile Capacity (tf)	Effective Cross Sectional Area (mm ²)
Carbon	CFRP (I)	Strand	12.5mm 7-strand	12.5	Multi	6- ϕ 12.5	Wedge	0.83	72.3	456.0
	CFRP (II)	Round Rod	8mm Round	R8	Multi	8-R8	Wedge	0.57	35.1	392.0
Aramid	AFRP (I)	Braided Rod	12.0mm Braid	12.0	Multi	6- ϕ 12.0	Wedge	0.58	40.4	540.0
	AFRP (II)	Deformed Rod Bundle	7 ϕ 6	30	Multi	7- ϕ 6	Mortar Grout	1.00	35.6	197.4

Table Comm.2.4 -- FRP Anchoring Coefficients after Improvement

Fiber	FRP Type	Configuration	FRP Tendon Nomenclature	Nominal Dia. (mm)	System	FRP Tendon Composition	Anchor-age Type	FRP Anchoring Coefficient R	Tensile Capacity (tf)	Effective Cross Sectional Area (mm ²)
Aramid	AFRP (I)	Braided Rod	12.7mm Braid	12.7	Multi	6- ϕ 12.7	Wedge	1.00	108.0	762.0

2.3 Sheaths

Sheaths should be of a suitable construction. They should not deform easily during handling or concreting and should not allow entry of cement paste along their seams and joints.

2.3.1 Sheath Material

Steel sheaths used should be in accordance with JIS G 3141, "Cold Rolled Carbon Steel Sheets and Strips".

Commentary:

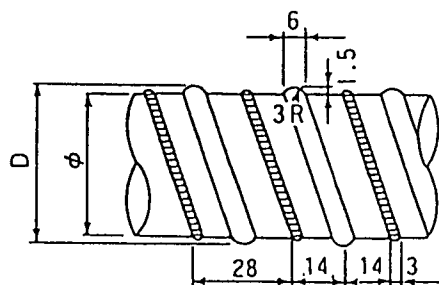
When a rigid corrugated polyethylene pipe is used instead, the product should meet the requirements of JIS C 3653 for a pipe of the "drawn-into-duct" type. See also commentary on Section 2.3.2 for further details.

2.3.2 Configuration and Dimensions of Sheaths

Steel sheaths of the configuration shown in Fig.2.1 and diameters given in Table 2.3 should be used. The sheath should be chosen according to the size of the FRP tendon.

Table 2.3 Dimensions of Steel Sheaths (Unit:mm)

Nominal Dia.	Inside Dia. ϕ	Outside Dia. D	Nominal Dia.	Inside Dia. ϕ	Outside Dia. D
20	20	22.5	70	70	73
23	23	25.5	72	72	75
28	28	30.5	75	75	78
30	30	33	80	80	83
32	32	35	85	85	88
38	38	41	90	90	93
40	40	43	95	95	98
42	42	45	100	100	103
45	45	48	105	105	108
50	50	53	110	110	113
52	52	55	115	115	118
55	55	58	120	120	123
60	60	63	125	125	128
65	65	68			



(Unit: mm)

Fig. 2.1 -- Configuration of Steel Sheaths

Commentary:

Corrugated rigid polyethylene pipe may be used as sheaths. The configuration is shown in Fig. Comm.2.3 and the dimensions are given in Table Comm.2.6.

Table Comm.2.6 Dimensions of Corrugated Rigid Polyethylene Pipe Sheaths*

Nominal Dia. (mm)	Outside Dia. (mm)	Inside Dia. (mm)	Shell Thickness (mm)	Pitch (mm)	Weight (kgf/m)
30	40	30	1.5	10	0.2
40	54	40	1.5	13	0.3
50	65	50	1.7	17	0.4
65	85	65	1.9	21	0.6
80	102	80	2.1	25	0.8
100	130	100	2.2	32	1.1
125	160	125	2.4	39	1.5
150	188	150	2.8	47	2.0
200	252	200	3.5	55	3.5

(*): Dimensions may vary.

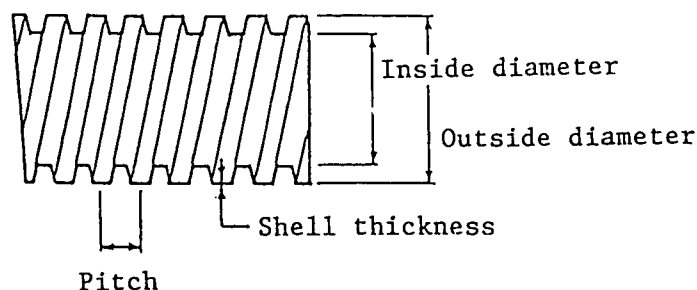


Fig. Comm.2.3 -- Configuration of Corrugated Rigid Polyethylene Pipe Sheath

2.4 Reinforcing Steel, Other

Epoxy resin-coated reinforcing bars should be used as reinforcing steel.

Commentary:

A bridge requiring the use of FRP tendons will often be in an environment where durability and weather resistance of the concrete structure are of prime importance. Therefore, when using stirrups, tensile and auxiliary steel reinforcement, only material with corrosion resistance such as reinforcing bars coated with epoxy resin should be used. Guidance for the use of epoxy resin-coated bars can be found in "Guidelines for Design and Construction Using Epoxy Resin-Coated Reinforcing Steel (Draft)" published by the Japan Society of Civil Engineers. Alternatively, FRP bars may be used but only products thoroughly checked by tests for safety should be specified.

CHAPTER 3 GENERAL MATTERS CONCERNING DESIGN

3.1 Design Principles

- (1) In designing a member, stresses in the member cross-section subject to the design loads and the strength of the member under the ultimate loads must be checked to ensure safety.
- (2) Combinations of the design loads and the ultimate loads should be as follows.
- (a) The design loads should be as described in Section 2.2 of I, General Volume, Highway Bridge Specifications.
 - (b) Combinations of the ultimate loads to be considered are:
 - (i) $1.3 \times (\text{Dead Load}) + 2.5 \times (\text{Live Load} + \text{Impact})$
 - (ii) $1.0 \times (\text{Dead Load}) + 2.5 \times (\text{Live Load} + \text{Impact})$
 - (iii) $1.7 \times (\text{Dead Load} + \text{Live Load} + \text{Impact})$
 - (iv) $1.3 \times (\text{Dead Load} + \text{Earthquake Load})$
 - (v) $1.0 \times (\text{Dead Load} + 1.3 \times \text{Earthquake Load})$
- (3) In the analysis of the member cross-section, forces in the section can be obtained by the elastic method in which the entire concrete cross-section is considered to be effective and the effects of the presence of FRP and steel reinforcement in the cross-section are ignored.

Commentary:

- (1) Under design loads, stresses in the member cross-section should be less than the allowable values. Under ultimate loads, the member should have sufficient strength against failure. These two conditions must be satisfied in the design of the member.
- (2) (a) When checking stresses in the member cross-section under the design loads, as obtained from Section 2.2 of the Highway Bridge Specifications, the effects of both the prestressing force immediately after tensioning and the effective prestress must be considered.
- (b) Combinations of the ultimate loads with corresponding load factors are given. In an indeterminate prestressed concrete structure, indeterminate forces occur due to prestressing, creep and drying shrinkage of the concrete. It is necessary to consider these when checking the ultimate load condition of the structure. These indeterminate forces are to be included using a load factor of 1.0 in the combination of ultimate loads.
- (3) Concrete is not a perfectly elastic material and its stress and strain are not linearly proportional. However, by considering it as elastic, calculation of the forces in the section becomes simple. Using this design principle, safety of the member is not impaired when compared to a design obtained by a more rigorous method.

Furthermore, forces in the member section is determined by the modular ratio of the constituents making up the member. In this consideration, the influence of the FRP and steel reinforcement is generally small. Therefore, it is satisfactory to use the sectional modulus of the entire concrete-section in calculating forces in the section.

3.2 Prestressing Force

When applying prestress to a structure, the followings should be considered in the design.

- (1) The prestressing force immediately after prestressing and the effective prestress after all losses should be considered. When a statically indeterminate force occurs as a result of prestressing, this also should be included.
- (2) Immediately after prestressing, the applied prestressing force to the concrete member at the tensioning end should be calculated with the following effects considered.
 - (a) Elastic deformation of concrete
 - (b) Friction between FRP tendon and sheath
 - (c) Take-up at anchoring device
- (3) Immediately after prestressing, the effective prestressing force should be calculated by considering the following additional effects.
 - (a) Creep of concrete under sustained loads (prestressing force immediately after prestressing + dead load)
 - (b) Drying shrinkage of concrete
 - (c) Relaxation of FRP tendon
- (4) In a statically indeterminate member, the indeterminate force at effective prestress can be obtained by multiplying the value of the indeterminate force immediately after prestressing by the average value of effective coefficient of tensile force over the entire length of the member.

Commentary:

- (1) The prestressing force considered must include the value immediately after prestressing, and the effective value after cessation of the subsequent creep and drying shrinkage of concrete and the relaxation of FRP tendons.
- (2) Immediately after prestressing, elastic deformation of the concrete must be considered when calculating prestress losses for a pretensioned member. For a post-tensioned member, apart from the loss due to elastic deformation, between FRP tendon and sheath, frictional loss at anchoring device and jack, and loss due to take-up at the anchoring device.
 - (a) For a pretensioning system, the loss of tensile stress in the FRP tendons due to elastic deformation occurs as soon as the prestress transferred to the concrete. This loss can be calculated by multiplying the concrete stress at the level of the centroid of the FRP tendons by the modular ratio between FRP and concrete.

For a post-tensioning system, tensioning is performed sequentially on single or group of tendons and the tensile force in the FRP tendons already anchored will change at each of the tensioning stages. These changes must be taken into consideration when calculating losses.

The average loss of tensile force in an FRP tendon due to elastic deformation of concrete can be calculated by the method as suggested in the commentary of Section 2.1.6 in I, General Volume, Highway Bridge Specifications.

(b) The loss of tensile force in an FRP tendon due to friction occurs mainly from friction between the tendon and sheath but as there is also frictional loss in the jack, this influence also should be considered.

Prestress loss due to friction between the FRP tendon and sheath varies according to the type, layout configuration, etc. of the tendon. In general, the tensile force in an FRP tendon can be calculated by the angular variation along the centerline and length of the tendon using the following equation.

$$P_x = P_i \cdot e^{-(\mu\alpha + \lambda x)} \quad (\text{Comm. 3.2.1})$$

Where, P_x : tensile force in FRP tendon at design cross-section (kgf)
 P_i : tensile force at jacking end of FRP tendon (kgf)
 μ : coefficient of friction per radian of angular variation of FRP tendon
 α : angular variation of FRP tendon (radian) and

$$\alpha = \sum_{i=1}^n \alpha_i$$

λ : coefficient of friction per meter length of FRP tendon
 x : length between tension end of FRP tendon and design cross-section (m)

When the length of FRP tendon is less than approximately 40 m and the angular variation of the entire tendon is less than about $\pi/6$ radian (30°). The tensile force in the FRP tendon after frictional losses may be calculated by the following equation.

$$P_x = P_i \cdot (1 - \mu\alpha - \lambda x) \quad (\text{Comm. 3.2.2})$$

For μ and λ in the above equations, the values given in Table Comm.3.2.1 are deemed to be satisfactory as these are based on results obtained in the Collaboration Research and from other sources.

Table Comm.3.2.1 -- Coefficients of Friction Between FRP Tendon and Sheath

Type of FRP Tendon	λ (/m)	μ (/rad)
CFRP(I)	0.004	0.3
CFRP(II)	0.004	0.3
AFRP(I)	0.003	0.25
AFRP(II)	0.003	0.25

(c) The loss of tensile force in an FRP tendon due to take-up at the anchoring device will differ depending on the anchoring system. In the threaded type of anchoring device, the take-up is found to be small and can be ignored.

The prestress loss in an FRP tendon due to take-up at the anchoring device may be calculated by the method suggested in the commentary of Section 2.1.6 in I, General Volume, Highway Bridge Specifications.

(3) The effective prestressing force may be determined by subtracting the amount of prestress losses, due to creep and drying shrinkage of the concrete as well as the apparent relaxation of the FRP tendon, from the prestressing force immediately after tensioning.

When the FRP tendon is bonded to the concrete, the loss of tensile stress in the tendon due to creep and drying shrinkage of the concrete may be calculated by the following equation.

$$\Delta \sigma_{p\psi} = \frac{n \cdot \psi \cdot \sigma_{cp} + E_p \cdot \epsilon_s}{1 + n \cdot \frac{\sigma_{cpt}}{\sigma_{pt}} \left[1 + \frac{\psi}{2} \right]} \quad (\text{Comm. 3.2.3})$$

where, $\Delta \sigma_{p\psi}$: loss of stress in FRP tendon due to creep and drying shrinkage of concrete (kgf/cm²)
 ψ : creep coefficient of concrete given in Table 2.1.8, I, General Volume, Highway Bridge Specifications.
 ϵ_s : strain in concrete due to drying shrinkage given in Table 2.1.9, I, General Volume, Highway Bridge Specifications
 n : modular ratio
 $n = E_p/E_c$
 E_p : value given in Table 2.2 (kgf/cm²)

E_c : value given in Table 3.3.3, I, General Volume, Highway Bridge Specifications (kgf/cm²)

- σ_{cp} : stress due to sustained load at concrete cross section at location of FRP tendon (kgf/cm²). The sustained load in this case is to be the prestressing force immediately after prestressing and dead load.
- σ_{pt} : tensile stress of FRP tendon immediately after prestressing
- σ_{cpt} : compressive stress at locating of FRP tendon immediately after prestressing (kgf/cm²)

However, if part of the dead load acts on the member after the transfer of prestress, it is advisable to take this into account.

The loss in tensile stress in an FRP tendon due to relaxation of the tendon may be calculated by Eq. Comm. 3.2.4 below.

$$\Delta \sigma_{pr} = \gamma \cdot \sigma_{pt} \quad (\text{Comm. 3.2.4})$$

- where, $\Delta \sigma_{pr}$: loss of tensile stress in FRP tendon due to relaxation of FRP (kgf/cm²)
- γ : apparent relaxation ratio of FRP tendon prescribed in Table Comm. 3.2.2
- σ_{pt} : tensile stress in FRP tendon immediately after prestressing (kgf/cm²)

Table Comm. 3.2.2 -- Apparent Relaxation Ratio of FRP Tendon (%)

FRP Tendon Type	Apparent Relaxation Ratio, γ in %
CFRP (I)	6
CFRP (II)	6
AFRP (I)	25
AFRP (II)	25

It should be noted from the above Table Comm. 3.2.2 that there is a large difference in the apparent relaxation ratio between the CFRP type of tendon and the AFRP type. As the Young's modulus of AFRP is considerably smaller than CFRP, the loss of tensile stress in the tendon due to creep and drying shrinkage of concrete is smaller. The effectiveness factor η is between 0.7 to 0.8 for either type of FRP tendon.

3.3 Bending Moment and Axial Force

3.3.1 Checking under Design Loads

(1) Stresses in the concrete, steel and FRP reinforcement at a member cross-section under design loads should be less than the allowable stress given in Chapter 4 of this document.

(2) When calculating stresses under design loads, the following assumptions can be made.

(a) The strain across the cross-section is proportional to its distance from the neutral axis in the plane of bending.

(b) The entire concrete cross-section is treated as effective.

The effective width of compression flange for calculating stresses should be based on the recommendations given in Section 2.2.2 of III, Concrete Bridge Volume, Highway Bridge Specifications.

Furthermore, in load combinations where impact or earthquake loading are included, when the calculated tensile stress in the concrete based on the above assumptions exceeds 30 kgf/cm², it is advisable to consider only that part of the concrete in compression as being effective.

(c) When calculation modular ratios, the values of Young's modulus for concrete and steel should be obtained from Table 3.3.1 and 3.3.3 of I, General Volume, Highway Bridge Specifications. The Young's modulus of FRP reinforcement is given in Table 2 in this document.

(3) For a member cross-section subject to bending moments in two orthogonal directions, it is advisable to check the stressed by considering the two bending moments to be acting simultaneously.

(4) When tensile stress occurs in the concrete cross-section under the design loads, the amount of tension reinforcement required based on the provisions of (5) and (6) below should be arranged in the tension zone of the concrete.

(5) The cross-sectional area of the tension reinforcement provided in the tension zone of the concrete should be greater than the values given below.

$$(a) \quad A_s = \frac{T_c}{\sigma_{sa}} \quad (3.3.1)$$

where, A_s : cross-sectional area of tension reinforcement (cm²)

T_c : tensile stress resultant in concrete (kgf)

σ_{sa} : allowable tensile stress of tension reinforcement (kgf/cm²)

(b) 0.5% of the cross-sectional area of concrete in tension.

(6) When both of the two conditions given below are satisfied, FRP tendons may be considered as contributing to the tension reinforcement.

(a) When the FRP tendons are bonded to the concrete.

(b) When the tensile stress in the FRP tendons, obtained from dividing the tensile force in the concrete by the cross-sectional area of the FRP tendons arranged in the tensile zone, is less than the allowable stress.

(7) When FRP tendons are considered as tension reinforcement according to provision (6) above, the allowable stress σ_{st} Eq. (3.3.1) should be taken as 1800 kgf/cm² for the principal load for other loads in accordance with the provisions in Section 4.1 of this document.

Commentary:

(1) By ensuring the stresses at a cross-section of the member under design loads to be less than their allowable values, excessive cracking of the concrete can be prevented in a normal reinforced concrete member. In prestressed concrete, it is possible to design a member to be uncracked by means of pre-compressing the concrete.

(2) (a) This is based on the usual assumption that plane sections remain plane during bending.

(b) In prestressed concrete, a member can be designed to remain uncracked under design loads. For loads due to impact and earthquakes, these only occur infrequently so that if cracking is prevented under such design loads, the required prestress becomes so great that the design is not necessarily satisfactory. Therefore, cracking is considered to be permissible under such loading and tension reinforcement is provided to control cracking. The amount of reinforcement required can be obtained, using the method given in provision (5) of this Section, by replacing the required capacity of the concrete in tension with the equivalent tensile capacity provided by the reinforcement. This is a simple method, and is based on the same principle as adopted in the design of reinforced concrete in which the tensile strength of concrete is ignored. The method is conservative and is suitable for a calculated tensile stress in concrete of up to 30 kgf/cm². Beyond this value, the amount of tension reinforcement may become excessive.

(3) When checking stresses in a prestressed concrete member, the sum of concrete stresses calculated in the orthogonal directions should be less than the allowable value

given in Chapter 4.

(4) In designing prestressed concrete members, it is permissible for tensile stress to occur in the concrete provided the stress is below the allowable value. In order to control cracking and prevent crack widths from becoming large, reinforcement bars are provided in the tension zone of the concrete.

For members with unbonded FRP tendons only, bending cracks which occur during overloading are not dispersed. Only few cracks appear and these are concentrated in the location of maximum bending moment. In order to prevent this, tension reinforcement is to be designed for the load combination of :

$$\text{Dead load} + 1.35 \times (\text{Live Load} + \text{Impact}) + \text{Effective Prestress}$$

additional to the original design loads. The reinforcement required for these two load cases are compared and large amount is to be arranged near the extreme tension face of the member to disperse the cracks.

(5) The method of calculating the amount of tension reinforcement to be provided is given. However, this provision is for those load combinations which exclude impact loading and to be included, the commentary for Section (2) should be referred to.

Referring to Fig. Comm. 3.3.1, equation (3.3.1) can be transformed as:

$$A_s = \frac{b \cdot x \cdot \sigma_{ct}}{2 \sigma_{sa}} \quad (\text{Comm. 3.3.2})$$

provided that $A_s \geq 0.005 b \cdot x$

where, A_s : amount of tension reinforcement (cm^2)

b : width of tension zone of member (cm)

x : distance from extreme tension fiber to neutral axis (cm)

σ_{ct} : tensile stress at extreme tension fiber of concrete under design load (kgf/cm^2)

σ_{sa} : allowable stress of tension reinforcement (kgf/cm^2)

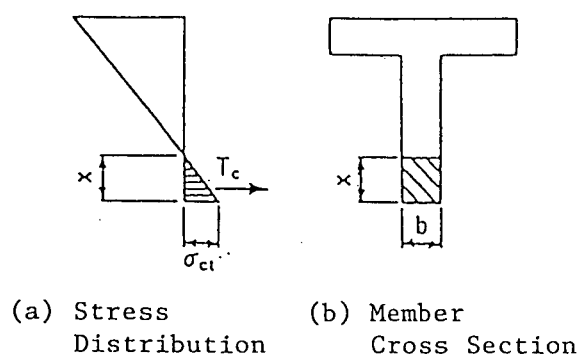


Fig. Comm.3.3.1 -- Tensile Stress Distribution in the Concrete Section

(6) Using the allowable stress approach where a suitable allowance has already been made, it was deemed that FRP tendons located in the tensile zone of the member could be considered as tension reinforcement similar to the case of prestressing using steel tendons. The amount of tension reinforcement required, as calculated from Eq. 3.3.1 or Eq. Comm.3.3.2, can be adjusted by deduction the amount of FRP tendons which can be considered as tension reinforcement.

(7) No additional comment.

3.3.2 Ultimate Load

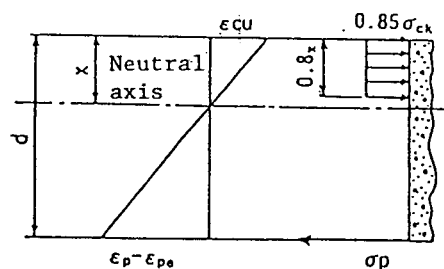
(1) The flexural capacity of a member should be greater than the maximum bending moment in the member under ultimate loads.

(2) The flexural capacity of the member should be calculated using the following assumptions:

- The strain across the cross-section is proportional to its distance from the neutral axis in the plane of bending.
- Tensile strength of the concrete is ignored.
- For a compressive failure of the concrete, the stress and strain distributions in the member cross-section are as shown in part (a) of Fig. 3.3.2.

For a tensile failure of the FRP tendons, the stress and strain distributions in the member cross-section are as shown in part (b) of Fig. 3.3.2. The compressive stress in the concrete can be calculated using the stress-strain curve as shown in Fig. 3.3.3.

where,

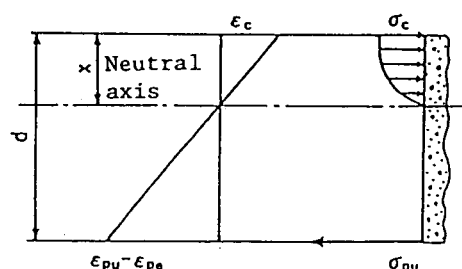


Strain Distribution Stress Distribution

(a) Compressive Failure of Concrete

- where,
- ϵ_{cu} : ultimate strain of concrete ($= 0.0035$)
 - ϵ_p : strain of FRP tendon
 - σ_{ck} : specified concrete strength (kgf/cm^2)
 - σ_p : stress of FRP tendon (kgf/cm^2)
 - d : effective height of member cross section (cm)
 - x : distance from compression fiber to neutral axis (cm)
 - ϵ_{pe} : strain of FRP tendon from effective prestressing force

where,



Strain Distribution Stress Distribution

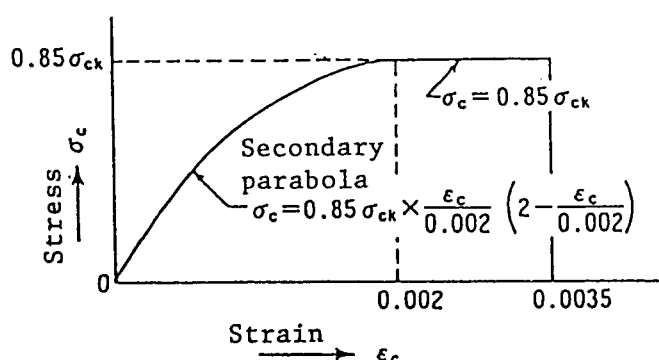
(b) Tensile Failure of FRP Tendon

- where,
- ϵ_c : strain of concrete
 - ϵ_{pu} : ultimate strain of FRP tendon
 - σ_c : concrete stress (kgf/cm^2)
 - d : effective height of member cross section (cm)
 - x : distance from compression fiber to neutral axis (cm)
 - ϵ_{pe} : strain of FRP tendon from effective prestressing force

Fig. 3.3.2 -- Stress and Strain Distributions for Calculating Flexural Capacity

(d) The stress-strain curve of FRP tendons is as shown in Fig. 3.3.4.

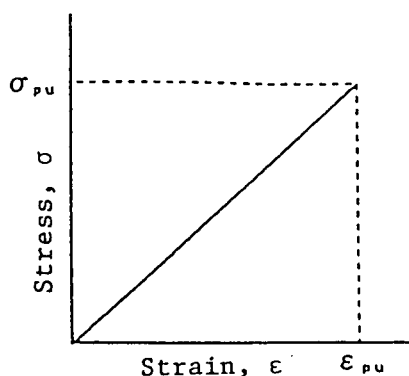
(3) The flexural capacity of a member subject to simultaneous bending moment and axial force should be calculated, using the assumptions given in provision (2) of this Section, with the axial force duly accounted for in the consideration of equilibrium at a cross-section of the member.



where,

σ_{ck} : specified concrete strength (kgf/cm²)
 σ_c : concrete stress (kgf/cm²)
 ϵ_c : concrete strain

Fig.3.3.3 -- Stress- Strain Curve of Concrete for Calculating Flexural Capacity



Young's modulus indicated by σ/ϵ

Fig.3.3.4 -- Stress-Strain Curve of FRP Tendon for Calculating Flexural Capacity

Commentary:

(1) This provision is to ensure that failure of the member due to bending will not occur. Flexural capacity of a member, calculated under the assumptions in provision (2) of this Section, is the maximum bending moment which can be resisted by the member.

(2) To calculate flexural capacity, it is necessary to consider the distribution of strain in the cross-section from which the stresses in both concrete and FRP tendons can be calculated. Hence the assumptions on stress and strain distributions in the concrete are given, together with the stress-strain relationships of both concrete and FRP tendons.

When the strains in both concrete and FRP tendons at a member cross-section attain their ultimate values simultaneously, it is called the equilibrium condition. The amount of tension FRP tendons under this condition, expressed as a ratio to the effective area of the concrete section, is called the ultimate equilibrium FRP tendon quantity ratio. This ratio can be calculated by the following equation for a concrete cross-section with a rectangular compression flange.

$$P_b = \frac{A_{sb}}{bd}$$
$$= \left[0.68 \frac{\epsilon_{cu}}{\epsilon_{cu} + \epsilon_{pu}} - \frac{N_d}{bd\sigma_{ck}} \right] \frac{\sigma_{ck}}{\sigma_{pu}} + \frac{A'_s}{bd} + \frac{A'_s}{bd} \cdot \frac{\sigma'_p}{\sigma_{pu}} \quad (\text{Comm.3.2.3})$$

where, P_b : ultimate equilibrium FRP tendon quantity ratio

A_{sb} : ultimate equilibrium tension FRP tendon quantity, i.e., total cross-sectional area of FRP tendons taken as tension reinforcement (cm²)

b : effective width of compression flange (cm)

ϵ_{cu} : ultimate strain for concrete (0.0035)

ϵ_{pu} : ultimate strain of tension FRP tendon calculated by

$$\epsilon_{pu} = \sigma_{pu} / E_p$$

E_p : Young's modulus of tension FRP tendon (kgf/cm²)

σ_{pu} : standard tensile strength of tension FRP tendon (kgf/cm²)

σ_{ck} : specified concrete strength (kgf/cm²)

N_d : ultimate axial force (kgf)

A'_s : amount of compression steel (cm²)

σ'_s : stress in compression steel (kgf/cm²)

$$\sigma'_s = [\epsilon_{cu} - (\epsilon_{cu} + \epsilon_{sy}) \frac{d'}{d}] E'_s \leq \sigma'_{sy}$$

d' : distance from top of compression flange to centroid of compression steel (cm)

E'_s : Young's modulus of compression steel (kgf/cm²)

σ'_{sy} : yield stress of compression steel (kgf/cm²)

When conventional prestressing steel is used for tensioning, the general practice is to provide less than 75% of the ultimate equilibrium steel quantity as tension steel in order to avoid a compressive failure of the concrete before yielding of the steel reinforcement. As no yield point is observed when FRP tendons are loaded in tension, there is a possibility of concrete failing in compression first when these are used as tension reinforcement. Two failure modes are possible for members using FRP tendons; either the concrete or the tension FRP tendons may reach the ultimate strain. In the design, it is necessary to identify and clearly state the mode of failure, having duly considered the type and significance of the structural member, the FRP used, etc.

In calculating the flexural capacity of a member using steel prestressing tendons, a material safety factor is applied to the steel stress. When FRP tendons are used, as failure of the tendons is determined by the ultimate strain rather than by yielding as in the case of steel tendons, it was decided that the standard tensile strengths set by FRP tendon manufacturers could be used without modifications. When making a comprehensive judgement on the flexural capacity of a member with FRP tendons, the Engineer is advised to focus on the failure mode and material strengths.

The two cases of flexural failure of members with FRP tendons are:

(a) Compressive Failure of Concrete

In calculating the flexural capacity of a member, the two conditional equations are:

$$N = C - T \quad (\text{Comm. 3.3.4})$$

$$\frac{x}{\epsilon_{cn}} = \frac{d-x}{\epsilon_p - \epsilon_{pe}} \quad (\text{Comm.3.3.5})$$

Where, T : tensile force resultant of FRP tendons (kgf)

C : compressive force resultant in concrete (kgf)

N : applied ultimate axial force (kgf)

$x, \epsilon_{cu}, d, \epsilon_p, \epsilon_{pe}$: see Fig. 3.3.2

Eq. Comm. 3.3.4 above represents the condition of equilibrium of forces at the cross-section whilst Eq. Comm. 3.3.5 is the condition of strain compatibility.

Referring to Fig. 3.3.2, flexural capacity of the member at a cross-section is governed by the condition of equilibrium of moments as below.

$$M_u = C \cdot y_1 + T \cdot y_2 \quad (\text{Comm. 3.3.6})$$

where, y_1, y_2 : distances from centroid of cross section to C and T (cm)

The distribution of compressive stress in the concrete of the member cross-section at failure shown in Fig. 3.3.1(a), adopted to simplify calculations at a constant value of $0.85 \sigma_{ck}$, has equivalent effect as the more realistic stress block shown in Fig. 3.3.3.

When the member is of a rectangular, I, T or box-shaped cross-section, the result of flexural capacity obtained using the stress distribution shown in Fig. 3.3.2(a) is approximately equal to that calculated using the more realistic stress block shown in Fig. 3.3.3. However, the location of the compressive force resultant C will be at the centroid of the compression zone of the member section as shown in Fig. 3.3.3 and is not necessarily at $0.4x$ from the extreme compressive fiber of the section.

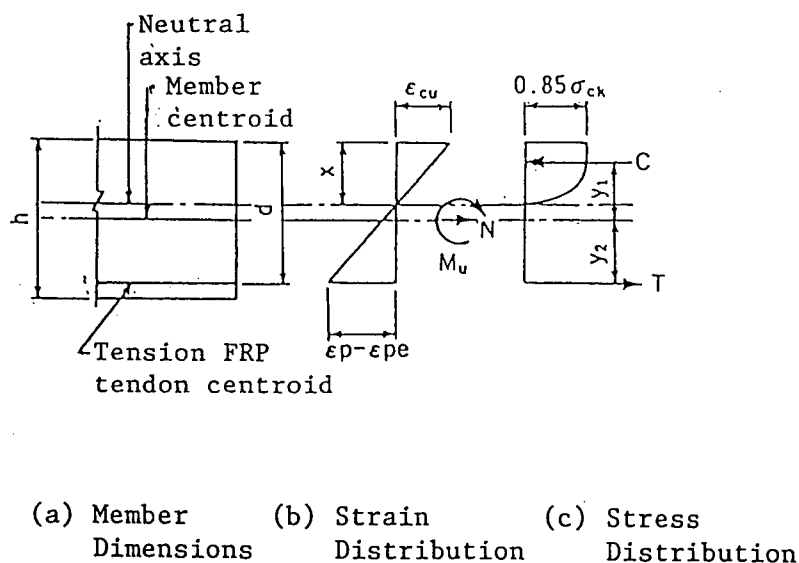
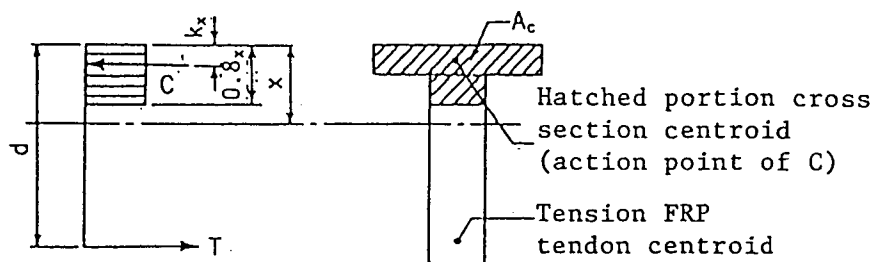


Fig. Comm.3.3.2 -- Stress and Strain Distributions at Compressive Failure of Concrete When Calculating Flexural Capacity



(a) Stress Distribution (b) Member Cross Section

Fig. Comm.3.3.3 -- Location of Resultant of Compressive Stress in Concrete Section

For members of cross-sectional shapes other than those mentioned earlier, the stress distributions should be based on that of Fig. 3.3.3 and the locations of the compressive force resultants calculated accordingly.

(b) Tensile Failure of FRP Tendons

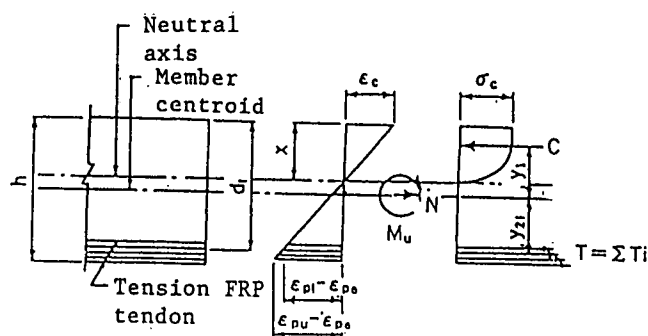
In this case, the strain distribution in the concrete is similar to (a) above. For the condition of equilibrium of forces at the cross-section, Eq. (Comm. 3.3.4) remains valid.

Referring to Fig. Comm. 3.3.4, the strains in the concrete and FRP tendons follow the relationship as below:

$$\frac{x}{\epsilon_c} = \frac{d_i - x}{\epsilon_{pi} - \epsilon_{pe}} \quad (\text{Comm.3.3.7})$$

where, d_i : effective height of i-th FRP tendon

ϵ_{pi} : strain of i-th FRP tendon



(a) Member Dimensions (b) Strain Distribution (c) Stress Distribution

Fig. Comm.3.3.4 -- Stress and Strain Distributions at Rupture Failure of FRP Tendons when Calculating Flexural Capacity

Flexural capacity of the member is calculated using Eq. (Comm. 3.3.6), representing

the condition of equilibrium of moments at the cross-section, together with Eq. (Comm. 3.3.4) and Eq. (Comm. 3.3.7). When the FRP tendons in the member are arranged in layers, tensile failure by rupturing of the outermost layer of FRP tendons will be the criterion for flexural capacity.

(3) General methods for calculating flexural capacity of a member were given in the previous section of commentary. These cover the situation when the member is subject to a simultaneous bending moment and axial force. In addition to the details given, the commentary of Clause 2.2.4 in III, Concrete Bridge volume, Highway Bridge Specifications may be referred to.

3.4 Shear Force

3.4.1 Checking under Design Loads

(1) When the average shear stress at a cross-section of the member is less than the appropriate value given in Table 3.4.1 below, diagonal tension reinforcement should be provided. The amount of reinforcement should be in excess of that stated in Clause 4.3(3) of III, Concrete Bridge Volume, Highway Bridge Specifications.

Table 3.4.1 -- Acceptable Average Shear Stress in Concrete (all units in kgf/cm²)

Specified concrete strength	210	240	270	300	400	500
Acceptable average shear stress in concrete	3.6	3.9	4.2	4.5	5.5	6.5

(2) When the average shear stress in the member is greater than the appropriate value given in Table 3.4.1, diagonal tension reinforcement must be provided. The amount of reinforcement should be in excess of that stated in Clause 4.3(3) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(3) Except for the load combination which includes earthquake loading, diagonal tensile stress at the member cross-section should be calculated. This should be less than the allowable diagonal tensile stress given in Chapter 4 of this document.

(4) For a member with small thickness in the direction of shear, the diagonal tensile stress at the member cross-section should be less than the allowable value. In this case, the provision of diagonal tension reinforcement is not required. Furthermore, checking of diagonal tensile stress at the member cross-section is not needed for the load combination which includes earthquake loading.

Commentary:

(1) The average shear stress at a cross-section should be calculated according to Eq. (2.3.2) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(2) Diagonal tension reinforcement should be proportioned by adopting Eq. (2.3.4) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(3) Diagonal tensile stress at a cross-section should be calculated by Eq. (2.3.3) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(4) This provision is for members of shallow depth or slabs.

3.4.2 Checking under Ultimate Loads

(1) The average shear stress in the concrete at a member cross-section should be less than the appropriate value given in Table 3.4.2 below.

Table 3.4.2 -- Maximum Value of Average Shear Stress in Concrete
(all units in kgf/cm²)

Specified concrete strength	210	240	270	300	400	500
Maximum value of average shear stress in concrete	28	32	36	40	53	60

(2) For a member with small thickness in the direction of shear, the average shear stress at the member cross-section should be less than the product of the shear stress given in Table 3.4.1 and the 'k' value obtained as below.

$$k = 1 + M_o / M_d \quad (3.3.2)$$

provided that $k \leq 2$

where, k : amplification factor for acceptable average shear stress in concrete
 M_d : bending moment acting on member cross-section under ultimate loads (kgf·cm)
 M_o : bending moment necessary to produce zero stress in the concrete at the extreme fiber (kgf·cm)

Commentary:

(1) The average shear stress in the concrete should be calculated by Eq. (2.3.2) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(2) No additional comment.

3.5 Torsional Moment

3.5.1 Checking under Design Loads

(1) When the shear stress in the concrete due to torsional moment, or the sum of shear stress due to torsional moment and average shear stress due to shear force is less than the appropriate value given in Table 3.4.1, torsional reinforcement is not required.

(2) When the shear stress in the concrete due to torsional moment, or the sum of shear stresses due to torsional moment and shear is greater than the value given in Table 3.4.1, torsional reinforcement in the transverse and longitudinal directions should be provided. The longitudinal reinforcing bars against torsional moment should be arranged symmetrically about the horizontal and vertical axes through the center of the cross-section.

(3) Apart from checking according to (1) and (2) above, the diagonal tensile stress in the concrete at the member cross-section should be less than the allowable value given in Chapter 4. Checking should be done for both the case of torsional moment only and the combined case of torsional moment and shear. Checking of diagonal tensile stress is not required for load combinations which include earthquake loading.

Commentary:

(1) Diagonal tensile stress should be calculated by Eq. (2.4.3) of III, Concrete Bridge Volume, Highway Bridge Specifications.

(2) Transverse and longitudinal reinforcement against torsional moment should be calculated by Eq. (2.4.4) of III, Concrete Bridge Volume, Highway Bridge Specifications.

As there are only a few research results on the effects of FRP tendons on torsional resistance of prestressed concrete beams, these tendons should not be considered as torsional reinforcement.

(3) Diagonal tensile stress should be calculated by Eq. (2.4.3) of III, Concrete Bridge Volume, Highway Bridge Specifications.

3.5.2 Checking under Ultimate Loads

Both the shear stress in the concrete due to torsional moment and the sum of shear stresses due to torsional moment and shear should be less than the appropriate values given in Table 3.5.1 below.

Table 3.5.1 -- Maximum Values of Shear Stress in Concrete (all units in kgf/cm^2)

Type of Stress	Specified Concrete Strength					
	210	240	270	300	400	500
Shear stress due to torsional moment	28	32	36	40	53	60
Sum of Shear Stress due to torsional moment and average shear stress due to shear force	36	40	44	48	61	68

CHAPTER 4 ALLOWABLE STRESSES

4.1 General

(1) The allowable values of stress in a cross-section of a prestressed concrete member subject to the principal load and a corresponding special load are given in the following Sections 4.2, 4.3 and 4.4.

(2) The allowable stresses associated with a secondary load and a corresponding special load should be the values given in Sections 4.2, 4.3 and 4.4, multiplied by an appropriate amplification factor given in Table 4.1.1.

However, the amplification factor for wind load or earthquake loading during erection additional to the construction load should be determined separately. Due considerations should be given to the site condition and the structural system under construction.

(3) Irrespective of the provisions given in (2) above, the allowable tensile stresses in the concrete of a prestressed member subject to a secondary load and a corresponding special load should have values according to those given in Clause 3.3.4 of III, Concrete Bridge Volume, Highway Bridge Specifications.

(4) The allowable tensile stress in an FRP tendon associated with a secondary load and a corresponding special load should have a value of less than 80% of the standard tensile strength of the tendon.

(5) No amplification should be applied to the allowable stresses immediately after prestressing for concrete and reinforcing steel as given in Sections 4.2 and 4.3 respectively.

- continued -

Table 4.1.1 -- Amplification Factors for Allowable Stresses

Combination of Loads	Amplification Factor
(1) Principal load (P) + special load corresponding to the principal load + effect of temperature change (T)	1.15
(2) Principal load (P) + special load corresponding to principal load + wind load (W)	1.25
(3) Principal load (P) + special load corresponding to principal load + effect of temperature change (T) + wind load (W)	1.35
(4) Principal load (P) + special load corresponding to principal load + braking load (BK)	1.25
(5) Principal load (P) + special load corresponding to principal load + collision load (CO)	1.50
(6) Live load and principal load other than impact + earthquake effect (BQ)	1.50
(7) Wind load (W) only	1.20
(8) Erection load (ER)	1.25

Commentary:

(1) Allowable stresses for concrete generally used for prestressed concrete members are given in Section 4.2. The specified strength covered ranges from 300 to 500 kgf/cm². For concrete of higher strengths, the allowable stresses should be determined by methods pertinent to prestressed concrete. In the case where the allowable stresses have been determined for a concrete of strength higher than that specified, the allowable stresses to be used for situations during checking, when the concrete has not yet achieved its specified strength, must be according to the concrete strength at

the time. For checking stresses immediately after prestressing, it is permissible to use those allowable stresses for the specified concrete strength provided that the requirements of Section 6.4.2 are satisfied.

(2) No additional comment.

(3) No additional comment.

(4) The allowable stress of an FRP tendon, when considering the case of a secondary load with the corresponding special load, may be amplified according to the provisions given in (2). An upper limit for the allowable stress at 80% of the standard tensile strength of the tendon was specified to prevent failure by rupturing under the design load.

4.2 Allowable Stresses in Concrete

(1) The allowable compressive stresses in concrete are given in Table 4.2.1 below.

Table 4.2.1 -- Allowable Compressive Stresses in Concrete (all units in kgf/cm²)

Type of Stress			Specified Concrete Strength		
			300	400	500
Immediately after prestress	Flexural compressive stress	(1) Rectangular cross section	150	190	210
		(2) T-shaped and box-shaped cross section	140	180	200
		(3) Axial compressive stress	110	145	160
Others	Flexural compressive stress	(4) Rectangular cross section	120	150	170
		(5) T-shaped and box-shaped cross section	110	140	160
		(6) Axial compressive stress	85	110	135

When a member is subject to simultaneous bending moments in two orthogonal directions, the allowable compressive stress in the concrete should be that for a rectangular member cross-section plus 10 kgf/cm².

(2) The allowable tensile stresses in concrete are given in Table 4.2.2.

Table 4.2.2 -- Allowable Tensile Stresses in Concrete (all units in kgf/cm²)

Type of Stress	Specified Concrete Strength		
	300	400	500
Flexural tensile stress (1) Immediately after pre-stressing (2) Live load and principal stress other than impact Principal load (3) Joint of and special blocks in load core-deck slab depending to and block principal load method (4) Other	12	15	18
	0	0	0
	0	0	0
	12	15	18
(5) Axial flexural stress	0	0	0

(3) The allowable diagonal tensile stresses in concrete are given in Table 4.2.3.

Table 4.2.3 -- Allowable Diagonal Tensile Stresses in Concrete (all units in kgf/cm²)

Type of Stress	Specified Concrete Strength		
	300	400	500
(1) When considering shear force only or torsional moment only	8	10	12
(2) When considering both shear force and torsional moment	11	13	15

(4) The allowable bond stress between concrete and reinforcing bars of diameters less than or equal to 32 mm are given in Table 4.2.4.

Table 4.2.4 -- Allowable Bond Stressed (all units in kgf/cm²)

Type of steel	Specified Concrete Strength		
	300	400	500
(1) Deformed steel bar	18	20	20
(2) Epoxy resin-coated reinforcing bar	14	16	16

Commentary:

(1) No additional comment.

(2) No additional comment.

(3) No additional comment.

(4) The allowable bond stresses between concrete and epoxy resin-coated reinforcing bars were made 80% of those for deformed bars. This is based on the "Guide to Design & Construction of Reinforced Concrete Using Epoxy Resin-Coated Reinforcing Bars (Draft)".

4.3 Allowable Stresses in Reinforcing Steel

Allowable stresses in reinforcing steel bars of diameters less than or equal to 32 mm are given in Table 4.3.1 below.

Table 4.3.1 -- Allowable Stresses in Reinforcing Steel (kgf/cm²)

Type of Stress, Member			K i n d o f Reinforcing Bar	
			SD295A SD295B	SD345
Tensile stress	Basic value when not including collision load or earthquake effect in load combination	(1) Member in general	1,800	1,800
		(2) Deck slab and slab bridge of span not more than 10m	1,400	1,400
		(3) Member installed underwater or below groundwater level	1,600	1,600
		(4) Basic value of allowable stress when including collision load or earthquake effect in load combination	1,800	2,000
		(5) Basic value when calculating reinforcing bar lap splice length or anchoring length	1,800	2,000
		(6) Compressive stress	1,800	2,000

Commentary:

Allowable stresses for reinforcing steel bars have been determined for members so that cracking of the concrete will not seriously affect durability. The allowable stress for (1) in Table 4.3.1 are also used for designing reinforced concrete members in general.

When dead load alone is acting, it is desirable to limit the allowable stress in reinforcing bars to $1,000 \text{ kgf/cm}^2$ and the same can be applied to bars with epoxy-resin coating.

In deck slabs and slab bridge with less than 10m spans, stress variations in the concrete due to live load are generally large. When repeated loading is applied, there are more harmful cracks occurring in the concrete compared to other types of reinforced concrete members. In general, damage to deck slabs and slab bridges due to rupturing of the tension reinforcement is infrequent. The most likely cause of damage is expected to arise from the continual widening of cracks already formed in the concrete under repeated loads, causing the concrete to split and spall eventually. Hence the allowable stresses for these applications are made smaller than those applied to reinforcing bars in general; it may be desirable to reduce the allowable stress of $1,400 \text{ kgf/cm}^2$ even further by a margin of say 200 kgf/cm^2 .

4.4 Allowable Stresses in FRP Tendons

Allowable tensile stresses in FRP tendons are given in Table 4.4.1 below.

Table 4.4.1 Allowable Tensile Stresses for FRP Tendons

Type of Stress	Allowable Tensile Stress	Remark
Pre-tensioning system (1) During prestressing (2) Immediately after prestressing (3) Under design load	$0.8 \sigma_{pu}$ $0.7 \sigma_{pu}$ $0.6 \sigma_{pu}$	σ_{pr} : standard tensile strength of FRP tendon (kgf/cm ²)
Post-tensioning system (1) During prestressing (2) Immediately after prestressing (3) Under design load	$0.8R \cdot \sigma_{pu}$ $0.7R \cdot \sigma_{pu}$ $0.6 \cdot \sigma_{pu}$	R : FRP anchoring coefficient

Commentary:

For an FRP tendon-anchoring device combination, the allowable tensile stress in the tendon may be determined at times by the performance of the anchoring device. Due to this reason, FRP anchoring coefficients are necessary considerations during prestressing and immediately after prestressing for a post-tensioning system. Under design loads, the consideration of FRP anchoring coefficient is not necessary when the ducts are filled with grout. Also, as the tensioning forces are relatively small and single tendons or rod bundles are generally used in a pretensioning system, the consideration of FRP coefficient is not required in this case.

CHAPTER 5 STRUCTURAL DETAILS

5.1 Minimum Amount of Reinforcement

(1) The cross-sectional area of longitudinal tension reinforcement in a prestressed concrete beam subject to bending should be greater than the value calculated by the equation:

$$A_t = 0.005 b_w \cdot d \quad (5.1.1)$$

Where A_t : cross-sectional area of longitudinal tension reinforcement (cm^2)
 b_w : web thickness of beam (cm)
 d : effective depth of beam (cm)

However, the above requirement need not apply when the longitudinal tension reinforcement provided is greater than 4/3 of the reinforcement cross-sectional area required.

(2) Additional bonded reinforcement of more than 0.15% of the member's cross-sectional area should be provided.

Commentary:

(1) As concrete has low tensile strength, the resistance to bending of a prestressed concrete beam is governed by the amount of tension reinforcement or the compressive capacity of the concrete in the beam section. Consequently, a beam with an extremely small amount of longitudinal tension reinforcement may fail by yielding and rupturing of the reinforcement, very soon after the appearance of flexural cracking in the concrete. This minimum reinforcement requirement is to prevent a sudden flexural tensile failure of the prestressed concrete beam. As it is possible that the FRP reinforcement is used in conjunction with prestressing or non-prestressed steel, it may not be appropriate to consider only the minimum amount of reinforcement without accounting for the different stress-strain characteristics of the various reinforcing materials concerned. A separate provision, based on the consideration of the ratio of the amount of tension reinforcement provided to what is required by calculations in the design, is therefore included to cover this mixed tension reinforcement situation.

(2) With a prestressed concrete member, cracking of the concrete due to shrinkage and temperature gradient may occur prior to the transfer of prestress or in a direction where there is no compressive stress. Therefore, it is necessary to provide additional bonded reinforcement to control cracking in the longitudinal and transverse directions of the member. Although FRP reinforcing materials generally, have excellent bond characteristics, they have lower values of Young's modulus than steel.

As the performance of the individual FRP material in controlling cracks are not fully known at present, further investigation must be made before applying FRP materials as additional reinforcement.

5.2 Arrangement of FRP Reinforcement

(1) For a curved FRP tendon profile, the radius of any bend should be greater than the values given below.

(a) tendon with sheaths: the greater of 5 m or 100 times the diameter of the sheath

(b) tendons without sheaths: minimum radius to be determined by tests or other suitable means

(2) The clear distance between FRP reinforcing materials should be in accordance with clause 4.4.2 of III, Concrete Bridge Volume, Highway Bridge Specifications.

(3) The minimum cover for FRP reinforcing materials should be greater than 2.5 cm or $4/3$ of the maximum size of the coarse aggregate.

Commentary:

(1) When the curvature of a tendon is small, the resultant force arising from the applied tension in the tendon can be significant. Therefore, the radius of any bend in the a tendon must be restricted in order that the effect of the force resultant can be alleviated. The value of 5 m as the minimum radius of bend for sheathed FRP tendons was ascertained by experiments. When sheaths are not used, confirmation of the suitability of a proposed small bend should be made by tests or any other means as useful data are not available at present. As FRP tendons are greatly affected by bending compared to the conventional prestressing steel, it is recommended that the radius of any bend should be made as large as possible.

(2) No additional comment.

(3) Since FRP reinforcing material is non-corrodable, the provision for minimum concrete cover based on durability considerations regarding matters more related to steel reinforcement has become unnecessary. The recommendation of a minimum of 2.5 cm cover is to avoid the possibility of bond cracking between the concrete and the FRP reinforcement. The additional recommendation for the cover being greater than $4/3$ times the maximum size of coarse aggregate is purely a consideration of

buildability. Where corrosion can occur to steel sheaths due to chloride attack, the use of corrugated rigid polyethylene pipe is recommended.

5.3 Anchorage Zone of FRP Tendons

- (1) In a pretensioned member, the length required for anchoring an FRP tendon may be taken as 65 times its diameter.
- (2) The concrete in the anchorage zone should be suitably reinforced against the bursting force produced in the transverse direction of the tendons.
- (3) Where a large number of anchoring devices must be located within the same plane, particular attention should be paid to the arrangement of the anchorages and the effect of the bursting forces generated by these anchorages within the concrete cross-section.

Commentary:

- (1) The FRP tendons for pretensioning as detailed in Table (Comm.2.1) all have bond strengths equal to or better than the equivalent prestressing steel strands. As it has been reported that the anchorage length is not more than 50 times the nominal diameter for FRP tendons, the provisions in the Highway Bridge Specifications were followed.
- (2) Reinforcement may be provided by methods similar to those used for prestressing steel anchorages. Where the anchorage of a tendon is effected by bond as in a pretensioning system, bond splitting is likely to occur because of the high bond strength of the FRP tendon. Adequate reinforcing of the anchorage zone is therefore necessary.
- (3) The minimum spacing and cover for anchoring devices should be decided by tests as there is no other reliable alternative method available at present.

CHAPTER 6 CONSTRUCTION

6.1 Scope of Application

This chapter concerns the construction of prestressed concrete highway bridges, using FRP tendons, with designs according to the provisions given in the earlier chapters in this document. If it becomes difficult for construction to be performed when following the provisions in this chapter, safety matters in the design should be re-examined.

Commentary:

This chapter describes general matters concerning construction of prestressed concrete highway bridges, using FRP tendons, which are designed according to the recommendations up to and including chapter 5 of this document. In actual construction, the provisions in this chapter alone may be inadequate at times. In such a case, the design provisions following those given in this document must be re-examined, particularly with regard to the allowable stress values, factors for the ultimate loads. etc., before the adoption of a proposed method of construction.

6.2 Handling of Materials

6.2.1 FRP Tendons

- (1) Only FRP tendons satisfying the material specification as detailed in Chapter 2 of this document should be used.
- (2) FRP tendons should be handled in a manner so as to avoid harmful deformation or impact.
- (3) During storage, placing FRP reinforcing materials directly on the ground should be avoided. Storage should be provided by storerooms or under suitable covers.
- (4) Surface of the FRP reinforcing materials should be maintained clean. Oils and other contaminations which may impair bond should be removed by suitable means.
- (5) FRP tendons and anchoring devices should be arranged in a suitable manner which satisfies the constructional tolerance requirements as detailed in the Highway Bridge Specifications. They should be securely fixed so as to avoid displacement during concreting or other disturbances.

Commentary:

(1) The FRP tendons considered are those presently used with carbon fiber and aramid fiber as base materials.

(2) In pretensioning, there is the risk of the FRP tendons being damaged from contact with the formwork at abutment or other objects during tensioning and compaction of the concrete. It is desirable to provide cushioning materials at such locations so as to isolate the FRP tendons.

(3) As the quality of FRP tendons can deteriorate rapidly as a result of damage or deformation by scuffing or due to ultra-violet rays, it is necessary to pay attention to their proper storage and handling.

FRP tendons stored in coils can be damaged or weakened if the winding radius is too small. Therefore, these tendons must be stored in coils with a radius not less than the specified minimum. When coils are stacked in multiple layers, harmful deformation can occur to the bottom layer due to the weight of the coils above. The number of layers of coils should be limited so that harmful deformation does not occur leading to deterioration in strength.

When cutting FRP reinforcing materials, it is desirable to use cutters of good performance so that the materials to be used are not damaged by cutting.

(4) No additional comment.

(5) Unless the FRP tendons are accurately arranged, it will not be possible for the required prestress to be induced in the member when a specified tension is applied to the tendons during prestressing. Therefore, the arrangement of the FRP tendons should be done following the recommendations in clause 16.13 of III, Concrete Bridge Volume, Highway Bridge Specifications.

As FRP tendons are lighter than the equivalent steel ones, it is also necessary to pay attention to buoyancy of the FRP tendons during concreting.

6.2.2 Anchoring Devices and Connectors

(1) Only anchoring devices and connectors conforming to the material specification as detailed in Chapter 2 of this document should be used.

(2) Anchoring devices and connectors should be stored indoors. Staining of these by oils and contamination should be prevented.

Commentary:

(1) FRP materials have strength only in the axial direction. When an FRP tendon is tensioned using an ordinary device for prestressing steel tendons, local compressive forces in the transverse direction can occur accompanied by shear, in addition to the tensile force in the longitudinal direction. Under this complex stress condition, rupturing of the FRP tendon can occur under a relatively low tension force in the tendon. Research and development in progress on anchoring methods specifically for FRP tendons are as follows.

a. Methods Using Wedges

These methods utilize special wedges and external casing tubes for anchoring FRP tendons in a manner similar to that used on steel tendons. The methods for anchoring the tendons include pushing in the wedges and tightening of the external casings with locknuts.

b. Method Using Die Cast

In this method, special alloys are melted and cast into metal dies fitted to the ends of FRP tendons gripped by wedges.

c. Method Using Resin or Cement Mortar

The end of the FRP tendon is fixed inside a cylindrical anchoring device by filling it with resin or cement mortar and anchoring is done using locknuts. As fixing depends on adhesion of the resin or cement mortar, the anchorage length required can become too long for FRP tendons with smooth surfaces and hence the method is more suitable for tendons with surface irregularities.

d. Method Using Expansive Agent

The end of the FRP tendon is threaded through a length of steel tube. By filling the tube with an expansive agent, the tendon is gripped inside the tube by compressive pressure arising from expansion of the agent. Anchoring of the tendon is done by wedges or locknuts.

6.2.3 Sheaths

- (1) Only sheaths conforming to the material specification as detailed in Chapter 2 of this document should be used.
- (2) Sheaths should be carefully stored in storerooms or under suitable cover to prevent staining due to oils, contamination, deformation, damage and, in particular, harmful corrosion in steel sheaths.
- (3) Sheaths should not be easily deformed during handling or concreting. Their seams and joints should not allow entry of the cement paste.

Commentary:

- (1) The reason for using FRP materials, as tendons for prestressed concrete bridges in areas where chloride attack can cause problems, is that the presence of chloride does not affect their performance. Hence it is necessary to select suitable materials for the sheaths on the same basis of durability as well as the requirements of flexibility and bonding to the concrete. It is also necessary to have an understanding of the effect of scuffing, between sheaths and tendons, on the FRP tendons themselves during tensioning.
- (2) No additional comment.
- (3) Sheaths which can deform, crush or let in cement paste during concreting will make subsequent insertion of the FRP tendons or grout injection difficult. Therefore, sheaths with ribs or corrugations which do not easily collapse in the transverse direction are preferred.

6.3 Concreting

6.3.1 Compaction

Internal vibrators for compaction of the concrete should be used with care to avoid damaging the FRP reinforcing materials.

Commentary:

As there is a risk of the FRP reinforcing materials being damaged when in direct contact with internal vibrators during compaction, it is desirable to use internal vibrators covered with a cushioning material such as polyurethane to reduce this risk.

6.3.2 Curing

When steam curing is used, heating should commence not earlier than 3 hours after casting. The temperature rise in the curing room should not be more than 15° C per hour with maximum curing temperature of 65° C, or that which will not affect the FRP reinforcement.

Commentary:

Depending on the FRP reinforcing material, there is a risk of changing quality when steam curing is used. Therefore, it is necessary to have a thorough understanding of the thermal characteristics of the FRP reinforcing materials and anchorages used when steam curing is applied.

6.4 Prestressing

6.4.1 General

- (1) FRP tendons should be tensioned in such a manner that the specified tensile force will be induced.
- (2) Special care should be exercised regarding precautions to ensure safety during the prestressing operation.

Commentary:

- (1) No additional comment.

(2) Since the tensile force induced in an FRP tendon is very large, there is a risk of harm being inflicted at the vicinity due to breakage of the anchoring device or the prestressing equipment. Therefore, as a precaution against accident, protective measures must be provided behind the prestressing equipment and personnel must not be allowed to stand behind the jack during tensioning.

6.4.2 Compressive Strength of Concrete during Prestressing

The compressive strength of concrete during prestressing should be in accordance with Clause 16.8.3 in III, Concrete Bridge Volume, Highway Bridge Specifications.

Commentary :

In the case of using FRP tendons of configurations with low bond values in pretensioning, a separate examination of the compressive strength of the concrete should be made.

6.4.3 Pretensioning System

- (1) The tensile force induced in an FRP tendon should achieve the specified value, taking into consideration losses due to friction along the tendon, slippage at the abutment, and all other relevant causes.
- (2) During prestressing, the locking device for each of the tensioned FRP tendons at the abutment should be released gradually in a manner such that all the tendons will be released uniformly.

Commentary:

(1) For individually tensioned FRP tendons using a wedge-type locking system, locking of the tendons occurs after the wedges are drawn into the collars. When the prestressing bench is comparatively long, the reduction of tension in the tendons due to draw-in of the wedges is not so significant and may be ignored. For a travelling bench system where the length of the bench is short or when the amount of draw-in is large, the reduction of tension in the tendons is considerable and cannot be ignored. Consequently, the loss of tensile force in the tendons due to draw-in of the wedges must be obtained beforehand by calculations or actual measurement. Tensioning of the tendons must be done in such a manner that the specified tensile force can be induced with all relevant losses accounted for.

(2) If the locking device for the FRP tendons at the abutment were to be released too suddenly, impact will be imparted to the concrete and there will be a risk of bonding between the FRP tendons and concrete being impaired. Therefore, when releasing the locking device to effect transfer of prestress to the concrete, it must be done gradually.

When high-temperature accelerated curing is used, there is a risk of the protruding ends of the tendons rupturing if the prestress is transferred after curing and cooling down has been completed. Hence it is desirable that the prestress should be transferred before the temperature in the concrete has dropped completely.

6.4.4 Post-tensioning System

- (1) The tensile force to be induced in an FRP tendon should account for losses due to friction, deformation or slippage at the anchoring device, and all other relevant causes.
- (2) In the event of tensioning in sequence, single tendons or groups of multiple tendons one at a time, care should be taken to prevent harmful stresses from occurring in the concrete at each stage. As the applied tensile force in each tendon or group will change due to elastic deformation of the concrete, this effect must be taken into consideration when determining the tensile force to be induced at the end of the FRP tendons.

Commentary:

(1) When inducing tensile force in an FRP tendon, the tensile force in the tendon becomes smaller with increasing distance from the tensioning end due to frictional loss. Therefore, in order to induce the specified tensile force in the FRP tendon at the design cross-section, it is necessary to apply a higher tensile force at the tensioning end of the tendon to account for frictional loss (see Section 3.2)

During stressing, the amount of frictional loss assumed in the design may differ from the actual value. Therefore, the magnitude of frictional loss must be measured according to the provisions as detailed in the following Section 6.4.6 and the tensile force to be applied to the end of the tendon should be adjusted accordingly. When it becomes necessary to apply an excessively large tensile force to the end of the FRP tendon in order to achieve the required tension at the design cross-section, it is advisable to coat the tendon with a water soluble lubricant or inject lubricant into the duct to reduce friction. In such a case, the lubricant must be flushed away before injection of grout. This is especially important when the FRP tendons are to be anchored by a wedge-type anchoring device. Care must be taken to ensure that the lubricant does not adhere to the wedges. Reduced friction between tendon and wedges will make the anchoring system ineffective and any lubricant in this area must be removed by washing thoroughly with water.

Furthermore, slippage at the anchoring device and the associated loss in tensile force in the tendon must be determined beforehand. The tensioning operation must be repeated if this pre-determined amount of slippage is exceeded.

(2) When tensioning is performed on a group of single or multiple tendons in sequence one at a time, there will be cases where, because only a part of the FRP tendons is pulled, twisting or lateral bending of the beam occurs depending on the size and location of the FRP tendons. In the case of an indeterminate structure, it can cause an indeterminate force to occur. Therefore, taking these effects into

consideration, the method and sequence of tensioning as well as the magnitude of the tensile force must be determined so that harmful stresses do not occur in the concrete during all stages of tensioning.

With a post-tensioning system, the amount of FRP tendon pulled out from the concrete member is normally measured and the elongation of the tendon is obtained by deducting the elastic deformation of the concrete from the amount pulled out. When all FRP tendons are tensioned simultaneously, the elastic deformation of the concrete can be ignored. When the FRP tendons are tensioned in sequence individually or as a group, the elastic deformation of the concrete due to each tendon or group of tendons will become smaller in inverse proportion to the number of single or groups of tendons. When the number is large, the amount of pull-out of the FRP tendons may be considered as elongation in relation to the total length. However, the tensile force in those FRP tendons tensioned previously will be reduced from their original value due to elastic deformation of the concrete caused by subsequent tensioning of other FRP tendons. Therefore, the tensile force to be induced in each FRP tendon must be adjusted by determining the reduction in average tensile force of the FRP tendons according to the method outlined in Section 3.2.

For calculating the amount of pull-out, the apparent Young's modulus of the FRP tendons obtained by testing on site must be used. The effect of the difference between the amount of pull-out and elongation of the FRP tendons mentioned above is included in the value of apparent Young's modulus.

6.4.5 Other Details

- (1) Formwork and supports for the prestressed concrete member should be constructed in such a manner that they will not suffer from harmful deformation or settlement due to prestressing.
- (2) The surface at the end of a member and the anchoring devices should be protected against damage or corrosion after prestressing.
- (3) For a pretensioning system, the protruding ends of the FRP tendons should be cut flush against the end of the beam after the transfer of prestress.

Commentary:

- (1) When the elastic deformation of the member due to prestressing is restrained by the formwork or supports, it will be impossible for the specified prestressing force to be induced in the member and there will be a risk of the support collapsing due to this effect. Therefore, it will be desirable to reduce the restraints on deformation of the member during prestressing by removing appropriate parts of the formwork

before prestressing.

(2) An anchoring device will always be in a state of high stress. Ample protection must be provided to prevent it from damage due to external impact and entry of rain water causing corrosion.

(3) If cutting of an FRP tendon is done by flame after the transfer of prestress, there will be adverse effects on properties of the tendon. Therefore, cutting should be done at ambient temperature using a cutter, shearing machine or similar. After cutting, the end of the FRP tendon does not require rust inhibiting treatment.

6.4.6 Control of Prestressing

Control of prestressing should be carried out following the provisions of Clause 16.8.6 in III, Concrete Bridge Volume, Highway Bridge Specifications.

Commentary:

Prestress using FRP tendons does not differ fundamentally from that using steel, and so the provisions of the Highway Bridge Specifications can be adopted.

It is advisable to control prestressing by preparing a control chart for each of the FRP tendons using the "Control Method based on Coefficient of Friction", taking care that an abnormal condition does not exist. The limit to the control of the coefficient of friction, μ , should be decided upon by examination of the design calculation when planning the prestress. When straight tendons are used or the profiles of the tendons have relatively small angle of inclination, it is advisable to exercise control based on elongation of the tendon at a load shown by the load gauge.

Furthermore, calibration of the prestressing equipment, the value of coefficient of friction, and the apparent Young's modulus are to be determined using provisions of the Highway Bridge Specifications. Measurement of the coefficient of friction must be done before the start of construction. This measurement must be repeated if abnormality is being detected during the controlled tensioning.

Values of Young's modulus and coefficient of friction for various FRP tendons can be found in Table 2.2 and Table Comm.2.6.

6.5 Grouting

Grout should afford adequate protection to the FRP tendons and be capable of securing the tendons to the concrete member monolithically.

Commentary:

Grout injection is the most important operation affecting durability of a prestressed concrete member. For the grouting operation, care must be exercised in the inspection of injection equipment, site conditions, and the quality of materials.

Grout injection should be carried out as soon as possible after transfer of prestress. Interior of ducts must be completely filled with grout.

CHAPTER 7 QUALITY CONTROL

7.1 General

Quality control must be applied to all materials and hardware, such as concrete, FRP reinforcement, reinforcing steel, grout, anchoring devices and connectors, to ensure compliance with the specifications when constructing prestressed concrete bridges.

Commentary:

Quality control must be exercised in all stages of construction of prestressed concrete bridges. To achieve this objective, the materials as well as machinery, facilities and even methods of working are considered to require proper control. As fundamental matters concerning quality control in prestress concrete bridges using FRP materials are not thought to be different from those for reinforced concrete or prestressed concrete structures using conventional steel, it was recommended that a standard specification for concrete as detailed in the "Guide to the Design and Methods of Construction for Prestressed Concrete" should be adopted. Furthermore, the publication entitled "Applications of Continuous Fiber Reinforcing Materials to Concrete Structures" should be referred to also.

7.2 Control by Testing

7.2.1 Test Methods

Test methods should be in accordance with those specified in the JIS or equivalent standards.

Commentary:

As there are no standards available at present specifying unique test methods for FRP tendons, anchoring devices and sheaths, the two references quoted in the commentary of Section 7.1 should be consulted in addition to the JIS.

7.2.2 Tests on FRP Tendons

FRP tendons should be used only upon performing tests on the items listed below and confirmation of quality.

- (1) Tensile strength
- (2) Young's modulus
- (3) Bond strength
- (4) Fatigue strength (static, dynamic)
- (5) Creep characteristics
- (6) Coefficient of thermal expansion
- (7) Relaxation
- (8) Weathering resistance

Commentary :

When adopting newly developed FRP tendons, the above tests must be performed from the point of view of obtaining those basic properties required for structural design and understanding the effects of environmental conditions on such basic properties.

Various types of FRP reinforcing material are available at present and their mechanical properties differ widely. Currently, there is a growing trend to attempt using these materials as substitutes for prestressing steel and reinforcing bars but data on material tests performed according to some standard or unified test methods are limited. There are difficulties in evaluating fundamental data required for design. This problem is exacerbated by the wide scatter of the values obtained. Another problem yet to be resolved is the establishment of the unified test methods and material standards but for the time being, it will be satisfactory to follow the recommendations in Section 7.1 regarding test methods. When the conditions during testing and actual construction are different or when site conditions require additional tests not listed above to be performed, the Engineer must exercise judgement in devising such additional test methods for implementation.

Even when ample tests have been performed on the material and its properties and constants required for design have been obtained, e.g., those listed in Table 2.1, it is considered necessary to perform at least simple tests on the tensile strength and Young's modulus of the material in order to ensure that the quality of the product to be used is the same as that assumed in the design.

7.2.3 Tests on Anchoring Devices and Connectors

- (1) Anchoring devices and connectors should be tested to ensure quality prior to application. Testing may be omitted if these are of guaranteed quality and proven performance.
- (2) Anchoring devices and connectors should be of such strength and construction so that they do not become excessively deformed or damaged at a load lower than that specified.
- (3) Tests to assess the quality of anchoring devices and connectors should be conducted by appropriate methods which simulate the conditions during prestressing and service.

Commentary:

(1) The performance of anchoring devices and connectors are of importance in the utilization of FRP tendons. It is possible to improve on those anchoring devices for prestressing tendons of CFRP (I), CFRP (II), AFRP (I), and AFRP (II) as listed in Table 2.1 When future improvements are made or non-metallic anchoring devices and connectors are developed, tests must be conducted to ascertain their quality.

(2) When assessing the performance of an anchoring device or a connector, the tests must be conducted in combinations of the anchoring device or connector with either concrete or a tendon. It is also advisable for the characteristics specific to the anchoring device to be obtained, e.g., the amount of take-up for an anchoring device using wedges.

Results of the tests are to satisfy the following requirements:

a. Test Combining Anchoring Device or Connector with Concrete

The anchorage (portion including anchoring device, connector and adjacent concrete) must be capable of withstanding a load not less than the product of the standard tensile load of the FRP tendon multiplied by the FRP anchoring coefficient, R .

b. Test Combining Anchoring Device or Connector with Tendon

The anchoring device or connector must be capable of safely holding a load equal to 95% of the product of the standard tensile load of the FRP tendon multiplied by the FRP anchoring Coefficient, R .

(3) When the service conditions of anchoring devices or connector in the actual structure is significantly different from test conditions, it will be essential to conduct partial model tests on the anchorage or connection emulating actual method of construction and service conditions rather than testing only the anchoring device or connector in isolation.

In actual structures, the temperature and environmental conditions causing deterioration can vary or the fatigue strength may become a cause of concern. Should it becomes necessary for tests to be conducted, the Engineer must devise the test methods with realistic test conditions.

7.2.4 Tests on Sheaths

Sheaths should be tested to ascertain their quality prior to application. Testing may be omitted if they are of guaranteed quality and proven performance. Tests on sheaths should be performed by appropriate methods which take material characteristics and performance into consideration.

Commentary :

The above provision covers possible development of sheaths using new materials which are non-corrodable. The information given in Section 7.1 can be referred to when a standard test method is required. Depending upon the material of the sheath, there will be cases where confirmation of performance of the sheath are required. The Engineer must conduct tests using appropriate methods and giving thorough consideration to the material and characteristics of the sheaths concerned. An example of the performance criteria for sheaths is as below.

- a. the induced tensile force in the tendon due to loading can be transmitted to the concrete as compression via the grout and sheath;
- b. temperature changes will not cause cracking of the concrete due to different coefficients of thermal expansion of the concrete, grout and sheath.

DATA SECTION

1. Other Tendons

Table A -- Other Tendons

Fiber	FRP Type	Configuration	FRP Tendon Composition	Wire, Rod Denomination	System	Anchoring System	Tensile Load (tf)	Effective Cross-Sectional Area (mm ²)
Carbon	CFRP (I)	Strand	1- ϕ 19.3	19.3mm	Single	Resin	28.3	180.2
			1- ϕ 20.3	19-strand 20.3mm	Single	Resin	30.3	193.9
			1- ϕ 21.8	19-strand 21.8mm	Single	Resin	34.7	222.2
			1- ϕ 25.0	19-strand 25.0mm	Single	Resin	45.5	290.9
			1- ϕ 28.0	19-strand 28.0mm	Single	Resin	58.5	374.1
			6- ϕ 15.2	19-strand 15.2mm	Multi	Wedge	97.4	681.6
			8- ϕ 15.2	7-strand 15.2mm	Multi	Wedge	129.9	908.8
			10- ϕ 15.2	7-strand 15.2mm	Multi	Wedge	162.4	1136.0
				7-strand				
	CFRP (II)	Indented rod	2- ϕ 8	8mm indented	Multi	Wedge	20.0	92.2
			3- ϕ 8	8mm indented	Multi	Wedge	30.0	138.3

DATA SECTION

Table A -- Other Tendons (Continued)

Fiber	FRP Type	Configuration	FRP Tendon Composition	Wire, Rod Denomination	System	Anchoring System	Tensile Load (tf)	Effective Cross-Sectional Area (mm ²)
Carbon	CFRP (II)	Indented rod	5- ϕ 8	8mm indented	Multi	Wedge	50.0	230.5
			7- ϕ 8	8mm indented	Multi	Wedge	70.0	322.7
			8- ϕ 8	8mm indented	Multi	Wedge	80.0	358.8
			9- ϕ 10	10mm indented	Multi	Wedge	135.0	662.4
Aramid	AFRP (I)	Braided rod	1- ϕ 10.4	10.4mm braided	Single	Wedge	12.0	85.0
			1- ϕ 12.7	12.7mm braided	Single	Wedge	18.0	127.0
			1- ϕ 14.7	14.7mm braided	Single	Wedge	24.0	170.0
			1- ϕ 18.0	18.0mm braided	Single	Wedge	35.0	254.0
			6- ϕ 10.4	10.4mm braided	Multi	Wedge	72.0	510.0
			3- ϕ 12.7	12.7mm braided	Multi	Wedge	54.0	381.0

DATA SECTION

Table A -- Other Tendons (Continued)

Fiber	FRP Type	Configuration	FRP Tendon Composition	Wire, Rod Denomination	System	Anchoring System	Tensile Load (tf)	Effective Cross-Sectional Area (mm ²)
Aramid	AFRP (I)	Braided rod	4- ϕ 14.7	14.7mm braided	Multi	Wedge	96.0	680.0
			6- ϕ 14.7	14.7mm braided	Multi	Wedge	144.0	1020.0
	AFRP (II)	Deformed rod bundle	3- ϕ 6	ϕ 6mm	Multi	Mortar injection	15.2	84.9
			4- ϕ 6	ϕ 6mm	Multi	Mortar injection	20.4	113.2
			19- ϕ 6	ϕ 6mm	Multi	Mortar injection	96.9	537.7
			2- ϕ 7.4	ϕ 7.4mm	Multi	Mortar injection	15.2	84.8
			3- ϕ 7.4	ϕ 7.4mm	Multi	Mortar injection	22.8	127.2
			9- ϕ 7.4	ϕ 7.4mm	Multi	Mortar injection	68.4	381.6
			12- ϕ 7.4	ϕ 7.4mm	Multi	Mortar injection	91.2	508.8

2. Anchoring Device Dimensions

(69)

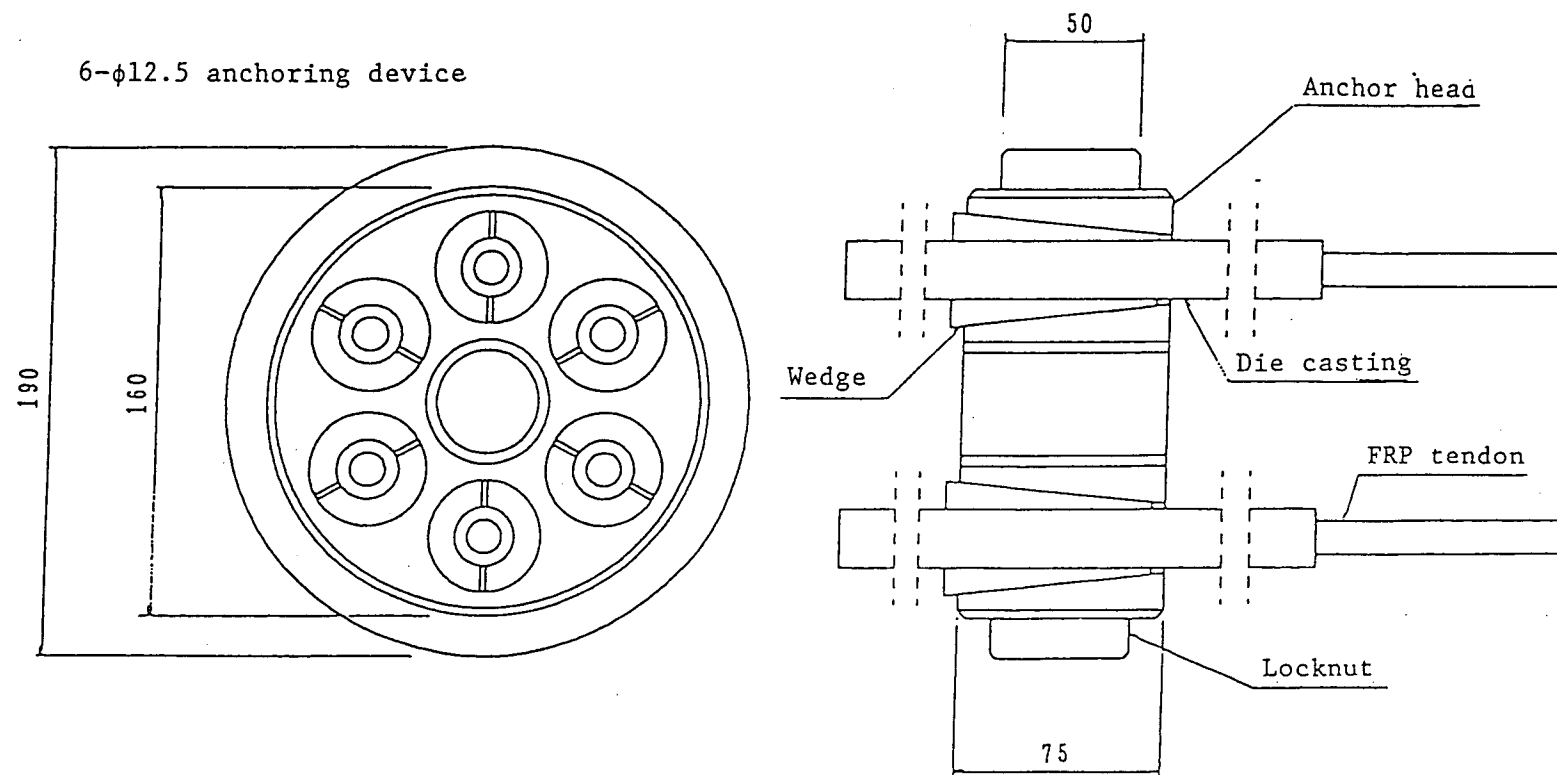
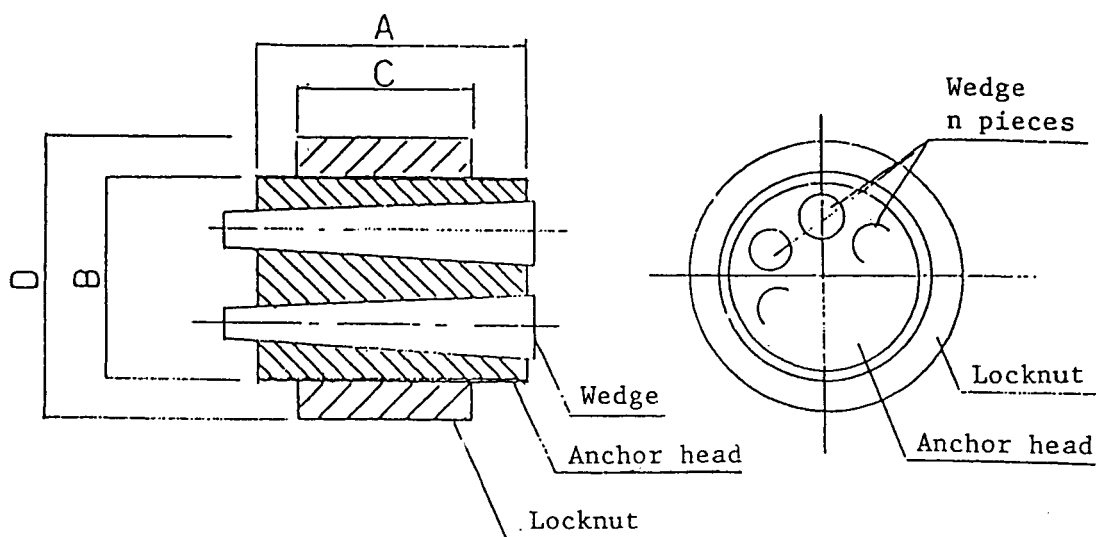
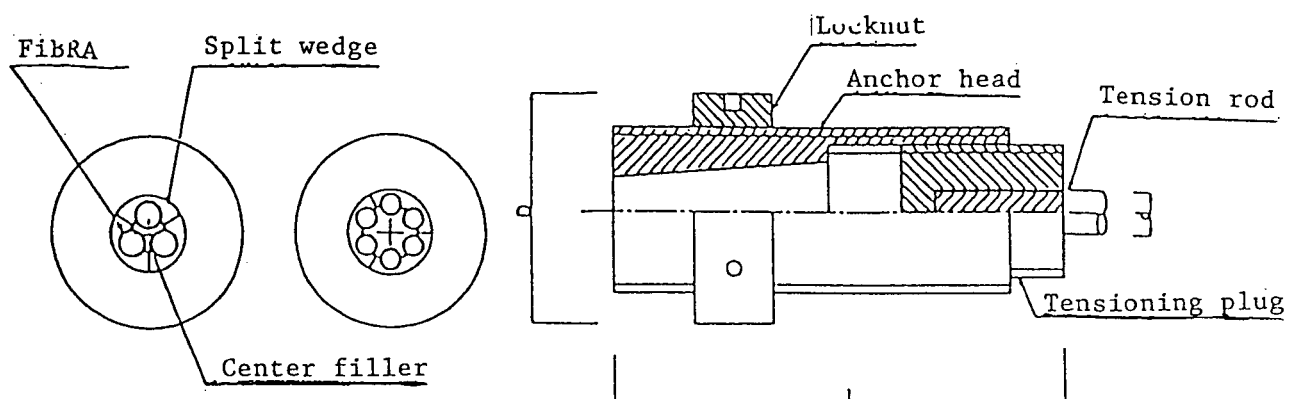


Fig. A -- Carbon (I) Anchoring Device Dimensions

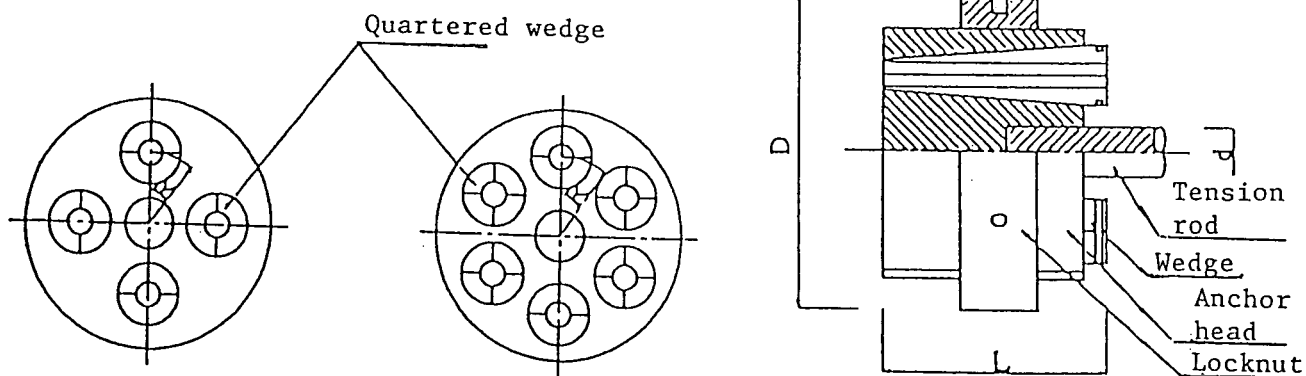


FRP Tendon Composition	A (mm)	B (mm)	C (mm)	D (mm)	Wedge Qty (n)
1- ϕ 8	75	36	50	60	1
2- ϕ 8	75	60	50	80	2
3- ϕ 8	75	60	50	80	3
4- ϕ 8	75	64	50	84	4
5- ϕ 8	75	74	50	84	5
7- ϕ 8	75	80	50	105	7
8- ϕ 8	75	80	50	115	8
1- ϕ 10	85	40	50	60	1
6- ϕ 10	85	85	50	110	6
7- ϕ 10	85	95	50	120	7
9- ϕ 10	85	100	50	125	9

Fig. B -- Carbon (II) Anchoring Device Dimensions

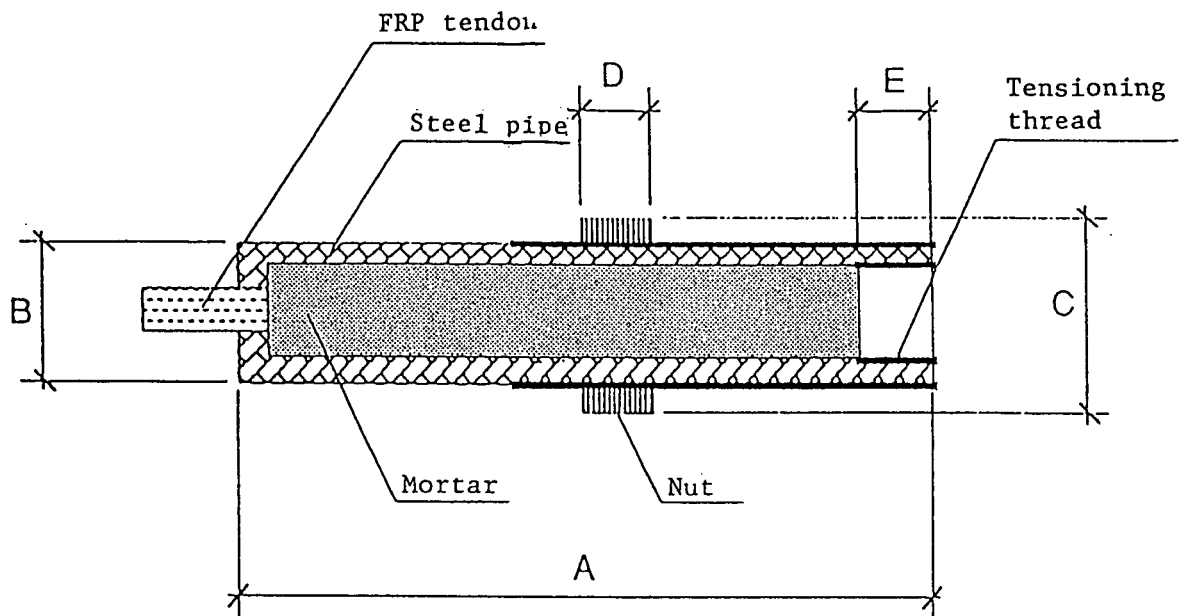


FRP Tendon Composition	D (mm)	L (mm)	d (mm)
6- ϕ 10.4	160	277	26
3- ϕ 12.7	140	277	26



FRP Tendon Composition	D (mm)	L (mm)	d (mm)
6- ϕ 12.7	190	110	40
4- ϕ 14.7	190	145	32
6- ϕ 14.7	200	145	32

Fig. C -- Aramid (I) Anchoring Device Dimensions



FRP Tendon Composition	Anchoring Device	A	B	C	D	E
7- ϕ 6	Tensioning side	560	61	90	40	50
	Fixed side	510	61	90	40	0
9- ϕ 7.4	Tensioning side	560	77	110	40	50
	Fixed side	510	77	110	40	0
12- ϕ 7.4	Tensioning side	570	102	130	40	50
	Fixed side	520	102	130	40	0
19- ϕ 6	Tensioning side	590	102	130	40	60
	Fixed side	530	102	130	40	0

Fig. D -- Aramid (II) Anchoring Device Dimensions

3. Model Method for Material Testing

A. Scope of Application

The suggested method given here for testing new materials is modelled on that used in the Collaboration Research. When testing FRP tendons, the method should be followed.

B. Tensile Test on FRP Tendons

(a) Test Environment

The temperature during testing should be $20^{\circ}\text{C} \pm 2^{\circ}$. The relative humidity at the test site should be maintained and recorded for the whole duration of the test.

(b) Tensile Test Apparatus

The apparatus used should satisfy the conditions as follows:

- (i) the apparatus should have a tensile capacity in excess of that of the test specimen;
- (ii) it can maintain a constant rate of loading as required;
- (iii) it should be of such a construction that the specimen will neither slip nor be damaged by the grips of the apparatus.

(c) Anchoring of the Specimen

- (i) Anchoring of the specimen should be achieved in such a manner that the specimen will not fracture or slip at this location during testing.
- (ii) The method of anchoring does not cause an eccentric load to be applied to the specimen.

(d) Specimen Dimensions

(i) Total length, L

The total length of the specimen should be sufficient to provide effective anchorage at each end. The length L is inclusive of the lengths of the anchorage and chuck portions of the apparatus, b.

(ii) Length of Test Section, L' (see Ref.1 in this Section)

This is the total length less the lengths of the anchorage and chuck portion and L' should be 400 mm, i.e., $L' = L - b = 400 \text{ mm}$.

(e) Test Specimens

- (i) These should be made from the actual FRP product. Fabrication or

modification to the specimens should not be carried out except for the anchorage portions.

(ii) Six specimens should be used in each tensile test.

(f) Rate of Loading

The rate of loading can be determined by either of the methods given below.

(i) The tensile load is applied to the material fibers at 50 ± 5 kg/mm²/min, giving consideration to the volumetric fiber content V_{fa} (see Ref. 2).

(ii) The tensile load is applied to the entire cross-sectional area of the specimen including resin at 50 ± 5 kg/mm²/min, irrespectively of the volumetric fiber content.

The cross-sectional areas of various FRP tendons and the respective volumetric fiber contents are given in Table B.

(g) Test Measurements and Records

(i) Loads

Loads applied to the specimens during testing should be measured by calibrated load cells.

(ii) Strains

Strains measurements during testing should be obtained by strain gauges or clip-on type linear transducers. Care should be taken to avoid the gauges being peeled off or the clips being dislodged.

(iii) Failure Condition

The failure condition and location of rupture of each specimen should be recorded by diagrams, photographs, etc.

(h) Test Results

Results in a test should be the statistical average of the 6 specimens including standard deviation as appropriate.

The following results should be obtained:

(i) Tensile Capacity (P_u)

This is the mean of the maximum loads recorded during tensile tests.

(ii) Tensile Strength (σ_{pu})

This is obtained from dividing the tensile capacity by the nominal cross-sectional area of the specimen (see Table B in this Data Section).

(iii) Stress-Strain ($\sigma - \epsilon$) Curve

The $\sigma - \epsilon$ curve should be determined by the nominal stress (load divided by the nominal cross-sectional area of the specimen) and the corresponding strain measured during tensile tests. The following should be indicated on the $\sigma - \epsilon$

curve (see Ref. 1).

- Tensile strength (σ_{pu}), strain under maximum tensile load (ε_{pu})
- Modulus of elasticity: The stress points used should be clearly indicated, and the secant modulus used.
- Yield point (σ_{py}), strain at yielding (ε_{py}): tensile stress, strain at point on $\sigma - \varepsilon$ curve where stress is not increased and strain begins to increase.
- Proportional limit (σ_{pel}), proportional limit strain (ε_{pel}): stress and strain when the $\sigma - \varepsilon$ curve begins to deviate from a straight line.
- Strength at rupture (σ_{ul}), strain at rupture

References :

1. "Evaluation Items and Evaluation Methods for New Reinforcing Materials and New Reinforced Concrete (Draft)"
Discussion Material 18-7, Architectural Institute of Japan
2. "Tentative Proposal Concerning Criteria and Testing Methods for New Base Material as Reinforcing Materials for Concrete"
Concrete Library, No. 68, Japan Society of Civil Engineers
Discussion Material 19-5-2

Table B -- Total and Fiber Content Cross-sectional Areas of Various FRP Tendons

	Carbon I	Carbon II	Aramid	Aramid	Glass
Total cross-sectional area A_r (mm ²)	76.0	44 49	84.95	28.3	50
Volumetric fiber content V_{fa} (%)	63.8	65 65	72.6	65.0	68
Cross-sectional area of fiber A_{fa} (mm ²)	48.5	29 32	61.7	18.4	34

Note) i) A_r : total cross-sectional area of tendon including resin content

A_{fa} : cross-sectional area of fiber content

$$A_{fa} = (V_{fa}/100) \times A_r$$

- ii) For the Carbon II group, the upper figures are applicable to tendons for pretensioning whilst the lower figures are for post-tensioning.