CHAPTER 3: DESIGN VALUES FOR MATERIALS

3.1 GENERAL

(1) The quality of concrete and reinforcing materials are expressed, in addition to compressive strength and tensile strength, in terms of material characteristics such as strength characteristics, Young's modulus, deformation characteristics, thermal characteristics, durability, water tightness etc., according to the design requirements. In the case of strength and deformation characteristics, loading velocity may have to be taken into consideration.

(2) The characteristic values given for material strength and ultimate strain of CFRM are minimum values the majority of test results are guaranteed to exceed, allowing for variations in test values.

(3) Values for the design strength of materials and the design ultimate strain of CFRM shall be obtained by dividing the relevant characteristic values by the material coefficients.

[COMMENT]:

(2) It is recognized that the tensile strengths obtained from tensile tests using the same CFRM show greater variation than does steel. The amount of variation in tensile strength differs depending on the type, geometry etc. of the continuous fibers and the fiber binding material, and variation is found even for the same CFRM depending on the length of the test piece and the anchoring method used during testing. The characteristic values for the material strength of CFRM are therefore minimum values the majority of test results are guaranteed to exceed.

3.2 CONCRETE

It shall be in accordance with JSCE Standard Specification (Design), 3.2.

3.3 STEEL

It shall be in accordance with JSCE Standard Specification (Design), 3.3.

3.4 CFRM

3.4.1 Capacity

(1) Characteristic values for tensile capacity of CFRM shall be determined on the basis of tensile tests. Tensile tests shall be conducted in accordance with "Test Method for Tensile Properties of Continuous Fiber Reinforced Materials (JSCE-E 531-1995)".

(2) For materials conforming to "Quality Specifications for Continuous Fiber Reinforced Materials (JSCE-E 131)", the tensile capacity may be taken to be identical to the guaranteed capacity.

(3) Where CFRM is to be shaped by bent portion or curved placement, or where CFRM are to be subjected to diagonal tensile forces, the capacity shall be determined based on the results of suitable tests.

(4) The design strength of bent portion of CFRM shall normally be calculated as follows:

$$f_{fbd} = f_{fbk} / g_{mfb} \quad (3.4.1)$$

where $$f_{fbk} = \left(0.05\frac{r}{h} + 0.3\right) f_{fuk} \quad (3.4.2)$$

If the right side of the above equation resolves to a value greater than f_{fuk}, f_{fbk} shall be taken as f_{fuk}.

f_{fbk} : characteristic value of strength of bent portion
f_{fuk} : characteristic value of unconfined tensile strength
r : internal radius of bend
h : cross-sectional height of CFRM
g_{mfb} : can generally be taken as 1.3

(5) The design strength of CFRM to be used in a curved placement may be obtained by subtracting the elastic bending stress of the curved portion from the design strength of the straight portion.

(6) The compressive capacity and shear capacity of CFRM may be ignored for design purposes.

(7) The material coefficient g_{mf} of CFRM shall be determined allowing for the quantity and deviation of test data, possible damage to CFRM during transportation and construction, differences in material characteristics between test pieces and actual structures, the effects of material characteristics on the limit state, service temperatures, environmental conditions etc. g_{mf} may generally be set between 1.15 and 1.3.

[COMMENTS]:

(1) CFRM are compound materials formed from continuous fibers and fiber binding materials. When forces act on CFRM, therefore, at the microscopic level the local stresses acting on individual fibers and the binding materials will vary. When considering CFRM as reinforcing material in concrete, however, it is simpler to treat the CFRM as a monolithic material. The strength of CFRM is thus taken to be the capacity of the entire section (at maximum load). If the nominal-cross sectional area of the CFRM is known, strength (maximum load / nominal cross-sectional area) may be used instead of capacity.

(3) If CFRM are to be used in bent portion or in curved placement, or if the CFRM are subjected to diagonal tensile forces such that diagonal cracks occur, the tensile capacity falls below the unconfined tensile capacity of the straight CFRM. In bent portion or curved placement, the rate of reduction has been confirmed experimentally to be dependent on the ratio of the radius of curvature of the bent portion or curved placement and the diameter of the CFRM, on the angle of the working tensile force if diagonal tensile forces are present, etc. In such cases, the capacity shall be determined on the basis of the results of suitable tests. When CFRM are to be used in curved placement, the capacity shall

normally be determined according to "Test Method for Flexural Tensile Properties of Continuous Fiber Reinforced Materials (JSCE-E 532-1995)".

(4) The strength of bent portion varies greatly even for the same type of fiber, depending on the bending technique, type of resin used etc., therefore the strength of the bent portion will generally be determined on the basis of suitable tests. From comparisons with existing test data, the strength of bent portion has been found to be derivable as a function of the internal radius of the bent section, from Eq. (3.4.1). The regression equation in **Fig. C 3.4.1** gives the averages of all test data. The design equation Eq. (3.4.2), based on this regression formula, gives an adequate margin of safety.

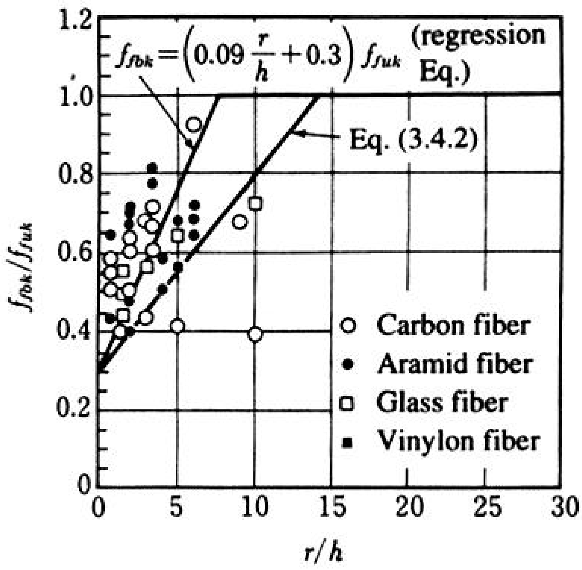

Fig. C 3.4.1: Strength of bent portion

(5) CFRM generally have a lower elastic modulus than steel reinforcement, so they can be bent and arranged within the elastic region. At small bending radii, though, the strength of the bent portion is reduced by the effects of elastic bending stress and bearing stress. The policy adopted here has been to approximate these effects by subtracting the elastic bending stress from the strength of the straight portion.

(6) CFRM consist of extremely fine collection of fibers, and therefore have extremely low compressive and shear capacity when used as reinforcing material. In normal designs, therefore, compressive and shear capacity of CFRM will be ignored.

3.4.2 Fatigue capacity

(1) The characteristic values for fatigue capacity of CFRM shall be determined based on fatigue capacity derived from fatigue tests conducted allowing for the type, size, anchoring, intensity and frequency of working stress, environmental conditions etc.

(2) The material coefficient g_{mf} relating to the design fatigue capacity of CFRM is determined allowing for the quantity and deviation of fatigue test data, service temperatures, environmental conditions etc. If the CFRM are liable to suffer damage during transportation and construction, the effects of such damage shall be allowed for in g_{mf}. g_{mf} may generally be set between 1.15 and 1.3.

[COMMENTS]:

(1) The quantity of research findings relating to the fatigue in CFRM is still inadequate, and further experimental investigations are required.

When CFRM is used as tendons in prestressed concrete, if cracking is not allowed, the variable stresses will be small and the effects of fatigue will be negligible, but if cracking is allowed, fatigue must be verified in the same way as if prestress was not present. The fatigue capacity of CFRM requires the fatigue characteristics not only of the CFRM, but also of the anchorages to be clarified. As loss of capacity due to secondary stresses in particular, is significant in CFRM, the fatigue characteristics including those of the anchorages are important.

The static capacity of bent portion is known to be considerably lower than that of straight portions for certain types of CFRM. The fatigue capacity of bent portion is still lower than the static capacity of bent portion.

Where slipping of CFRM occurs at intersections with cracks etc., fatigue strength is known to be reduced even in conventional steel reinforcement, but the fatigue capacity in CFRM is reduced still further because the static capacity is also reduced. This reduction of fatigue capacity occurs at the intersections with shear cracks of both shear and tensile reinforcement.

3.4.3 Tensile force-strain relationship

(1) The tensile force-strain curve of CFRM used in verification of ultimate limit state may be assumed to follow the model shown in **Fig. 3.4.1**, in which a straight line connects tensile capacity obtained from tests and the corresponding ultimate strain points with the origin.

(2) The tensile force-strain curve used in verification of the serviceability limit state of CFRM may be assumed to follow the model shown in **Fig. 3.4.2**, in which a straight line connects the tensile rigidity calculated in accordance with "Test Method for Tensile Properties of Continuous Fiber Reinforcing Materials (JSCE-E 531-1995)".

(3) The tensile force-strain curve used in verification of the fatigue limit state of CFRM shall be the same as that used in verification of the serviceability limit state.

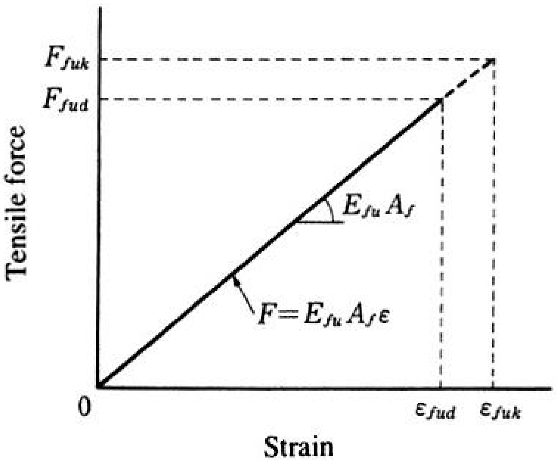

Fig. 3.4.1 Tensile force-strain curve used for the design of ultimate limit state

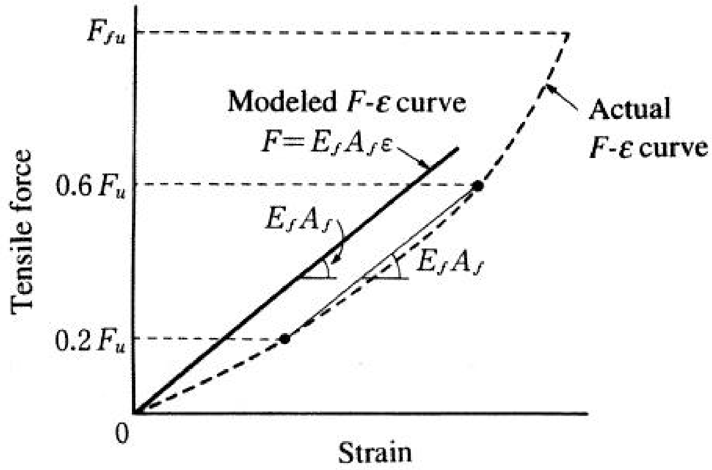

Fig. 3.4.2 Tensile force-strain curve used for the design of serviceability limit state

[COMMENTS]:

(1) The tensile force-strain curves for CFRM vary slightly depending on the type of fiber, but in general the tangential rigidity varies with the load level as shown in **Fig. 3.4.2**, therefore models have been set up for each limit state. For the tensile force-strain curve used in verification of ultimate limit state, test for tensile strength according to JSCE-E 531 is carried out and the bearing characteristics of capacity are calculated according to JSCE-E 131. The design capacity is obtained by dividing this by the material coefficient, and the design ultimate strain is obtained by dividing this by the nominal cross sectional area and Young's modulus.

(2) The tensile force-strain curve used in verification of the serviceability limit state is the tensile force-strain curve obtained according to JSCE-E 531, assumed to be a straight line through the origin having the same gradient as the line connecting the points corresponding to tensile capacity of 20% and 60%.

3.4.4 Coefficient of thermal expansion

The coefficient of thermal expansion of CFRM shall generally be as given in **Table 3.4.1**.

Table 3.4.1 Thermal expansion coefficient of CFRM

Type of CFRM	Thermal expansion coefficient ($\times 10^{-6}$/°C)
Aramid fiber	-6
Carbon fiber	0
Glass fiber	10

[COMMENT]:

The coefficients of thermal expansion of CFRM in the axial direction vary depending on the type of fiber, within the ranges shown in **Table C 3.4.1**. The values given in **Table C 3.4.1** for glass fiber are the same as those for concrete. Conservative values are given for other types of fiber, where the coefficients of thermal expansion are different from those of concrete.

Table C 3.4.1 Thermal expansion coefficient of CFRM

Type of CFRM	Thermal expansion coefficient ($\times 10^{-6}/ ^{\circ}C$)
Aramid fiber	-2 ~ -6
Carbon fiber	0.6 ~ 1
Glass fiber	9 ~ 10

3.4.5 Relaxation rate

(1) Relaxation rate for CFRM shall generally be as calculated according to "Test Method for Long-Term Relaxation of Continuous Fiber Reinforcing Materials (JSCE-E 534-1995)".

(2) The apparent relaxation rate to be used in calculating prestress loss shall be based on the relaxation rate of the CFRM, allowing for the effects of drying shrinkage and creep of the concrete.

[COMMENTS]:

(1) As little data is available relating to relaxation rate of CFRM, and long-term data (more than 1000 hours) is especially lacking, it has been decided to use the values obtained according to JSCE-E 534. The relaxation rate corresponding to a service life of 100 years is taken to be the value for 1 million hours, extrapolated from the relaxation values for times in excess of 1000 hours. Where the service life of the structure is determined in advance, the relaxation value corresponding to the predetermined service life may be applied.

(2) Little experimental data is currently available on which to base an equation for the calculation of apparent relaxation rate. This may therefore be estimated on the basis of test data, or if necessary the net relaxation rate may be used.

3.4.6 Creep failure capacity

The creep failure capacity of CFRM shall be calculated according to "Test Method for Creep Failure of Continuous Fiber Reinforcing Materials (JSCE-E 533-1995)".

[COMMENT]:

CFRM subjected to sustained stresses for long periods may undergo rupture (creep failure) at less than the static bearing capacity. This creep failure capacity varies depending on the fiber type. Tensioning must therefore be carried out allowing for the creep failure capacity when CFRM is used as tendons. For design purposes, the creep failure capacity is that corresponding to a design service life of 100 years and the creep failure capacity based on the 1 million hour creep failure - limit load ratio given in JSCE-E 533 shall be applied. Where the service life of the structure is determined in advance, the creep failure capacity corresponding to the predetermined service life may be estimated from the 1 million hour creep failure - limit load ratio.