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APPLICATION OF CONTINUOUS FIBER REINFORCING MATERIALS TO CONCRETE STRUCTURES

(Translation from the CONCRETE LIBRARY NO.72 published by JSCE, April 1992)

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SYNOPSIS

As fiber made of materials like glass, carbon, aramid and vinylon, are very high resistance to corrosion, more and more attempts are being made to utilize continuous fiber reinforcing materials (CFRM) in reinforced and prestressed concrete structures instead of steel. However, CFRM is a composite material composed of millions of fibers and binding material, and has little plastic behavior. The mechanical behavior of reinforced concrete using CFRM is quite different compared to conventional reinforced concrete. As of now there is no general agreement relating to the methodology to be adopted in the case of design or testing methods of such fibers.

The Concrete Committee of the JSCE (Japan Society of Civil Engineers)under the chairman ship of K. Kobayashi set up a subcommittee in 1989 for the research on continuous fiber reinforced material. JSCE was entrusted by Association of composite material using continuous fiber for concrete reinforcement (CCC President: Minoru SUGITA) to perform further research on CFRM. The subcommittee set up three working groups and also asked the members to perform individual research.

The results obtained from this subcommittee are as follows:

(1) Design Concept for Concrete members using Continuous Fiber Reinforced Materials
(Chief: Yoshio KAKUTA)
(2) Test Methods for Continuous Fiber Reinforced Materials
(Chief: Atsuhiko MACHIDA)
(3) Concept for Durability of Continuous Fiber Reinforced Materials
(Chief: Hiroshi SEKI)
(4) A State-of-the-Art Report on Continuous Fiber Reinforced Materials for Concrete Structures

Among these, (1) to (3) are contained in this paper.

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I. DESIGN CONCEPT FOR CONCRETE MEMBERS USING CONTINUOUS FIBER REINFORCING MATERIALS

CONTENTS

1. Introduction

In recent years, durability and other features of continuous fiber reinforcing materials (CFRM) have been focused on, and technical research and developments have been done to use them as reinforcing material for concrete in place of steel reinforcing bars, or prestressing steel tendons.

This Report discusses design concept when using CFRM as reinforcement or tendons in concrete structures. Matters not discussed here are considered to be the same as steel reinforcement in reinforced concrete or prestressed concrete, and "JSCE" standard specification for design and construction of concrete structures shall be applied.

Test methods for determining characteristic values of CFRM have not yet been established. The mechanical properties of reinforced concrete members and prestressed concrete members using CFRM as reinforcements are still under study, and there are many points which are not clear yet. Ample performance records as with reinforcing steel and prestressing steel are also lacking. However, from a practical point of view, recommended ranges of values for design have been provided here tentatively regarding material factors and member factors using CFRM. We hope that with further studies and accumulation of data, there will be convergence to values of higher reliability.

One of the problems in using CFRM is the concern about low ductilities as members. Not all structures, members, or parts necessarily require great ductilities, but when using CFRM for structures which had conventionally been designed expecting ductility, it is necessary to thoroughly consider this point. Designing with high safety factor is one the methods of dealing with the problem. In this report, such a case is to be considered by member factor.

2. Terms Concerning Continuous Fibers

Continuous fiber: It is a general term for fibers used to reinforce concrete. For example, carbon fibers, glass fibers, aramid fibers, etc.. are frequently used.

Fiber binding material: Binder used to solidify continuous fibers together. For example in most cases plastic such as epoxy resin is used.

Fiber content: The ratio of the volume of actual fiber and volume of strand arranged in the direction of strengthening of the CFRM.

Continuous fiber reinforcing material (CFRM): General term for dimensionally strengthened material used for the purpose of reinforcing concrete on being formed by impregnating and hardening continuous fiber with fiber binding material, or only continuous fibers bundled or woven together.

Effective cross-sectional area of continuous fiber reinforcing materials: Volume of CFRM divided by its length.

Continuous fiber bar: CFRM in the form of bar similar to reinforcing steel.

Continuous fiber shape: CFRM in the form of H, T, L, I etc, sectional steel shape.

Continuous fiber prestressing material: CFRM used as prestressing material to induce prestress in concrete. Mostly in bar and strand forms.

Continuous fiber reinforced concrete: Concrete reinforced with CFRM .

Continuous fiber prestressed concrete: Concrete reinforced by inducing prestress with CFRM.

Besides the terms mentioned above, those below will be tentatively used in this Report I.

Bent shaping of continuous fibers: Shaping of continuous fibers in curved state hardened in bent form by fiber binding material. Available in spiral and stirrup forms.

Static fatigue: Phenomenon of fracture of continuous fiber or CFRM over time when continuous static tensile load acts on the material.

Static fatigue strength: Strength at failure (static fatigue failure or delayed failure) due to static fatigue.

Fiber rupture-type flexural failure: In continuous fiber reinforced concrete subject to flexure, the type of failure in which the CFRM ruptures before the compression zone of the concrete fails.

Fiber rupture-type shear failure: In continuous fiber reinforced concrete subject to shear force, the type of failure in which the CFRM used as shear reinforcement ruptures before the concrete fails.

3. Types, Methods and Properties of Continuous Fiber Reinforcing Materials

3.1 Types of Continuous Fiber Reinforcing Materials

(1) The CFRM considered here is a reinforcing material of fiber reinforced plastic or the like, developed as a substitute for concrete reinforcing steel for which there are available basic data concerning characteristic values required for designing.

(2) Generally, this type of reinforcing material consists of a multiple number (more than a million) of continuous fibers bundled together using a binding material such as resin. This type of

CFRM will have different physical properties depending on the material characteristics of the fiber used, fiber content, and cross–sectional and surface configurations of the reinforcing material. The fibers generally used are carbon fiber, aramid fiber, glass fiber, and vinylon fiber. As for binding material, epoxy resin and vinyl ester resin are mostly used. The configurations of reinforcing material may be classified to one dimensional bars, grids, and three–dimensional fabrics. One dimensional bars include continuous fiber bars in straight form, strand form, or braid form, and with fiber wound around the surface, or with silica sand adhering to the surface.

(3) The physical characteristics of a CFRM will differ depending on its configuration, the fiber used, binding material, manufacturing method, etc., and are thus difficult to determine. Therefore, it is necessary to obtain characteristic values required for designing by tests. When reliable characteristic values confirmed by tests are furnished by the manufacturer, it is permissible to use those values. And in case of a CFRM indicating a specific physical property, it is necessary to check its influence and confirm safety.

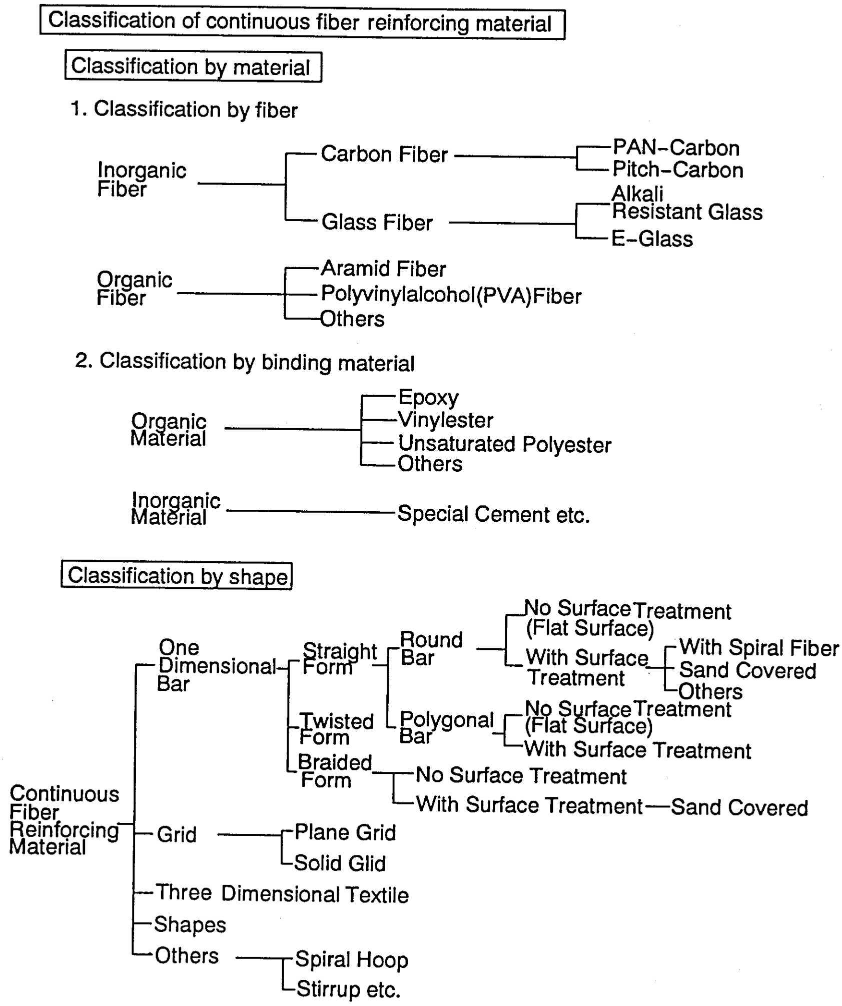


Fig. 3.1 Classification of continuous fiber reinforcing material

3.2 Methods of Use as Concrete Reinforcing Material

3.2.1 Features of Continuous Fiber Reinforcing

In general, a CFRM possesses the following features:

(1) High corrosion resistance: Unlike steel, continuous fibers in general such as of carbon, aramid, glass, vinylon, etc., and binding material of resin, do not corrode in chloride environment with strength loss.

(2) High strength: The tensile strength of continuous fibers is high with equivalent or higher strength compared with prestressing steel.

(3) Light weight: The specific gravities of continuous fibers are around 1.3 to 2.7 and they are extremely light weight compared with steel (about one–third or less).

(4) Nonmagnetic or less magnetic property: Unlike metal materials such as steel in general, the material is not magnetized.

(5) Others: Radio wave transmission property, radio wave shielding property, etc.

3.2.2 Modes of Utilization of Continuous Fiber Reinforcing Material

Taking advantage of the features listed in the above, the following modes of utilization are conceivable.

(1) Reinforced concrete bars and mesh

Utilization of CFRM substituting steel reinforcing bars in marine structures such as artificial islands, oil rigs, and pier fenders taking advantage of the high corrosion resistance.

Utilization of CFRM substituting steel reinforcing bars and wire mesh in slope protection concrete, and tunnel lining taking advantage of high corrosion resistance and light weight.

Utilization of CFRM as reinforcing material substituting steel reinforcing bars in sound–insulating walls and stay–in–place forms taking advantage of high corrosion resistance, high strength, and light weight.

(2) Prestressed Concrete Tendons

Utilizing of CFRM as tendons in prestressed concrete members such as prestressed concrete girders of high corrosion resistance and high strength.
Utilization of CFRM in track girders of magnetic levitation trains and office automation floors taking advantage of high corrosion resistance, high strength, and non magnetic properties.

(3) Reinforcing and Stiffening of Existing Reinforced Concrete Structures

Utilization of CFRM in reinforcing and stiffening of existing reinforced concrete structures such as in reinforcing of bridge piers for earthquake resistance (winding of fiber), reinforcing of girders (attachment of plates), etc. taking advantage of high corrosion resistance, high strength, and light weight.

(4) Other

There is a possibility for future utilization as hangers and cables of bridges taking advantage of high corrosion resistance,high strength, and light weight.

3.3 Mechanical Properties of Continuous Fiber Reinforcing Materials

3.3.1 Strength

The tensile strengths of CFRM are generally equal to or up to about two times higher than those of prestressing steel rods, and fairly high compared with ordinary steel. On the other hand, because CFRM are composed of extremely fine filaments that have been bundled, the compressive strength as reinforcing material is low.

3.3.2 Young's Modulus

The Young's modulus of CFRM are generally lower than that of steel. Therefore, when used as prestressing material for prestressed concrete, reduction of prestress due to creep of concrete and drying shrinkage is smaller. As a consequence, together with the fact that tensile strength is high, the advantage of CFRM can be effectively utilized if used as prestressing tendon for prestressed concrete.

On the other hand, because Young' s modulus is low and strength high, elastic strain of a concrete member becomes large. Due to this, crack width and deflection of concrete member become larger than steel reinforced concrete after cracking has occurred.

Furthermore, if the crack width and member deformation becomes larger it will affect the mechanical behaviors of members, and shear strength may reduce compared to steel reinforcement.

3.3.3 Stress–Strain Relationship

There is no plastic range to the stress–strain relationship of CFRM with the stress increasing linearly from the origin to the point of maximum stress, at which point failure occurs. The following problems arise because of this property.

(1) Flexural Failure is of Brittle Nature

In design of concrete members using steel as reinforcing material, yielding of the steel is designed to occur in advance to prevent brittle failure. However, since CFRM failures without a yielding phenomenon, failure of reinforced concrete is either failure of reinforcing material or crushing of concrete, and thus both are brittle failures.

(2) Summation of Ultimate Tensile Loads is not Valid

The ultimate load of a flexural member is governed by the elongation capacity (failure strain) of CFRM. When CFRM are arranged in the same strain plane in multiple numbers, the reinforcing material of the lowest failure strain breaks, and in general, the sum of the tensile forces of the individual reinforcing materials at the time of the break is the resisting tensile force. Even when reinforcing materials of identical failure strains are used, in case of the materials being arranged in multiple layers, the ultimate load is governed by the rupturing of the reinforcing material at the location of greatest strain. In other words, summation in the form of $T = \Sigma_s f_y$ as with steel will not be valid.

(3) Redistribution of Moments at Ultimate Stage

Because of little plastic strain, it is necessary to consider redistribution of moments at ultimate stage in statically indeterminate structures such as continuous beams and slabs.

(4) Strength Decline when CFRM is Subject to Local Flexure

(i) When flexural or shear force acts on CFRM subject to tensile force and if it bends, a secondary stress initiates unevenly in the CFRM and the stress and strain at the outer surface of the cross section becomes greater. And since the CFRM breaks when the strain at the outer surface of the bend reaches failure strain, the apparent tensile strength decreases.

(ii) When straight bars are arranged in a curve, and (iii) when tensile force acts on a bent portion such as of shear reinforcement, uneven stresses occur in the CFRM and the apparent strength is decreased. Bent portion in this case means continuous fibers hardened in a bent state with fiber binding material.

Thus, reduction in ultimate load of the member occurs due to strength reductions of bent shapes such as of shear reinforcement, dowel action of main reinforcement, or shearing action at shear crack intersections on shear reinforcement. Reduction of apparent strength or consideration local stresses in the reinforcing material are two possible methods of dealing with this problem.

3.3.4 Composite Characteristics of Fibers and Binder

CFRM is a composite of fibers and binder materials, of completely different characteristics. Thus with the fact that CFRM is an isotropic material in the axial direction and in the direction perpendicular to the axis, the mechanical properties of the reinforcing material become complex. These properties will differ depending on the character of the binding material and the method of putting the fibers together.

3.3.5 Bond Characteristics

(1) One-dimensional Bar

For use as tendons for pretensioned members, it is desirable to have a material of high bond strength. But some CFRM has low bond strength depending on surface properties, and when bond strength is low, development length must be made long. Further, depending on the difference in bond strengths, cracking properties (crack initiation location, crack spacing, crack width) of flexural and shear cracks will differ. Thus this will result in differences in overall deformation, ultimate load in flexure, and shear, etc.

When used for post-tensioning reinforcement, anchorage devices will be necessary. With regard to anchorage devices, there are many points which are not clear, as durability and breakage of tendons at anchorages.

(2) Grid

Bond with concrete for CFRM of grid form or three-dimensional fabric form is caused by mechanical action at intersecting points of the grid, which may increase the bond to large extent. As a result, there is an advantage to reduce anchorage length, but at the same time high shear and flexural stresses occur locally at grid intersections. Since shear strength of a grid intersection is dependent on the strength of binder, it is necessary to consider the properties of the binder including time dependent properties .

3.3.6 Temperature Characteristics

Since material characteristics such as tensile strength, Young' s modulus, or relaxation ratio are sensitive to temperature, it is necessary to consider temperature dependence when determining their values.

The coefficients of thermal expansion of CFRM are generally lower than of concrete ($10 \times 10^{-6}/°C$), and the difference with concrete is 12 to 16 x $10^{-6}/°C$ for aramid fiber, and 9 x $10^{-6}/°C$ for carbon fiber, but there are cases when these differences will pose problems. For example, consideration should be given in design regarding variation in amount of prestress depending on temperature and increase or decrease in internal stress due to variation in temperature.

3.3.7 Fatigue Strength

It has been reported that in case of aramid fiber reinforcing material in braid form, as a result of varying upper limit stress with the lower limit stress fixed to 50% of static tensile strength, 2-million-cycle fatigue strength is approximately 80% of the static tensile strength. It has also been reported that in fatigue tests carried out for aramid fiber reinforcing material with lower -limit stress as 10% of tensile strength , 1-million-cycle fatigue strength is approximately 45% of tensile strength, roughly equal to prestressing steel wire. However, little data related to fatigue strength tests are available, and it is thought advisable that in designing, appropriate fatigue tests shall be carried out and designed based on the results obtained.

3.3.8 Static Fatigue Strength

CFRM may failure (due to static fatigue) when stressed continuously for long period of time even the stress is lower than the static strength. In case of use as prestressing material for prestressed concrete, it is to be seen to what level prestressing force is allowed relation to tensile strength.

3.3.9 Creep and Relaxation

It has been reported that as a result of relaxation tests at 20 °C when prestressing CFRM is loaded from 70 to 80% of its tensile strength, the relationship between pure relaxation ratio and logarithm of time is linear. Estimating the relaxation ratio at the age of 30 years, it is approximately 14% regardless of the type of fiber, which is roughly equal to that of prestressing steel wire and double that of prestressing steel rods. Because of limited date, this is not clearly known as yet. It has also been reported that the relaxation ratio becomes higher with temperature, and with initial load in a range of 50 to 80% of tensile strength, the amount of initial load has hardly any effect on relaxation ratio.

3.3.10 Fire Resistance

It is considered that fire resistance as evaluated in terms of tensile strength of fibers used in CFRM is inferior to that of ordinary steel. It is also said that the temperature that can be resisted by synthetic resins, generally used as binders for CFRM, is about 150°C. Therefore, it will be necessary for considerations to be given regarding matters such as extent of cover in design of structures for which fire resistance performances are demanded.

3.3.11 Durability

Depending on the environmental conditions to which the structure is to be exposed, it may be necessary to design considering chemical resistance of CFRM with regard to alkali resistance, moisture resistance, ultraviolet-ray resistance, and acid resistance etc.

3.3.12 Nonmagnetic and Weak Magnetic Property

Since CFRM is nonmagnetic or weakly magnetic, it is difficult for induction current to occur due to variation in the magnetic field. This characteristic is completely different from ordinary steels making it an extremely advantageous material depending on the type of structure, but non magnetism need not be a matter of concern in structural design.

4. Design Concept

4.1 Design Values of Materials

4.1.1 Strength

(1) CFRM is a composite material consisting of continuous fibers and binding material. Consequently, when a force acts on the CFRM, seen from a microscopic viewpoint, the local stresses acting on the individual fibers and the binder such as of resin will be different. However, when the strength of CFRM as reinforcement of concrete is considered, it is more rational and convenient to handle the CFRM as a single material. Therefore, the average strength (maximum load/effective cross-sectional area) of the system as a whole is to be used as the strength of the CFRM. In case the effective cross-sectional area of the CFRM is unknown, the maximum carrying load (ultimate load) may be used in lieu of strength.

(2) CFRM are generally used as tensile reinforcement, and compressive strength and shear strength as compression or shear reinforcement are not to be considered.

(3) Compared to steel, the variation of tensile strength using identical CFRM has been recognized to be greater. The variation differs depending on the types, configurations, etc. of the fibers and binders and also the test length and method of anchoring at the time of testing. Therefore, upon assuming variation in test values, the characteristic value of CFRM is to be a value guaranteed that the majority of test values will not be lower than it.

(4) In the event a standard value or guaranteed ultimate load is specified elsewhere for the material strength of the CFRM, the characteristic value of material strength is to be the standard value or guaranteed ultimate load multiplied by an appropriate material correction factor. However, when the standard value or guaranteed ultimate load satisfies the conditions of (3) above, that value may be taken as the characteristic value.

(5) When making continuous fibers into a bent shape or when arranging straight CFRM in curved form, the tensile strength decreases compared to the uniaxial tensile strength. It has been ascertained through experiments that the rate of decrease differs according to the ratio of the curvature radius of the bent shape or the curved portion to the diameter of the CFRM. Therefore, the material strength when continuous fibers are bent or when CFRM are arranged in curved form, is to be determined based on the results of appropriate tests.

4.1.2 Design Strength

The design tensile strength (or design ultimate tensile load) of CFRM is to be the characteristic tensile strength divided by the material factor γ_m. The material factor γ_m is to be determined considering the influences of the following numbers and deviations of experimental data used in tension tests: damage to CFRM which may occur during construction and transportation, differences in material characteristics between experimental specimens and the structure, the effect of material characteristic on the limit state, temperature during use, environmental conditions, etc. In general, γ_m may be taken to be between 1.0 to 1.3.

4.1.3 Design Fatigue Strength

(1) The characteristic value for fatigue strength of CFRM is to be determined based on fatigue strength obtained from fatigue tests, taking into consideration type of fiber, dimensions, anchorage device, size of acting stress and frequency of action, environmental conditions, etc. Research results concerning fatigue of CFRM are presently not adequate, and it is necessary to conduct further experiments.

(2) The design fatigue strength of a CFRM is to be the characteristic value of fatigue strength divided by the material factor γ_m. The material factor γ_m is to be determined considering the influences of the number and deviations of experimental data used in fatigue tests, temperature during use, environmental conditions, etc. In the event it is conceivable that damage to the CFRM may occur during construction or transportation, the effect is to be considered in the value of γ_m. In general, γ_m may be taken to be between 1.1 to 1.3.

4.1.4 Strain

CFRM does not have an inelastic range differing from steel, and failure is brittle. Therefore, in order to consider safety of a concrete member against failure of CFRM, it is advisable to newly add limit strain (elongation) to design values. The methods of determining characteristic value and design value of limit strain, and design fatigue value of CFRM are to follow the methods for strength.

4.1.5 Young's Modulus (or Tensile Rigidity)

The Young's modulus of a CFRM differs, depending on types of fiber and binder, fiber content, cross-sectional configuration, etc. Therefore, the Young's modulus of a CFRM is to be determined based on results of appropriate tests. In the event the effective cross-sectional area of the CFRM is unknown, it is permissible for tensile load to be employed in place of stress. In this case, the value of tensile rigidity (tensile load/strain) is to be determined.

4.1.6 Coefficient of Thermal Expansion

In case of reinforced concrete using steel reinforcement, it is possible to ignore the effect of reinforcing steel in regard to thermal stress, since the coefficients of thermal expansion of reinforcing steel and concrete are almost the same $10 \times 10^{-6}/°C$. However, since the coefficients of thermal expansion of CFRM are approximately -2 to $-6 \times 10^{-6}/°C$ for aramid fiber reinforced material, approximately $1 \times 10^{-6}/°C$ for carbon fiber reinforcing material, and approximately $10 \times 10^{-6}/°C$ for glass fiber reinforcing material, it is necessary to consider the effects of temperature in the cases of aramid fibers and carbon fibers. In case of determining the thermal coefficient of expansion of a CFRM, it is to be based on the results obtained by appropriate tests. However, there are almost no examples of research done in connection with this field, and it is necessary for further studies to be made in the future.

4.1.7 Relaxation Ratio

In case of using CFRM as prestressing material for prestressed concrete, the relaxation characteristics of the material will be a problem. The relaxation ratio of CFRM is to be determined based on results obtained by appropriate tests. In this case, the relaxation ratio must take into account the influence of temperature and stress level (initial tensile stress intensity/tensile strength). However, there are little experimental data available at present, and it is necessary for further studies to be made in the future.

4.2 Load

(1) In design, loads likely to act during construction and service life, and their appropriate combinations are to be considered. Even in case of using CFRM, it is permissible to use the same value of load factor as in case of using steel. However, this is predicated on the characteristic value of load correctly evaluated from the load actually acting.

(2) With prestressed concrete members using CFRM as tendons, there are cases when deformations at the ultimate stages are smaller than when using prestressing steel. Also, when members reinforced with CFRM suddenly fail due to rupturing of the reinforcing materials, there are cases when it can be judged that the members are lacking in ductility compared with members reinforced with steel. To deal with this, measures which are conceivable are to reduce cross-sectional load at the ultimate stage, and to raise section force by increasing the safety factor against load. Since it is not rational to change the safety factor for determining design section force according to the type of reinforcing material, it will be dealt with by increasing the member factor.

4.3 Structural Analysis

(1) Unlike steel, CFRM does not show plastic deformation, and its failure is brittle. In concrete also, except for when special restraining reinforcement is provided, it cannot generally be expected that there will be plastic deformation. Consequently, the mechanical properties of concrete members reinforced with CFRM are elastic, and it may be considered that there is hardly any plastic deformation property demonstrated. Therefore, in calculation of section force for examining the ultimate limit state, it is advisable not to consider redistribution of bending moments due to plastic deformation. However, the effect of reduction in rigidity of a member due to cracks is to be considered.

(2) In case when the influence of temperature is conceivable due to difference in coefficients of thermal expansion of CFRM and concrete, structural analysis considering thermal stresses is to be performed as necessary.

(3) JSCE "Standard Specifications for Design and Construction of Concrete Structures (1991)" are to be followed for cases not covered above.

4.4 Consideration of Ultimate Limit State

4.4.1. Ultimate Failure Mode and Safety Factor

With reinforced concrete or prestressed concrete using steel as reinforcing material, it is common for the ultimate failure mode to be that of flexural failure preceding shear failure. Further, it may be said that flexural failure designing is done so that tensile steel failure due to flexure will occur in consideration of safety of the structure and of using materials economically and rationally. However, CFRM are brittle materials with no plastic ranges, while concrete is generally a brittle material also. To briefly comment on shear and flexural failure of reinforced concrete, it is conceivable for shear failure to be either failure due to crushing of concrete at the web or compression zone, or failure due to breaking of CFRM used as shear reinforcement, with both being brittle failures. On the other hand, with flexural failure, a broad division may be made into failure due to failure of the CFRM (hereafter referred to as fiber rupture-type flexural failure) and failure due to failure of the compression zone of concrete (hereafter referred to as flexural compressive failure), and both failure modes may be said to be brittle types. Consequently, what will be a problem is the kind of ultimate failure mode which will be desirable in case of using CFRM as main reinforcement.

On scrutiny of the research results obtained up till now, it is difficult under present circumstances to estimate ultimate shear failure load with good precision, but is has been recognized that ultimate flexural failure load can be estimated with fairly good accuracy. And in flexural failure, it has been ascertained that by restraining concrete in the compression zone by a suitable method, the compressive failure properties due to flexure can be improved. Thus, it is considered that ductile performance may be improved for compressive flexural failure compared with the case of reinforcing material failure.

Taking into consideration the failure properties and precision of strength evaluation described above, the most appropriate ultimate failure mode is to be determined according to the structural form, type of load, degree of safety against the failure demanded, economical and rational method of using material, etc. Furthermore, it is necessary to use an appropriate member factor in accordance with the ultimate failure mode.

4.4.2 Bending Moment and Axial Force

(1) Fiber Rupture-Type Flexural Failure

Method of Calculating Ultimate Load

Since CFRM do not yield or have an plastic range, rupturing will occur from the reinforcing material in which strain has reached the failure strain. Due to this, the first failure of CFRM will be the ultimate stage of the member. Therefore, in the method of calculating ultimate load, the strain distribution within the cross section is calculated by the same method as for reinforced concrete or prestressed concrete, assuming plane retention when using steel, and the ultimate load is obtained from the stress distribution at the time the strain at any reinforcing material reaches the design value of failure strain.

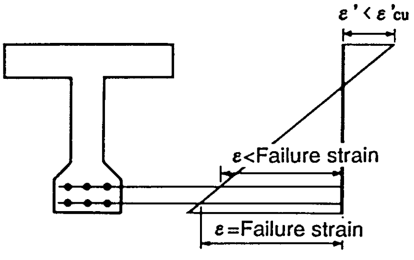


Fig. 4.1 Bending tensile ultimate state (main reinforcement arranged in multiple layers)

For example, in case of steel main reinforcement has been arranged in multiple layers, it is permissible in the current design method for stress to be evaluated at the centroid, but in case of CFRM have been used, fiber rupture-type failure will occur when the outermost main reinforcement has reached failure strain as shown in Fig. 4.1. Also, when different types of CFRM have been used in the same cross section, or when reinforcing materials with and without bond are used in combination, it will be necessary to calculate ultimate load taking this into consideration.

Local Stress on Tensile Reinforcement at Crack Location

(1)Shear force (dowel action) will occur in tensile reinforcement at a crack location inside a shear span. When there is a possibility for ultimate load to be lowered by this dowel action, an appropriate safety factor must be used.

Sustained Load (Static Fatigue)

Regarding static fatigue failure of CFRM when used as prestressing material in prestressed concrete, it will suffice to specify the limit value of stress in the prestressing material within a range which will not be problematic.

It will be necessary to examine whether the tensile strength of the prestressing material after relaxation decreases below the initial strength.

(2) Compressive Failure in Flexure

It appears that ultimate load can be estimated with accuracy even when current stress-strain relationship of concrete is applied. The way of thinking is just the same as in the design method for reinforced concrete or prestressed concrete using steel.

(3) Member Factor

The member factor γ_b for bending moment and axial force may generally be taken as between 1.15 to 1.3.

4.4.3 Shear Force, Torsion

(1) Failure Mode and Ultimate Load Calculation Method.

Since diagonal tensile failure, compressive failure in shear, failure due to failure of shear reinforcement, and compressive failure of web concrete are all brittle failures, when ultimate limit state is shear mode, design may be done for any one of the failure modes. However, it will be necessary to use a member factor considering enough safety according to each failure mode. Further, when the ultimate shear and flexural loads are close to each other in magnitude, there will be a possibility of failure under a load smaller than the calculated ultimate load obtained from failure of shear reinforcement due to change in failure mode. Therefore, as for the method of calculating ultimate load, it is advisable to make confirmations by experiments or to raise the safety factor.

(2) Diagonal Crack Initiation Load

Since the Young's modulus of tensile reinforcement will have an influence, it is advisable to use an equation which takes that into account.

(3) Rupture Load of Shear Reinforcement

The ultimate shear load according to failure of shear reinforcement in a member using CFRM will be lower than that calculated using the current design method, replacing the yield strength of steel by the failure strength of CFRM. The reasons for this are the reduction in V_c of $V = V_c + V_s$ with enlargement of cracks, reduction in strength of bent shape of shear reinforcement, unevenness of tensile force carried by shear reinforcement, etc. This ultimate load reduction phenomenon considered will differ depending on the rigidity and bond characteristics of the CFRM used as main or shear reinforcement, beam depth, angle and spacing of shear reinforcement, etc., so that an equation taking these into consideration is to used.

(4) Ultimate Torsion Load

With regard to ultimate torsion load, it is thought that, basically, the same way of thinking as for shear will suffice, but only few studies have yet been made and thus it is not clear.

(5) Member Factor

The member factor γ_b for shear force and torsion may generally be taken as between 1.3 to 1.5.

4.5 Limit State of Serviceability

4.5.1 Consideration of Flexural Cracking

(1) Limit State of Flexural Cracking

One of the limit states of flexural cracking indicated in (i) to (iii) below is to be selected in accordance with the function and purpose of the concrete member.

(i) A limit state of stress intensity of concrete due to bending moment and axial force not reaching tensile stress intensity (tensile stress initiation limit state).

(ii) A limit state of the stress intensity of concrete due to bending moment and axial force not exceeding 60% of the design tensile strength of the concrete (flexural crack initiation limit state).

(iii) A limit state of flexural crack width not exceeding the allowable crack width (flexural crack width limit state).

(2) Allowable Crack Width

CFRM are considered not to involve problems of corrosion. Accordingly, it is not necessary to set allowable crack width from the point of view of corrosion. However, excessively large cracks are not desirable since they will be a problem from the standpoint of the a aesthetics of a structure, or will present an appearance causing uneasiness about safety. Consequently, it is desirable to study conditions with and without cracks, and when crack initiation is to be allowed, an appropriate allowable crack width shall be decided in accordance with the type of structure and distance from which it is seen by the people, so that there will be no problem from the standpoints of aesthetics and outward appearance. In general, when prestress is not induced in the main reinforcement, crack width will become fairly large even under low-level load. Further, in case of combined use with deformed bars, it is necessary to decide on an allowable crack width considering corrosion of the steel. In general, allowable crack width may be taken to be between 0.3 to 0.5 mm.

(3) Calculation of Flexural Cracking

The widths and spacings of flexural cracks are mainly influenced by the bond properties of the reinforcing material and the concrete. The shaping methods and surface configurations of CFRM are of various kinds, being of strand form, braid form, wound-on form, cut form, grid form,etc., and the bond properties may be considered to differ individually. According to experimental results obtained up to this time, CFRM with good bond properties have performances equal to deformed bars. In general, CFRM have bond properties between plain round bars and deformed bars. Therefore, calculation of flexural crack width may be done appropriately selecting constants representing influences of bond properties according to the variety of the CFRM. However, continuous fiber grids are completely bonded only at grid intersections, with almost no bond at the other part, and so that the method of calculating crack width needs to be considered separately. Further, the degree of variation of bond properties under variable load will differ according to the variety of the CFRM, and therefore, it is desirable for this also to be evaluated appropriately.

4.5.2 Consideration of Stress Intensity

(1) Limiting of Stress Intensity

The compressive stress intensity of concrete and tensile stress intensity of prestressing material due to bending moment and axial force are respectively not to exceed the limiting values indicated in (i) and (ii) below.

(i) The limiting values of flexural compressive stress intensity and axial compressive stress intensity of concrete under action of permanent load may be made $0.4.f'_{ck}$ (f'_{ck}: characteristic value of compressive strength of concrete).

(ii) The limiting value of tensile stress intensity of CFRM is to be 60% of the characteristic value of tensile strength. However, this must be reduced, when necessary, when factors such as static fatigue are considered. The material coefficient for static fatigue strength, in general, may be taken as between 1.2 to 1.3.

(2) Calculation of Stress Intensity

The stress intensities of concrete and CFRM at the cross section of a member may be calculated adapting the methods for reinforced concrete and prestressed concrete using steel. The calculations are to be performed properly considering drying shrinkage and creep of concrete and relaxation of CFRM. Further, when selecting the flexural crack width limit state as the limit state of flexural cracking, the secondary stresses occurring in the prestressing material (stresses due to local bending, friction, etc. of prestressing material) after initiation of cracking are also properly to be considered.

4.5.3 Consideration of Displacement and Deformation

It is necessary for displacements and deformations of members to be considered by appropriate methods so that the functions, serviceability, durability and aesthetic of the structure will not be impaired. Since the Young's module of CFRM are generally lower than those of steel, the deformations of members after initiation of cracks will be greater than when using steel. In case of using CFRM for stirrups and hoops, the shear deformation of the member will also become large. Therefore, when selecting the limit state of flexural crack width, it will be advisable to calculate deformation appropriately taking the influences of these into account.

4.5.4 Consideration of Shear and Torsion

(1) The diagonal tensile stress intensity of a member satisfying the limit state of tensile stress initiation is not to exceed 35% of the design tensile strength when considering either one of shear force and torsional moment, and 50% when considering both.

(2) The diagonal tensile stress intensity of a member satisfying the limit state of flexural crack initiation is not to exceed 75% of the design tensile strength when considering either one of shear force and torsional moment, and 95% when considering both.

(3) Consideration of cracking is to be given by an appropriate method regarding a member satisfying the limit state of flexural crack width. However, when the design shear force and design torsional moment are sufficiently small compared with the ultimate shear load without shear reinforcement and torsion reinforcement, consideration need not be given to cracks. Ultimate shear load in case of no shear reinforcement and design ultimate torsional load in case of no torsion reinforcement are to be calculated adapting the method of 4.4.3.

4.5.5 Others

(1) When executing work, the tensile stress intensities of continuous fiber prestressing materials

during prestressing operations and immediately after prestressing operations are to be limited under a value appropriately selected considering safety against failure of the respective prestressing materi-als.

(2) It is necessary for anchorage devices to be arranged in a manner that the prestress required at each design cross section is effectively induced, and the continuous fiber prestressing materials are safely and securely anchored. However, since it may be considered that anchorage devices themselves are presently in the process of being developed, appropriate tests are to be performed beforehand, and a reliable device is to be used.

4.6 General Structural Details

4.6.1 Cover

The minimum value of cover must be determined considering anchorage, bond performance, fire resistance capacity, etc.of the member. The anchorage, bond performance, and fire resistance will differ depending on the reinforcing material, and it is advisable to determine them on carrying out various tests on the reinforcing material to be used.

4.6.2 Development Length

Similar to members using steel, it is advisable for development length to be determined obtaining bond characteristics taking into consideration cover and transverse direction material.

4.6.3 Splices

The performances of splices will differ depending on the types of CFRM and the method of splicing, and it is advisable to carry out appropriate tests to determine details of splices.

4.6.4 Bent Shaping of Reinforcing Material

Reinforcing steel can be subjected to bending by plastic fabrication, but in case of CFRM, bending fabrication cannot be done. Consequently, when using CFRM as reinforcement having bent portions like stirrups and hoops, reinforcing material made into the required configurations by bent shaping needs to be used.

The strength of a bent shape of shear reinforcement and design of ultimate load of member are not independent of each other, and the strength of the bent shape must be in accordance with the design strength. The strength of the bent shape portion will differ depending on the variety of the reinforcing material, method of shaping, bending radius, etc. When the method of bent shaping has been decided beforehand, the strength of the bent shape portion may be determined by an appropriate test and this can be used for calculating ultimate load. As for when the strength of the bent shape portion has been determined by ultimate load calculations, the bending radius may be selected carrying out appropriate tests so that the strength of the bent shape portion will be higher than the design values.

4.6.3 Curved Arrangement of Straight Reinforcing Material

When arranging straight CFRM in curved form, tests must be performed beforehand regarding the bending radius making possible a curved condition by elastic deformation without damage. Since secondary stress will occur in reinforcement at a curved portion, it is necessary to give consideration that a difference will not occur between the bending radii in design and in construction along with giving consideration to the effect on strength of the reinforcing material.

4.7 Design of Members

(1) Since a CFRM will have a large elastic strain compared with steel, it is conceivable that section force according to linear analysis using the total concrete cross section will differ greatly from the actual value. Therefore, when considering the ultimate limit state or when allowing cracking at limit

state of serviceability, it is advisable to calculate section force considering reduction in rigidity after occurrence of cracking. The redistribution of moments due to plastic deformation is not to be considered at the ultimate limit state.

(2) Since a CFRM has small inelastic strain and failure is of brittle nature, it is expected that reliability against failure will be higher with a plate member such as a slab with a multiple number of main reinforcing bars arranged in the same strain plans. However, there has been little research on cases of applying CFRM to plate members such as slabs, and it is advisable for effective width and other factors to be decided after confirmations through appropriate tests. As for punching shear load, it is imaginable that is load will be small compared to steel, and it is necessary for confirmation to be made through appropriate tests since there are still many points which are not clarified.

(3) Regarding restraining effect on concrete and buckling prevention effect for compression bars when using CFRM for stirrups and hoops in beams and columns, a unified opinion has not been attained as yet. Therefore, with beams and columns in which ductility is required and these effects are necessary, it is advisable for the effects to be ascertained through appropriate tests and the appropriate reinforcement quantities and spacings to be decided.

4.8 Requirements for Earthquake Resistance

According to the current Standard Specification for Design and Construction of Concrete Structures, it is required that for earthquake-resistant design of structures to be carried out based on safety during earthquake and serviceability of the structure after earthquake. Earthquake load is set considering the response characteristics of the ground and structure under the design hypothetical earthquake and plastic deformation capacity, and the degree of damage allowable after the earthquake. However, with a concrete structure using CFRM, it is extremely unlikely that plastic deformation can be expected. This means that it is necessary for a structure to be in the elastic range at all times during an earthquake, while regarding the degree of damage suffered, it is required for soundness to be maintained. Consequently, when carrying out earthquake-resistant design of a concrete structure reinforced with CFRM, it is necessary for the structure to have strength greater than the earthquake force acting, with the structure behaving elastically at all times. Furthermore, when safety is to be examined, appropriate member factors and structural analysis coefficients are to be used.

4.9 Consideration of Fatigue Limit State

In general, when the proportion of variable load and frequency of action are high, it is necessary for considerations to be given to fatigue. For beam members it is necessary for considerations of fatigue to be given for both tensile reinforcement and shear reinforcement.

II. TENTATIVE PROPOSALS ON TEST METHODS FOR CONTINUOUS FIBER REINFORCING MATERIALS

CONTENTS

1. Introduction

At present there are more than ten companies in Japan which are manufacturing and selling various types of continuous fiber reinforcing material (CFRM), whose physical characteristics also cover an extremely wide range. There is need to use these as reinforcing materials for reinforced concrete structures and it is necessary to understand the material characteristics required for designing of structures. However, presently individual companies are carrying out tests of material characteristics according to their own original methods, and there are no established standards for test methods. Therefore, basic data required for design cannot be compared on common ground and furnished.

Thus, standard test methods and material standards must be urgently established. However, due to the fact that the characteristics of CFRM cover a broad range, also the characteristics demanded for CFRM from the standpoint of the performances required for concrete structures has not been made clear, it was judged premature for material standards to be established and it was decided that only testing methods would be set up. The test methods proposed here were selected from the viewpoint of furnishing data required in designing concrete structures. Four test methods were proposed concerning tensile strength, failure strain, and modulus of elasticity, bond characteristics, relaxation characteristics, and coefficient of thermal expansion.

In making proposals, the various methods of testing concerning CFRM proposed by the Subcommittee on Planning and Adjustment of the Japan Society of Civil Engineers were used as references, along with which the Japan Society of Civil Engineers Standards and Japan Industrial Standards were referred to, and considerations were given for application to as many materials as possible. Also, past research results were referred to, and considerations given so that uncertain results due to material characteristics of CFRM would not be obtained. Details of these are as described in section 2. below.

The test methods proposed here, are all tentatively proposed test methods. This takes into account the fact that these test methods have no track records, and also it is not clear whether the above mentioned considerations have been fully taken. The task to be carried out hereafter is to make necessary modifications based on the records of these test methods, and to aim for unification of test methods of the same kind now being examined in various circles.

2. Physical Characteristics of Continuous Fiber Reinforcing Materials and Concept of Test Methods

2.1 Test Method for Tensile properties of Continuous Fiber Reinforcing Material (Tentative Proposal)

Of the physical characteristics of CFRM, tensile strength and tensile rigidity may first be mentioned as basic indices. Since the makers and users of the materials have each adopted their own original tensile testing methods, the numerical values presented cannot be normally compared. A standard tensile test method is being called for.

The feature of a tensile test for CFRM is that it is difficult to directly grip the reinforcing material by chuck and apply tensile force as with steel reinforcing bars. Accordingly, it is necessary to provide an anchoring section on the test piece so that failure will not occur at this part. Further, as a rule, test pieces are to be made from actual products and not be subjected to any processing. However, provisions were not especially made regarding the configuration and dimensions of the anchoring section.

When the length of the test section becomes large, there are cases when tensile strength will be greatly lowered depending on the variety of the fiber, the fiber content, and kind of the fiber binding material. Therefore, it was prescribed that the length of the test section is to be 100 mm added to 40 times the standard diameter of the CFRM at which the influence of length of the test section would be small. For material of stranded type, the longer of either the above mentioned length or twice the stranding pitch plus 100 mm is to be employed.

When the testing temperature differs, there are CFRM of which tensile strengths and tensile rigidities will differ greatly, and for materials sensitive to temperature variation, 20 ±2 °C was made standard, while on agreement between manufacturer and user, tests at 0 °C and 60 °C would be performed. However, as the length of CFRM to be tested may become quite long to maintain temperature constant at ±2 °C of the specified temperature, it would require a large-scale facility. Therefore, the temperature was set in the range of 5 to 35 °C as in a laboratory room, with only the stipulation that the testing temperature is to be recorded.

The tensile characteristics of a CFRM will also differ depending on the rate of loading. In order to reach failure load within a certain time minutes, the rate of loading was set using the fiber content Vf so that tensile stress would act on the continuous fiber itself at a rate of 50 ±5 kgf/mm^2/min.

2.2 Test Method for Long-time Relaxation of Continuous Fiber Reinforcing Material (Tentative Proposal)

When CFRM is to be used as prestressing material, it is necessary for its relaxation characteristics over a long time, which will cause reduction in prestress, to be made clear. Relaxation characteristics will differ greatly depending on the testing method, adapted from the JSCE Standard, "Test Method for Long-time Relaxation of Prestressing Steel (Draft)" (1975, JSCE, Architectural Institute of Japan). Furthermore, by slightly altering this test method, it is also possible to obtain the static fatigue strength of the CFRM.

The testing apparatus follow the JSCE Standards, and the gripping device, precision of initial load, accuracy of load detection, and strain variation were made the same as for prestressing steel. The rate of loading was set considering fiber content Vf so that tensile stress would act at a rate of 50 $\pm$5 kgf/mm^2/min on the continuous fiber itself from the 20 $\pm$5 kgf/mm^2/min of prestressing steel.

As a rule, test pieces are to be made from actual products and are not to be processed, but the anchoring section of the test piece is to be processed in a manner that failure will not occur in that portion. The length of the test section is to be the same as in the method of tensile tests.

Initial load is to be decided considering the range of stress level in using prestressing material. Sixty percent of the guaranteed value of tensile failure load which is slightly smaller than the value specified for steel in the JSCE Standards, was proposed as initial load. Further, at the time of applying initial load, when attaching strain measuring apparatus to the test piece, load in the range of 10% to 40% of initial load is to be applied to the test piece to straighten it.

The period of measurement was made 1,000 hours following the JSCE. And as the relaxation value of CFRM to have a linear relationship generally with the logarithmic axis, it was stipulated that the estimated value of relaxation corresponding with the design service life considered in design would also be obtained. The testing temperature was made 20 $\pm$2 °C as a standard adopting the JSCE Standards. If relaxation characteristics greatly depend on temperature, testing is to be done at 0 °C and 60 °C temperature also when agreed upon by the manufacturer and user.

2.3 Test Method for Coefficient of Thermal Expansion of Continuous Fiber Reinforcing Material (Tentative Proposal)

The coefficient of thermal expansion of CFRM differs depending on kind of fiber and the fiber binding material used, and moreover, differs from the coefficient of thermal expansion of concrete. Due to the difference in expansion and contraction between the reinforcing material and concrete, when a concrete member using CFRM is subjected to temperature variation, depending on the tensile rigidity of the reinforcing material, it is conceivable that the statically indeterminate force occurring inside the member will be a problem. Therefore, it becomes necessary to standardize the test method for coefficient of thermal expansion of CFRM.

Since CFRM is a new material, presently, the standards of Japan as with JIS, and the standards of various other countries, do not prescribe test methods for obtaining the coefficient of thermal expansion of this material. Hence, in order to consider a new testing method, it was first decided to study the available methods of testing for similar materials like ceramics, plastics, and glass. The relevant JIS and ASTM standards are listed below:

(1) JIS C 2141, "Testing Method of Ceramic Insulators for Electrical and Electronic Applications"

(2) JIS K 6911, "Testing Method for Thermosetting Plastics"

(3) JIS R 3102, "Testing Method for Average Linear Thermal Expansion of Glass"

(4) ASTM E 228, "Linear Thermal Expansion of Rigid Solid with a Vitreous Silica Dilatometer"

(5) ASTM D 696, "Coefficient of Linear Thermal Expansion of Plastics"

The various materials have different coefficients of thermal expansion, while the methods of use also differ, and therefore, beginning with dimensions of test pieces, the scopes of application such as measuring accuracies, testing temperatures, etc. are different. Comparisons of these are given in Table 2.3.1.

It was decided to modify the existing testing method of ceramics with comparatively similar coefficients of thermal expansion. Further, since the CFRM is a composite material, in testing the coefficient of thermal expansion, it is necessary to test the actual fiber to be used of a suitable length. What has been taken up as the test method (tentative proposal) is the method of using a differential transformer with which the principle of measurement is simple. However, the commercial testing apparatus do not use standard samples for comparisons such as shown in the reference figure of this tentative proposal, but make corrections for the characteristics of the apparatus beforehand so that results are obtained automatically. It was stipulated that in such case, the type of the apparatus is to be recorded in the report of results and the data obtained can be used without modification.

Further, for the sake of reference, the approximate values of coefficients of thermal expansion of various materials are given in Table 2.3.2.

Table 2.3.1 Comparison of test methods for coefficient of thermal expansion of material

	JIS C 2141 -1988 Ceramics	JIS K 6991 -1979 Plastics	JIS R 3102 -1986 Glasses	ASTM E 226 -1971 Rigid solids	ASTM D 696 -1970 Plastics
Shape and dimensions of specimen	sectional area 7 - 25mm^2 length 20 - 50mm	section 10*10mm length 120mm	bar length 100±2.5mm	min.thickness or min. diameter 4.8mm length 50 - 125mm	section 12.5*6.3mm length 50 - 125mm
Measuring apparatus for length of specimen; an accuracy	micrometer	micrometer	slide caliper	micrometer 25μm	micrometer etc. 25μm
Accuracy of measuring length of dilation	1μm	10μm(0.01μm)	1μm by micrometer	1.3mm	10μm dial gauge etc.
Temperature variation in electrical furnace	Isothermal zone shall be less than 2°C		Surface temperature of specimen shall be less than 2°C	Surface temperature of specimen shall be less than 2°C	Specimen shall be stored in liquid bath,less than+0.2°C
Temperture range at test	room temperature-	room temperature - 80°C	0°C - 300°C		-30 - 30°C
Heating rate	After keeping at room temperature for 15 minutes, 2 - 5°C/min	Temperature shall reach 80°C after 1 hour	Cooled specimen at 0°C shall be stored in the furnace at 300,and maintain for 25min.	less than 200 °C/hr (less than 3.3°C/min)	Measuring at -30°C and 30°C
Accuracy of thermometer	thermocouple less than ±1.5%	Min. division of scale; 1°C	Control temperature within ±1°C	thermocouple; ±0.5°C	thermocouple; ±0.1°C

Table 2.3.2 Approximate coefficient of thermal expansion of material

Materials	α (10^{-6}/°C)
Concrete	6.8 - 12.7
CFRP	0.6 - 1.0
AFRP	-6 - -2
GFRP	9 - 10
Ceramics	3 - 6
Epoxy Resin	30 - 50
Glasses	8 - 10
Silica-Glass	0.4
Prestressing steel	12

2.4 Test Method for Bond of Continuous Fiber Reinforcing Material (Tentative Proposal)

In case of using CFRM as reinforcement for concrete in place of conventional prestressing materials and reinforcing bars, it is important to know the characteristics of bond with concrete.

The CFRM presently used contains various kinds of fibers such as carbon, aramid and glass the physical properties of which are of a diverse nature. Surface configurations which greatly influence bond strength are varied, being in the forms of strands, plates, braids, and twill weaves. Therefore, it was thought necessary to know the bond strengths of CFRM through a standard testing method, thus this following tentative proposal is made.

At present, in general, bond tests for reinforcing steel and concrete include, pull-out tests, axially-loaded tension tests, and beam tests. Now in Japan, the two testing methods generally used are of the JSCE, "Test Method for Bond Strength of Reinforcing Steel and Concrete by Pull-out (Draft) (JSCE-1988)" and the Method of Test for Bond (Draft) of the Japan Concrete Institute. The results of these testing methods do not necessarily reflect the bond characteristics inside concrete members and there is a risk that this will become prominent with CFRM which have low modulus of elasticity compared with steel. However, since tests are simple to perform, the advantage is that large amount of data can be obtained easily. Here, it was considered that accumulation of data is important and the present method of testing (tentative proposal) was prepared. Therefore, after bond tests of various kinds of CFRM have been performed with this testing method, it would be desirable for member tests to be carried out and the bond performances inside the members evaluated.

2.5 Test Method of Test for Fatigue of Continuous Fiber Reinforced Concrete (Tentative Proposal)

In the event of using CFRM for concrete structures where repetitive loads of vehicles and waves are predominant, it is necessary to ascertain its fatigue characteristics and so, it is required that a standard fatigue strength test methods be established. Standards which could be used as reference for developing such a method are listed below.

(1) JIS K 7118, "General Rules for Testing Fatigue of Rigid Plastics"

(2) JIS K 7119, "Testing Method of Flexural Fatigue of Rigid Plastics by Plane Bending."

(3) JIS Z 2773, "General Rule for Fatigue Testing of Metals"

(4) JSCE Standard, "Method of Test for Fatigue of Reinforcing Bar Splices"

Of the above mentioned tests, as their titles suggest, (1) and (2) have been applied to plastics, (3) to metals and (4) to splices of reinforcing bars.

To find the fatigue characteristics of CFRM, the method of testing with a concrete member provided with this reinforcing material will not entail problems such as rupturing at anchorage portions, and practical results can surely be obtained. However, with tests on members, it will be on a large scale and not be suitable for accumulation of data. The fatigue test method (tentative proposal) in which CFRM itself are tested has thus been proposed. When fatigue tests of CFRM using this test method have been performed in various circles and a certain data and experience has been accumulated, confirmations of fatigue characteristics by tests on members will become necessary.

3 Test Methods for Continuous Fiber Reinforcing Material

3.1 Test Method for Tensile properties of Continuous Fiber Reinforcing Material (Tentative Proposal)

The test method to determine mechanical characteristics such as tensile failure load, tensile rigidity, Young's modulus, and tensile failure strain of the test piece using general testing facilities are prescribed. The followings are the difficulties compared with steel. Firstly, test pieces are liable to break at anchorages such as chucks, secondly, the influence of length of the test piece will be greater, thirdly, the influence of testing temperature will be prominent, and fourthly innovation is required for calculating the nominal cross sectional area of the test piece. Since substantial elongation, such as with steel, is not demonstrated and failure occurs abruptly, special attention will be required in measurement of elongation and strain. Specifications for test pieces are broadly divided into testing and anchoring sections.

3.1.1 Scope of Application

This standard mainly specifies the method for testing of CFRM in tension

3.1.2 Definitions

The definitions of the principal terms used in this Standard shall be as follows:

(1) Test section: The middle portion of the test piece. The parallel section with the same cross section shall be the portion to be tested.

(2) Anchoring section: Parts at ends of the test piece. Parts transmitting load from the testing machine to the test section through the medium of a gripping device or anchoring sections securing device.

(3) Gauge length: The distance between two gauge points provided at the parallel section and the length to be used as reference in measurement of elongation.

(4) Gripping device: An apparatus which directly grips the anchoring section of the test piece to transmit load from the testing machine to the test piece.

(5) Anchoring section securing device: A device transmitting load to the anchoring section of a test piece to transmit load from the testing machine to the test piece.

(6) Tensile failure load: The tensile load at the time of failure of the test piece.

(7) Guaranteed value of tensile failure load: Assuming the variation in tensile failure loads, most of test values will not be lower than that value.

(8) Tensile failure strain: The strain corresponding with the tensile failure load.

(9) Guaranteed value of tensile failure strain: The strain corresponding with the guaranteed value of tensile failure load.

(10) Tensile rigidity: The ratio of the tensile load within the proportional limits of tension to the corresponding strain.

3.1.3 Test Piece

(1) A test piece, as a rule, shall not be subjected to any processing. However, processing will be permissible for an anchoring section to be provided in the test piece.

(2) In obtaining and preparing a test piece, deformation and heating to cause variation in the quality of the test section of the test piece shall be avoided.

(3) Processing of a test piece is to be avoided as much as possible. In case processing is unavoidable, a method least affecting the quality shall be used.

(4) The length of the testing section shall be 40 times the standard diameter of the CFRM plus 100 mm. For CFRM in strand form, the length shall not be less than 40 times the standard diameter plus 100 mm, and moreover, not less than twice the stranding pitch plus 100 mm.

(5) The number of test pieces shall not be less than five.

3.1.4 Testing Machine

(1) The testing machine to be used in tensile tests shall be in accordance with JIS B 7721 (Tensile Testing Machines).

(2) The testing machine shall possess the capacity to apply load to the test piece at a rate of A x V_f x (50 ±5) kgf per minute, where A is nominal cross-sectional area of the test piece (mm^2), and V_f is the fiber content which resists tensile force.

(3) The gripping device or the anchoring section securing device shall be suited to the configuration of the test piece, and reliably transmit the load from the testing machine to the test section of the test piece. These shall be of such construction that only axial load will be transmitted to the test piece, and torsional or flexural force will not be transmitted.

(4) The testing machine shall be installed correctly on a firm base and the straight line connecting the gripping device or anchoring section securing device shall be correctly vertical or horizontal.

(5) In case a principal part of the testing machine has been dismantled and reassembled, modification or repair has been carried out, or relocation has been done, the testing machine shall be inspected again and used only after confirming that it satisfies the requirements of JIS B 7721.

(6) Although not corresponding to the case of the preceding clause, the testing machine shall be periodically checked to reconfirm the accuracy in accordance with the number of times it is used.

3.1.5 Extensometer and Strain Gauge

(1) The extensometer shall be capable of recording all variations in gauge length during the test in accordance with elapse of time and shall have a mechanism by which it will be possible to indicate elongation at the loading rate set with an accuracy of ±1% or better.

(2) In case of measuring tensile failure strain, employing a strain gauge for elongation detection, a strain gauge and an adhesive capable of following the CFRM to tensile failure strain shall be used. In case of obtaining Poisson's ratio, a strain gauge shall be attached in a manner that lateral strain can also be measured.

3.1.6 Testing Temperature

The testing temperature shall be in the range of 5 to 35 °C in general, and the temperature at which testing is done shall be recorded. However, for a material sensitive to temperature variation, 20 °C shall be standard. In addition, depending on agreement between the manufacturer and user, testing shall be performed at 0 °C and 60 °C.

3.1.7 Test Method

(1) In mounting the test piece onto the testing machine, care shall be exercised that the longer axis of the test piece will coincide with the imaginary line on which the two gripping devices or anchoring section securing devices are attached.

(2) An extensometer or strain gauge shall be attached as necessary. The gauge length when using an extensometer shall be 4 times the standard diameter of the CFRM. Further, in case of using a strain gauge, it shall be placed in the middle of the parallel section of the test piece. The extensometer shall be used for measuring tensile rigidities in the range under the tensile failure load, and when tensile failure strain is to be measured directly, it is advisable to use a strain gauge. When using a strain gauge, surface of the CFRM may not be smooth, or may not be possible to attach the strain gauge parallel or perpendicular to the longer axis (tension direction) of the test piece. Thus it will be necessary for an appropriate measure to be taken for attachment.

(3) The rate of loading shall be A x V_f x (50±5) kgf per minute as a standard, where A is nominal cross sectional area of the test piece (mm^2), and V_f is the fiber content which resists tensile force.

(4) The measurements below shall be made in accordance with the purpose of the test.

i) The load–elongation (strain) curve shall be recorded at suitable, roughly uniform intervals.

ii) Load at failure

(5) In case of attempting measurement of tensile rigidity, an extensometer or strain gauge shall be attached to the test pieces, with the measurements made according to the procedure of 3.1.7 (4) i).

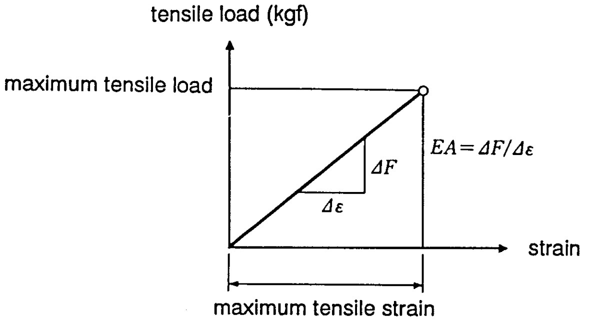
3.1.8 Calculation of Test Results

(1) The average value of tensile failure loads and standard deviation of all test pieces shall be obtained. Further, the result of a test piece failed at an anchoring section shall also be regarded as one of the test values.

(2) Tensile rigidity shall be calculated by the following equation using a range of 10% to 50% of the guaranteed value of tensile failure load of the load–elongation (strain) curve obtained by extensometer or strain gauge.

$$EA = \Delta F/\Delta e$$

where,
EA: tensile rigidity (kgf)
ΔF: load difference between two points (10% to 50% of tensile failure load guaranteed value) on straight line (kgf)
Δe: strain difference between the same two points



(3) Tensile failure strain shall be obtained from the load–elongation (strain) curve.

3.1.9 Report

The following items shall be necessary in the report of the test results:

(1) Date of test
(2) Number or marking of test piece
(3) Name of CFRM
(4) Designation, standard diameter, maximum diameter, nominal cross–sectional area
(5) Variety of fiber and fiber content V_f
(6) Number of test pieces
(7) Loading rate

(8) Testing temperature
(9) Tensile failure load, average value and standard deviation of tensile failure loads, tensile rigidity, tensile failure strain, Young's modulus, Poisson's ratio

3.1.10 Others

This test shall be performed in case a change has occurred in the material or manufacturing method of the CFRM.

3.2 Test Method for Long–Time Relaxation of Continuous Fiber Reinforcing Material (Tentative Proposal)

This test method is proposed adopting the JSCE Standard "Test Method for Long–Time Relaxation of Prestressing Steel". Compared to the JSCE standard, in this proposal, initial load has been reduced from 70% to 60% of the guaranteed value of tensile failure load, and that the rate of loading is a function of the fiber content, the length of the test section is made longer and the testing temperature restricted.

3.2.1 Scope of Application

This Standard prescribes the test method for long–time relaxation of CFRM under a given temperature and a given strain.

3.2.2 Definitions

Relaxation as mentioned here concerns stress relaxation, and means the phenomenon of load decreasing with time when a specified initial load is applied to a CFRM subjected to a given temperature and the strain of the material is maintained constant.

In general, after initial load has been applied and strain has been fixed, the percentage of the reduction in load after a given period of time in relation to initial load is the relaxation value.

3.2.3 Initial Load

Specifically agreed upon by the manufacturer and user, the initial load shall correspond to 60% of the guaranteed value of tensile failure load of the continuous fiber prestressing material.

Note: The guaranteed value of tensile failure load as mentioned here is the value guaranteed that most of the values will not be lower considering the variation of test values from the results of tensile tests carried out by the manufacturer.

3.2.4 Testing Machine

The relaxation testing machine shall possess the capabilities listed below.

(1) Gripping Device

The device for gripping the test piece shall be of a construction that securely holds the test piece throughout the period of test to prevent slipping at the anchoring section, transmitting only axial load to the test piece and not applying torsional or flexural force.

(2) Precision of Initial Load

The precision of the initial load to be applied to the test piece shall be as follows. For testing machine of loading capacity less than 100 tons: specified load ±1.0%, and for testing machine of loading capacity 100 tons or over: specified load ±2.0%

(3) Precision of Load Detection

The reading of the load applied to the test piece or the automatic recorder shall be more accurate than 0.1% of the initial load.

(4) Rate of Loading

The testing machine shall possess the capacity to apply load to the test piece at a rate of A x V_f x (50 ±5) kgf per minute, where A is nominal cross-sectional area of the test piece (mm^2), and Vf is the fiber content which resists tensile force.

(5) Strain Variation

The testing machine, after fixing strain of the test piece, shall be such as not to apply strain variation of ±25 x 10^{-6} or more to the test piece during the period of test. In the event CFRM is drawn out from the anchoring section, the amount drawn out shall be compensated.

3.2.5 Test Piece

The test piece, as a rule, shall not be subjected to any processing. However, a test piece with processing applied to its anchoring section may be used by agreement between the manufacturer and the user.

The length of the testing section shall be 40 times the standard diameter of the CFRM plus 100 mm. For a CFRM in strand form, the length shall not be less than 40 times the standard diameter plus 100 mm, and moreover, not less than twice the stranding pitch plus 100 mm.

3.2.6 Testing Temperature

The temperature shall be maintained at 20 ±2 °C through out the test duration. The relaxation characteristics of the CFRM depend greatly on temperature. Also when agreed upon by the manufacturer and user, test shall be performed at temperatures of 0 °C and 60 °C. In such a case also, it will be desirable for temperature variation to be maintained within ±2 °C.

3.2.7 Test Method

(1) Mounting of Test Piece

In mounting the test piece onto the testing machine, care shall be exercised that the longer axis of the test piece coincides with the imaginary line on which the two gripping devices are attached to the testing machine.

(2) Prestretching

In case of attaching a strain detector to the test piece, 10 to 40% of the specified initial load shall be applied to the test piece to straighten it, after which the strain detector shall be attached and correctly adjusted.

(3) Application of Initial Load

Initial load shall be applied at a rate of A x V_f x (50 ±5) kgf per minute in a manner not to exert impact or vibration to the test piece, where A is nominal cross-sectional area of the test piece (mm^2), and V_f is the fiber content.

(4) Period of Testing

Measurement of load reduction shall, as a rule, be performed for not less than 1,000 hours, after applying initial load to the test piece and maintaining that load for 120 ±2 seconds and then fixing the strain of the test piece.

The condition of load reduction shall be automatically recorded by a recorder attached to the testing machine. However, when a recorder is not attached, measurements shall be made at the times below and recorded.

1, 3, 6, 9, 15, 30, 40 min
1, 1.5, 2, 4, 10, 24, 48, 72, 96, 120 hr
Subsequently, every 24 hr or at least once every 120 hr

3.2.8 Calculation of Test Results

As a rule the test results shall be expressed, by a curve using the fourth quadrant of a graph having ordinary scales on the ordinate and logarithmic scales on the abscissa, with testing time (hr) beginning from 0.1 hr on the abscissa and the relaxation value (%) on the ordinate.

3.2.9 Report

The following items shall be entered as necessary in the report of test results besides the relaxation curve:

(1) Date of test
(2) Number or marking of test piece
(3) Name of CFRM
(4) Designation, standard diameter, maximum diameter, nominal cross-sectional area A
(5) Variety of fiber and fiber content V_f
(6) Guaranteed value of tensile failure load
(7) Initial load
(8) Ratio of initial load to guaranteed value of tensile failure load
(9) Rate of application of initial load
(10) Testing temperature and variation there of
(11) Relaxation values at 10, 120, and 1,000 hours and the estimated value of relaxation corresponding to the design service period considered in design.
(12) Type of testing machine

3.2.10 Others

The test shall be performed again in case a change has occurred in the material or manufacturing method of CFRM.

3.3 Test Method of Test for Coefficient of Thermal Expansion of Continuous Fiber Reinforcing Material (Tentative Proposal)

Various testing methods exist for measurement of coefficient of thermal expansion, but, the method using a differential transformer was thought to be the most suitable for testing CFRM and has thus been prescribed.

The outline of the measuring apparatus shall be as shown in the reference figure with the test piece and a standard sample (quartz) of known coefficient of thermal expansion set on two detection rods. The difference in the thermal expansions at various temperatures when temperatures is raised at equal speed is detected by a differential transformer.

3.3.1 Scope of Application

This Standard prescribes the test method for determination of coefficient of thermal expansion of CFRM used as reinforcement for concrete structures substituting for reinforcing and prestressing steel.

3.3.2 Test Piece

(1) A test piece shall be directly obtained from CFRM actually used, and the length of the test piece

shall be such that it represents the whole of the CFRM.

(2) The ends of the test piece shall be polished perpendicularly and made parallel.

(3) The length of a test piece shall be measured by a micrometer or any other instrument up to the accuracy of 1 μm units.

3.3.3 Testing Apparatus

An example of a testing apparatus is shown in the reference figure. The apparatus shall possess the capabilities listed below.

(1) Elongation Detector

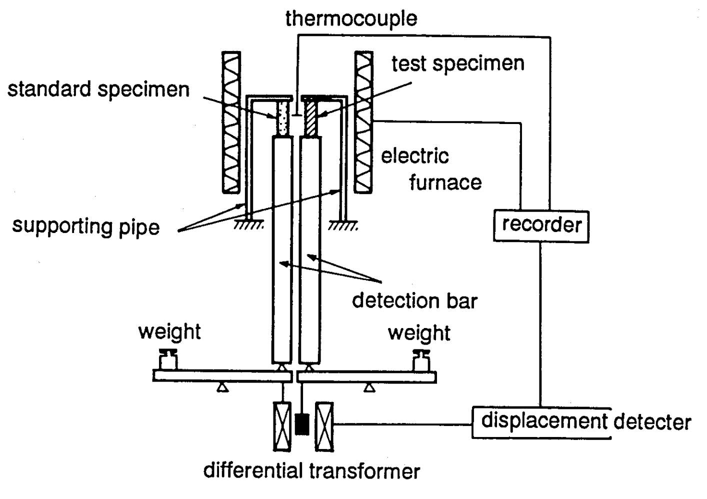
The elongation detector shall be a differential type or a push–rod type of quartz glass and capable of detecting displacement up to 1 μm.

(2) Electric Furnace

The electric furnace shall be capable of raising the temperature from room temperature to maximum testing temperature at a rate of 2 to 5 °C per minute, and also have the capacity to maintain temperature differential of not more than 2 °C in a range of the entire length of the test piece inside the furnace.

(3) Temperature Measuring Instrument

A thermo couple temperature measuring instrument with a precision at least of Class C as prescribed in JIS Z 8704 (Electrical Methods of Temperature Measurements) shall be used.



(Reference Fig.) Example of apparatus for measuring coefficient of thermal expansion

3.3.4 Test Method

The test piece shall be set in an electric furnace adjusted to the specified initial temperature (normally, room temperature) and left standing for 15 minutes. The temperature shall then be raised 2 to 5 °C per minute, and the elongation of the test piece measured up to 80 °C at every not–more–than–20 °C temperature interval.

Note) In the event the cross–sectional dimensions of the CFRM are large, a temperature difference is liable to occur between interior and exterior of the test piece, and it will be necessary to contemplate beforehand, the rate of temperature rise to be used.

3.3.5 Calculation of Test Results

(1) The amount of expansion of the test piece shall be obtained by Eq. (A) from the difference in expansion of the test piece and the standard sample (quartz) obtained by measurements. Further, the coefficient of thermal expansion of the test piece shall be obtained at the temperature of T °C determined by Eq. (B).

$$dL(T) = dL'(T) + dLa(T) \qquad (A)$$

where,
dL(T) : expansion of test piece when temperature rises T °C from specified initial temperature
dL'(T) : difference in expansion between test piece and standard sample (quartz) when tempera ture rises T °C from specified initial temperature
dLa(T) : expansion of standard sample (quartz) when temperature rises T °C from specified initial temperature, provided that average coefficient of expansion of quartz may taken to be 0.54 x 10^{-6}/°C

$$\alpha(T) = dL(T)/(Lo \times T) \qquad (B)$$

where,
$\alpha(T)$: coefficient of thermal expansion of test piece when temperature rises T °C from specified initial temperature
L_o : length of test piece at specified initial temperature

Note) Depending on the testing apparatus, the process of obtaining coefficient of thermal expansion from measurement results has been programmed and coefficient of thermal expansion can be directly obtained. In such a case, it will be permissible to use the results thereof.

(2) The values of coefficient of thermal expansion obtained by the above procedure shall be taken at three or more points in the range of temperature measurement and the average value taken as the coefficient of thermal expansion of the test piece.

(3) Indication of the coefficient of thermal expansion shall be expressed using effective numbers of two digits.

3.3.6 Report

The following items shall be entered as necessary in the report of test results:

(1) Date of test
(2) Type of testing apparatus
(3) Number of test pieces
(4) Name of CFRM
(5) Type of fiber and fiber content of fiber V_f
(6) Designation, standard diameter, maximum diameter, nominal cross–sectional area A
(7) Length of test piece
(8) Rate of temperature rise (°C/min)
(9) Measuring temperature and coefficient of thermal expansion at that time (3 or more points)
(10) Range of measuring temperature and average coefficient of thermal expansion

Note) The principle of this apparatus is that a standard sample (quartz) of known coefficient of ther–

mal expansion is used and the difference in elongation or contraction between the material, (test piece) and the standard sample occurring with temperature under a given load, is detected by differential transformer. The weights are for applying a given load to the test piece.

3.4 Test Method for Bond of Continuous Fiber Reinforcing Material (Tentative Proposal)

A test method for bond of CFRM has been proposed, based on JSCE Standard, " Test Method for Bond Strength of Reinforcing Steel and Concrete by Pull-out Test (Draft) (JSCE-1988)" and the "Test Method for Bond (Draft)" of the Japan Concrete Institute. The point in which the proposed method differs greatly from those two is that application to CFRM in plate form has been made possible. Further, care shall be required regarding test pieces and testing machine, similarly to pull-out tests, so that rupturing of test pieces will not occur at chucks etc.

3.4.1 Scope of Application

This Standard prescribes the test method for bond properties of CFRM by pull-out test.

3.4.2 Concrete Specimen

(1) The specimen shall be of cubic form, as per the dimensions in Table 3.4.1 and according to the dimensions of the CFRM to be tested. In case of determining the bond length of CFRM in plate form, it shall be considered as a cylinder of identical cross-sectional area.

(2) The diameter of spiral steel bars for reinforcement shall be 6 mm, with spirals at a pitch of 4 cm, the ends of spiral bars being welded or provided with 1.5 times extra winding.

(3) Concrete shall have ordinary aggregates of maximum size of coarse aggregate 20 mm or 25 mm, slump of 10 ±2 cm, and compressive strength at 28-day age of 300 ±30 (kgf/ cm^2).

(4) Concrete shall be cast with CFRM set in a horizontal position.

(5) Curing of specimens shall be in water of 18 to 24 °C.

(6) The number of specimens shall not be less than five.

Table 3.4.1 Dimensions of concrete specimen

Diameter of continuous fiber reinforcing material (mm)	Dimensions of concrete specimen (cm)	Bonded length of CFRM (4D)cm	Un-bonded length of CFRM (cm)	Outside diameter of spiral steel bars for reinforcement (cm)
below ϕ16	10*10*10	6.4	3.6	8 - 10
ϕ19-ϕ29	15*15*15	7.6 - 11.6	3.4 - 7.4	12 - 15

3.4.3. Test Method

(1) The testing machine used for pull-out tests shall conform to JIS B 7721 (Tensile Testing Machines).

(2) The specimen shall be placed correctly on the loading plate with a spherical seat placed underneath, and eccentric load shall not be applied to the specimen.

(3) The diameter of the hole in the loading plate shall be 2 to 3 times the diameter of the CFRM.

(4) Load shall be applied uniformly as far as possible in a manner not to exert impact, and the rate of loading shall be set for the average bond stress intensity with the CFRM to be of the specified value.

(5) The dial gauge to be attached to the free end of the CFRM shall be such that readings can be made to less than 1/1,000 mm.

(6) The amount of slip of the free end shall be measured at about 10 points at roughly equal intervals up to failure, the loads at the individual amounts of slip read, and a load–slip curve plotted.

(7) The age at which testing is done shall be 28 days.

3.4.4 Calculation of Results

(1) The bond stress intensities when slips at the free end of 0.05 mm, 0.10 mm, and 0.25 mm occur, and the maximum bond stress intensity at maximum load shall be calculated by the following equation:

$$\tau_o = \frac{P}{Ul} \cdot \alpha$$

where,

τ_o : bond stress intensity (kgf/ cm^2)
P : tensile load (kgf)
u : circumferential length of CFRM
l : bond length (cm)
α : correction factor for compressive strength of concrete ($\alpha = 300/f'_c$)
f'_c: compressive strength at 28–day age of cylindrical specimen made at the same time (kgf/ cm^2)

3.4.5 Report

The following items shall be entered as necessary in the report of the test results:

(1) Date of test
(2) Name of CFRM
(3) Designation, standard diameter, maximum diameter, nominal cross–sectional area A
(4) Type of fiber and fiber content V_f
(5) Number of specimen
(6) Dimensions of specimen
(7) Concrete mix proportions, slump (cm), and compressive strength (kgf/cm^2) at 28 days
(8) Bond stress intensity–slip curve
(9) Average bond stress for amounts of slip of 0.05 mm, 0,10 mm, and 0.25 mm, and maximum bond stress intensity (kgf/cm^2), and condition of failure

3.5 Test Method for Fatigue of Continuous Fiber Reinforcing Material (Tentative Proposal)

A fatigue test method for CFRM has been proposed on the basis of the available JIS specification on testing of rigid plastics and metallic materials and the JSCE Standard concerning splices of reinforcing bars. The point in which this test method differs greatly from others is that assuming the conditions of CFRM being subjected to loading stress inside a concrete member, two types of loading methods were proposed. In carrying out tests, it will be especially important to exercise care that fracture of CFRM does not occur at anchoring sections.

3.5.1 Scope of Application

This Standard prescribes a method of test for fatigue of CFRM of bar form.

3.5.2 Terminology

The definition of the terms used in this Standard shall be according to JIS Z 2273 (General Rules for Fatigue Testing of Metals).

3.5.3 Test Piece

(1) A test piece, as a rule, shall be of circular or rectangular cross section.

(2) The length of a test piece shall not be less than 20 times its diameter. For CFRM of rectangular cross section, the equivalent diameter shall be calculated assuming a circular cross section with identical area.

(3) As a rule, the number of test pieces shall not be less than eight. In the vicinity of stress that the S–N curve diagram becomes horizontal, tests of two test pieces shall be performed for identical stresses.

(4) Cross-sectional dimensions of a test piece shall be measured with a precision of at least 0.5%. However, in case of a dimension of 2 mm or under, measurements shall be to a precision of 0.01 mm. In the event the test piece is of deformed cross section, the nominal cross-sectional area may be used.

(5) The anchoring section of the CFRM shall be devised in a manner that fatigue failure will not occur at that section.

3.5.4 Testing Machine

The testing machine shall be capable of applying the required load to the test piece as rapidly as possible, and the load applied shall be stable. The testing machine shall be equipped with a device by which it will be possible to determine the number of cycles of loading up to failure of the test piece. The testing machine shall be equipped with an apparatus to prevent automatic restarting when it stops due to power failure or any other cause.

3.5.5 Testing Method

(1) There are two loading method: varying upper stress amplitude with lower limit stress fixed at 50% of the tensile strength of CFRM, and varying upper limit stress on setting the lower limit stress by partial pulsating loading. These shall be used selectively depending on the objective. As a rule, loading shall be by axial tension.

(2) The upper limit of repetitions shall be 2 million (2×10^6) cycles in a general case.

(3) A series of tests shall be conducted with the same loading speed, and it shall be confirmed that temperature rise of the test piece does not occur.

3.5.6 Organization of Test Results

(1) The method of organizing test results and preparation of the S–N curve diagram shall be done in accordance with JIS Z 2273, "General Rules for Fatigue Testing of Metals."

(2) Two-million-cycle (2×10^6) fatigue tests of three test pieces shall be performed and if all the three test pieces do not fail, the stress amplitude at that stress shall be taken as the ascertained fatigue strength of that CFRM.

3.5.7 Report of Test Results

The following items shall be entered as necessary in the report of the test results:

(1) Date of test
(2) Number or marking of test piece
(3) Name of CFRM

(4) Designation, standard diameter, maximum diameter, nominal cross-sectional area A
(5) Type of fiber and fiber content V_f
(6) Type of stress, rate of repetition
(7) Temperature, humidity
(8) Table of test results
(9) S–N curve diagram, fatigue limit, ascertained fatigue strength
(10) Name, type and capacity of testing machine

III. CONCEPT FOR DURABILITY OF CONTINUOUS FIBER REINFORCING MATERIAL

CONTENTS

1. Introduction

It is generally considered that durability of a concrete structure will be improved by application of CFRM as concrete reinforcement. However, performance records of concrete structures using CFRM, and information concerning durability of concrete members using this material is not sufficient. And it can be said that adequate evaluations have not been made as to the degree that durability of a concrete structure using CFRM is superior compared to steel reinforced concrete structures. Also, there are many types of fibers and fiber binding materials, and the durability of a concrete structure will differ with each type.

Taking the above into account, durability in case of applying CFRM to a concrete structure is discussed here. The discussion will focus on two issues: (i) durability of CFRM itself and tests for evaluating the durability and (ii) results of a survey by questionnaire concerning allowable crack width in a concrete structure.

With regard to (i), it was first examined as to what is demanded in the way of durability of CFRM. The problems concerning durability of CFRM were cited and the points to be considered when applying to concrete members were indicated. Further, it was proposed concerning evaluation and test method for durability of CFRM. Since the same consideration will be necessary for durability of concrete itself, the durability of concrete is not studied here.

With regard to (ii), a questionnaire survey was made concerning allowable crack width considering durability. But due to the difficulty in setting an allowable crack width from the viewpoint of durability it was decided to grade allowable crack width from the viewpoints of appearance and feeling of safety.

2. Problems Related to Durability and Standard Test Method for Continuous Fiber Reinforcing Material (Tentative Proposals)

2.1 Introduction

Due to scarcity of available data concerning continuous fiber shapes, bundled continuous fibers, etc. This report confines itself to the discussion concerning CFRM in the shape of 'bars' using resin based binding material. This will be here after referred to as fiber reinforced plastic bar (FRP bar)

The use of FRP bars as reinforcing material for concrete is mainly because of two reasons. One is to improve durability of reinforcement as corrosion does not occur, and the other is to use in structures for magnetic levitation trains utilizing nonmagnetic property of FRP bars.

Here, two items are taken up: (1) Performance and durability demanded for FRP bars, and the present knowledge and problems with regard to verifying methods of durability , and (2) the concept of standard test methods for these bars on the basis of available past testing methods related to durability.

2.2 Performance and Durability Demanded of Fiber Reinforced Plastic Bar as Concrete Reinforcement

2.2.1 General Concept Regarding Durability of FRP Bar

Although FRP bars are generally not considered to be subject to corrosion as steel is, it is not that durability is guaranteed semi-permanently. When considering the durability of FRP bars, the problem lies in the durability of the resin used as fiber binding material (hereinafter referred to as "resin") although problem also exists in fiber durability in case of glass fiber reinforced plastic bars.

In case of using FRP bars for reinforcement of concrete, since the bars are generally embedded inside concrete, deterioration due to ultraviolet rays will hardly be a problem, but durability in the alkaline solution inside concrete will be a problem. This may be an unavoidable problem in case especially of contemplating to improve durability of concrete members which are often in moist states in marine and other environments. Although this is discussed in Chapter 3 of The-State-of-the-Art-Report on Continuous Fiber Reinforcing Material to Concrete Structures[1)], the fundamental concept regarding durability of FRP is as summarized below[1)].

In short, durability of FRP fundamentally depends on the performance of resin used as the fiber binding material, but the corrosion behavior and mechanism of resin have not yet been adequately understood. Particularly, with polymer materials, there is no concept of corrosion rate such as in corrosion of metals, and this makes it difficult for rational corrosion prevention design to be carried out. In general, in deterioration of polymer materials in a liquid environment, besides physical deterioration due to swelling, there is chemical deterioration which breaks molecular chains by chemical reaction. The phenomenon of a material deterioration due to chemical reaction can be classified as "corrosion" in a broad sense, and above mentioned deterioration may be included in this category. The hydrolysis reaction of ester occurring in aqueous solution due to acid and alkali is a representative of corrosion of resin for corrosion-resistant FRP.

Because of this, even in FRP bars, a certain kind of corrosion (especially of resin) may occur, and a part of resin may be lost in a long term, and deterioration may be unavoidable. Thus, it may be necessary to clarify what kind of fiber binding has been used, what kind of deterioration mode may occur, what kind of effect will be on the performance demanded as reinforcing material for concrete, and at when it may reach the serviceability limit state or ultimate limit state of the concrete member.

2.2.2 Performance Demanded of FRP Bar as Reinforcing Material for Concrete

(1) Durability from Standpoint of Aesthetic Appearance

The difference in corrosion of FRP bars from corrosion of steel reinforcing bars is that rust does not occur. This is especially important from the standpoint of aesthetic appearance to use FRP bars to avoid rust stains.

(2) Durability when Only Tensile Strength is Demanded of FRP Bars

When special considerations are given and the performance demanded of FRP bars is only tensile strength, it may be acceptable for the resin portion to be lost, even when the resin is needed to manufacture FRP bars.

As examples of this, the case of unbonded prestressed concrete in which adequate consideration has been given to the anchorage portion, and the case of design with bond between FRP bars and concrete is not expected and taking into account the decline in strength due to resin loss are conceivable. However, even when design has been done taking into account the decline in strength due to resin loss, it will be necessary to give thorough consideration to effects like loss of protection to the FRP bar due to resin loss.

(3) Durability when Expecting Bond Strength between FRP Bar and Concrete

In the cases of ordinary reinforced concrete members or pretensioned prestressed concrete members, reduction of bond strength will mean reductions in the serviceability limit state and ultimate limit state demanded of the said member. In such case, deterioration or loss of the resin surface will result in a serious limit state. Some kind of consideration will be necessary, especially, with regard to use of resin resulting in (a) surface reaction type corrosion and (b) layer formation type corrosion among the corrosion modes indicated in Chapter 3 of The State–of–the–Art–Report on Continuous Fiber Reinforcing Material to Concrete Structures.

2.2.3 Concept for Service Life

(1) Relation with Performance Demanded

In relation to 2.2.2, the concept for service life will differ depending on what kind of demand will be made regarding performance of the FRP bar. In case the performance demanded cannot be met on slightest deterioration of the surface resin, it will be unavoidable to specify an extremely short service life, while conversely, if the design allows partial or total loss of resin, it may be possible for a service life of several tens of years or more to be set up.

(2) Relations with Environmental Conditions

Resin deteriorates mainly through hydrolysis, and it may be considered that deterioration of resin will be slow in dry concrete. Accordingly, it may be considered that the service life will be substantially different for a place where a dry condition can be maintained and a place which where concrete is mostly wet, such as in marine environment.

(3) Relation with Stress (Load) Conditions

It is known that FRP bars under stress show greater decline in strength compared to a stress free state. Here, it is desirable for service life to be determined on the basis of corrosion of resin or fiber under stress, or the mode and mechanism of strength decline.

(4) Use of FRP Bar against Salt Damage

Because of the fact that FRP bars do not corrode like steel, they are being contemplated for use in structures where corrosion of steel due to salt poses a problem. However, it is conceivable that hydrolysis of resin is liable to occur since concrete members in a marine environment will be in moist condition, as mentioned in 2.2.3(2).

Therefore, in such an environment, it will be necessary for application to be made upon having clarified the mechanism of corrosion or deterioration of FRP bars.

(5) Evaluation of Deterioration

In 2.2.2(1), it was indicated that FRP bars are advantageous from the standpoint of aesthetic appearance, because rust is not produced even when corrosion (deterioration) occurs, but conversely, the state of resin having been lost will not become apparent, so that it is desirable for a study to be made for a method of diagnosis before an accident occurs.

2.2.4 Conditions Desired for Durability Tests (Accelerated Tests)

In general, the conditions desired of an accelerated test for durability are the following two[4]:

(i) A compound accelerated deterioration test method carried out under conditions close to the actual meteorology and environment (even though it is impossible to simulate all meteorological and environmental conditions), or causing deterioration in an accelerated manner deterioration similar to that in an actual environment.

(ii) A method to investigate quantitatively the chemical or physical deterioration.

From a survey of relevant standard methods of test as JIS etc., it was found that there are many standard methods with regard to fundamental physical properties, such as, thermal and strength characteristics and durability properties such as resistance to chemicals and weather resistance of fiber binding materials. But most of these test methods are mainly for physical characteristics such as flexural strength and tensile strength, and there is hardly any standard method of test regarding continuous fibers. Although there was no standard method of test considering FRP bars, there were numerous methods adapting the previously-mentioned testing methods for fiber binding material adopted for FRP plate materials in general. Further, even though compound accelerated tests are being carried out in a form close to actual environmental conditions, the situation is that examinations of the similarities of testing conditions and evaluations of deterioration from a chemical point of view were not being made. This is a problem to be dealt with in examining standard methods of test concerning FRP bars hereafter.

2.3 Concept for Standard Test Method

2.3.1 Prerequisites for Durability Evaluation

Since FRP bar is a composite of continuous fibers and fiber binding material, evaluation of durability needs to be done by evaluating the durability of both. The durability of the FRP bar can be evaluated as shown in Fig.2.1. With regard to evaluation of the fiber binding material (Standard Test (1)) and evaluation of the continuous fibers (Standard Test (2)), it is preconditioned that the manufacturer is to carry out quality control and manufacturing control and make the evaluations.

In effect, these are handled as being clearly indicated by the manufacturer that the fiber binding material and the continuous fibers possess sufficient durability, and that these are materials for which manufacturing control has been properly provided (it being considered that adequate information concerning durability is not available under present conditions). Accordingly, it is discussed here on evaluation of durability of the FRP bar, and the concept for standard test method 3.

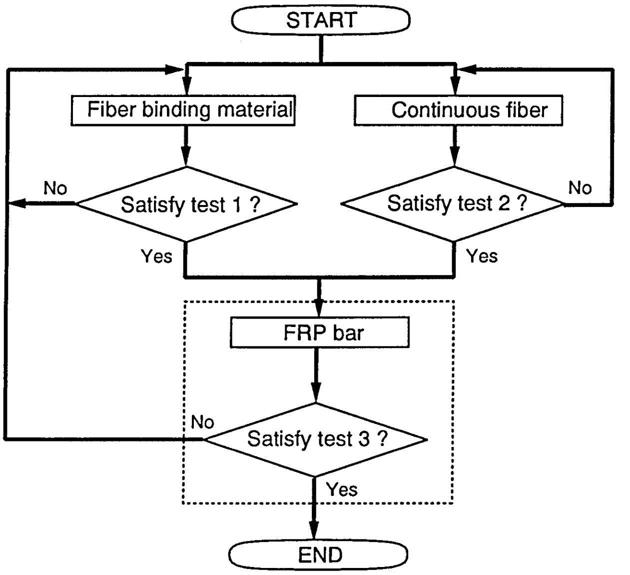


Fig. 2.1 Procedure for evaluating durability of FRP bars

2.3.2 Concept for Durability Evaluation of FRP Bar

An example of the method of examination concerning evaluation of durability for FRP bars (Standard Test (3)) is shown in Fig.2.2. The basic idea is that the test should be done in three stages.

In the first stage, the method of application of FRP bars is considered. The cases included are evaluation of durability in strong alkali environment of concrete, and in ultraviolet rays to which they may be exposed in case as external tendons. However, durability in strong alkali will especially be considered in this report.

The state of stress of the FRP bar is considered in the second stage. The case of FRP bars being used as reinforcing material for reinforced concrete or prestressed concrete structure may be cited, and in such a case it is necessary to set the conditions whether the FRP bar is to be evaluated at low stress or at high stress.

In the third stage, various environments are taken into consideration. For this purpose, conditions regarding temperature variation of the environment (high–temperature, normal–temperature, low–temperature environment, or cycles, etc.) are especially set. In case of applying to salt environment or hot springs zone, evaluations are to be made under the given conditions.

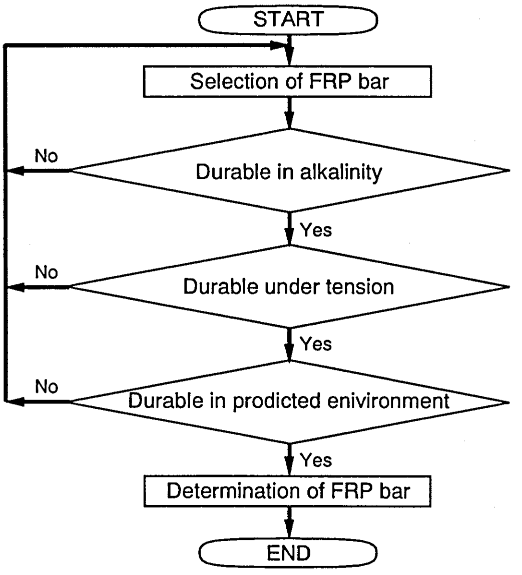


Fig.2.2 Procedure for evaluating standard test(3)

2.3.3 Summary of Existing Data

Based on the above concept, and with the cooperation of the CCC Association (Association of Composite Material Using Continuous Fiber for Concrete Reinforcement), a questionnaire survey was conducted on past tests carried out on durability evaluations of FRP bars, mainly concerning immersion tests, and information regarding testing methods and testing conditions.

(1) Immersion Solution

Tests immersing FRP bars in an aqueous solution with pH of about 13, simulating the strong alkalinity of concrete are apparently most popular, but it appears immersion tests in salt solution and sulfuric acid solution are also being performed separately. In many cases tests are performed with aqueous solution temperature at around 60 °C.

(2) Immersion Period

With regard to immersion period there is a spread from around 7 days to 1 year, but on average, it seems an immersion period of about 1 month is required. Especially, where there is lack of information concerning durability, it is thought necessary to provide for a comparatively long immersion period.

Here, a correlation can be recognized between immersion temperature and immersion period regarding amount of deterioration (corrosion) of the fiber binding material. Therefore, when there are correlations confirmed between amount of deterioration of FRP bar and immersion temperature and immersion period, it may be possible for immersion temperature to be set higher and immersion time set shorter with the aim of accelerating the test.

(3) Stress Conditions

The state of stress is evaluated by the tensile stress condition of 0.5 x P_u to 0.7 x P_u (P_u: ultimate load), and it appears that on an average there are many cases of evaluation made under the condition of 0.6 x Pu. This may be said to be in the range of current design conditions. Although it is expected that even stricter stress conditions will be demanded hereafter, it is necessary for evaluation to be made under the same tensioned state as also the designed conditions regarding whether there will be decrease in ultimate load which may be a problem in the standpoint of design.

Further, evaluations are also made in case of unstressed condition, but it is considered necessary to carry out the evaluation in a condition of low stress, even in the case of non-prestressed reinforced concrete structure.

(4) Evaluation Items

With regard to the items of evaluation carried out after immersion, mainly strength characteristics such as tensile strength and tensile elasticities are considered. Further more it appears that investigations of weight change, maximum elongation, etc. are also carried out. These physical investigations may be said to be the most standardized quantitative evaluation methods at present.

However, as described in 2.2.4, it is considered necessary for observations to be made regarding changes in the surfaces and cross sections of FRP bars, and further, chemical investigations in certain cases such as of ester bonding concentration and binder composition to clarify the deterioration and corrosion mechanisms of fiber binding material.

As for precuring of samples done after immersion until evaluation tests are conducted, various conditions have been used such as evaluation immediately upon taking out from the immersion solution, evaluation after curing in a condition of low temperature for a day, etc. In the event the evaluation will be affected by wetting of samples, it may be necessary to standardize conditions and periods for precuring.

2.3.4 Durability Evaluation Tests

Based on the method of study shown in Fig.2.2 as an example of durability evaluation methods for FRP bars and results of the questionnaire survey concerning durability evaluations, the test method which can serve as a case study in the future will be discussed.

Further, the evaluation method given here assumes a case of using FRP bars in a state of being subjected to tensile stress in concrete, and evaluates the conditions of the first to third stages together as shown in Fig.2.2. Further, for tensile stress conditions, the methods of constant strain condition and constant load condition may be cited, but here, the one of constant load condition considering convenience of testing is adopted.

(1) Scope of Application

This test mainly considers cases of applying FRP bars to prestressed concrete structures. In case of a reinforced concrete structure without prestress, application will be possible by making constant tensile load small, and carrying out the evaluation in a state of low stress.

(2) Measurement Items

. Investigation of changes in appearance and depth of deterioration (cross section)
. Weight change
. Reduction in tensile strength, reduction in tensile elasticity

(3) Test Method

The test method is to be done in accordance with JIS K 7108, "Testing Methods for Chemical Resistance of Plastics under Constant Tensile Load" as shown in Fig.2.3.

(4) Immersion Solution
. A strong alkali mixed solution of pH about 13
. Aqueous solution temperature: 60 °C

(5) Loading Condition
. Constant tensile load: 0.6 x P_u or following design conditions (P_u: ultimate load)

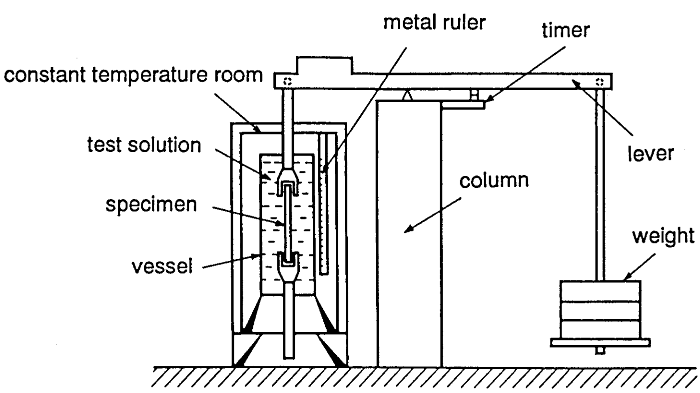


Fig.2.3 Tensile test equipments (sustained load JIS K 7108)

2.4 Summary

Durability of FRP bars is governed fundamentally by the durability of the resin which is the fiber binding material. However, the mechanism of corrosion (deterioration) of resin in an FRP bar has not yet been adequately explained.

With regard to alkali resistance and moisture resistance, which are to be especially required by FRP bar, test results of resin which has adequate durability and good bond with continuous fiber have not yet been found.

Therefore, in order to evaluate the durability of FRP bar, it will be necessary to clarify the mechanism of the deterioration. To achieve this, it is important to obtain data concerning what type of deterioration has occurred, how that will affect the performance demanded as a reinforcing material for concrete, and when the serviceability limit state or ultimate limit state will be affected, when a certain resin is used.

At present, it is difficult to set up a standard test method to evaluate the durability covering all conditions such as the application method and environmental conditions. But it is considered that a standard test method which is more simple and has general applicability will be established hereafter by clarifying the deterioration mechanism of resin based on the evaluation methods cited here, upon which case studies would be made under various conditions, and the respective correlations regarding variety of resin, solution, stresses level, etc. made clear.