I. RECOMMENDATIONS FOR UPGRADING OF CONCRETE STRUCTURES WITH USE OF CONTINUOUS FIBER SHEETS

I. RECOMMENDATIONS FOR UPGADING OF CONCRETE STRUCTURES WITH USE OF CONTINUOUS FIBER SHEETS

CONTENTS

CHAPTER1 GENERAL 1
1.1 Scope 1
1.2 Definitions……………………………..………...3
CHAPTER2 BASICS OF UPGRADING...4
2.1 General..4
2.2 Upgrading process...6
CHAPTER3 MATERIALS..9
3.1 General...9
3.2 Quality of Materials..9
3.2.1 Continuous fiber sheets and continuous fiber strands..9
3.2.2 Impregnation resin...10
3.2.3 Primer..11
3.2.4 Smoothing agent...12
3.2.5 0thermaterials...12
3.3 Characteristic Values and Design Values of Materials..13
3.3.1 General..13
3.3.2 Continuous fiber sheets..14
3.3.3 Continuous fiber strands...17
CHAPTER4 LOADS AND ENVIRONMENTAL ACTIONS 20
CHAPTER5 DETAILED INSPECTION OF EXISTING CONCRETE STRUCTURES...21
5.1 General...21
5.2 Detailed inspection USING DOCUMENT,RECORDS,ETC..21
5.3 Detailed inspection at the site..22
CHAPTER6
PERFORMANCE VERIFICATION FOR UPGRADED CONCRETE STRUCTUKS.......... 24
6.1 General...24
6.2 Design strength of materials in existing structures...25
6.2.1 General...25
6.2.2 Concrete...27
6.2.3 Steel...29
6.3 Safety factor..30
6.4 Verification of Safety...31
6.4.1 Design flexural and axial load-carrying capacity..31
6.4.2 Design shear capacity for bar members..35
6.4.3 Design flexural fatigue resistance...46
6.4.4 Design punching shear fatigue resistance of planar members...47
6.4.5 Safety with respect to seismic action..48
6.4.5.1 Design ductility ratio of members..48
6.4.5.2 Member restoration force model...51
6.4.6 Fire safety...52
6.4.7 Collision safety..55

6.5 Verification of serviceability..57
6.5.1 Stress level...57
6.5.2 Crack width..58
6.5.3 Displacement/deformation.. 59
6.6 Restorability...60
6.6.1 Restorability after earthquake...60
6.7 Changes of performance of upgraded structures with the elapse of time…………………..61
6.7.1 General...61
6.7.2 Verification of the effect of using continuous fiber sheets to prevent
intrusion of chloride ions...62
6.8 Verification of structural details 65
6.8.1 General...65
6.8.2 Corner angles of members...66
6.8.3 Overlap splices of continuous fiber sheets...66
6.8.4 Anchoring of continuous fiber strands...67
6.8.5 Mechanical anchoring of continuous fiber sheets...68
CHAPTER7 UPGRADING WORK...69
7.1 General..69
7.2 Work plan...70
7.3 Handling of materials..71
7.4 Surface preparation..72
7.5 Bonding and jacketing..74
7.6 Finishing work...76
7.7 Inspections...78
7.7.1 General...78
7.7.2 Receiving inspection for materials...78
7.7.3 Inspection of material storage condition..79
7.7.4 Inspection of surface preparation, primer coating and smoothing...................79
7.7.5 Inspection of continuous fiber sheets and continuous fiber strands during
and after construction...80
CHAPTER8 WORK RECORDS...82
CHAPTER9 MAINTENANCE OF UPGRADED CONCRETE STRUCTURES................83
9.1 General..83
9.2 Inspections and evaluations...84
9.3 Countermeasures 86
References...87

CHAPTER 1 GENERAL

1.1 Scope

(1) These recommendations provide design and construction standards for the upgrading of existing concrete structures through bonding or jacketing with continuous fiber sheets.

(2) These recommendations may also be applicable to the upgrading of structures by wrapping with continuous fiber strands.

[Commentary]

(1) These recommendations consist of design and construction standards for the upgrading of existing concrete structures using continuous fiber sheets with the aim of improving their strength and durability. The recommendations include standards not only for repair and strengthening as described in the Recommendations for Maintenance of Concrete Structures (Draft), but also for the recovery of structural functionality, such as by reducing deflection, and for measures to ameliorate adverse effects on third parties by preventing spalling of concrete.

The recommendations are predicated on a process that involves bonding fiber sheets onto the structure or jacketing the structure with such sheets at the site, then impregnating them with epoxy resin. The types of continuous fiber covered by these recommendations are carbon and aramid fibers, with which Japan has considerable experience. Both have a mass per unit area of less than 400 g/m^2. When applying these recommendations to cases where another material, such as glass fiber, is to be used, or where the unit mass of the fiber sheet is greater than stated above, or the prefabricated sheets are used, performance should be verified through experimental tests or by other means.

Continuous fiber sheets are light, very strong, durable, and resistant to corrosion. Upgrading of structures using such sheets offers the following advantages in design and construction:

Advantages in design

- Since the continuous fibers are arranged in a single orientation, the maximum reinforcing effect can be achieved by bonding or jacketing with the fibers aligned in the direction designated in the design.
- Any required volume for upgrading can be easily obtained by increasing/decreasing the unit mass and the number of plies.
- The dead weight added to an upgraded structure is minimized because of the light weight of fiber sheets.
- The fiber sheets protect the concrete from deterioration while also protecting reinforcing steel from corrosion because the matrix itself is highly resistant to corrosion and can block external influences.

Advantages in construction

- Upgrading manually is possible, because the work entails simply bonding fiber sheets to the structure or jacketing the structure with sheets using cold-setting resins
- Because the materials are light in weight, upgrading can be carried out by a small number of workers over a short period, and there is no need for heavy construction equipment or large preparation areas.
- Since the fiber sheets are easily shaped on site, the method is suitable even when a structure has complicated shape.

(2) Even when upgrading existing concrete structures by jacketing with continuous fiber strands, the same performance as with continuous fiber sheets can be anticipated. Therefore, these recommendations can be applied to continuous fiber strands as well. However, they are not applicable to flexural strengthening or to punching shear strengthening for planar members.

One of the advantages of upgrading by jacketing with continuous fiber strands is that it is possible to reduce manpower by using a winding equipment.

What are not covered in these recommendations shall conform to the following Standard Specifications and Recommendations.

Standard Specifications for Design and Construction of Concrete Structures (Design) (Seismic Design) (Construction) established 1996	1996
Standard Specifications for Design and Construction of Concrete Structures (Construction) "Durability Verification Standards" established 1999	1999
Recommendations for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials	1996
Recommendations for Maintenance of Concrete Structures	1995
Recommendations for Retrofit of Concrete Structures	1999

1.2 Definitions

The following terms are defined in these recommendations:

Continuous fiber strand:

Several thousand to several tens of thousands of continuous fibers bound together, each fiber measuring from several micrometers to a dozen or more micrometers in thickness

Continuous fiber sheet:

Continuous fiber strands arranged in a sheet-like or textile-like form in one or two planar directions

Fiber mass per unit area:

The mass of fibers in a continuous fiber sheet per square meter. In the case of strands, this value is defined for the wound interval.

Impregnation resin:

The resin used to impregnate and bond the continuous fiber filaments and give them the functions of a composite material, and to attach the continuous fiber sheet to the surface of concrete

Interfacial fracture energy:

The amount of energy per unit bonding area needed to produce interfacial failure

CHAPTER 2 BASICS OF UPGRADING

2.1 General

When upgrading concrete structures with continuous fiber sheets, suitable methods shall be used to verify that the performance requirements for the upgraded structure are adequately maintained. In addition to the feasibility of upgrading work and the ease of maintenance after its completion, economy shall also be considered.

[Commentary]

In general, the performance required for concrete structures during the service life is specified in advance. Nevertheless, the performance level of concrete structures may sometimes decline to a greater degree than expected, due to excessive deterioration caused by changing environmental conditions or by unforeseeable disasters or the like. In other cases, a higher performance level may be required, or new performance criteria had been introduced due to changes in load conditions and purpose of use accompanying the revision of standards. In such cases, the concrete structures are generally upgraded.

Concrete structures are subject to a wide variety of performance requirements, and appropriate techniques are needed to verify these performance requirements. Table C2.1.1 shows some examples of verification items and performance requirements extracted from the Recommendations for Retrofit of Concrete Structures. However, when verifying the performance of upgraded concrete structures, unlike with new structures, suitable verification techniques for upgrading should be employed.

Upgrading using the continuous fiber sheets covered by these recommendations is done by bonding the continuous fiber sheets onto the structure or jacketing the structure with such sheets. Consequently, it is expected not only to improve the load-carrying performance of the concrete structure but to block the intrusion of substances in the surrounding environment that might cause deterioration of concrete. This method can also be applied to prevent spalling of deteriorated concrete, ameliorating the adverse effects on third parties.

However, these features can only be realized with quantitative evaluation methods and appropriate verification techniques. Previous research has empirically demonstrated the improvement of load-carrying performance of upgraded concrete structures, and evaluation methods have also become quantitative to a considerable extent based on the mechanical properties of continuous fibers. Based on these achievements, methods for the quantitative evaluation of how the sheet contributes to improving safety (flexural load-carrying capacity, shear capacity and ductility) and to improving serviceability (restraining flexural deformation and flexural cracking widths) are proposed in these recommendations.

When selecting an upgrading method, whether the upgraded concrete structure will satisfy the specified performance requirements or not should be considered. In addition, economy throughout the entire life cycle, including ease of construction and ease of maintenance and should also be considered. Continuous fiber sheets and strands have major advantages such as they are lightweight, can be placed manually, and can be easily shaped on site to cope with complex shapes. They can also easily accommodate additional upgrading. However, quantitative methods for evaluating these advantages, as in the case of changes over time in the performance of concrete structures after upgrading, have not yet been established. Future research is expected to result in the further utilization of these advantages.

Table C2.1.1 Sample indicies for verifying the performance of concrete structures upgraded with continuous fiber sheets

Performance	Item	Indicies for conventional evaluation methods	Indicies for elaborated evaluation methods
Safety	Failure and collapse	Flexural load-carrying capacity, shear capacity, torsional capacity, fatigue capacity, response displacement, ductility ratio, etc.	Deformation of or damage to structure due to application of anticipated load (evaluation and verification by numerical simulations)
	Rigid body safety	Over-turning moment resistance, sliding resistance, vertical bearing capacity, etc.	
	Fire	Self-extinguishing ability, fire spreading resistance	
Serviceability	Driving comfort/walking comfort	Displacement/deformation, rigidity, smoothness of road surface, level differences, vibration characteristics of structure and foundation, velocity, acceleration, vibration level, sound pressure, etc. transmitted to users and neighbors	Sense on the part of users and neighbors of the structure's response to the application of anticipated load and the effect of the environment (evaluation and verification of the interrelationship between the structure's response and human sensations)
	Vibration resistance		
	Noise resistance		
	Watertightness/ airtightness	Crack width, coefficient of water permeability, coefficient of air permeability, etc.	
	Appearance	Crack width, crack density, size of stained area, density of stains, color of materials used, paint color, etc.	
	Visual safety	Displacement, deformation, crack width, crack density, sheet peeling area, etc.	
Restorability	Restoration time/restoration cost	Failure mode, response displacement, residual displacement, residual crack width, degree of damage to constituent materials, fire-resistance rating of materials, wear strength and impact strength of materials, etc.	Deformation and failure of structure due to application of anticipated load, and decomposition of constituent materials due to environmental actions

2.2 Upgrading process

The upgrading of concrete structures using continuous fiber sheets shall be in accordance with the procedures specified in the Recommendations for Retrofit of Concrete Structures.

[Commentary]

When upgrading concrete structures, the required performance level for the structure is first set up and an appropriate upgrading method is selected to satisfy the requirements. When the method of using continuous fiber sheets is selected, the process from planning through construction is implemented as shown in the flow chart in Figure C2.2.1.

Specifically, upgrading should be performed using the following procedure.

(1) A plan for the upgrading of existing concrete structures using continuous fiber sheets is drafted covering the steps from detailed inspection through design of the structure, implementation of upgrading work, and maintenance.

(2) A detailed inspection of the structure is performed in accordance with Chapter 5 "Detailed Inspection of Existing Concrete Structures."

(3) Considering the performance of the structure after upgrading, the current condition of the structure and the conditions for construction, the following items are set up: the continuous fiber material (carbon fiber or aramid fiber), fiber mass, number of plies, scope of use, impregnation resin material, smoothing of existing concrete surfaces, other upgrading specifications and the construction method (bonding or jacketing).

(4) The verification is done to confirm that the upgraded structures using continuous fiber sheets will satisfy the performance requirements at all points during the remaining design service life. The method specified in Chapter 6 "Performance Verification for Upgraded Concrete Structures" should be used for the verification. Since the strengthening of some members may alter the failure mode of the entire structure, due consideration should be given not only to the performance of the members to be strengthened but also to that of the entire structure.

(5) After the structure has been verified to satisfy the performance requirements with use of the specifications and the construction method for upgrading, the upgrading work is implemented in accordance with Chapter 7 "Upgrading Work," and after completion maintenance is conducted in accordance with Chapter 9 "Maintenance of Upgraded Concrete Structures."

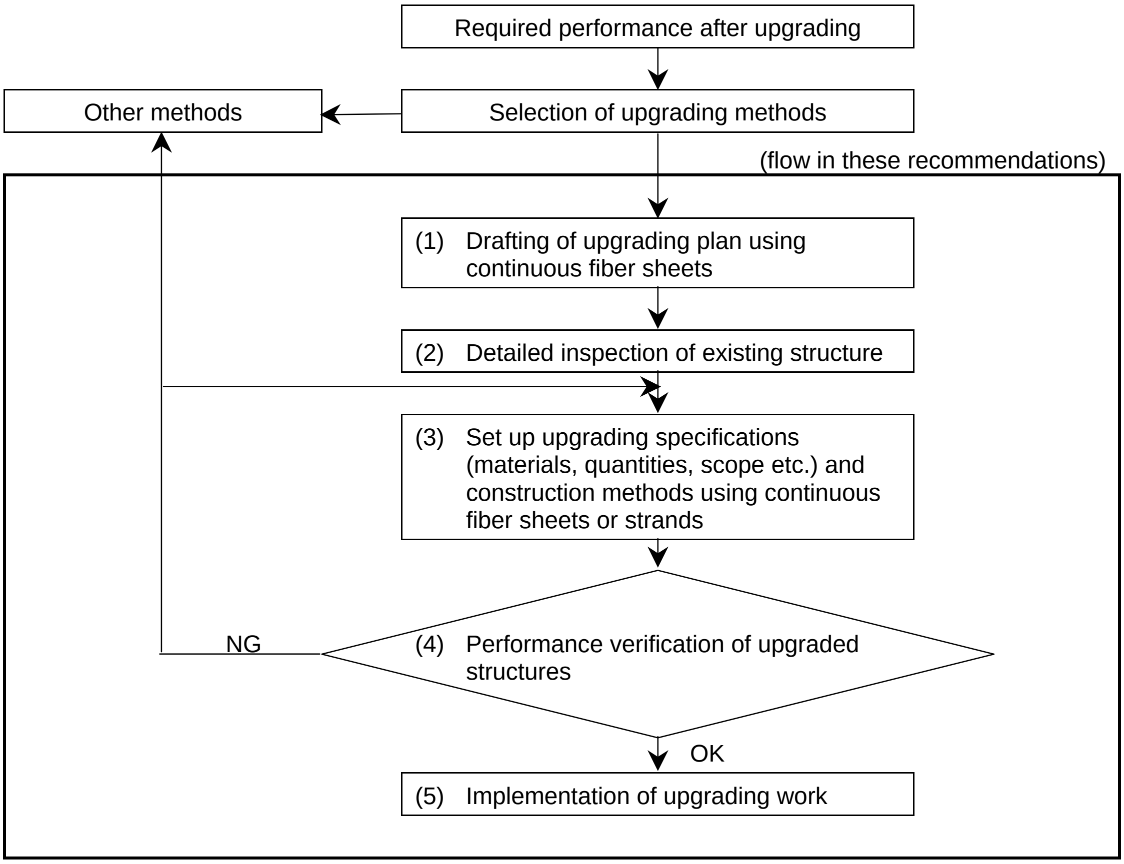


Figure C2.2.1 Upgrading using continuous fiber sheets

CHAPTER 3 MATERIALS

3.1 General

The continuous fiber sheets or continuous fiber strands used for upgrading shall be those whose quality has been confirmed. Quality shall be confirmed for the primer, the impregnation resin, and the smoothing material and surface preparation material for concrete surfaces.

[Commentary]

The upgrading method by bonding continuous fiber sheets to concrete structures or jacketing with the sheets (continuous fiber sheet method) or with continuous fiber strands (continuous fiber strand method) are those in which upgrading is carried out after impregnation resin applied to the continuous fibers hardens and bonds to concrete surface.. In addition to continuous fiber sheets, continuous fiber strands, and impregnation resin, the materials used include smoothing agents (used to smooth the surface irregularities and level differences in the concrete), surface preparation material, grout for filling cracks on the surface, and primer to improve bonding.

The effect of upgrading using continuous fibers varies depending on the quality of the materials and their combination. Therefore, the quality of each material should be confirmed in advance.

3.2 Quality of Materials

3.2.1 Continuous fiber sheets and continuous fiber strands

The quality of continuous fiber sheets and continuous fiber strands shall be specified in terms of the characteristic values of tensile strength, Young's modulus, and ultimate strain with the combination of impregnated resin.

[Commentary]

The continuous fibers covered by these recommendations are carbon fibers or aramid fibers. Both of these fibers have excellent properties (lightweight, high strength, high flexibility and high resistance to corrosion), making it possible to select the fiber with the quality required for the application. However, different from the ordinary steel reinforcement, these materials are quite elastic up to fracture without yield phenomena.

The tensile strength and Young's modulus depend on the type and use conditions of the impregnation resin. Therefore, the characteristic values of continuous fibers and those combined with the impregnation resin should be confirmed in accordance with the JSCE-E 541 "Test method for tensile properties of continuous fiber sheets."

3.2.2 Impregnation resin

Impregnation resin shall satisfy the following requirements.

(1) As a binding material of fibers, it shall have a suitable viscosity and work life for the operation. It shall also impregnate the continuous fiber sheets and continuous fiber strands and harden thoroughly.
(2) After the impregnated continuous fibers have hardened, the quality of the composite shall be ensured.
(3) The quality required for the bonding of the continuous fiber sheets to concrete surface through the primer or smoothing agent shall be ensured.
(4) The quality required for the overlap splice for continuous fiber sheets shall be ensured.

[Commentary]

(1) Hardening of the impregnation resin produces the binding of continuous fibers to one another, and creates a composite material with the appropriate strength, Young's modulus, and other properties. Accordingly, the impregnation resin should thoroughly impregnate the continuous fiber sheets or continuous fiber strands. Also, during the construction process, it should have suitable viscosity to hold the sheet in place during attachment work. As the viscosity varies depending on the temperature, a resin with good viscosity at the anticipated temperature during construction should be selected. It is also important for the resin to have a certain work life for the completion of operation without dripping during upward application.

(2) The quality of continuous fiber sheets or that of continuous fiber strands is evaluated after the impregnation resin has hardened, and a composite material has formed. Without the impregnation resin, the fibers break one after another under tension force, as in a rope, and it is impossible to effectively use the strength of individual fibers. Moreover, even if the fibers are thoroughly impregnated with the impregnation resin, differences in the type of impregnation resin and the forming method result in different tensile strength and Young's modulus. Therefore, a suitable impregnation resin should be selected and the composite should be tested in accordance with the JSCE-E 541 "Test method for tensile properties of continuous fiber sheets" to ensure the quality required for continuous fiber sheets.

(4) When it is necessary to place an overlap splice between the continuous fiber sheets, , the bond strength of the overlap splice should be confirmed in accordance with the JSCE-E 542 "Test method for overlap splice strength of continuous fiber sheets" to prevent the overlap splice from becoming a weak point.

3.2.3 Primer

The primer shall have the required bond strength for bonding continuous fiber sheets to concrete surfaces.

[Commentary]

The primer is applied to the concrete surface in advance to ensure a thorough bond between concrete surface and the continuous fiber sheets. The primer also prevents air bubbles from developing between the continuous fiber sheets and the surface of concrete during construction or curing as a result of exposure to direct sunlight. In other words, the primer penetrates the surface of concrete and strengthens the surface layer, creating the required bond strength between the continuous fiber sheets and the surface of concrete. As noted previously, the bond strength of the primer should be confirmed by examining the combination of the primer with the impregnation resin.

3.2.4 Smoothing agent

(1) The smoothing agent shall be able to smooth level differences and comparatively small irregularities in the concrete surface. It shall also have sufficient viscosity and stickiness to enable the application work to be performed smoothly.
(2) The smoothing agent shall be able to bond sufficiently with the primer and impregnation resin.

[Commentary]

(1) If there is any unevenness caused by the joints of formwork or traces of bubbles in the surface of concrete, construction defects such as wrinkles, new bubbles, and resin accumulations tend to occur. Also, the continuous fiber sheets that contact the overhangs tend to break. Large overhangs should be removed with a disc sander or the like, but minor irregularities can be smoothed by coating with a smoothing agent. To ensure that the smoothing work is accomplished without any problem, it is important to select a proper smoothing agent which has viscosity, stickiness and work life that matches the temperature, climate and other construction conditions. In general, epoxy resin putties or the like can be used.

(2) In the verification of upgrading performance, the smoothing agent should have the required bond strength with the primer when the continuous fiber sheets are expected to be bonded to the existing concrete.

3.2.5 Other materials

(1) Surface preparation materials shall have sufficient bond strength at the damaged sections of the existing concrete, and their strength shall be at least equal to that of the existing concrete.
(2) Crack grout shall penetrate to the deepest portion of the cracks, shall have the bond strength needed to bond with the concrete, and shall be able to prevent infiltration of water through the cracks.
(3) Surface protection materials shall maintain the required quality of continuous fiber sheets or continuous fiber strands during the prescribed period of time.

[Commentary]

(1) If the cover of the existing concrete is missing in places, these sections are restored to the original condition by coating with surface preparation materials. If the surface preparation material tends to come loose from the existing concrete or has low strength, the transmission of force is hindered between the continuous fibers and the existing concrete. Normally, resin mortar and polymer cement mortar with high adhesion properties and high strength are used as surface preparation materials.

(2) Both epoxy resin type and cement type crack grout are available and a suitable material should be selected to match the situation of cracking and water leakage.

(3) through both the continuous fiber sheet method and the continuous fiber strand method, the composite material made of continuous fibers with impregnation resin is placed on the outer surface of the structure. In order to prevent deterioration of the continuous fiber composite material during the service life, a protective layer should be created by coating the surface with paint, concrete, or mortar when necessary. However, surface protection is not necessary if it can be confirmed that the quality of the continuous fiber composite material will not change over time by the results of suitable numerical simulations and accelerated exposure tests (JSCE-E 547 "Test method for accelerated artificial exposure of continuous fiber sheets") or actual exposure tests, or, that the required quality can be maintained.

If a noncombustible cover or flame-resistant cover is needed for protection against fire, or if protection against impacts caused by drifting wood or automobiles or other type of protection is needed, a surface protection material should be selected to match the environment where the structure is located.

3.3 Characteristic Values and Design Values of Materials

3.3.1 General

The following method shall be used to determine characteristic values and design values for continuous fiber sheets and continuous fiber strands.

(1) The characteristic values for material strength and ultimate strain of continuous fiber sheets and continuous fiber strands shall be defined as the values which ensure that most of the test results do not fall below the values, assuming variations in the test results.
(2) The design material strength and design ultimate strain for continuous fiber sheets and continuous fiber strands shall be obtained by dividing the characteristic value by the material factor.

[Commentary]

The continuous fiber sheet method and continuous fiber strand method involve primer and impregnation resin as supplementary materials. For this reason, the tensile strength, Young's modulus and other values of continuous fiber sheets or continuous fiber strands used for upgrading design should generally be determined for the composite material formed after impregnating with resin and allowing it to harden. Accordingly, the method used to determine the characteristic values and design values for continuous fiber sheets and continuous fiber strands is described here.

3.3.2 Continuous fiber sheets

(1) As a rule, the characteristic value for the tensile strength of continuous fiber sheets shall be determined based on the test results. The tension test shall be done in accordance with the JSCE-E 541 "Test method for tensile properties of continuous fiber sheets."
(2) As a rule, the characteristic values for the bond strength of continuous fiber sheets to concrete, the characteristic values for the interfacial fracture energy and the relationship between bond stress and relative displacement shall be determined by the bond test. The bond test shall be done in accordance with the JSCE-E 543 "Test method for bond properties of continuous fiber sheets to concrete."
(3) The compressive strength and shear strength of continuous fiber sheets shall not be considered in the design.
(4) As a rule, the Young's modulus for continuous fiber sheets shall be determined by the tension test. The tension test shall be done in accordance with the JSCE-E 541 "Test method for tensile properties of continuous fiber sheets (draft)."

(5) The tensile stress-strain relationship for continuous fiber sheets, used to verify safety and serviceability, may be a straight line passing through the origin with the Young's modulus.

(6) The coefficient of thermal expansion for continuous fiber sheets shall be calculated from the coefficient of thermal expansion, Young's modulus and the volume ratio of the constituent materials, such as the continuous fibers and impregnation resin.

(7) As a rule, the characteristic values for the tensile fatigue strength shall be determined by the tensile fatigue test. The tensile fatigue test shall be done in accordance with the JSCE-E 546 "Test method for tensile fatigue strength of continuous fiber sheets."

(8) The material factors for continuous fiber sheets shall be determined using Section 2.6 (2) in the Standard Specifications for Design and Construction of Concrete Structures (Design).

[Commentary]

(1) Continuous fiber sheets function as a composite material with continuous fibers bonded using impregnation resin. Even if the same strengthening fibers are used, the strength of continuous fiber sheets may vary depending on the shape of the sheets and the bond with the impregnation resin. Therefore, this value is measured using the condition of the composite material after the sheet is impregnated with the resin and it has hardened. It is known that variations in the tensile strength of continuous fiber sheets are generally greater than those of steel, but the distribution can be thought of as conforming almost completely to a normal distribution. In general, the characteristic value for tensile strength is derived by subtracting three times the standard deviation (σ_n) from the mean strength (X):(X-3σ_n). This is equivalent to a 99.9% confidence limit for the tensile strength. However, if the material manufacturer has established guaranteed strengths based on sufficient test results, these values may be used as the characteristic values for the tensile strength of continuous fiber sheets.

(2) The bond strength between continuous fiber sheets to concrete, the relationship between interfacial fracture energy, bonding stress and relative displacement vary depending on the type of continuous fiber sheet and number of plies, the type of primer and impregnation resin, the strength and surface processing

condition of the concrete and other factors. Therefore, as a rule, these values should be determined through testing.

(3) Since continuous fiber sheets are extremely thin compared to the size of the members to be upgraded, they have little influence on the compressive rigidity/load-carrying capacity and shear rigidity/ of the members. For this reason, the compression rigidity/strength and shear rigidity/strength of continuous fiber sheets are not considered in the design.

(4) In general, the mean value obtained through testing may be used as the Young's modulus for continuous fiber sheets. If the material manufacturer has established a value for Young's modulus based on sufficient test results, the value may be used as a characteristic value.

(6) At present, there is almost no sample measurement for the coefficient of thermal expansion of continuous fiber sheets. However, it is known that the coefficient of thermal expansion for unidirectional strengthened fiber-reinforced composite materials can be estimated from the thermal expansion coefficients and Young's modulus values of each constituent material, such as the continuous fibers and impregnation resin, and the specific volume of continuous fibers, using Equation C3.3.1.

$$\alpha_L = \frac{E_f \cdot \alpha_f \cdot V_f + E_m \cdot \alpha_m \cdot (1 - V_f)}{E_f \cdot V_f + E_m \cdot (1 - V_f)} \quad \text{...(C3.3.1)}$$

where:

α_L : Coefficient of thermal expansion of the continuous fiber sheet in the direction of the fibers

α_f : Coefficient of thermal expansion of continuous fibers

α_m : Coefficient of thermal expansion of impregnation resin

E_f : Young's modulus of continuous fibers

E_m : Young's modulus of impregnation resin

V_f : Specific volume of continuous fibers in continuous fiber sheet

(7) When the characteristic values for fatigue strength is determined through testing, considerations should be given to the type of continuous fiber sheet, the size and frequency of applied stress, and the environmental conditions.

(8) In general, when appropriate construction and protection are conducted, the values used in Table C3.3.1 may be used as the material factors for the continuous fiber sheets.

Table C3.3.1 Standard values for material factor of continuous fiber sheets

Type of verification	Material factor
Safety and restorability	1.2-1.3
Serviceability	1.0

3.3.3 Continuous fiber strands

(1) As a rule, the characteristic values for the tensile strength of continuous fiber strands shall be determined through the tension test.
(2) The compressive strength and shear strength of continuous fiber strands shall not be considered in design.
(3) As a rule, the bond strength between continuous fiber strands and concrete shall not be considered in design.
(4) As a rule, the Young's modulus for continuous fiber strands shall be determined through the tension test.
(5) The tensile stress-strain relationship for continuous fiber strands, used to verify safety and serviceability, may be a straight line passing through the origin with the Young's modulus derived from the tension test.
(6) The coefficient of thermal expansion for continuous fiber strands shall be calculated from the thermal expansion coefficient, Young's modulus and the volume ratio of the constituent materials, such as the continuous fibers and impregnation resin.
(7) As a rule, the characteristic value for the fatigue strength of continuous fiber strands shall be determined through the fatigue test.
(8) The material factor for continuous fiber strands shall be determined using Section 2.6 (2) in the Standard Specifications for Design and Construction of Concrete Structures (Design).

[Commentary]

(1) JIS R 7601 "Testing methods for carbon fibers" should be used as the standard for tensile properties tests for continuous fiber strands. However, when the material manufacturer has established guaranteed strength values based on adequate test results, those values may be used as the characteristic values for the tensile strength of continuous fiber strands.

(2) Since continuous fiber strands have extremely tiny cross-sectional area in comparison with the members to be upgraded, they have little influence on the compressive rigidity/load-carrying capacity and shear rigidity/ of the members. For this reason, the compressive rigidity and strength and shear rigidity and strength of the continuous fiber strands are not considered in the design.

(3) With the method of winding continuous fiber strands, the continuous fiber strands and concrete in contact with the bond area of each strand is very small. There is little data on the bond strength of the continuous fiber strands to concrete. Therefore, as a rule, the bond strength of the continuous fiber strands to concrete is not considered in design.

(4) JIS R 7601 "Testing methods for carbon fibers" should be used as the standard for tensile properties tests. In general, the cross-sectional area used to calculate Young's modulus of the continuous fiber strands is that of the continuous fibers only, as calculated from the fiber weight. If the material manufacturer has established values for Young's modulus based on adequate test results, these values may be used as Young's modulus of the continuous fiber strands.

(6) The coefficient of thermal expansion in the axial direction of the continuous fiber strands should be calculated using equation (C3.3.1) for unidirectional fiber-reinforced composite materials, in the same manner as for continuous fiber sheets.

(7) When characteristic values for fatigue strength is determined through testing, considerations should be given to the type of continuous fiber strand, the size and frequency of applied stress, and the environmental conditions.

(8) When appropriate construction and protection are conducted, the values used in Table C3.3.2 may be used as the material factors for continuous fiber strands.

Table C3.3.2 Standard values for material factor of continuous fiber strands

Type of verification	Material factor
Safety and restorability	1.2-1.3
Serviceability	1.0

CHAPTER 4 LOADS AND ENVIRONMENTAL ACTIONS

In general, the loads and the environmental actions shall be considered in accordance with the Standard Specifications for Design and Construction of Concrete Structures 1996 (Design) (Seismic Design) (Construction) and the Standard Specifications for Design and Construction of Concrete Structures 1999 (Construction).

[Commentary]

The type of load, combination of loads, characteristic value for loads, load factors and other values should be considered in accordance with the Standard Specifications for Design and Construction of Concrete Structures (Design). Moreover, the seismic actions should be considered as "accidental load" in accordance with Standard Specifications for Design and Construction of Concrete Structures (Seismic Design).

Environmental actions imply the successive actions on the structure during its service life, causing the materials in the structure to change and deteriorate over time. These actions include temperature, humidity, the influence of dryness and moisture, salts, acids, alkaline, chemical substance, ultraviolet light, wear caused by drifting sand, and so on.

In addition, when preparing upgrading design using continuous fiber sheets or continuous fiber strands, it is important to consider impacts from drifting rocks, drifting wood, vehicles, flying objects, and the effects of fire as factors causing change and deterioration to upgraded materials, in accordance with the structure environment. At present, there is no general established methods for expressing the magnitude of the actions and the change over time for most types of environmental actions. However, suitable values for environmental actions may be established after referring to these recommendations, the Standard Specifications for Design and Construction of Concrete Structures (Design) (Construction), the Recommendations for Durability design of Concrete Structures, the Recommendations for Maintenance of Concrete Structures.

CHAPTER 5 DETAILED INSPECTION OF EXISTING CONCRETE STRUCTURES

5.1 General

When upgrading using continuous fiber sheets, a detailed inspection of documents, records and the conditions at the site shall be conducted taking account of the mechanical properties of materials and special conditions for construction.

[Commentary]

These recommendations are to be used as reference documents when studying measures for upgrading existing concrete structures, and as specific design and construction recommendations for the use of continuous fiber sheets as the method of upgrading. The inspection and verification of performance of the existing structure and the method of selecting the upgrading techniques are not within the scope of these recommendations. They should be done based on the Recommendations for Retrofit of Concrete Structures and Recommendations for Maintenance of Concrete Structures.

Here, only the detailed inspection items deemed particularly necessary for conducting upgrading design and construction using continuous fiber sheets are described. Although continuous fiber sheets and continuous fiber strands are lightweight, they are easily damaged and are extremely weak with respect to shearing force as compared to high tensile resistance in the fiber direction. Moreover, the quality of construction with resin has a large influence on the performance after upgrading. Accordingly, a detailed inspection of these properties is needed through an inspection of documents and records in advance and an inspection at the site.

5.2 Detailed inspection using documents, records, etc.

(1) For the selection of resin and the Quality Control Plan, the meteorological conditions at the site during construction shall be studied in detail by perusing documents, records, etc.

(2) To ensure that the construction goes smoothly, the geographical conditions at the site shall be studied in detail by perusing documents, topographical maps, etc.

[Commentary]

(1) In general, the viscosity of resins is greatly affected by temperature. The use of a resin with adequate viscosity is crucial for ensuring the ease of the operation and the success of the work. In addition, the hardening time for the resin is dependent on the temperature of the resin. At low temperatures, the hardening time increases dramatically. If this happens, it affects the processes to be performed after hardening of resin. For these reasons, it is necessary to determine the climatic conditions at the site during the period in which the work is planned.

(2) Upgrading using continuous fiber sheets can be performed easily even under cramped conditions. However, a minimum space for work is required. Before drafting specific work plans, it is necessary to determine the restrictions at the site.

5.3 Detailed inspection at the site

At the site, a detailed inspection of the existing concrete structure shall be conducted in terms of the following aspects:

(1) Progress of deterioration after upgrading
(2) Bond with continuous fiber sheets
(3) Conditions for work practice
(4) Necessity for surface protection

[Commentary]

(1) The deterioration progress of the upgraded concrete structure depends on the type and degree of the causes of deterioration. Accordingly, when damaged concrete structures are upgraded, it is necessary to pre-examine the type and degree of external factors causing deterioration. Particularly when concrete damaged by alkali aggregate reaction is upgraded, volumetric expansion may occur after construction. Therefore, the quantity and area of continuous fiber

sheets for upgrading should be determined taking account of the amount of residual expansion.

(2) When upgrading using continuous fiber sheets, bond of the continuous fibers to the existing structure is crucial to obtain the desired effect of upgrading. Necessary measures should be implemented to ensure proper bond by inspecting the surface deterioration and damage of the existing structure.

(3) The completion of construction is greatly affected by irregularities in the surface of the existing structure. The irregularities tend to cause residual bubbles and impair bond and durability. Failure to remove them invites the danger that the required performance after upgrading may not be attained. For this reason, smoothing should be performed as needed and the condition of irregularities on the surface of the existing structure should be examined in advance.

Due to construction errors, existing structures may not necessarily have been completed as specified in the design documents. When using continuous fiber sheets, it is possible that there may be too much or too little material at the site. For this reason, the finished dimensions of the existing structure should be ascertained in advance.

The occurrence of bubbles or whitening while the resin is hardening may adversely influence the effectiveness of upgrading. Therefore, curing should be implemented as needed in such cases. Accordingly, it is necessary to determine the wind, sunshine, temperature changes and other conditions at the site in advance.

(4) When the continuous fibers are damaged by impacts from drifting stones, drifting wood or other sources, it is necessary to study whether surface protection should be implemented. In such cases, the material and thickness of the surface protection should be determined through consideration of the degree of damage from impacts to the existing structure. Accordingly, the potential for damage to the continuous fibers through impacts and the degree of damage to the existing structure from the impacts should be estimated.

CHAPTER 6 PERFORMANCE VERIFICATION FOR UPGRADED CONCRETE STRUCTURES

6.1 General

The performance of concrete structures upgraded with continuous fiber sheets shall be verified through appropriate evaluation of the effect of upgrading in addition to the evaluation of the performance of the existing structure.

[Commentary]

For concrete structures to be upgraded with continuous fiber sheets, various performances should be verified to determine whether the performance requirements have been satisfied, based on the assumed materials, structural specifications, and construction methods. The performance of upgraded structures is achieved through the overall performance of both existing sections and upgraded sections.

This chapter presents the methods used to verify the performance of ordinary concrete structures upgraded with continuous fiber sheets. Verification of performance other than those presented in this chapter may be done through testing or through numerical analysis, but it should be done based on reliable research results and achievements.

Almost all performance verification methods presented in this chapter are established, through test results, with the standard construction methods in Chapter 7 "Upgrading Work." Accordingly, when performance verification methods presented in this chapter are used, strict adherence to the work methods stipulated in Chapter 7 is required. If the work methods differ from those prescribed in Chapter 7 or if less stringent construction specifications are to be approved, the content of such specifications should be clearly noted in the design documents.

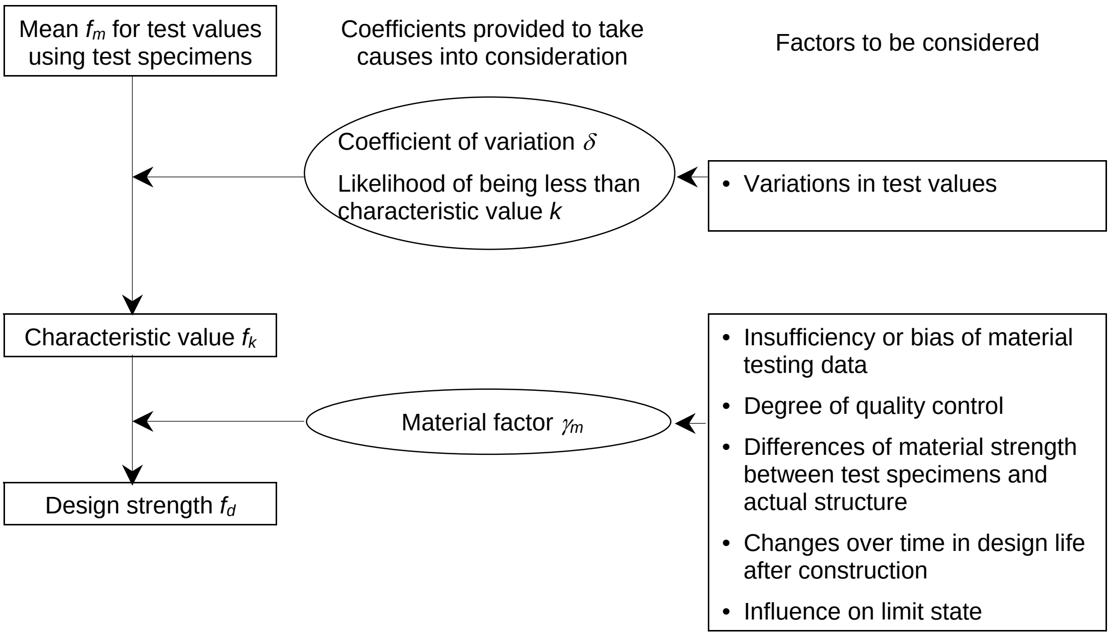
6.2 Design strength of materials in existing structures

6.2.1 General

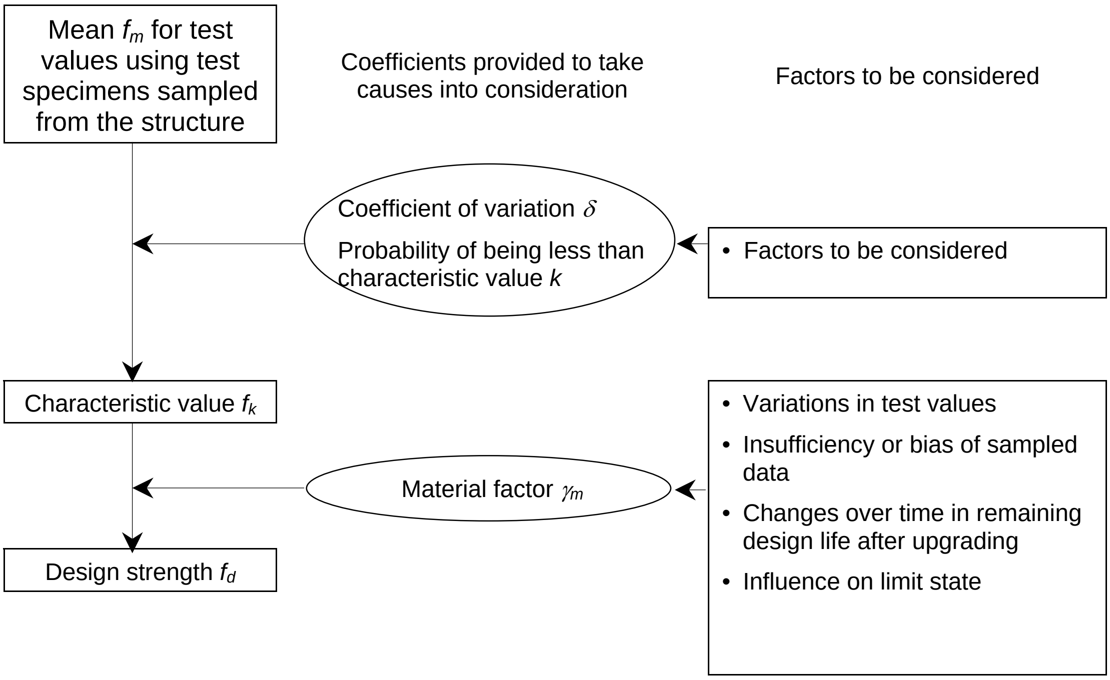
As a rule, the design strength of the materials used in the existing structure shall be determined through the test of the specimens sampled from the structure. When testing is not possible, the determination may be made based on the characteristic values used in the original design.

[Commentary]

Figure C6.2.1 shows the method for determining the design strength of the materials in the existing structure for upgrading of the structure.



S6.2.1 (a) Cases of new structures and existing structures without sampling of core concrete



S6.2.1 (b) Case of existing structures with sampling of core concrete

Figure C6.2.1 Determination of design strength of materials in existing structure

In the upgrading of existing structures, the design strengths of the materials should be determined by sample testing specimens taken from the structure in question with appropriate considerations given to various coefficients and to the discrepancies in the test values shown in the figure and other uncertain factors, as shown in Figure C6.2.1 (b). Note that the factors to be considered differ from those considered in the original design of structures as shown in Figure C6.2.1 (a). Accordingly, the material factor γ_m and other coefficients for which various factors are considered may not necessarily be the same for existing structures as for new structures.

When the inspection of the existing structure does not find deterioration or change in the materials in the structure, the design strength may be determined without conducting tests of the material strength. In such cases, the characteristic values and material factors used when the structure was built may be used in accordance with the procedure shown in Figure C6.2.1 (a).

6.2.2 Concrete

(1) As a rule, the characteristic value f'_{ck} for the compressive strength of the concrete in the existing structure shall be determined based on the test results of core samples taken from the structure.

(2) The characteristic value f'_{ck} shall be determined so as to ensure that most test results do not fall below this value, assuming variations in the test results of core samples.

(3) The design compressive strength f'_{cd} of the concrete in the existing structure shall be obtained by dividing the characteristic value f'_{ck} by the material factor γ_c determined with considerations given to inadequate or biased sampling data, changes over time in the remaining designs life after upgrading.

(4) When not taking core samples, the design strength f'_{cd} may be determined by taking the characteristic strength f'_{ck} in the original design divided by the material factor γ_c, in which the deterioration identified through inspection should be taken into account.

[Commentary]

(1) When an unexpected deterioration is observed through the test results of the concrete strength in the structure, the results should be reflected accurately in the upgrading design. If the strength is higher than the necessary level of the original design this should also be effectively considered in upgrading design.

(2) The characteristic value f'_{ck} for the compressive strength of concrete in the existing structure should generally be determined using Equation C6.2.1.

$$f'_{ck} = f'_{cm}(1 - k\delta) \quad \text{(C6.2.1)}$$

where:

f'_{cm} : Mean value of tested compressive strength by core samples

δ : Coefficient of variation of the test results of compressive strength determined from core samples

k : Coefficient

The coefficient of variation δ for the compressive strength test results may generally be assumed to be 10%. The coefficient k should be determined from the probability of a tested value being lower than the characteristic value and the distribution pattern of the test results. In general, the distribution pattern can be assumed to be a normal distribution. If the probability that the test value is lower than the characteristic value is 5%, the coefficient k will be 1.64.

(3) Table C6.2.1 shows a comparison (with new structures) of the factors that should be considered using the material factor γ_c when the strength of the concrete in the structure is actually measured in the upgrading of existing structures. Table C6.2.2 shows the standard values for concrete material factors γ_c used in upgrading design.

Table C6.2.1 Differences of material factors for new and existing structures

	New Structure	Existing Structure	Remarks
Data insufficiency/bias	Small	Great	Due to limitations on the number of core samples taken and sampling locations
Degree of quality control	Considered	–	No need to consider for existing structures
Difference between test specimen and material in actual structure	Considered	–	No need to consider for existing structures
Changes over time	Large	Small	Because, for existing structures, only the deterioration during the remaining design life after upgrading need be considered
Influence on limit state	Considered	Considered	Same as new structures

Table C6.2.2 Standard material factors for concrete

Verification item	Material factor γ_c
Safety and restorability	1.3 or 1.5
Serviceability	1.0

In general, the number of core samples from existing structures is limited for statistic treatment. This should be compensated for by using material factors. However, it is possible to reduce the insufficiency or bias of the data by increasing the number of core samples taken and taking them from locations that are more appropriate for evaluation of the performance of the structure, and to this extent the material factor may be made smaller.

(4) If the inspection of the existing structures finds no deterioration and change in concrete of the structure and the structure is considered to meet the quality

requirements of the original design, the design concrete strength f'_{cd} for the concrete in the existing structure may be determined without conducting concrete strength tests with core samples. In such cases, the characteristic value f'_{ck} for compressive strength and the material factor γ_c in the original design may be employed.

Even when it is difficult to take core samples from the existing structure to be upgraded, the design compressive strength f'_{cd} for the concrete in the existing structures should be determined regardless of whether tests are conducted. In such cases as well, the value used when the structure was built may be used for the characteristic value f'_{ck} for compressive strength. However, the material factor γ_c should be set to an appropriate value matching the condition of deterioration discovered in the inspection and a suitable value for design compressive strength f'_{cd} determined. If the deterioration is greater than that anticipated when the structure was built, the material factor γ_c should be made greater than the value of the original design.

6.2.3 Steel

(1) When the inspection of the existing structure finds no particular rusting of the steel in the structure, the characteristic value for steel strength and the material factor used in the original design may be used, and the design strength may be determined based on these values.

(2) When the inspection of the existing structure finds rusting of the steel in the structure, the material factor γ_s shall be set to an appropriate value matching the degree of rusting.

[Commentary]

(1) Table C6.2.3 shows the standard values for the material factor γ_s for steel used in upgrading design.

Table C6.2.3 Standard material factors for steel

Verification item	Material factor γ_s
Safety and restorability	1.0 or 1.05
Serviceability	1.0

(2) When the characteristic value of steel strength is used as the value in the original design without testing of samples, not only the condition of deterioration at the time of upgrading but the progress of deterioration during the remaining design life after upgrading should be considered and the material factor γ_s set to an appropriate value. When the characteristic value for steel strength is determined based on tests of the samples taken from the existing structure, , the changes over time considered by means of the material factor γ_s need only the progress of deterioration during the remaining design life after upgrading. In either case, if intrusion of corrosive substances is expected to be prevented by bonding continuous fiber sheets to the structure, this effect may be taken into account for the progress of deterioration in the steel after upgrading.

Rusting of steel reduces the cross-sectional area, but for simplicity this is taken as a reduction of material strength in the design. Accordingly, even if rusting occurs, the nominal value should be used for the cross-sectional area of the steel.

6.3 Safety factor

The safety factor used to verify the performance of existing concrete structures shall be determined appropriately based on the detailed inspection of the structure and tests of the materials in the structure.

(1) The characteristic value f_k for the strength of the material in the existing structure and the material factor γ_m shall be determined in accordance with 6.2.
(2) The characteristic value f_k for the strength of continuous fiber sheets and continuous fiber strands and the material factor γ_m shall be determined in accordance with Chapter 3.
(3) The member factor γ_b for the sections of the upgraded structure shall be determined by considering the uncertainty in the calculations of the load-carrying capacity of members and the influence of the variations of member size discovered during inspections.
(4) The characteristic value for load F_k and the load factor γ_f shall be determined by considering the actual loads for the existing structure and changes of the loads during the remaining design life of the structure after upgrading.

(5) The structural analysis factor γ_a shall be determined by considering the uncertainty in the structural analysis when calculating sectional forces. When general structural analysis techniques are used, this value may be set at 1.0.

(6) The structure factor γ_i shall be determined by considering the importance of the upgraded structure and the impact on society when it reaches the limit state. In general, this value shall be set to 1.0 - 1.2.

[Commentary]

The characteristic values for material strength, load, and the significance of the safety factors mean the same for both new and existing structures. However, for existing structures, most of the unknown quantities at the time of construction are found out through inspections. Accordingly, the characteristic values and safety factors for upgrading of existing structures may not be the same as those for new structures. Appropriate values may be determined in accordance with the present condition of the structure.

6.4 Verification of Safety

6.4.1 Design flexural and axial load-carrying capacity

(1) The design flexural and axial load-carrying capacity of members upgraded by bonding continuous fiber sheets to the surfaces to which tensile stresses are acted shall be determined by an appropriate method concerned with the failure mode, giving consideration as to whether the peeling failure of the continuous fiber sheets occurs or not.

Peeling failure stress of the continuous fiber sheets may be determined using Equation 6.4.1. In other words, no peeling of the continuous fiber sheet occurs when the stress σ_b of the continuous fiber sheet at the location of flexural cracking caused by the maximum bending moment in the member satisfies Equation 6.4.1.

$$\sigma_f \leq \sqrt{\frac{2G_f E_f}{n_f \cdot t_f}} \quad \text{......} \quad (6.4.1)$$

where:

n_f : Number of plies of continuous fiber sheets

E_f : Modulus of elasticity for continuous fiber sheet (N/mm^2)

t_f : Thickness of one layer of continuous fiber sheet (mm)

G_f : Interfacial fracture energy between continuous fiber sheet and concrete (N/mm)

(i) If peeling failure of the continuous fiber sheet does not occur, the design flexural capacity and axial load-carrying capacity of the member may be determined using the same method as for reinforced concrete members. In other words, the fiber strain of the continuous fiber sheet is assumed to be proportional to the distance from the neutral axis of the section, and this value may be determined using the method specified in Section 6.2.1 (2) of the Standard Specifications for Design and Construction of Concrete Structures (Design). In general, the material factor γ_b may be set to 1.15.

(ii) If peeling or breakage of the continuous fiber sheets occurs, the presumed failure mode for (1) and (2) below shall be determined and the load-carrying capacity in each case shall be calculated. The smaller value shall be used for the design flexural capacity and axial load-carrying capacity of the member. In general, the material factor γ_b may be set to 1.15.

(1) If the ultimate failure mode of the member is not peeling failure of the continuous fiber sheet, or even though the continuous fiber sheet peels in places, the flexural capacity bending and axial load-carrying capacity of the member may be calculated by the method in (i) multiplied by the reduction factor of 0.9.

(2) If member failure occurs due to peeling failure of the continuous fiber sheet caused by the progress of interfacial fracture that started from the end of flexural cracking or shear cracking, the flexural capacity and axial load-carrying capacity of the member may be calculated in such a way that the maximum value $\Delta\sigma_f$ for the difference in tensile stress occurring in the continuous fiber sheet satisfies Equation C6.4.2.

$$\Delta\sigma_f = \sqrt{\frac{2G_f E_f}{n_f \cdot t_f}} \quad \text{.......} \quad (6.4.2)$$

Where,

$\Delta\sigma_f$: Maximum value of the differences in tensile stress in the continuous fiber sheet between the flexural cracking location and at the next cracking location due to the maximum bending moment (N/mm^2)

(2) The design axial compressive load-bearing capacity for members upgraded by wrapping with continuous fiber sheets may be determined by an appropriate evaluation method taking account of the effect of such reinforcement.

[Commentary]

(1) The flexural failure modes for members upgraded with continuous fiber sheets are classified as follows:

- Breakage of the continuous fiber sheet after yielding of steel reinforcement
- Crushing of concrete after yielding of steel reinforcement
- Crushing of concrete
- Anchorage failure of the continuous fiber sheet
- Interfacial fracture of the continuous fiber sheet to concrete due to the progress of flexural cracking and shear cracking

These failure modes should be suitably considered when determining flexural capacity and axial load-carrying capacity.

For members subjected to bending and axial force, it is best to prevent the peeling failure except in cases where suitable evaluation of peeling failure can be performed.

Researches regarding the criteria of peeling of continuous fiber sheet peeling are currently underway.[1)] Peeling can be prevented when the maximum value for tensile stress applied to continuous fiber sheets satisfies Equation 6.4.1. The value G_f for interfacial fracture energy used in this method can be derived from the bond strength test of continuous fiber sheets to concrete. When a test is not conducted, a value of G_f = 0.5 N/mm may be used. The interfacial fracture energy G_f is a physical property relating to the surface strength of the concrete and the interfacial bond conditions, and it may vary depending on the type and number of plies of the continuous fiber sheet, the anchoring reinforcement of the bond surfaces. Accordingly, this value should be determined through testing in cases where detailed consideration of the effect of these factors is needed and when a more accurate value is desired.

(1) (i) When peeling failure of the continuous fiber sheet does not occur, the flexural capacity and axial load-carrying capacity may be determined based on the conventional flexural theory for reinforced concrete members.

(1) (ii) When peeling failure of the continuous fiber sheet occurs in places, the hypothesis that plane sections remain plane does not hold true. The flexural capacity may be less than the value derived based on the conventional flexural theory for reinforced concrete members. Since recent research has found that the degree of reduction is about 10% at most, a reduction coefficient of 0.9 is used.

(1) (ii) 2. Equation C6.4.2 expresses the maximum stress gradient for peeling failure. It is known that the interval between the position at which flexural cracking occurs due to the maximum bending moment, and the flexural cracking in the surrounding area, is related to the number of plies of continuous fiber sheets. However, when the number of plies of continuous fiber sheets n_f is less than 3, in general a value of 150 - 250 mm should be used. It is assumed that the stress on the continuous fiber sheet at each flexural cracking location is proportional to the distance from the neutral axis of the section.

(2) According to past experiments,[2)3)] members jacketed with continuous fiber sheets exhibit increased axial compressive load-carrying capacity and ductility, but currently no calculation techniques have been established for quantitatively evaluating the effect of these properties. Accordingly, as a rule, the value for design axial compressive load-carrying capacity should be based on testing. However, when the load-carrying capacity is predicted from the experimental results, the size effects should be considered.

6.4.2 Design shear capacity for bar members

The design shear capacity V_{fyd} for bar members upgraded with continuous fiber sheets may be determined by Equation 6.4.3.

$$V_{fyd} = V_{cd} + V_{sd} + V_{fd} \quad \text{(6.4.3)}$$

where:

V_{cd} : Design shear contribution due to concrete (according to Equation 6.4.4)

$$V_{cd} = \beta_d \cdot \beta_p \cdot \beta_n \cdot f_{vcd} \cdot b_w \cdot d / \gamma_b \quad \text{(6.4.4)}$$

$f_{vcd} = 0.20\sqrt[3]{f'_{cd}}$ (N/mm^2), however, $f_{vcd} \leq 0.72$ (N/mm^2) .... (6.4.5)

$\beta_d = \sqrt[4]{1/d}$ (d:m), 1.5 when $\beta_d > 1.5$

$\beta_p = \sqrt[3]{100 p_w}$ (d:m), 1.5 when $\beta_p > 1.5$

$\beta_n = 1 + M_0 / M_d \, (N'_d \geq 0)$, when $\beta_n > 2$

$\quad = 1 + 2M_0 / M_d \, (N'_d \geq 0)$, when $\beta_n > 0$

N'_d : Design axial compressive force

M_d : Design bending moment

M_0 : Decompression moment

b_w : Web width

d : Effective depth

p_w : $A_s/(b_w \times d)$

A_s : Cross-sectional area of reinforcing bars in tension side

f'_{cd} : Design compressive strength of concrete (unit: N/mm^2)

γ_b : Member factor (in general, may be set to 1.3)

V_{sd} : Design shear contribution due to shear reinforcing bars (according to Equation 6.4.6)

$$V_{sd} = \left\lfloor A_w \cdot f_{wyd} (\sin\alpha_s + \cos\alpha_s) / s_s \right\rfloor \cdot z / \gamma_b \quad \text{(6.4.6)}$$

A_w : Total cross-sectional area of shear reinforcement in space s_s

f_{wyd} : Design tension yield strength of shear reinforcement (400 N/mm^2 max.)

α_s : Angle formed by shear reinforcement about the member axis

s_s : Spacing of shear reinforcement

z : Lever arm length (generally may be set to d/1.15)

γ_b : Member factor (generally may be set to 1.15)

V_{fd} : Design shear contribution due to continuous fiber sheets obtained by either method (1) or method (2) in the following clauses.

(1) Method in which the coefficient expressing the shear reinforcing efficiency of the continuous fiber sheet is used to evaluate the ultimate mean stress of the sheet and to determine the shear contribution of the sheet

$$V_{fd} = K \cdot [A_f \cdot f_{fud} (\sin\alpha_f + \cos\alpha_f)/ s_f] \cdot z / \gamma_b \quad \text{(6.4.7)}$$

K : Shear reinforcing efficiency of continuous fiber sheets according to Equation 6.4.8

$$K = 1.68 - 0.67R, \text{ however, } 0.4 \le K \le 0.8 \quad \text{(6.4.8)}$$

$$R = (\rho_f \cdot E_f)^{1/4} \left(\frac{f_{fud}}{E_f} \right)^{2/3} \left(\frac{1}{f'_{cd}} \right)^{1/3}, \text{ however, } 0.5 \le R \le 2.0$$

$$\rho_f = A_f / (b_w \cdot s_f)$$

A_f : Total cross-sectional area of continuous fiber sheets in space s_f

s_f : Spacing of continuous fiber sheet

f_{fud} : Design tensile strength of continuous fiber sheet (N/mm^2)

E_f : Modulus of elasticity of continuous fiber sheet (kN/mm^2)

ρ_f : Angle formed by continuous fiber sheet about the member axis

γ_b : Member factor (generally may be set to 1.25)

(2) Method in which the stress distribution of the continuous fiber sheets is evaluated based on the bond constitutive law to determine the shear contribution of the sheet

This method uses numerical calculation based on the following hypothesis to evaluate the stress distribution of the continuous fiber sheet in upgraded members for determining the shear contribution of the sheet.

(i) Shear crack forms a 35° angle about the member axis.

(ii) Member deformation after shear crack has occurred is expressed by a rigid body rotation model with the end of a shear crack as the center of rotation.

(iii) The progress of sheet peeling that traverses the shear crack is evaluated through stress analysis assuming that the concrete is a rigid body, the sheet is an elastic body, and there is a linear relationship between the relative displacement and bond stress between the sheet and the concrete (the bond constitutive law).

(iv) The strain of concrete in compression sections is expressed as a function of the angle of rotation of the members for which rigid body rotation is assumed.

The member factor used for this method is generally 1.25.

[Commentary]

As shown by Equation 6.4.3, the design shear capacity with continuous fiber sheets V_{fyd} may be expressed as the sum of the concrete contribution V_{cd} , the steel contribution V_{sd} , and the contribution of continuous fiber sheet V_{fd}.

It has been confirmed that Equation 6.4.3 is applicable to members reinforced with carbon fiber sheets, carbon fiber strands and aramid fiber sheets. When using other types of continuous fiber sheets, the applicability should be confirmed through testing.

The usual failure mode of the members reinforced with continuous fiber sheets is one of the following:

(1) Failure following peeling of the continuous fiber sheet
(2) Breakage of the continuous fiber sheet and compression failure of the concrete in the compression zone occurring almost simultaneously
(3) Compressive failure of concrete in the compression zone.
When the percentage of reinforcement with continuous fiber sheets is extremely low, a fourth mode may occur:
(4) Breakage of the continuous fiber sheet before peeling occurs

(1) Equation 6.4.8 is obtained through regression of the test results[4)-9)] for failure modes (1) (2) and (3). However, this equation excludes some data in failure mode (1) showing high reinforcement efficiency and the data for failure mode (4). The equation corresponds to failure mode (1) when the value of R is approximately R<1.3 and K=0.8. The contribution of continuous fiber sheet V_{fd} is expressed using the truss analogy with an angle of 45° as the same as the steel

contribution V_{sd} . Failure modes (2) and (3) correspond to 0.4<*K*< 0.8, and *K* decreases linearly from 0.8 to 0.4. Here it is assumed that the truss analogy holds until the member concrete contribution V_{cd} decreases suddenly. The reinforcement efficiency *K* of the continuous fiber sheet is a variable corresponding to the *R* value of the member. For V_{sd} , the contribution of bent-up bar members in the axial direction is generally considered in addition to stirrups and lateral ties. However, when alternating load is applied, the contribution of bent-up bars should be deleted.

Equation 6.4.8 shows the mean of the test data shown in Figure C6.4.1. The applicable range of this equation is approximately 1.0<*R*<1.8. A value of 0.8 was used as the value for reinforcement efficiency *K* and the lower limit was made 0.4 from the applicable range for *R*. In other words, Equation 6.4.8 cannot be applied when *K* is less than 0.4. The member factor was determined as a 95% confidence limit through consideration of the variations in the test data.

This equation matches adequately the numerical test results from analysis using the finite element method. It is formulated such that the greater the tension load-carrying capacity of the continuous fiber sheet, the smaller the tension rigidity of the continuous fiber sheet, and that the lower the strength of the concrete strength, the smaller the value of *K*. The problems with this equation are that there are few test results for failure mode (3). Failure mode (4) cannot be evaluated in the domain in which *R* is small. Factors such as member shape and size have not been studied.

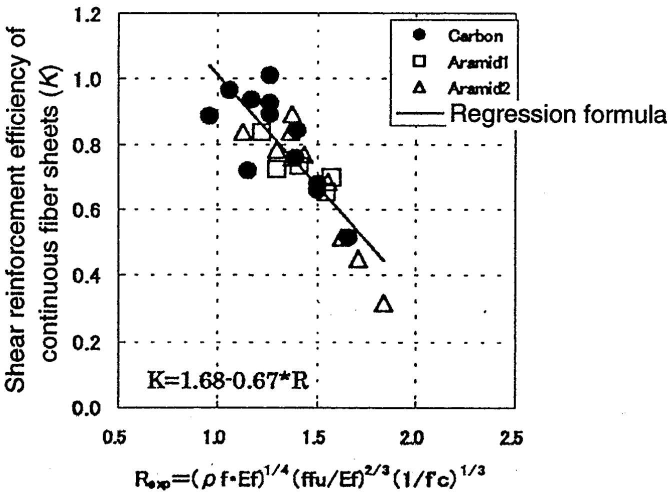


Figure C6.4.1 Relationship between coefficients *R* and *K* (experimental equation)

(2) This method is used to evaluate the stress distribution of the continuous fiber sheets in the members in order to determine the shear capacity of the sheet, through numerical calculations in accordance with the flow shown in Figure C6.4.2.[10] The method assumes programming and the use of a computer for calculation.

The scope of the method is as follows:

- The method can be applied whether the shear failure mode for members is sheet failure mode (1) (2) (4) or concrete compression failure mode (2) (3).
- The method can be applied when the entire circumference of the member is jacketed with sheets and when the end is anchored using mechanical anchoring that can be expected to provide complete anchoring.
- If the mechanical characteristic values for the sheet, bond and peeling of the sheet to concrete are provided, the method can be applied regardless of the type of sheet.
- The method can be applied if the form of failure is one in which a single shear crack or a small number of shear cracks is predominant.

Calculations at each step in the flow may be performed as follows (see Figure C6.4.3).

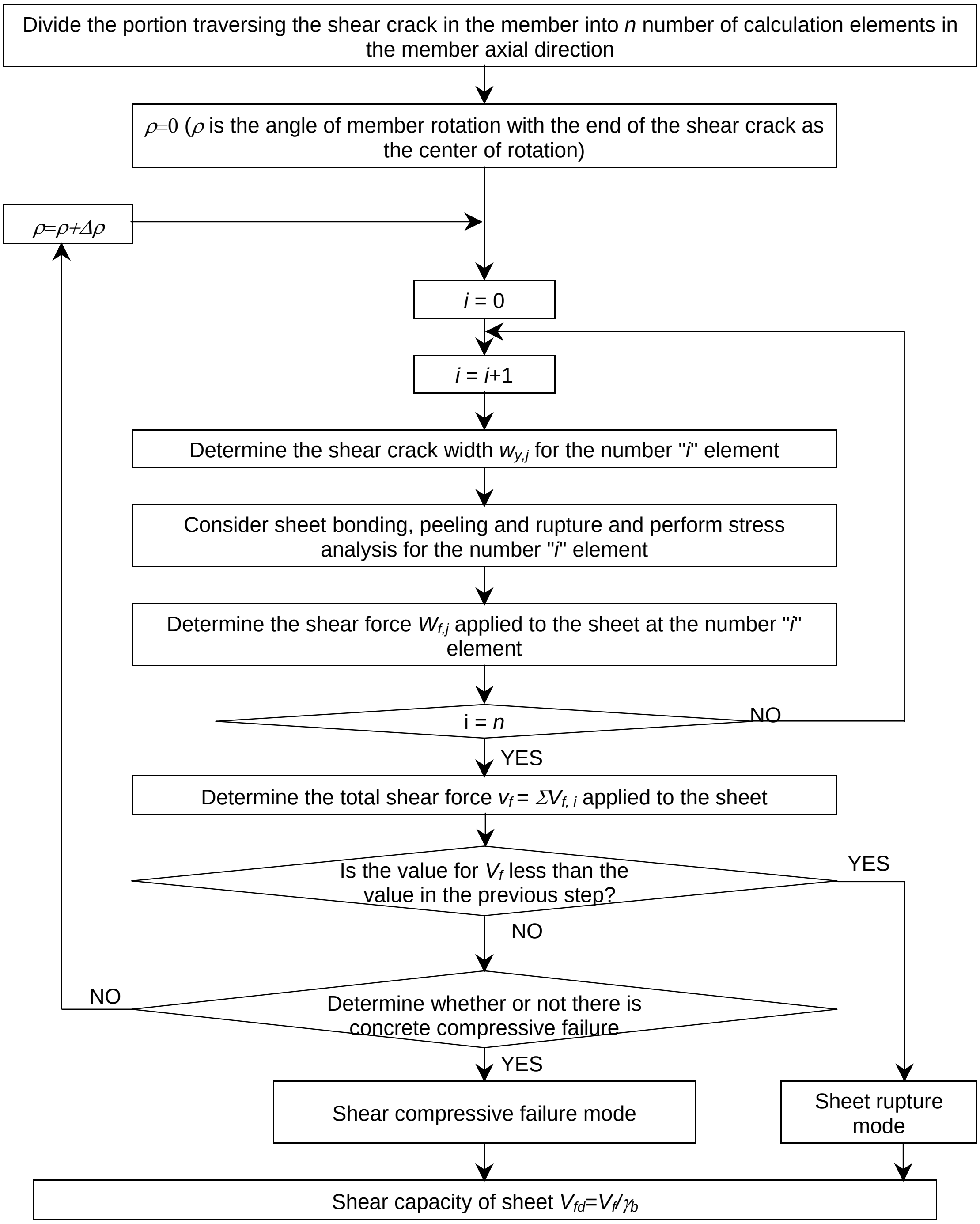


Figure C6.4.2 Flow of calculating shear capacity based on the bond constitutive law for continuous fiber sheets

Modeling of shear crack

The angle of diagonal shear crack θ is assumed to be 35° and the distance y_e from the end of the shear crack to the upper edge is assumed to be $0.1d$ (d: effective depth).

Division into elements

The portion of the member for which calculations are to be performed is the region which is traversed by diagonal shear crack, and the portion is divided into equal parts. It is recommended that the number of parts n is at least 10.

Modeling of the deformation of members after shear cracks occur

The deformation of the member after shear cracks have occurred is modeled through a rigid body rotation with the end of the shear crack as the center of rotation. The vertical component $w_{y,i}$ of crack width in the number "i" element is expressed as follows:

$$w_{y,i} = \rho L_{x,i} \qquad \text{(C6.4.1)}$$

where:

$L_{x,i}$: The horizontal distance from the center of rotation to the center of the number "i" element.

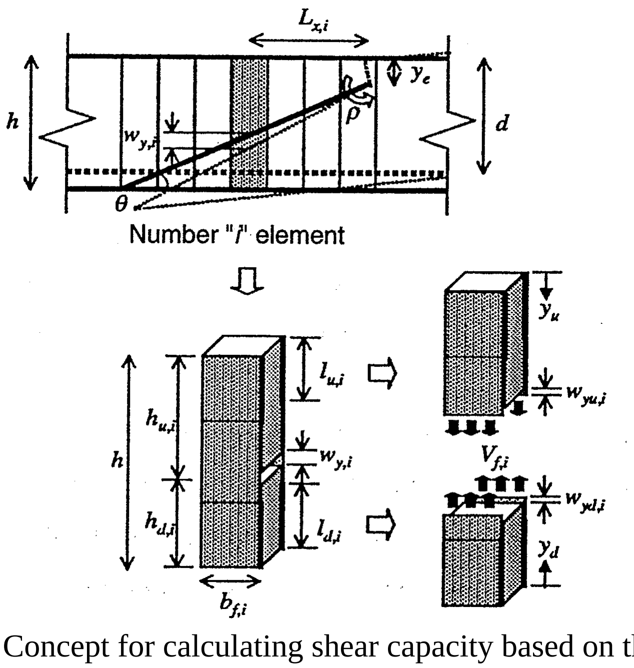


Figure C6.4.3 Concept for calculating shear capacity based on the bond constitutive law for continuous fiber sheets

The distance from the upper edge to the crack $h_{u,i}$ and the distance from the lower edge to the crack $h_{d,i}$ are expressed as follows:

$$h_{u,i} = y_e + L_{x,i} \tan\theta \qquad \text{(C6.4.2)}$$
$$h_{d,i} = h - h_{u,i} \qquad \text{(C6.4.3)}$$

<u>Stress analysis for each element</u>

Stress analysis is conducted for each element and the tensile force $V_{f,i}$ on the sheet is determined when the width of cracks in the element is $w_{y,i}$ (Equation C6.4.3). Stress analysis should be based on the following assumptions:

- Cracked concrete is a rigid body.
- The sheet is an elastic body. The modulus of elasticity and tensile strength (or rupture strain) of the sheet are provided based on material tests.
- The elasto-peeling model shown in Figure C6.4.4 may be used as the bond constitutive law for the sheet and concrete (the relationship between relative displacement δ and bonding stress τ). The material constant for the bond constitutive model can be determined using the method shown in the Commentary for the bonding test methods for continuous fiber sheets to concrete. It is known that, for ordinary adhesive resins and standard construction, the values are approximately τ_u=7.5 N/mm^2, and δ_u= 0.2 mm regardless of the type of sheet.

The solutions to stress analysis based on the above assumptions are as follows.

Figure C6.4.5 shows the relationship between the width of crack in the element $w_{y,i}$ and the tensile force $v_{f,i}$. With the opening of the crack, peeling of the continuous fiber sheet progresses through the following stages.

Stage I ($0<w_{y,i}<w_1$): sheet does not yet peel
Stage II ($w_1<w_{y,i}<w_2$): The sheet peels on the side above or below cracks where the initial anchoring length was greater
Stage III ($w_2<w_{y,i}$): sheet peels at both top and bottom of crack

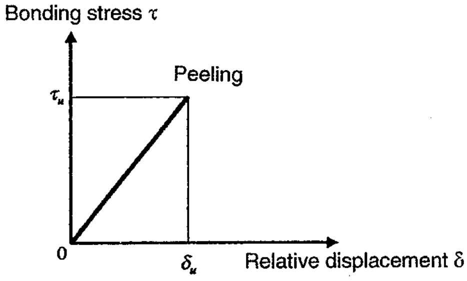


Figure C6.4.4 Bond constitutive law for sheet and concrete

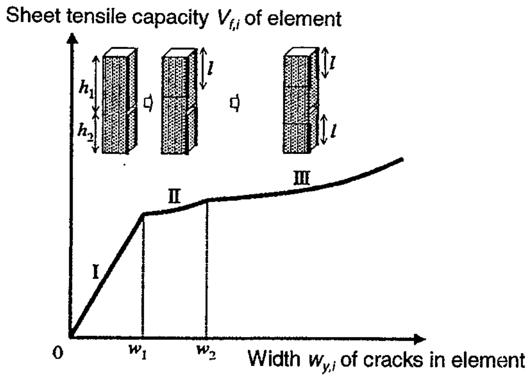


Figure C6.4.5 Relationship between element crack width $w_{y,i}$ and tensile strength $V_{f,I}$

Hereafter, of the above and below ($h_{u,i}$ and $h_{d,i}$) cracks, the longer one is written as h_1 (= max ($h_{u,i}$, $h_{d,i}$) and the shorter as h_2 (= min ($hu_{,i}$, $h_{d,i}$). The value for k is set at $k{=}\tau u/(E_f t_f \delta_u)$

Crack widths w_1 and w_2 in Figure 6.4.5 alter peeling are determined by Equations S6.4.4 and S6.4.5, respectively.

$$w_1 = \delta_u \left\{ 1 + \frac{\tanh\left(h_2\sqrt{k}\right)}{\tanh\left(h_1\sqrt{k}\right)} \right\} \text{..........(C6.4.4)}$$

$$w_2 = \delta \left\{ 2 + \frac{\left(h_1 - h_2\right)\sqrt{k}}{\tanh\left(h_2\sqrt{k}\right)} \right\} \text{..........(C6.4.5)}$$

The relationship between crack width $w_{y,i}$ and tensile strength $V_{f,i}$ at each stage is as follows:

Stage I ($0<w_{y,i}<w_1$)

$$V_{f,i} = \frac{2w_{y,i}E_f t_f b_{f,i}\sqrt{k}}{\tanh\left(h_1\sqrt{k}\right) + \tanh\left(h_2\sqrt{k}\right)} \text{..........(C6.4.6)}$$

Stage II ($w_1<w_{y,i}<w_2$) and Stage III ($w_2<w_{y,i}$)

$$V_{f,i} = \frac{2\delta_u E_f t_f b_{f,i}\sqrt{k}}{\tanh\left(l\sqrt{k}\right)} \quad \text{(C6.4.7)}$$

Here l is the anchorage length on the side where peeling progresses; in Stage II and Stage III, this value satisfies Equations S6.4.8 and S6.4.9, respectively. In these equations, l is not expressed in a positive form, but if the crack width $w_{y,i}$ is provided, the value can be determined through repeated calculation.

Stage II:

$$w_{y,i} = \delta\left\{\frac{(h_1 - l)\sqrt{k} + \tanh\left(h_2\sqrt{k}\right)}{\tanh\left(l\sqrt{k}\right)}\right\} \quad \text{(C6.4.8)}$$

Stage III:

$$w_{y,i} = \delta\left\{2 + \frac{(h - 2l)\sqrt{k}}{\tanh\left(l\sqrt{k}\right)}\right\} \quad \text{(C6.4.9)}$$

When the value for $V_{f,i}$ determined through the above procedure is $V_{f,i} \geq 2b_{f,i} t_f E_f \varepsilon_{fu}$ (ε_{fu} being the breakage strain of the sheet), the sheet has broken at that element, so $V_{f,i}$=0.

Determination of the member failure mode and ultimate shear capacity of the sheet

If member deformation progresses and the sheet breaks at a certain element, the total shear force supported by the sheet V_f begins to decline. In such cases, the member failure mode is judged to be sheet rupture mode and the maximum value for V_f becomes the ultimate shear force (Figure C6.4.6).

If member deformation has progressed without the sheet rupture, the failure mode is concrete compression failure. The compressive edge strain ε_b' of the concrete should be calculated with the following equation.

$$\varepsilon_b' = \rho\sqrt{y_e / d} \quad \text{(C6.4.10)}$$

The compressive strain of the concrete at the compression failure should be set to ε_b' = 0.0025. The value for V_f is the ultimate shear force of the sheet when compression failure of concrete occurs (Figure C6.4.6).

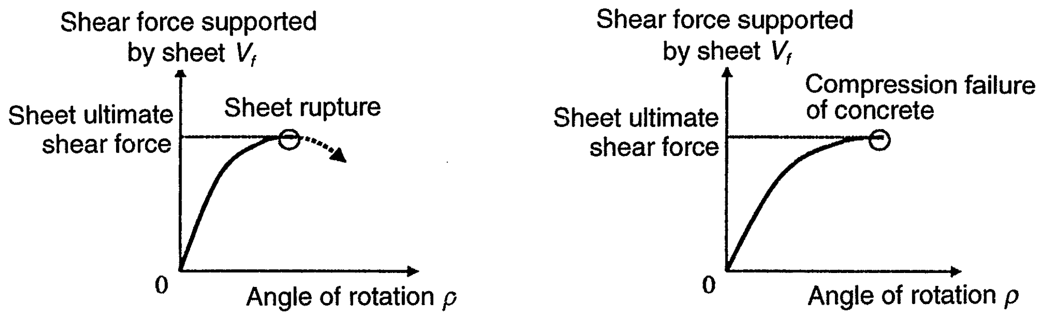


Figure C6.4.6 Determination of failure mode and shear capacity

The accuracy of the shear force supported by the sheet (V_f) that is calculated with this method also depends on the portion contributed by the concrete (V_c) and the portion contributed by the shear reinforcement (V_s) determined through testing. Therefore, after an overall determination of these values, the member factor (γ_b) was set to 1.25.

6.4.3 Design flexural fatigue resistance

The design flexural fatigue resistance of members upgraded with continuous fiber sheets shall be calculated considering the flexural fatigue characteristics of existing sections, the fatigue characteristics of the continuous fiber sheet and the characteristics of interfacial peeling fatigue failure between the continuous fiber sheet and the concrete.

The member factor γ_b is generally set to 1.0 - 1.1.

[Commentary]

Methods for accurate calculation of the flexural capacity fatigue resistance of members upgraded with continuous fiber sheets have not yet been established. Therefore, the resistance should be evaluated based on a reliable test data or through testing conducted for the purpose.

When mechanical anchorages are used, the fatigue behavior should be examined.

The safety with regard to interfacial peeling fatigue failure between the continuous fiber sheet and concrete at the location of flexural cracks should be confirmed by examining whether the maximum value for tensile stress σ_f acting on the continuous fiber sheet satisfies Equation C6.4.11.

$$\sigma_f \leq \sqrt{\frac{2\mu G_f E_f}{n_f \cdot t_f}} \qquad \text{(C6.4.11)}$$

Here μ is the reduction factor, due to the influence of fatigue load on the interfacial fracture energy relating to the bond of continuous fiber sheets to concrete. In general, this value may be set to 0.7.

6.4.4 Design punching shear fatigue resistance of planar members

The design punching shear fatigue resistance of planar members upgraded with continuous fiber sheets shall be calculated by adequately considering the punching shear fatigue characteristics of existing members as well as the fatigue rupture of continuous fiber sheets and the characteristics of interfacial peeling fatigue failure of the continuous fiber sheets and concrete.

The member factor γ_b is generally set to 1.0 - 1.1.

[Commentary]

It has been confirmed that planar members in the deck slabs of highway bridges subjected to repeated traveling loads suffer fatigue damage caused by the occurrence and progression of bidirectional cracks ultimately leading to punching shear failure. This failure mode is a typical phenomenon of reinforced concrete deck slabs subjected to repeated **running wheel load**, in which cracks occur unidirectionally and progress bidirectionally and then penetrate deck slabs, reducing the continuity of the deck slab in the transverse reinforcement direction and leading to failure through a complex mechanism known as punching shear failure. When repeated loads are applied at a fixed point, the bidirectional cracks do not occur. With the same magnitude of loads, the number of loads until failure is much lower for running wheel loads. Also, if water has penetrated from the upper surface of the deck, the fatigue life of the deck is greatly reduced.

Existing research has confirmed that bonding continuous fiber sheets to the bottom (tension) surface of the reinforced concrete deck slabs elongates the fatigue life of the deck slabs.[11) 12)] This is because the continuous fiber sheets restrict the opening and closing of cracks caused by the bending moment, prevent crack propagation in the deck depth direction and reduce the deflection caused by bend and the degree of stress on the reinforcement, and thereby increasing the life of the member.

Verification of the punching shear fatigue resistance of planar members reinforced with continuous fiber sheets should be done through wheel load running tests or other test methods capable of reproducing the mechanism by which planar members suffer fatigue damage. In verifying the punching shear fatigue resistance of planar members reinforced with continuous fiber sheets, adequate consideration should be given to the fatigue failure characteristics of the concrete in planar members as well as the fatigue breakage of continuous fiber sheets and the interfacial peeling fatigue failure of continuous fiber sheets and concrete. However, in general, the repeated tensile strain occurring in the bottom surface under normal use conditions is less than the breakage strain of continuous fibers. Therefore, in most cases the fatigue breakage of continuous fiber sheets need not be examined.

In addition, the effect of reinforcement is primarily dependent on the tensile rigidity of the continuous fiber sheets (the product of the Young's modulus of the continuous fiber sheets and the cross-sectional area). Therefore, the type and number of plies of the continuous fiber sheet should be considered in verification. In many cases, bidirectional cracks occur in the lower surface of the deck, and generally continuous fiber sheets are bonded in two directions. Since the condition of damage before reinforcement has a large influence on punching shear fatigue resistance after reinforcement, the condition of damage before reinforcement is considered, the suitability of the continuous fiber sheet bonding method should be examined carefully. In the reference,[13)] a general guide is given for the degree of damage to existing deck slabs, the applicability of the carbon fiber sheet method, and the standard reinforcement amounts for carbon fiber sheets, based on the results of the reinforced concrete deck slabs of highway bridges by running wheel load tests.

6.4.5 Safety with respect to seismic action

6.4.5.1 Design ductility ratio of members

The ductility ratio μ_{fd} of upgraded members may be determined by Equation 6.4.9.

$$\mu_{fd} = \left[1.16 \cdot \frac{(0.5 \cdot V_c + V_s)}{V_{mu}} \cdot \left\{ 1 + \alpha_0 \frac{\varepsilon_{fu} \cdot \rho\phi}{V_{mud} / (B \cdot z)} \right\} + 3.58 \right] / \gamma_{bf} \leq 10 \quad \text{.. (6.4.9)}$$

where:

μ_{fd} : Ductility ratio of members upgraded with continuous fiber sheets

V_c : Shear contribution due to concrete (both material factor and member factor are calculated as 1.0 with Equation 6.4.4 in 6.4.2 "Design shear capacity for bar members")

V_s : Shear contribution due to shear reinforcing bar members (both material factor and member factor are calculated as 1.0 with Equation 6.4.6 in 6.4.2 "Design shear capacity for bar members")

V_{mu} : Maximum shear force when a member reaches the existing flexural load-carrying capacity M_u

1.0 is used as the material factor, material correction factor and member factor for the reinforcement and concrete.

γ_{bf} : Member factor used for calculation of μ_{fd} (generally set to 1.3)

ε_{fu} : Ultimate strain of continuous fiber sheet (design tensile strength of continuous fiber sheet divided by the characteristic value of modulus of elasticity)

$$\varepsilon_{fu} = f_{fud} / E_f = \left(f_{fuk} / \gamma_{mf}\right) / E_f$$

f_{fud} : Design tensile strength of continuous fiber sheet (unit: N/mm^2)

f_{fuk} : Characteristic value of tensile strength of continuous fiber sheet (unit: N/mm^2)

E_f : Characteristic value of modulus of elasticity of continuous fiber sheet (unit: N/mm^2)

γ_{mf} : Material factor of continuous fiber sheet (generally set to 1.2)

ρ_f : Shear reinforcement ratio of continuous fiber sheet

$$\rho_f = A_f / \left(S_f \cdot B\right) = 2 \cdot n_f \cdot t_f \cdot S'_f / \left(S_f \cdot B\right)$$

S_f : Spacing of continuous fiber sheets (unit: mm)

t_f : Thickness of one ply of continuous fiber sheet (unit: mm)

n_f : Number of plies of continuous fiber sheets

S'_f : Width of continuous fiber sheet (unit: mm)

α_0 : Coefficient used to calculate member ductility ratio (for columns shear-reinforced with lateral ties, α_0 may be used as the modulus of elasticity for the lateral ties)

$$\alpha_0 = Es$$

B : Member width (unit: mm)

z : Lever arm length (generally set to d/1.15)

[Commentary]

Referring to the results[14)-20)] of members reinforced by lateral ties under reversed cyclic load tests , the experimental data on the contribution of continuous fiber sheets are organized in terms of the relationship between the ductility ratio μ_{fd} and

$(0.5 \cdot V_c + V_s)/V_{mu} \cdot \{1 + \alpha_0 \cdot \varepsilon_{fu} \cdot \rho_f / V_{mu} / (B \cdot z)\}$. The results are shown in Figure C6.4.7. The values for shear capacity of each test specimen and the maximum shear force when the member reaches the existing flexural capacity are calculated using the mean values of the material strengths for continuous fiber sheets, concrete and steel, and with all material factors and member factors set to 1.0. The ductility ratio μ_{fd} of upgraded members is determined using the envelope in the hysteresis curve for load-peak displacement (P-δ curve) obtained through reversed cyclic load tests. The limit displacement δ_{limit} at which the load-carrying capacity at the yield point δ_y can be maintained is divided by the yield displacement. However, the ductility ratio u_{fd} in the figure is set to the average for positive direction load and negative direction load.

From Figure C6.4.7 it can be seen that, by organizing the ductility of the members reinforced with carbon fiber sheets and aramid fiber sheets in terms of the relationship with $(0.5 \cdot V_c + V_s)/V_{mu} \cdot \{1 + \alpha_0 \cdot \varepsilon_{fu} \cdot \rho_f / V_{mu} / (B \cdot z)\}$, it is possible to integrate both and evaluate them as a linear relationship.

However, as can be seen from the horizontal axis in the figure, the proposed function for evaluating ductility ratio is a relatively accurate one developed through various trials. In these recommendations, a member factor is introduced based on the regression equation for the test results in order to propose a calculation equation (6.4.9).

In addition, the values for the modulus of elasticity E_f and shear reinforcement ratio ρ_f for the continuous fiber sheets used in previous tests are in the range of 80 - 235 kN/mm^2 and 0 - 2.54 x 10^{-3}, respectively. Therefore, it is important to note that Equation 6.4.9 is only applicable within these ranges. The spacing (S_f) and sheet width (S'_f) of continuous fiber sheets used to calculate the shear reinforcement ratio ρ_f for the continuous fiber sheets are shown in Figure 6.4.8.

Equation 6.4.9 confirms that ductility ratio can be ensured for reinforcement of reinforced concrete columns with the typical rectangular section using carbon fiber sheets and aramid fiber sheets. Accordingly, when the conditions are markedly different from those of rectangular reinforced concrete columns, a separate safety study is required.

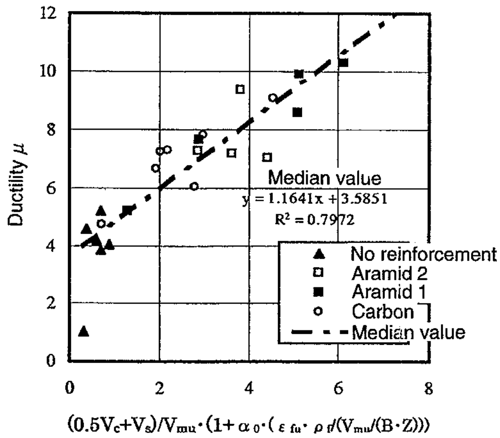


Figure C6.4.7 Ductility ratio of members upgraded with continuous fiber sheets

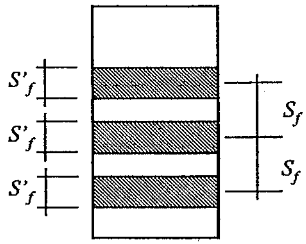


Figure C6.4.8 Spacing (S_f) and sheet width (S'_f) for continuous fiber sheets

6.4.5.2 Member restoration force model

The restoration force model used to calculate the response displacement shall be in accordance with Chapter 3 of the Standard Specifications for Design and Construction of Concrete Structures (Seismic Design).

[Commentary]

A suitable model may be used to evaluate the restoration force characteristics of members upgraded using continuous fiber sheets. It has been confirmed that, in general, analytical models used for ordinary reinforced concrete members may be applied to the restoration force characteristics of members upgraded using continuous fiber sheets. Accordingly, this is set in accordance with Chapter 3 of the Standard Specifications for Design and Construction of Concrete Structures (Seismic Design).

The restoration force model shown in Figure C6.4.9 is an example of calculation of the envelope of members upgraded with continuous fiber sheets and modeling with the hysteresis characteristics used for reinforced concrete members.[22)]

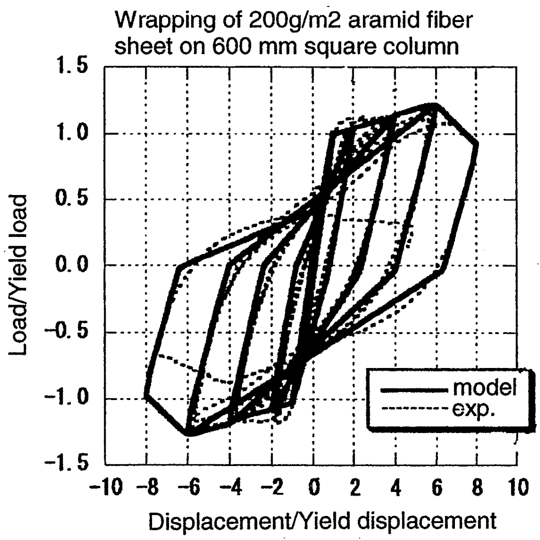


Figure C6.4.9 Sample restoration force model

6.4.6 Fire safety

To ensure the required safety of upgraded concrete structures with respect to safety, suitable covering of the surface shall be performed as needed. When structures are covered with noncombustible or fire-resistant coverings to ensure fire safety, their effect may be considered.

[Commentary]

The required level of fire safety depends on the structure to be upgraded and the surrounding environment. In general, three levels of safety required can be categorized for structures upgraded with continuous fiber sheets.

(1) Flame-retardant:

The combustibility of the continuous fiber sheets is low and it can be confirmed that, even if they are damaged in a fire, they can be repaired

(2) Noncombustible and quasi-noncombustible:

In a fire, the continuous fiber sheets are not ignited and no harmful fumes are produced. However, the continuous fiber sheets are not required to maintain their load-carrying capacity during and after the fire.

(3) Fire-resistant:

The continuous fiber sheets are required to maintain the effect of upgrading during and after the fire without repair.

Table C6.4.1 shows the fire safety categories and required fire safety levels.

Table C6.4.1 Fire safety categories and required fire safety levels

Category	Required Safety Level
Flame retardant	In the event of a fire, the structure does not collapse even without the upgrading effect of continuous fiber sheets. The quantity of flammable substances due to continuous fiber sheets on the surface is low and the scale of the fire does not increase.
Noncombustible/ quasi	In the event of a fire, continuous fiber sheets are not ignited (restrictions on interior furnishings according to Building Standard Law). In the event of a fire, the structure does not collapse even without the upgrading effect of continuous fiber sheets. After the fire, the continuous fiber sheets that have suffered damage are repaired.
Fire-resistant (1)	In the event of a fire, the structure does not collapse even without the upgrading effect of continuous fiber sheets. After the fire, when the temperature has returned to normal, the continuous fiber sheets demonstrate the same strength as before the fire and repair is not necessary.
Fire-resistant (2)	Even in the event of a fire, the continuous fiber sheets should demonstrate the upgrading effect. During the fire, the continuous fiber sheets maintain the required strength for the duration of the design fire-resistant period.

For verification of fire safety, a test specimen with the same surface covering as the actual structure should be manufactured and subjected to combustion tests. During the combustion test, ignition, the generation of gases, harmful surface deformation, changes in the quality of the continuous fiber sheets after the fire are studied according to the level of fire safety required.

One method of performing the combustion test to check category 1 (flame retardant) is to bring a burner flame near the continuous fiber sheet, and see whether the sheet is ignited and whether there is any residual flame on the surface of the test specimen when the burner flame is removed. When the surface is to be covered in order to ensure flame retardancy, a test specimen with surface covering provided on the continuous fiber sheet is used. For continuous fiber strands, the test is performed in the same manner.

In a normal fire, the carbon fibers used in continuous fiber sheets do not combust or produce a chemical reaction. However, with aramid and other organic fibers, the fibers are flame retardant but thermal decomposition occurs under high temperatures. In addition, impregnation resin and other resin materials are flammable. When attached to the concrete surface, the heat capacity of the concrete is great and the combustibility of the continuous fiber sheets is not great, and it has been confirmed with carbon fibers that, even when ignited with an external flame, the fibers are self-extinguishing once the flame is removed. Therefore, they are thought to be flame retardant even without surface covering.

In general, with the continuous fiber sheet method, existing concrete structures support dead loads and other permanent loads, while continuous fiber sheets support live loads and other fluctuating loads, seismic loads and so on. In such cases, even if continuous fiber sheets fail to function due to a fire, there is no danger of the structure collapsing immediately. If there is little danger of a fire occurring, and no danger of the fire spreading even if a fire should occur, and if adequate refugee space is available and there is little likelihood of danger to human life, there is no particular need to provide flame resistant covering on the continuous fiber sheets.

When covering the surface to ensure fire safety, the condition of use and surrounding environment of the upgraded structure should be considered and the covering material and thickness selected to match the requirements for fire resistant performance.

When the surface of continuous fiber sheet has been covered in order to test category 2 (noncombustible and quasi-noncombustible), the method given in the supplementary materials for the recommendations entitled "II Test Methods for Continuous Fiber Sheets/11. Test method for flame retardancy of surface of protective materials for continuous fiber sheets" should be used.

When preventing combustion during a fire is an objective and nonflammable or quasi-nonflammable coverings based on the premise that the sheets will be repaired after the fire are used, these should generally consist of mortar, rock wall or other coverings.

(3) One method of checking the flame resistance in category 3 is to fabricate a test specimen by bonding continuous fiber sheets to the concrete members or jacketing with such sheets and covering the surface, then heating the test specimen in a furnace

at the prescribed temperature for the prescribed duration and measuring the temperature of the continuous fiber sheets during heating in order to see if the properties of the continuous fiber sheets are altered in undesirable ways.

When the continuous fiber sheets are expected to provide the upgrading effect without repair even after the fire, the temperature of the continuous fiber sheets during the fire should be kept below that at which resin decomposes (for epoxy resins, about 260°C). They should be covered with approximately 50 mm of mortar.

6.4.7 Collision safety

(1) When there is a possibility that the upgraded structures with continuous fiber sheets may be subjected to impacts, one of the following methods shall be used to confirm that the performance requirements are satisfied even after the impact.
   (i) The magnitude of impacts during the service life of the structure shall be estimated through statistical data, and the performance requirements under the impacts shall be verified by conducting impact load test or the equivalent method.
   (ii) The possible impacts during its service life shall be estimated based on the damage surveys of structures thought to have been subjected to the same impacts as the structure being verified, and the performance requirements under the impacts shall be verified by conducting impact load test or the equivalent method..

(2) When the structure is subjected to impacts only on very rare occasions during its service life, verification may be conducted to ensure that, even if the performance drops temporarily after an impact, the structure can be quickly restored.

(3) When suitable protective facilities are in place for the structures to be upgraded with continuous fiber sheets, or such facilities are provided at the same time as the upgrading work, the effect of this protection may be considered.

[Commentary]

(1) Structures to be upgraded using continuous fiber sheets may be subjected to impacts such as those listed in Table C6.4.2.

Table C6.4.2 Sample impacts

Type of structure	Impact	Location subjected to impact before upgrading with continuous fibers
Bridge piers in river	Boulders and drifting wood	Cover
Bridge piers subjected to wave erosion	Waves/sand/rocks	Breakwater blocks/covering
Bridge piers in parks, etc.	Defacement	Cover
Bridge piers in parking structures	Vehicle collisions	Guard fences/cover
Bridge piers near highways and railways	Vehicle and train collisions	Guard fences/concrete blocks
Bridge piers in harbors and waterways	Ship collisions	Fenders
Bridge piers in regions where landslides or pyroclastic flows may occur	Landslides/ pyroclastic flows	Check dams, etc.
Superstructures that have intersections with low clearances	Vehicles	Girder protection
Bridge superstructures/substructures near coasts	Blowing sand	Cover

(1) (i) With the exception of special impacts, the normal impact resistance of the structure can be evaluated through drop impact tests and pendulum impact tests. The degree of impact recreated through testings should be estimated by considering the type and likelihood of impacts applied to the structure during its service life. For example, impacts applied to bridge piers in rivers by boulders and drifting wood can be estimated statistically from the planned water flow of the river, the mass and hardness of rocks upstream and other factors.

(1) (ii) When it is difficult to make statistical calculations of the impacts applied to the structure during its service life, simple methods that consider the urgency of upgrading, costs required for study, the accuracy of the study, and ease of restoration in the event of damage can be used, based on the results of the survey of existing structures.

(2) In the case of seismic retrofit, as the likelihood of occurrence is extremely low for both earthquakes and impacts, it is thought that they do not occur simultaneously. Accordingly, damage to upgraded materials through impacts has little effect on reducing the safety of the structure. This is true if the structure has the required load-carrying capacity regardless of whether normal upgrading has been performed or whether the structure has not yet been repaired or reinforced. With this type of upgrading, if speedy and appropriate upgrading are

conducted for impacts that occur only rarely, it is judged that the performance requirements of the structure may have been satisfied. However, when the upgrading should be conducted in an extremely difficult location or damage to upgrading materials in a short period of time will have a great impact on safety, the effect of these factors should be verified.

(3) Of the items shown in Table C6.4.2, for example in the case of superstructures that have intersections with low clearances, portal type girder protectors or the like are usually installed, and there is little chance that the structure itself will be subjected to external impacts. For the design of other structures such as bridge piers in rivers, on the other hand, no special measures are devised. Only the cover concrete should enable the structure to maintain serviceability for the several times to several dozen times of impacts from boulders and drifting wood during its service life. In such cases, the impact protection is expected of the continuous fiber sheets bonded on the surface of structures.

6.5 Verification of serviceability

6.5.1 Stress level

(1) The stresses of concrete and steel in upgraded member sections may be evaluated in accordance with Section 7.2 of the Standard Specifications for Design and Construction of Concrete Structures (Design).

(2) The stresses due to the permanent loads applied before upgrading may be calculated using the existing sections. The stresses due to permanent loads added after upgrading and variable loads may be calculated using composite sections made up of the existing sections and the upgraded sections. The overall stress shall be evaluated by adding these values together.

(3) The member factor γ_b is generally set to 1.0.

[Commentary]

The limit value of stress level in Section 7.3 of the Standard Specifications for Design and Construction of Concrete Structures (Design) is recommended as the limit value for the stress level under ordinary load conditions.

To calculate the stress level when continuous fiber sheets are used, the direction of the continuous fiber sheets should be considered. When the existing sections and the continuous fiber sheets have bonded, calculation of the stress level produced in the concrete, steel and continuous fiber sheets in member sections is based on the assumptions in 1 - 5 below:

1. Fiber strain is proportional to distance from the neutral axis of the section.
2. Concrete, steel and continuous fiber sheets are elastic bodies.
3. The tensile stress of concrete is ignored.
4. As a rule, the stress-strain curve for concrete and steel should be in accordance with Chapter 3 of the Standard Specifications for Design and Construction of Concrete Structures (Design).
5. The Young's modulus of continuous fiber sheets should be in accordance with Chapter 3 "Materials" in the recommendations.

When there is thought to be no bonding force between the continuous fiber sheets and the concrete, the individual stress levels should be calculated using a suitable method.

6.5.2 Crack width

(1) The flexural crack widths shall be calculated taking into account the effect of continuous fiber sheets.

(2) The member factor γ_b may generally be set to 1.0.

[Commentary]

If the crack interval of members upgraded with continuous fiber sheets is the same as those for reinforced concrete members, a safe value for the crack width can be determined by substituting the stress level of the reinforcement derived through consideration of the effect of continuous fiber sheets in Equation C7.4.1 in the Standard Specifications for Design and Construction of Concrete Structures (Design).

In general, cracks in members to which continuous fiber sheets have been bonded are dispersed, and accordingly, the crack width is reduced. In pull-out tensile strength tests of members bonded with carbon fiber sheets, the crack width is almost proportional to the average strain of the sheet and reinforcement, and is almost independent of the concrete cover, the steel diameter, the rigidity of the continuous fiber sheets and the compressive strength of concrete. At the level just before the yield point of the reinforcement, the crack width is approximately 0.3 to 0.7 times the width of cracks in members not bonded with sheets.

However, when cracks have already occurred in a structure governed by dead loads, it is not clear whether the effect of the distribution of further cracking can be anticipated even if upgrading with continuous fiber sheets is conducted. For this reason, in structures with large dead loads, the crack width calculated with Equation 7.4.1 in the Standard Specifications for Design and Construction of Concrete Structures (Design) may be used for the flexural crack width when continuous fiber sheets are attached to the underside of the girders. In other words, the crack width after upgrading should be the width of cracks produced in the existing structure by drying shrinkage and dead loads, added to the additional crack width caused by the additional load (live loads, etc.) after upgrading with continuous fiber sheets. To calculate the additional crack width, the reinforcement strain caused by the additional load considering the continuous fiber sheets should be used.

Even when the dead load is large, for structures with no cracking or those governed by live loads, the flexural crack width may be calculated using Equation C6.5.1, in which the crack width calculated with Equation 7.4.1 in the Standard Specifications for Design and Construction of Concrete Structures (Design) is multiplied by the maximum crack width ratio of 0.7.

$$w = 0.7k\left[4c + 0.7(C_s - \Phi)\right]\left[\frac{\sigma_{se}}{E_s}\left(\text{or}\,\frac{\sigma_{pe}}{E_p}\right) + \varepsilon'_{cs}\right] \text{..............................(C6.5.1)}$$

For shear cracks, the mechanism of initiation and propagation of cracks is different from flexural cracks., It should be studied using appropriate methods. Examination of crack widths is not necessary for concrete structures upgraded with continuous fiber sheets since the surface is protected.

6.5.3 Displacement/deformation

(1) The amount of displacement and deformation of upgraded members shall be determined according to Section 7.5.3 of the Standard Specifications for Design and Construction of Concrete Structures (Design)

(2) The member factor γ_b may generally be set to 1.0.

[Commentary]

The amount of displacement and deformation of upgraded members should be calculated by evaluating the effects of cracks at a suitable rigidity. If the width of cracks produced in existing members is large, the cracks are generally filled with crack grout as surface preparation before upgrading. The effect of this factor should be considered when calculating the amount of displacement and deformation of upgraded members.

In general, if it has been only a few years since the structure was erected, it is possible that additional displacement and deformation may occur due to concrete compression and creep after upgrading. This should be suitably evaluated and added.

6.6 Restorability

6.6.1 Restorability after earthquake

Restorability of an upgraded structure after earthquake shall be evaluated by the extent of damage to the structure, the location of damage in the structure and the restoration method to be used.

[Commentary]

As quantitative indices for judging whether an upgraded structure damaged by an earthquake can be restored or not, the maximum response displacement of the structure during the earthquake and the residual displacement after the earthquake may be taken. These displacement values can be obtained by conducting a dynamic response analysis taking the upgraded structure in a suitable dynamic model. The analytical model and dynamic response analysis for the upgraded structure can be derived in the same manner as the those for ordinary reinforced concrete structures, as shown in 6.4.5.2 "Member restoration force model," based on the Standard Specifications for Design and Construction of Concrete Structures (Seismic Design).

6.7 Changes of performance of upgraded structures with the elapse of time

6.7.1 General

(1) Upgraded structures shall satisfy various performance requirements throughout the entire remaining design service life under the load and environmental conditions. This may be done by evaluating the changes of the performance of the upgraded structures with the elapse of time under the given conditions.

(2) When upgrading is introduced to prevent the deterioration of the performance of the structure, suitable methods shall be used to ensure the attainment of the required effect.

[Commentary]

(1) The material factor γ_m used to verify the performance of the structure involves the deterioration of materials in the structure over time. In general, changes in the performance of the structure over time are not only those produced by deterioration in material strength. In practice however, the reduction of material strength may only be considered when upgrading is conducted to improve the dynamic performance of the structure. It is important to consider the material strength, dimensions and condition of deterioration of the existing sections at the time of upgrading, based on detailed inspections of the structure, as well as to ensure that the upgrading work conforms to Chapter 7 of these recommendations, and to consider the deterioration in material strength in the existing sections and the upgraded sections after upgrading in the respective material factors.

(2) Continuous fiber sheets not only improve the dynamic performance of the structure but prevent intrusion of harmful substances, protect existing concrete and prevent deterioration in the performance of the structure over time. Nevertheless, although progress is being made in research on the changes in the performance over time of structures upgraded using continuous fiber sheets, quantitative techniques for forecasting such changes have not yet been established and test data is not yet sufficient. Accordingly, when conducting upgrading with continuous fiber sheets with the primary objective of preventing a decline in performance, or when conducting upgrading in the hope of both

improving dynamic performance and preventing deterioration, suitable methods should be used to ensure that the required effects are achieved.

Section 6.7.2 describes methods to verify the effect of using continuous fiber sheets to block salts.

6.7.2 Verification of the effect of using continuous fiber sheets to prevent intrusion of chloride ions

The effect of continuous fiber sheets attached to concrete surfaces to prevent intrusion of chloride ions shall be verified by confirming that the chloride ion concentration C_d at the locations of steel reinforcement is less than the value of the corrosion limit concentration $C_{\lim}$ during the remaining design life, divided by the structure factor.

$$C_d \le C_{\lim} / \gamma_i \quad \text{(6.7.1)}$$

where:

γ_i : Structure factor (may generally be set to 1.0)

$C_{\lim}$: Corrosion limit value of chloride ion concentration for steel (May generally be set to 1.2 kg/m^3)

C_d : Chloride ion concentration at the locations of the steel reinforcement (may be derived from Equation 6.7.2 for structures upgraded with continuous fiber sheets)

$$C_d = \gamma_{cl}\left[(C_0 - C_i)\left\{1 - erf\left(\frac{0.1 \cdot c}{2\sqrt{D_d(t - t_f)}}\right)\right\} + C_i\right] \left(\text{however, } t > t_f\right) . \quad \text{(6.7.2)}$$

$erf(x)$: the error function, expressed as $erf(x) = \dfrac{2}{\sqrt{\pi}}\int_0^x e^{-\xi^2} d\xi$.

where:

γ_{cl} : Safety factor that covers the uncertainty of calculations of chloride ion concentration at the locations of steel reinforcement (may generally be set to 1.3)

C_0 : Chloride ion concentration on the surface of the structure (kg/m^2). The values in Table 6.7.1 may be used.

Table 6.7.1 Chloride ion concentration C_0 (kg/m^3) on surface of structure

Splash zone	Distance from coast (km)				
	Shoreline	0.1	0.25	0.5	1.0
13.0	9.0	4.5	3.0	2.0	1.5

Regarding heights near the coast when determining C_0: one meter of height corresponds to 25 meters of distance from the shoreline.

C_1: Chloride ion concentration (kg/m^3) at the locations of steel reinforcement at the time of upgrading. If chloride ions do not exist before upgrading, this value may be set to 0 if suitable desalinization treatment, etc. is conducted during upgrading.

c: Cover thickness (mm). It would be best to use the measured value obtained from inspecting existing structures.

D_d: Dispersion coefficient of chloride ions for cover concrete (cm^2/year). This value shall be determined based on the results of the inspection of the existing structure.

t: Remaining design life (years). The period from the time of upgrading to the estimated end of service.

t_f: The period the continuous fiber sheets are expected to block chloride ions (years). The values in Table 6.7.2. may be used.

Table 6.7.2 Expected period for continuous fiber sheets to block chloride ions (years)

Number of plies	Environmental category	
	Ordinary environments	Environments with harsh climatic conditions
Only one sheet	10	5
Two or more sheets	15	7.5

"Environments with harsh climatic conditions" refers to environments in which the blocking effect may be impaired due to physical deterioration of the boundary between continuous fiber sheets and concrete due to the impact of freezing and thawing, repeated dryness and moisture and so on. Ordinary environments refers to environments other than those with harsh climatic conditions.

[Commentary]

The verification of the effectiveness of continuous fiber sheets to prevent the intrusion of chloride ions may be done by examining whether the concentration of chloride ions at the steel locations in concrete would reach the corrosion limit concentration for steel during the remaining design life. The verification method presented here conforms to the method entitled "Verification of steel corrosion accompanying the intrusion of chloride ions" adopted in the "Durability Verification Standards" in the 1999 Standard Specifications for Design and Construction of Concrete Structures (Construction).

Equation 6.7.2 is derived based on the hypothesis that the movement of chloride ions in concrete is shown by Fick's law. Chloride ion movement models and numerical analysis methods other than those presented here may be used. For example, the finite element method, the finite differential method and other numerical analysis methods make it possible to consider fluctuations in environmental conditions over time, enabling the use of movement models capable of elaborate consideration of the non-linearity of material properties, the coupled movement of multiple substances that accelerate corrosion and other factors.

In some cases chloride ions have already penetrated the structure before upgrading. The effect of these ions is considered with C_i in Equation 6.7.2. The values used for calculation, such as cover thickness c, concentration of chloride ion C_i at steel location in the existing structure, and dispersion coefficient D_d for chloride ions in the concrete, should be determined by the actual measurement. However, if measurement cannot be taken, the values may be estimated using suitable methods. In such cases, the uncertainty of the estimations of the values should be considered using a safety factor. For example, if the dispersion coefficient D_d for chloride ions in the concrete cannot be determined through testing, this value may calculated using Equation C6.7.1 based on the water-cement ratio W/C for the existing concrete.

$$\log D_d = [4.5(W/C)^2 + 0.14(W/C) - 8.47] + \log\left(3.15\times 10^7\right) \quad \text{..................(C6.7.1)}$$

When cracks exist in the existing sections of the cover concrete, the dispersion coefficient obtained from Equation C6.7.1 should be increased to consider the effects.

In the recommendations, it is specified to express the effectiveness of continuous fiber sheets in blocking chloride ions in the form of complete blockage for a certain period of time after upgrading and complete loss of blocking capability thereafter. It is also specified that the values in Table 6.7.2 may be used as the number of years that the blocking effect will continue. The blocking effect of continuous fiber sheets in ordinary environments is set at 10 years after referring to the effect of the paint layer used for making repairs. When more than one layer of continuous fiber sheets is used, the blocking effect may increase. However, since there is insufficient quantitative evidence, it is assumed that two or more layers would increase the duration of blocking effectiveness 1.5 times that of a single layer. In environments with considerable impact from freezing and thawing and repeated dryness and moisture, peeling progresses at the boundary between the continuous fiber sheets and the concrete. There is a possibility that the blocking effect may be impaired. In such environments, the reduction in the blocking effect is set at a reduction by half. Nevertheless, in either case the values shown in Table 6.7.2 are not based on sufficient performance results, and it is hoped that future research will result in a further accumulation of knowledge.

6.8 Verification of structural details

6.8.1 General

Methods for verifying the performance of upgraded structures shown in the recommendations are based on the premise that continuous fiber sheets keep the strength at corner angles and overlap splices, and that the anchorage has sufficient anchoring strength. This section covers verification methods for these structural details.

[Commentary]

The continuous fiber sheet method is based on the premise that the continuous fiber sheets are either bonded to the surface of the concrete to form a unit or wrapped tightly around the structural members, such that stress is appropriately transmitted between the sheets and the existing concrete surface, and that the overlap splice sections of the reinforcing materials, corner angles and other areas have sufficient strength.

6.8.2 Corner angles of members

The corner angles of members when continuous fiber sheets are jacketed shall be verified by confirming that the continuous fiber sheet has a sufficient radius of curvature at the corner angles to ensure the required strength.

[Commentary]

When the radius of curvature at the corner angles is small, the concentration of stress and the out-of-plane shear force will decrease the apparent tensile strength of the continuous fiber sheet. These sections should be chamfered to reduce the stress concentration. In general, the chamfer radius is set to approximately 10 mm - 50 mm. The type and thickness of continuous fiber sheet and the thickness of the strands have a large influence on the necessary chamfer radius. When determining the necessary chamfer radius through testing, these conditions should be considered before conducting the test. In the reference test methods described in II "Test Methods for Continuous Fiber Sheets" is one entitled "Test method for flexural tensile strength of continuous fiber sheets."

6.8.3 Overlap splices of continuous fiber sheets

The overlap splice sections of continuous fiber sheets shall be verified by confirming that the overlap splice length needed to ensure the required overlap splice strength is secured. As a rule, the necessary overlap splice length shall be determined through testing in accordance with the JSCE-E 542 "Test method for overlap splice strength of continuous fiber sheets."

[Commentary]

The overlap splices of continuous fiber sheets are placed in the fiber direction to transmit loads. When the overlap length is short, the overlap splice strength varies depending on the overlap length. If the overlap length is long enough, the overlap splice strength may become the tensile strength of sheet. If possible, it is desirable to take the overlap length which ensures that peeling failure in the overlap splice section does not occur. Nevertheless, depending on the type of continuous fiber sheet and the type of impregnation resin, the overlap splice strength may be lower than the tensile strength of the continuous fiber sheet and failure may occur in the bonded layers even if the overlap length is increased. Therefore, the strength of the overlap splice section should be confirmed through testing and the tested value should be used for the design since the minimum overlap splice length required to ensure a stable overlap splice strength depends on the type of continuous fiber sheet and the type of adhesive, an appropriate combination of materials should be determined through testing. The carbon fiber sheets and aramid fiber sheets used today require the overlap splice length of approximately 100 mm at the lower stress level produced in the splice zone and about 200 mm for strengthening of shear capacity and ductility.

When only one layer of continuous fiber sheet is used for reinforcement, the variations in the overlap splice strength due to construction error may influence the safety of the upgraded structure at a great extent. In such cases, it is recommended to elongate the overlap spice length and to attach one more layer of continuous fiber sheet at the overlap splice section.

Overlap splices should be placed so as to avoid positions subjected to large bending moment. When more than one layer is used, the overlap splices should not be placed at the same section, since this reduces the overlap splice strength.

6.8.4 Anchoring of continuous fiber strands

The end anchorage of continuous fiber strands shall be verified by confirming that the continuous fiber strand is wound with the required number of turns at the section to be anchored. As a rule, the required number of turns for continuous fiber strands shall be determined through testing.

[Commentary]

Continuous fiber strands are anchored by winding them several times at the same section of the bar member. As a rule, the number of wraps should be confirmed through testing. It has been proven that one to two wraps is sufficient for carbon fiber strands composed of 12,000 filaments.

6.8.5 Mechanical anchoring of continuous fiber sheets

Mechanical anchorage accomplished with anchor bolts and anchor plates shall be verified by confirming that the anchorage has sufficient strength to prevent anchorage failure.

[Commentary]

In the reinforcement of bridge pier foundations, mechanical anchoring by means of anchor plates and anchor bolts may be necessary because attaching the continuous fiber sheets to the footing surface is not good enough for anchorage. For girder members, when continuous fiber sheets are bonded to the sides of the members for shear reinforcement , anchoring should be ensured mechanically through anchor bolts and anchor plates. In such cases, the tensile force of the continuous fiber sheet is transmitted through the bond to the anchor plate. It is necessary to confirm that peeling failure does not occur between the continuous fiber sheet and the plate under the design loads, and that failure does not occur at the anchor bolts or in concrete.

CHAPTER 7 UPGRADING WORK

7.1 General

(1) As a rule, upgrading work using continuous fiber sheets and continuous fiber strands shall be conducted in accordance with the provisions of this chapter.

(2) As a rule, the upgrading work shall be performed under the supervision of an engineer who has thorough knowledge of these tasks.

[Commentary]

The continuous fiber sheet method and continuous fiber strand method involves using impregnation resin to bond or seal continuous fiber sheets and continuous fiber strands to the surface of the concrete. The reinforcement and the existing concrete structure become a single unit and demonstrate the required upgrading performance. Accordingly, in order to achieve this, appropriate techniques, material selection, construction and construction supervision are essential, and suitable maintenance should be performed to ensure that the performance requirements are maintained after upgrading.

In this chapter, considerations regarding the construction needed to achieve the designed upgrading performance are described. Upgrading using continuous fiber sheets and continuous fiber strands involves applying impregnation resin to the continuous fiber sheets and continuous fiber strands at the site in order to ensure the upgrading performance. Therefore, decisions should be made taking account of the condition of the work site and based on the unique operational and environmental conditions at the site, and the skill of the work supervisor who supervises the construction and the work personnel will have a comparatively great influence on the process. A qualification system for skills should be required and has been established in some areas. For these reasons, when implementing these techniques, it is important to consider qualifications, experience when selecting supervisors and work personnel.

7.2 Work plan

(1) The work using continuous fiber sheets and continuous fiber strands shall be done so as to satisfy the work requirements in accordance with a work plan based on the upgrading design of the concrete structure with considerations given to the construction and environmental conditions.
(2) The work plan shall specify the work procedure, processes and quality control methods.

[Commentary]

The quality of the work plan is a major factor on the reliability and safety of the structure. For this reason, necessary preliminary studies should be performed to ensure the performance requirements for the design and a work plan drafted based on the results.

To ensure that the work is performed reliably, the work plan should include the followings.

1. Reasonable work schedule considering possible working period
2. Adequate space for work
3. Preparation of necessary amount of materials with sufficient quality
4. Employment of construction workers with the necessary capabilities and adequate experience

The following items should be taken into account to ensure the safety of the work:

1. Measures to ensure the safety of work personnel.
2. Measures to ensure the safety of third parties.
3. Measures to prevent damage to shared facilities.
4. Establishment of a system for quick countermeasures in the event of an accident.
5. Measures for waste processing.

(2) The continuous fibers used to upgrade concrete structures include those in sheet form and strand form. Work procedures should be established that utilize the characteristics by selecting the type that best satisfies the performance requirements of the design.

The following are the standard work procedures for upgrading using continuous fiber sheets and continuous fiber strands.

1. Delivery and storage of materials to be used
2. Preparation work
3. Surface preparation work
4. Primer coating work
5. Bonding of continuous fiber sheets and jacketing with continuous fiber strands
6. Finishing
7. Restoration of existing facilities

The procedures should include the environmental conditions at the construction site, the work period and other restrictions. They should also specify processes that match the construction tasks and quality control methods to ensure the performance requirements of the design.

7.3 Handling of materials

The handling precautions relating to material deterioration and safety during delivery, storage, mixing and processing, and use shall be confirmed in advance and strictly observed.

[Commentary]

Materials used in the continuous fiber sheet method and continuous fiber strand method should be those for which quality has been confirmed, not only the mechanic characteristics of the continuous fiber sheets and continuous fiber strands but the quality of impregnation resin and all other materials. Moreover, the performance of the composite of all of these materials is crucial, and materials whose strength, deterioration characteristics and other properties as a composite have been confirmed through testing should be used.

Since the quality of the materials affects the effectiveness of upgrading, the quality should be confirmed upon receipt. In general, the materials are manufactured in accordance with the quality standards of the manufacturer. Therefore, their quality may be checked by the test results submitted by the manufacturer.

If reinforcements, adhesives and other materials deteriorate during shipment, storage, mixing and processing, it is very difficult to ensure required upgrading performance. For this reason, materials should be properly shipped and stored considering material properties to ensure that no deterioration occurs during shipment and storage. Continuous fiber sheets and continuous fiber strands are easily damaged before being impregnated with impregnation resin, and some types of continuous fibers may deteriorate if exposed to ultraviolet light and moisture. Therefore, thorough precautions should be taken to ensure that they are handled properly. In general, to prevent deterioration of the resin materials used for bonding, the materials should be stored in a cool dark place without being exposed to direct sunlight.

Resins that contain diluents are harmful to the human body when the concentration of the fumes emitted exceeds a certain level. Accordingly, the container should be sealed securely and stored in a cool dark place. These resins are also flammable and fire precautions should be observed and the storage quantities kept within the limits prescribed by the Fire Defense Law (Class 4 primary petroleum products: designated quantity 200 or 400 liters). In addition, considerations should be given for material deterioration and safety in the handling of materials in accordance with the handling manuals prepared by the material manufacturer.

7.4 Surface preparation

(1) Construction defects, remarkable deterioration and cracking in the surface of concrete shall be repaired appropriately.

(2) Embrittled sections and projections, level differences and other unevenness in the surface of concrete shall be removed through chipping or polishing to make the surface smooth.

(3) When continuous fiber sheets and continuous fiber strands are placed perpendicular to corner angles, the corner angles shall be rounded through chipping or polishing, or through the use of a smoothing agent.

[Commentary]

(1) To ensure that the continuous fiber sheet method and continuous fiber strand method satisfy performance requirements, the continuous fiber sheets and continuous fiber strands should be properly bonded or sealed to the surface of the concrete. For this reason, suitable methods should be used to prepare the surface of the concrete. Surface preparation includes scouring, **sectional repair**, smoothing and so on, and should ensure that the condition of the concrete surface is as required for upgrading of the structure.

If there are rock pockets, honeycombs or other construction defects on the concrete surface, or if there is remarkable deterioration or cracking, the defects impairs the required performance even if there are no problems with the continuous fiber sheets or continuous fiber strands. Imperfection of surface reduces the effect of upgrading with continuous fiber sheets or continuous fiber strands. Accordingly, before attaching continuous fiber sheets or jacketing with continuous fiber strands, suitable methods should be used to repair the existing concrete surface.

(2) (3) To ensure proper bond between the continuous fiber sheets or continuous fiber strands to the surface of concrete, deteriorated layers, oils and fats should be removed from the surface, and unevenness and projections that might hinder the bonding of the continuous fiber sheets or continuous fiber strands should be chipped away or removed with a smoothing agent.

Sharp projections, level differences, corner angles on the concrete surface are likely to reduce the strength of the continuous fiber sheets or continuous fiber strands by stress concentration. Accordingly, these projections and level differences should be cut away or smoothed using putty and mortar. Corner angles should be rounded by cutting them away or coating them with mortar. However, the strength reduction depends on the type of continuous fiber sheet or continuous fiber strand. Measures should be devised to match the type of continuous fiber sheets or continuous fiber strands.

7.5 Bonding and jacketing

Bonding and sealing or wrapping with continuous fiber sheets and continuous fiber strands shall be done so as to ensure the performance requirements for upgrading. To ensure the reliability of construction, the following items shall be checked at each stage of the work.

(1) The environmental conditions for the work is suitable.
(2) Surface preparation is suitably performed.
(3) Mixing and coating of primer are appropriately performed.
(4) Mixing and coating of smoothing agent are appropriately performed.
(5) When using continuous fiber sheets:
  a) The sheets are attached at the specified position in the specified direction, with the specified number of plies.
  b) The sheet is bonded or sealed securely to the concrete surface.
  c) The impregnation resin is suitably mixed and applied and has thoroughly impregnated the sheet.
  d) The impregnation resin is cured thoroughly.
(6) When using continuous fiber strands:
  a) The strand winding interval is appropriate.
  b) The strand winding tension is constant.
  c) The strand winding speed is appropriate and the strands are thoroughly impregnated with impregnation resin that has been suitably mixed and applied.
  d) The impregnation resin is cured thoroughly.

[Commentary]

(1) In general, epoxy resin is used as the primer, smoothing agent, and impregnation resin. Since the viscosity, work life, and setting time are affected by the atmospheric temperature at the site and the surface temperature of the concrete, the proper type should be selected to match the temperature during the work (summer, winter and spring/fall types are available). In the case of epoxy resins, the environmental conditions that match the construction are a temperature of 5°C or higher and humidity of no more than 85%.

When the atmospheric temperature and the surface temperature of the concrete at the site are low (less than 5°C), the construction site should be warmed or low-temperature primer and resin may be used. If the surface of the concrete is not dry, special primers for wet surfaces should be used.

(2) (3) (4) The level of smoothness matching the objective of upgrading should be confirmed for the prepared surface. In addition, the primer and smoothing agent should be mixed and agitated with the proper mix proportions. In general, the work life of epoxy resin depends on the mixing amount and temperature. Thus, the atmospheric temperature and concrete surface temperature should be carefully measured. The coat of primer and smoothing agent should be allowed to harden until it is firm to the touch, and should be checked visually and by touch to make sure there is no dust or moisture on the surface. If the primer and smoothing agent take a long time to harden causing a problem with bond to the surface, a countermeasure such as roughen the surface with sandpaper should be taken to increase its adhesion properties. To prevent improper hardening of the primer and smoothing agent, the materials should be applied to a dry surface. If there is condensation or other moisture on the surface before the initial hardening, causing whitening, that area should be wiped with solvent or removed with sandpaper.

(5) A working schedule diagram matching the actual structure should be prepared based on the design. The diagram should clearly identify the reference point for attachment, the overlap splice positions and the number of plies to enable the sheets to be attached properly. After the primer and smoothing agent have been applied, the guide should be placed in accordance with the diagram and the continuous fiber sheets attached carefully along the guide.

The work should ensure that reliable bond strength is attained when stress is transmitted by the bond between the continuous fiber sheets and concrete surface. However, when the design requirements do not specify the bond strength, the concrete surface may be treated with finishing mortar or paint.

The continuous fiber sheets should be impregnated with impregnation resin for fibers being bonded together - each of the fibers is bonded and the entire sheet receives external stress evenly up to the specified strength. For this reason, the impregnation resin should be made to thoroughly impregnate the sheet. Particularly in the overlap splice sections, the impregnation resin should thoroughly penetrate between the fibers and sheets to make them a unit.

After attaching the continuous fiber sheets, the inspection should be done visually or through sounding with regard to lift, swelling, peeling, slackness, wrinkles, and epoxy resin impregnation condition.

After the impregnation resin is applied, it should be cured for a suitable period of time before the next sheet is attached. Before the initial setting of the impregnation resin begins, the surface should also be covered with vinyl sheets to protect it from rain or dust and to prevent it from being affected by sudden climatic changes.

(6) When carbon fiber strands are wound by hand, the tension force applied to continuous fiber strands is not constant, resulting in variations of stress distribution in the continuous fiber strands after completion. Moreover, since the winding speed is not constant, there may also be variations in the degree of permeation of the impregnation resin. Problems may remain with respect to ensuring the tensile strength of the continuous fiber strands. For these reasons, the use of a machine to wind the continuous fiber strands, to control the winding interval, tension and speed is recommended.

7.6 Finishing work

Upgraded surfaces shall be finished appropriately to ensure that the performance requirements including weatherproofing, fire resistance, shock resistance, and appearance are satisfied.

[Commentary]

Performance requirements for finishing include the following:

(1) Resistance to direct sunlight
(2) Shock resistance

(3) Fire resistance (or noncombustability)
(4) Appearance
(5) Brightness
(6) Roughness

Finishing work includes painting work for durability and appearance; surface protection work such as noncombustible cover and fire-resistant cover. The excellent durability of continuous fiber sheets after application of impregnation resin has been confirmed through outdoor exposure tests and accelerated exposure test. However, depending on the type of fiber, durability may be impaired by use conditions. In such cases, the finishing should be planned after carefully considering the properties of the fiber. The impregnation resin surface deteriorates and whitens when exposed to ultraviolet light and ozone, and its appearance is easily marred. Accordingly, when an aesthetic appearance and illumination are required in the environments exposed to direct sunlight, it should be finished with protective paint.

Materials shown in Table C7.6.1 may be used for finishing work. Finishing work is generally performed after confirming that the initial setting of the impregnation resin is complete.

Table C7.6.1 Finishing Work

Finishing Work	Applicable Objective	Sample Specification
Painting	Measures to prevent exposure to ultraviolet light Surface protection	Resin coating
Surface protection	Measures to prevent exposure to ultraviolet light Surface protection Measures to prevent external damage and collision damage	Mortar spraying Composite paint film Mortar spraying Mortar coating
Noncombustible cover Fire-resistant cover	Noncombustible cover Fire-resistant cover	Mortar coating Attachment of fire-resistant panels

7.7 Inspections

7.7.1 General

(1) Necessary inspections shall be conducted for upgraded concrete structures at each stage of the work to ensure that they have the required performance.

(2) In general, the inspections needed at each stage of the work shall consist of receiving inspections for continuous fiber sheets or continuous fiber strands, primer, smoothing agent, impregnation resin and other materials; inspections of the storage condition of these materials; surface preparation inspections; and inspections of the bonding or jacketing condition of the continuous fiber sheets or continuous fiber strands after the work is completed.

(3) If the work is judged to fail the inspection, suitable corrective measures shall be taken.

[Commentary]

Even when continuous fiber sheets or continuous fiber strands are used, the importance of quality control, quality assurance and inspections is the same as when conventional materials are used.

Upgrading with continuous fiber sheets or continuous fiber strands is done by using impregnation resin to make the continuous fiber sheets or continuous fiber strands harden on the concrete surface, and to make the continuous fiber sheets and the existing concrete structure bond together to achieve the required upgrading performance. The upgrading performance should last for a long period of time after completion. Accordingly, the performance of the composite formed by the combination of these materials is of importance, and therefore materials whose physical properties, deterioration and other properties should be confirmed and whose quality should be assured through the tests of the composites.

7.7.2 Receiving inspection for materials

(1) Continuous fiber sheets or continuous fiber strands, primer, smoothing agent, impregnation resin and other materials shall be inspected at the time they are received to determine whether or not they are of the required quality.

(2) If the inspection finds that the quality is unsuitable, the material shall be changed or other appropriate measures taken.

[Commentary]

To confirm that each of the materials used for upgrading has the required quality, the material should be inspected at the time it is received and before work begins.

Inspection of materials should be done in accordance with the quality assurance sheet, test results or other documents issued by the manufacturer. However, if the materials have suffered significant damage during shipment, during long-term storage at the site, or due to errors during construction work, they should be tested to confirm the quality, even if they appear to be all right.

7.7.3 Inspection of material storage condition

(1) Material storage condition shall be inspected to ensure that materials are being stored appropriately.
(2) If the inspection finds that the storage condition is unsuitable, the method of storage shall be improved.

[Commentary]

In general, the materials should be stored indoors in a well-ventilated location away from direct sunlight, flame, humidity, and rain, and at appropriate temperature and humidity conditions to ensure that their quality is not adversely affected. Laws relating to storage should be strictly observed.

7.7.4 Inspection of surface preparation, primer coating and smoothing

(1) Surface preparation shall be inspected regarding the completeness of sectional restoration work, surface smoothness, processing of corner angles, primer coating and smoothing condition.
(2) If the inspection finds that the condition of surface preparation is unsuitable, measures to improve the situation shall be implemented.

[Commentary]

It should be confirmed by surface inspections that the objective of upgrading the concrete structure and the construction conditions at the site are maintained as shown in the upgrading design. The inspection items should include the completed condition of surface repair, surface smoothness and corner angle processing condition.

7.7.5 Inspection of continuous fiber sheets and continuous fiber strands during and after construction

(1) During and after construction, continuous fiber sheets shall be inspected for attached position, lifting, peeling, slackness, wrinkles, overlap splice length, number of plies, and quantity of impregnation resin coated.

(2) Bond strength test shall be conducted as needed for continuous fiber sheets bonded or used for jacketing, to check the bonding performance to concrete.

(3) Continuous fiber strands shall be inspected for winding position, winding interval, winding tension and winding speed to ensure that these values are appropriate, and that they are thoroughly impregnated with impregnation resin.

(4) If the inspection finds that the bonding or jacketing condition of continuous fiber sheets and continuous fiber strands is unsuitable, this situation shall be improved.

[Commentary]

(2) The performance of continuous fiber sheets during and after construction can be confirmed by the bond strength test. The tensile strength performance of continuous fiber sheets during construction is generally checked by means of existing test data obtained under similar construction environments and conditions. However, if the scale of construction is large or the construction conditions are severe, it would be best to conduct confirmation tests using test specimens fabricated at the site.

The same materials as those used at the site should be used for tests, and as a rule the test should be performed on the concrete at the site. However, if it is difficult to perform the test on the concrete at the site, the test may be performed on a slab specimen whose concrete properties have been identified.

(3) The performance of continuous fiber strands can be confirmed after construction by conducting a tensile strength test on a continuous fiber strand test specimen that has been bonded with impregnation resin. Accordingly, during construction, the quality can be checked by conducting inspections to make sure that the winding position, winding interval, winding tension and winding speed are appropriate and that the impregnation resin has impregnated the strands thoroughly. The tensile strength performance of the continuous fiber strands during construction is generally confirmed using existing test data. However, when necessary, it would be best to conduct confirmation tests using test specimens fabricated at the site.

CHAPTER 8 WORK RECORDS

Work records consisting of necessary data selected and compiled from construction procedures during the work process, work procedures, curing methods, weather and climate, quality control and inspections, inspections of structures shall be provided for long-term storage.

[Commentary]

In general, continuous fiber sheets and continuous fiber strands, as materials for reinforcing structures, have a higher corrosion resistance with respect to chloride ions than the conventional steel reinforcements. As a result, the durability of concrete structures upgraded with continuous fiber sheets and continuous fiber strands is also excellent. However, in the longer term, the continuous fiber sheets and continuous fiber strands are thought to exhibit complex behavior under a variety of environmental conditions, both by themselves and in combination with concrete. Consequently, work records should be kept and stored on a long-term basis to enable basic reference materials to be submitted for the maintenance of structures.

CHAPTER 9 MAINTENANCE OF UPGRADED CONCRETE STRUCTURES

9.1 General

(1) Concrete structures upgraded with continuous fiber sheets and continuous fiber strands shall be appropriately maintained throughout their service life to ensure that they continue to satisfy performance requirements.
(2) Upgraded concrete structures shall be maintained through a systematic combination of prediction of deterioration, inspections, evaluations and judgements, countermeasures and records.

[Commentary]

The maintenance of concrete structures upgraded with continuous fiber sheets and continuous fiber strands should be implemented in accordance with the Recommendations for Maintenance of Concrete Structures. For this reason, this chapter is prepared to complement the Recommendations for Maintenance of Concrete Structures, with additional knowledge acquired since 1995 when the Recommendations were issued.

(1) As a rule, concrete structures upgraded with continuous fiber sheets and continuous fiber strands should maintain performance requirement throughout their service life after upgrading.

(2) To achieve the objective stated in (1), maintenance should be conducted through a systematic combination of the items listed below.

1. Repairs to prevent anticipated deterioration:
   Anticipated deterioration at the time of upgrading design should be repaired during maintenance, and more accurate predictions of deterioration should be made.
2. Inspections:
   Inspections consist of initial, daily, periodic, detailed and extraordinary inspections. These should be based on the performance requirements of the owner and the predictions of deterioration of the performance.

3. Evaluations and judgements:

   There are two stages of evaluations and judgements: those based primarily on visual inspections, and those based on detailed inspections. In the visual inspections, a judgement is made as to whether detailed inspections are required or not. In the detailed inspections, the need for countermeasures is judged and the type of countermeasure is selected.
4. Countermeasures:

   These include stricter inspections, service restrictions, repair of continuous fiber sheets and continuous fiber strands, additional upgrading, improvement of appearance, dismantling and disposal.
5. Records:

   To implement suitable maintenance, the results of design, construction, inspection, evaluations and judgements, repair of continuous fiber sheets and continuous fiber strands, additional upgrading and so on are recorded and the records should be stored.

The ease of maintenance is affected by the upgrading plans, and by design and construction. More specifically, the placement of inspection routes, and monitoring equipment ensure the ease of maintenance. These increase the initial investment, but it can be expected to reduce maintenance costs during the service life of the structure and to increase the reliability of the structure. For this reason, it would be best to give thorough consideration to ease of maintenance in the upgrading plan, and in design and construction.

9.2 Inspections and evaluations

(1) Inspections shall be conducted visually or using appropriate inspection equipment, with consideration given to both performance requirements and the mechanism of deterioration.

(2) Based on the results of inspections, the performance requirements from the owner shall be evaluated; if the requirements are not satisfied, necessary countermeasures shall be taken.

[Commentary]

(1) (2) Deterioration of the concrete structures upgraded with continuous fiber sheets or continuous fiber strands consists of deterioration of the continuous fiber sheets or continuous fiber strands, deterioration of the resin, deterioration as a composite material (interfacial deterioration) and deterioration of bond to the concrete. The cause may be not only a single factor but a combination of factors. The visual features of this deterioration mechanism may include the following:

Swelling, peeling, lifting, softening, discoloration, whitening, choking, cracking, wearing, erosion, pinholes, scratches, deformation, and embrittlement,

The following changes in properties may also occur:

Changes in weight, changes in volume, changes in mechanical properties (hardness, bond strength to concrete, tensile strength, modulus of elasticity, elongation, etc.), changes in physical properties (electrical properties, thermal properties, optical properties, etc.)

Inspections may reveal the deterioration mechanism for each required performance element and, in order to obtain data on visual features and changes in properties, a combination of visual inspections and inspections using suitable inspection equipment should be conducted.

In concrete structures upgraded with continuous fiber sheets, the continuous fiber sheets can be expected to block or limit the intrusion of various external substances. Improved durability by attachment of the sheets can be anticipated with respect to the salt attack, carbonation, freezing resistance, alkali aggregate reaction, chemical attacks, fatigue and other deterioration for the existing concrete structure.

9.3 Countermeasures

Countermeasures shall be conducted to satisfy the level of performance requirements, based on the results of evaluation and judgement.

[Commentary]

Countermeasures include stricter inspections, service restrictions, repair of continuous fiber sheets and continuous fiber strands, additional upgrading, improvement of appearance, dismantling and disposal. They should be selected based on the results of evaluation and judgement.

For minor deterioration, countermeasures should consist primarily of stricter inspections and repair of continuous fiber sheets and continuous fiber strands. The method of countermeasures should be selected depending on the appeared features of the deterioration mechanism and the extent of changes of physical properties, but the following methods can be considered:

For swelling, peeling, lifting, etc.:	Resin fill
For cracking, wearing, erosion, etc.:	Patching

When serious deterioration or deterioration over a wide area is observed, primarily additional upgrading should be conducted. In such cases, as a rule, the existing continuous fiber sheets and continuous fiber strands should be removed and the upgrading plan examined again.

References

1) Wu, Zc and Niu, H.: Study on Debonding Failure Load of RC Beam Strengthened with FRP Sheet, Journal of Structural Engineering, JSCE, Vol.46A, 2000.4.

2) Ohno, T. and et a1.: Compressive Behavior of Concrete Confined by Wrapping of Carbon Fiber, Proceedings of the 47th JSCE Annual Conference, Part V, pp.736-737, 1992.9. (in Japanese)

3) Hosoya, M. and et a1.: Formulation of Stress-Strain Relationship of Concrete Confined by Carbon Fiber Sheet, Proceedings of the JSCE, No.592N-39, pp.37-52, 1998.5. (in Japanese)

4) Katsumata, H. and Kobatake, K: A Study on The Retrofit of RC Columns using Non-metalic Reinforcement (Part 3: Shear Capacity of RC Members Wrapped by Carbon Fiber Strand), Proceedings of the AlJ Annual Conference, pp.825～826, 1988.10. (in Japanese)

5) Ando, H. and et a1.: A Study on The Contribution of Carbon Fiber to The Strengthening of Shear Capacity, Proceedings of the 49th JSCE Annual Conference, V-467, pp.934～935, 1994.9. (in Japanese)

6) Okano, M. and et a1.: Shear Strengthening of Railway Viaduct Columns by Carbon Fiber Sheet, Proceedings of the JCl, Vo1.19, No.2, pp.249～254, 1997.10. (in Japanese)

7) Oda, M. and et al.: Shear Strengthening of RC Columns by Wrapping of Aramid Fiber Strand, Proceedings of the JCI, Vo1.15, No.2, 1993.10. (in Japanese)

8) Umezu, K and et al.: Shear Behavior of RC Beams with Aramid Fiber Sheet, Japan Concrete Institute, Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Vo1.1, pp.491-498, 1997. 10

9) Nakajima, N. and et a1.: Shear Behavior of Railway Viaduct Columns with Aramid Fiber Sheet, Proceedings of the JCI, vo1. 19, No.2, 1997.10. (in Japanese)

10) Kamiharako, A. and et a1/. A Study on the Evaluation of Shear Capacity of Concrete Members Strengthened by Continuous Fiber Sheets, Proceedings of the JSCE, No.648N-47, pp.217-226, 2000.5. (in Japanese)

ll) Mori, S. and et a1.: A Study on The Effectiveness of Retrofit of RC Slab with Carbon Fiber Sheet, Bridge and Foundation, pp25-32, 1995.3. (in Japanese)

12)Public Research Institute of Ministry of Construction: Technical Report of the Collaboration Research Work on Repair and Strengthening of Concrete Members - Part 1: A Study on The Effectiveness of Retrofit of Concrete Members by Attaching of Carbon Fiber Sheet, No.220, 1999.3. (in Japanese)

13) Public Research Institute of Ministry of Construction: Technical Report of the Collaboration Research Work on Repair and Strengthening of Concrete Members - Part 3: A Study on The Effectiveness of Retrofit of Concrete Members by Attaching of Carbon Fiber Sheet, No.235, 19993. (in Japanese)

14) Railway Technical Research Institute (RTRI): Design/Construction Guidelines on the Seismic Retrofitting of Railway Viaduct Columns using Carbon Fiber Sheet, 1996. (in Japanese).

15) Railway Technical Research Institute (RTRI): Design/Construction Guidelines on the Seismic Retrofitting of Railway Viaduct Columns using Aramid Fiber Sheet, 1996. (in Japanese).

16) Research Institute on Strengthening of Concrete Structures by Aramid Fibers: Design/Construction Guidelines on the Retrofit of RC Piers using Aramid Fiber Sheet, 1997.8. (in Japanese).

17) Masukawa, J. and et al... Seismic Retrofit of RC Piers Using Carbon Fiber and Aramid Fiber Sheets, Proceedings of the Symposium on Utilization of Non-Metallic Materials for Concrete Structures, pp.193-198. 1996.ll. (in Japanese)

18) Osada, K. and et al.: Seismic Retrofit of RC Piers Using Carbon Fiber, Concrete Research and Technology, JCI, pp.189-203, 1997.1. (in Japanese)

19) Hakamada, F.: Experimental and Analytical Study on Seismic Retrofit of RC Wall Type Piers and Seismic Retrofit of RC Structures Using Carbon Fiber Reinforcing Polymers, Proceedings of the Symposium on Seismic Resistant Technology of Concrete Structures, 1997.4. (in Japanese)

20) Ohno, S. and et al.: Experimental Study on Seismic Retrofit of RC Piers Using Carbon Fiber, Proceedings of the 51th JSCE Anual Conference, Part V, pp.950-951, 1996.9. (in Japanese)

21) Architectural Institute of Japan: Data Book on Ultimate Strength Design of Reinforced Concrete Structures - Part 8: Variation of Quality of Steel Reinforcing Bars, pp.34-36, 1987.9. (in Japanese)

22) Machida, A. and et a1.: Seismic Retrofitting of Reinforced Concrete Bridge Piers By Wrapping of Aramid Fiber Sheet, Developments in Short and Medium Span Bridge Engineering '98.