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