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.

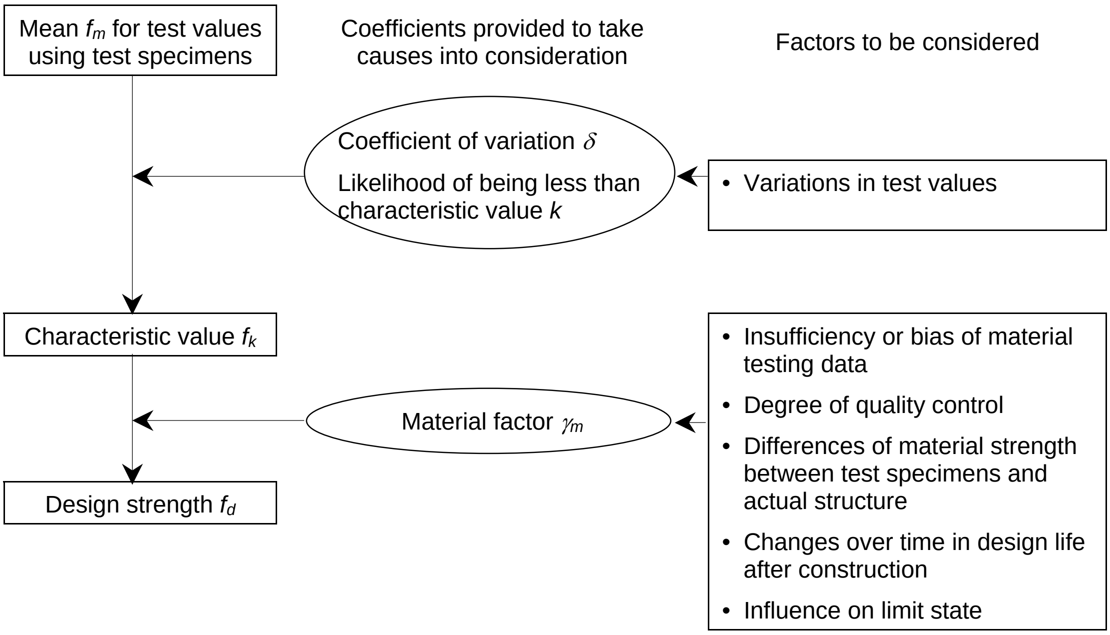
6.2 Design strength of materials in existing structures

6.2.1 General

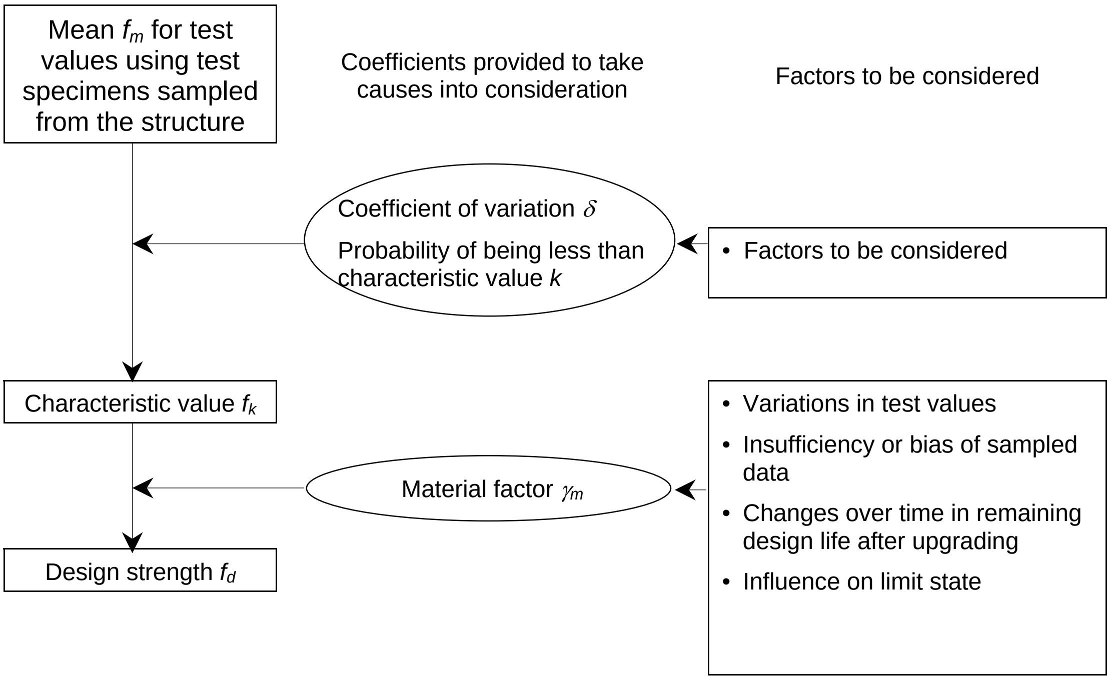
As a rule, the design strength of the materials used in the existing structure shall be determined through the test of the specimens sampled from the structure. When testing is not possible, the determination may be made based on the characteristic values used in the original design.

[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 $\beta_n > 2$

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

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

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.

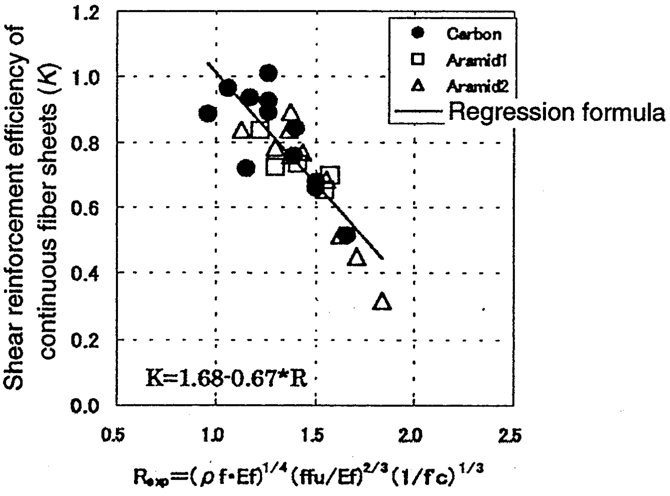


Figure C6.4.1 Relationship between coefficients R and K (experimental equation)

(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).

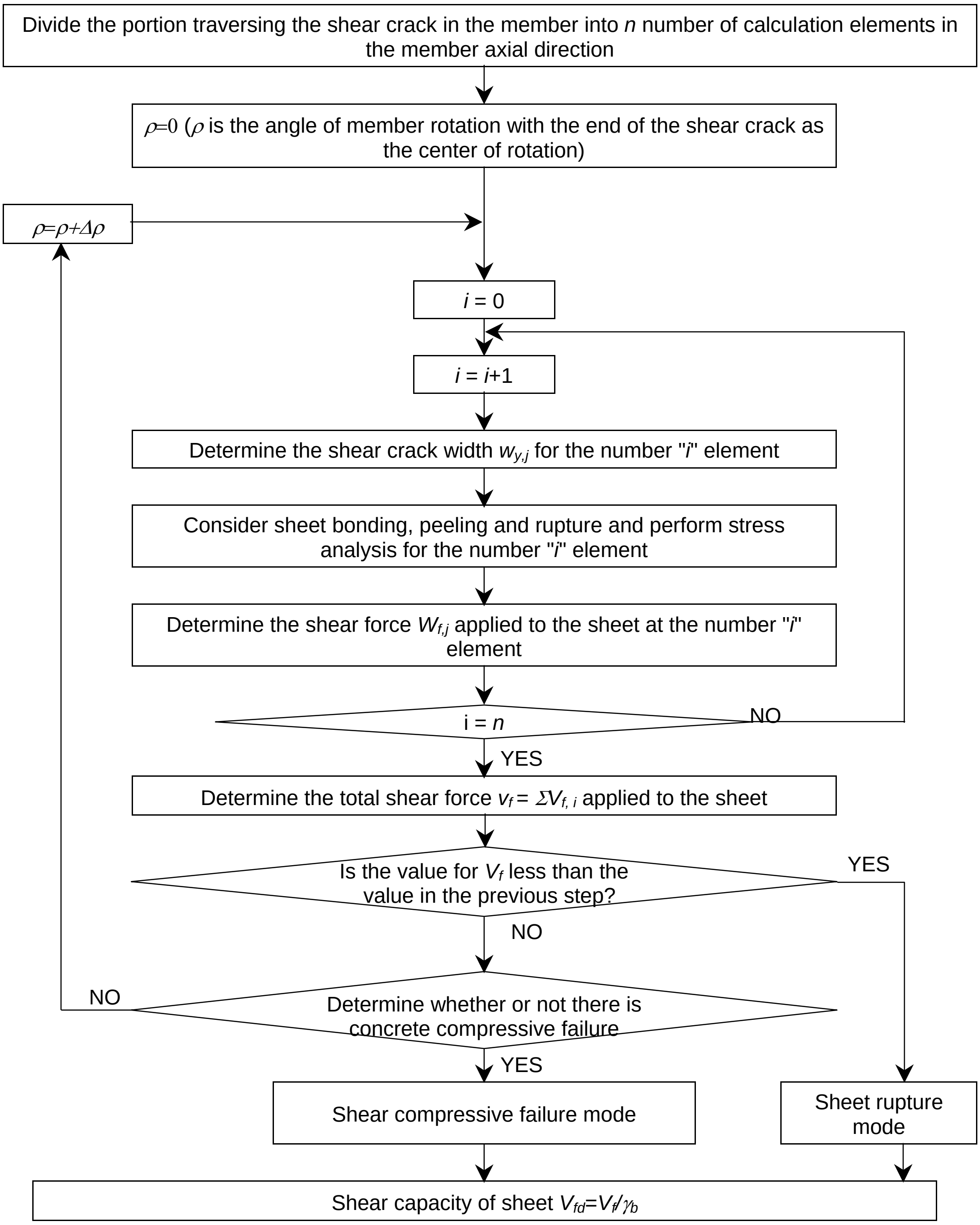


Figure C6.4.2 Flow of calculating shear capacity based on the bond constitutive law for continuous fiber sheets

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:

$$w_{y,i} = \rho L_{x,i} \tag{C6.4.1}$$

where:

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

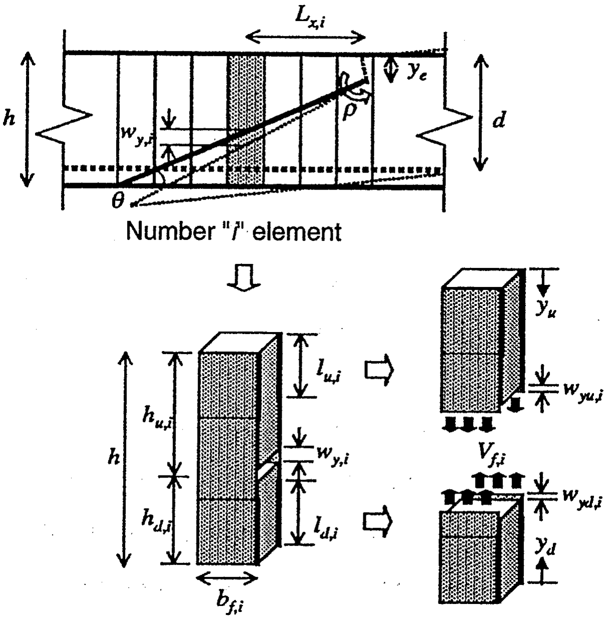


Figure C6.4.3 Concept for calculating shear capacity based on the bond constitutive law for continuous fiber sheets

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:

$$h_{u,i} = y_e + L_{x,i} \tan\theta \quad \text{(C6.4.2)}$$

$$h_{d,i} = h - h_{u,i} \quad \text{(C6.4.3)}$$

Stress analysis for each element

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

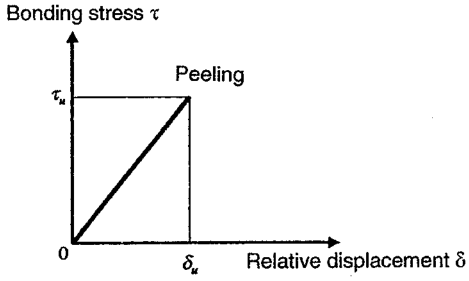


Figure C6.4.4 Bond constitutive law for sheet and concrete

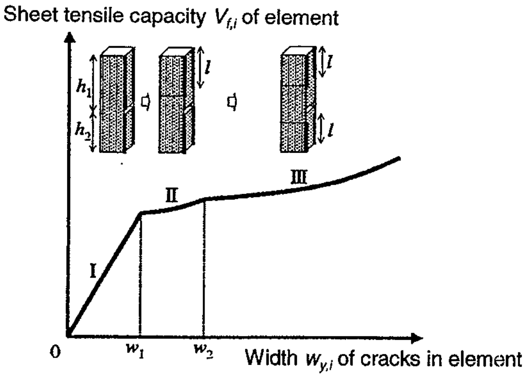


Figure C6.4.5 Relationship between element crack width $w_{y,i}$ and tensile strength $V_{f,I}$

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.

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

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

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

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

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

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 $\varepsilon_b' = 0.0025$. The value for V_f is the ultimate shear force of the sheet when compression failure of concrete occurs (Figure C6.4.6).

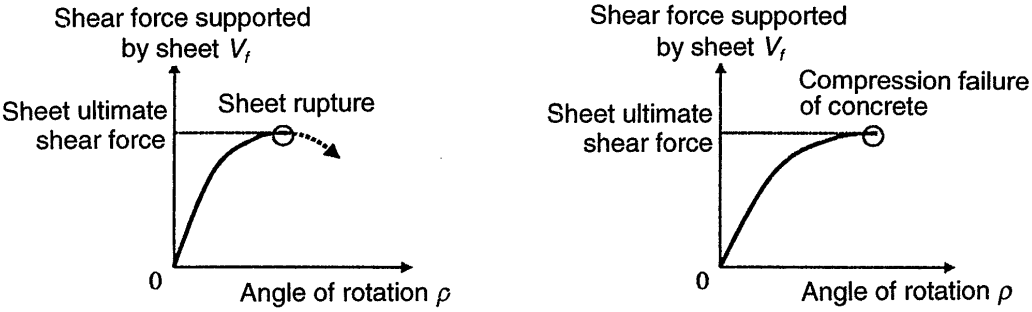


Figure C6.4.6 Determination of failure mode and shear capacity

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.

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

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.

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

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$^{14)\text{-}20)}$ 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

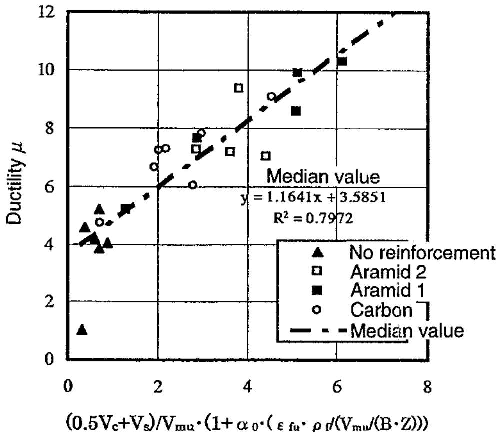
$\left(0.5 \cdot V_c + V_s\right)/V_{mu} \cdot \left\{1 + \alpha_0 \cdot \varepsilon_{fu} \cdot \rho_f / V_{mu} / \left(B \cdot z\right)\right\}$. The results are shown in Figure C6.4.7. The values for shear capacity of each test specimen and the maximum shear force when the member reaches the existing 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 $\left(0.5 \cdot V_c + V_s\right)/V_{mu} \cdot \left\{1 + \alpha_0 \cdot \varepsilon_{fu} \cdot \rho_f / V_{mu} / \left(B \cdot z\right)\right\}$, 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.



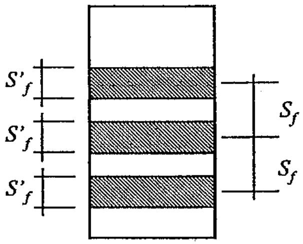


Figure C6.4.7 Ductility ratio of members upgraded with continuous fiber sheets

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)]

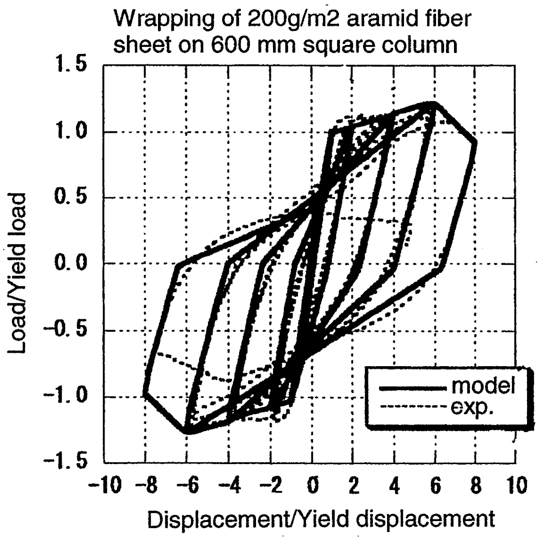


Figure C6.4.9 Sample restoration force model

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.

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

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 $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\xi^2} d\xi$.

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.

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

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.