

Chapter 3 Design Values of Materials

3.1 General

(1) This chapter provides general guidelines on the material characteristics of the UFC, particularly required for design activities. The material characteristics of reinforcing steel and prestressing tendons shall be considered and decided in accordance with the “Standard Specifications — Examination of Structural Performance: Chapter 3 Design Values of Materials.”

(2) The quality of the UFC is expressed in many ways. Compression strength and tensile strength are mostly used for the examination of structure performances. However, Young’s modulus, deformation, heat, durability, water tightness, and other pertinent characteristics must be evaluated on an as-needed basis. In evaluating strength and deformation, effects of fiber reinforcement shall be considered. As required, the effects by rate of loading shall be considered as well.

(3) The characteristic value of material strength (f_k) shall be set in a way to ensure that most of the test values, assuming there are some data dispersion, will not fall below the set value.

(4) The design material strength (f_d) is defined as the value of characteristic value of material strength (f_k) divided by a material factor (γ_m).

[Comments]

(1) The structures made with UFC and conventional concrete use the types of reinforcing bar and prestressing tendons. As there is nothing particularly different about this point, the recommendations do not provide any specifications about reinforcing steel. However, material characteristics of steel reinforcement shall comply with “Standard Specifications — Examination of Structural Performance: Chapter 3 Design Values of Materials.”

(2) Properties of UFC vary depending on the materials used, curing method employed, etc. In addition, containing fiber reinforcement has significant effects on the compressive strength and the tension softening area in the stress-strain curve. Therefore, when fabricating members or constructing a structure using UFC, special care should be paid to choose the proper materials. Consider the purpose of use, environmental conditions, design life, and construction conditions, etc., when choosing the materials.

The values of material characteristics shown in this chapter are permitted for use in the evaluation of limit states against an imposed load both static and dynamic. Use data obtained by reliable tests, when the very high rate of strain such as impact-loading, has to be accounted for.

3.2 Strength

3.2.1 Characteristic Values

- (1) Characteristic values on the strength of the UFC shall be determined at the proper age of the material after completion of heat curing.
- (2) If heat curing is not employed, characteristic values on the strength of the UFC may be determined considering the usage purpose of a structure, the timing when the main load is applied, the construction plan, etc., with test results obtained at proper age of the materials.
- (3) Material factor of the tensile strength shall be determined taking into account the orientation of the reinforcing fibers.
- (4) In general, the material factor (γ_c) of the UFC can be set to 1.3 to evaluate ULS, and 1.0 to evaluate SLS.

[Comments]

(1) Heat curing considerably accelerates strength in the UFC. As the hardened state of the UFC is stable, the difference in age has minimal effect on the strength.

Figure C3.2.1 shows the compression strength after the curing of UFC, which is made with the standard mixed ingredients with steel fiber content of 2% by volume (tensile strength: 2700 N/mm², 15 mm in length and 0.2 mm in diameter). As it shows clearly, the compression strength keeps approximately the same value regardless of the age. Therefore, the characteristic value of the material strength can be decided at a proper time after the curing, if such decision is based on test results.

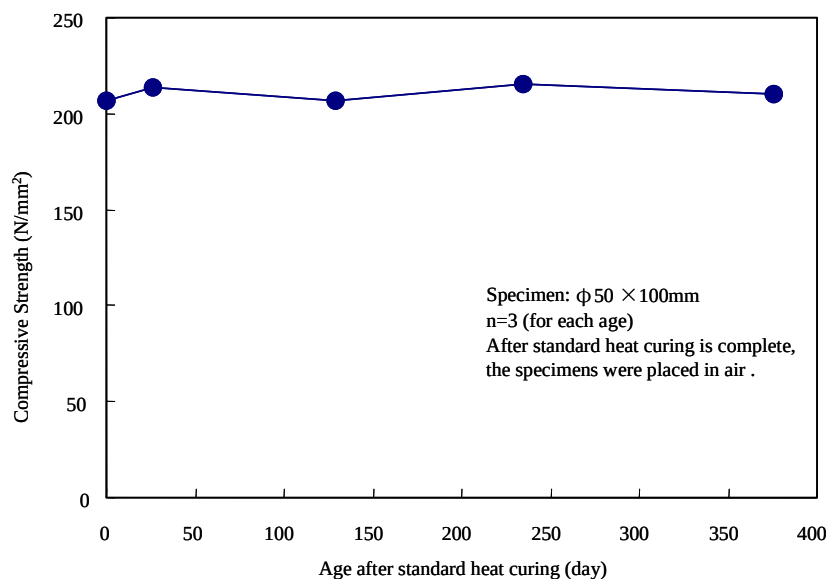


Figure C3.2.1 Long-term strength test results of UFC by age after heat curing

(2) Even without heat curing, the UFC increases the strength over time in the same way as conventional concrete does so far as it undergoes proper curing. Therefore, it was decided that the characteristic values of the material strength could be determined according to the purpose of use, timing when the primary load is applied, the construction plan, etc., and test results obtained at the proper age of the UFC.

(3) (4) The “Standard Specifications” and the “Reference Documents for Revision of Standard Specifications ” require that following points be considered to set material factors.

- Variation of data going in undesirable directions (disparity and shortage of test data, etc.).
- Differences in material characteristics between test specimens and the concrete in the actual structure
- Influence of material characteristics on limit states
- Aging of materials, etc
- Differences between test specimens and the concrete in the actual structure from construction procedures
- Effects from aging of materials and continuous loading

These documents also define the coefficient k_1 , which signifies that the compressive strength of a structure is smaller than that of a test specimen. The documents further stipulate that the coefficient k_1 shall only be used for the calculation of the ultimate strength of a concrete member, which is subjected to flexural and axial forces. If above points are applied to UFC, the differences between specimens and the concrete in the actual structure arising out of construction processes can be considered as follows.

- Members made with UFC will have less thickness than those of conventional concrete. Therefore, although non-uniform internal heat will be generated by hydration reactions, this non-uniformity of heat will have smaller effects on the strength of the members than conventional concrete.
- Members made with UFC will be processed with a prescribed heat curing. Therefore, non-uniform internal heat caused by environmental conditions (location, curing methods, outdoor temperatures, etc.) immediately before and after casting will have smaller effects on the strength of the members than conventional concrete.
- In addition to the self-compacting capability, the concrete's internal matrix is highly uniform due to a limited range of particle sizes allowed for blending. Therefore, defects like pores are unlikely to occur.

Furthermore, by undergoing a prescribed heat curing, there will be a significant decrease in shrinkage and creep, while there is a substantial increase in durability. Therefore, compared to

conventional concrete, the UFC would be less vulnerable to time-dependent changes and sustained loading. Considering the above, there seem to be several factors that may make the value of the material factor (γ_c) of the UFC smaller than that of conventional concrete. However, there are not sufficient data that quantitatively support this theory. With not enough data available, the recommendations decided that the material factor (γ_c) of the UFC should be left as 1.3. If quantitative evaluations are conducted in future, this material factor (γ_c) may be revised.

With respect to the differences between specimens and the actual structure, there is one type of difference not considered in conventional concrete but important in UFC; that is, the orientation of fibers. For example, the SETRA/AFGC Guidelines of France, which specify the same sort of ultra high strength fiber reinforced concrete, defined the orientation factor (K_f) with which one can consider the difference in fiber orientation between test specimens and the actual structure in service. (More specifically, it is a ratio of tensile strength that can be obtained by comparing two test samples: one taken from a test specimen prepared for quality control, and the other taken from the concrete inside the structure during service.) The SETRA/AFGC Guidelines require that a value obtained by dividing the tensile strength of a test specimen by the coefficient (K_f) be accounted for in the design of fiber reinforcement. It is also a recommendation of the SETRA/AFGC Guidelines that the coefficient (K_f) be defined either by using the actual concrete samples or by models and simulation tests to actually use the value in a construction project. If tests are not practical and need to be abridged, the SETRA/AFGC Guidelines recommend using $K_f = 1.25$ (for usual axial, flexural, and shear forces) and $K_f = 1.75$ (for loading on limited areas). In the process to evaluate the material factor, it is remarkably important to consider the effect of this orientation factor appropriately.

In designing a structure using UFC (made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed), setting the material factor $\gamma_c = 1.3$ is sufficient enough to secure the safety of the structure. However, in actual practice to implement the value on the construction site, the material factor (γ_c) may be determined through a variety of tests using either actual concrete or models, and a close study of the orientation factor.

3.2.2 Compressive Strength

The characteristic value (f_{ck}) that signifies the compressive strength of the UFC shall be determined by appropriate tests.

[Comments]

The compression tests of UFC shall be performed in accordance with the JIS A 1108 “Method of

Test for Strength of Concrete” to which test methods on plain concrete have been applied. To determine the characteristic value, it is desirable to use 100 mm diameter cylindrical specimens.

Figure C3.2.2 is the frequency distribution of compression test results, performed by using 100 mm diameter cylinders of UFC (made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed). The test results show the average compressive strength was 194 N/mm² with a standard deviation of 7.7 N/mm². Assuming a normal distribution, the value that makes the risk rate 5% is 181.4 N/mm². Considering a margin of safety, the characteristic value should be set to 180 N/mm².

Using 100 mm diameter cylinders is not mandatory, but the minimum diameter size is 50 mm. If using cylinders whose diameter is less than 100 mm, it is desirable to calculate the ratio to 100 mm and convert the test results corresponding to the 100 mm diameter cylinders.

Figure C3.2.3 shows the test results of cylinders with two different sizes. According to the diagram, the compressive strength of 50 mm diameter cylinders and 100 mm diameter cylinders are almost identical.

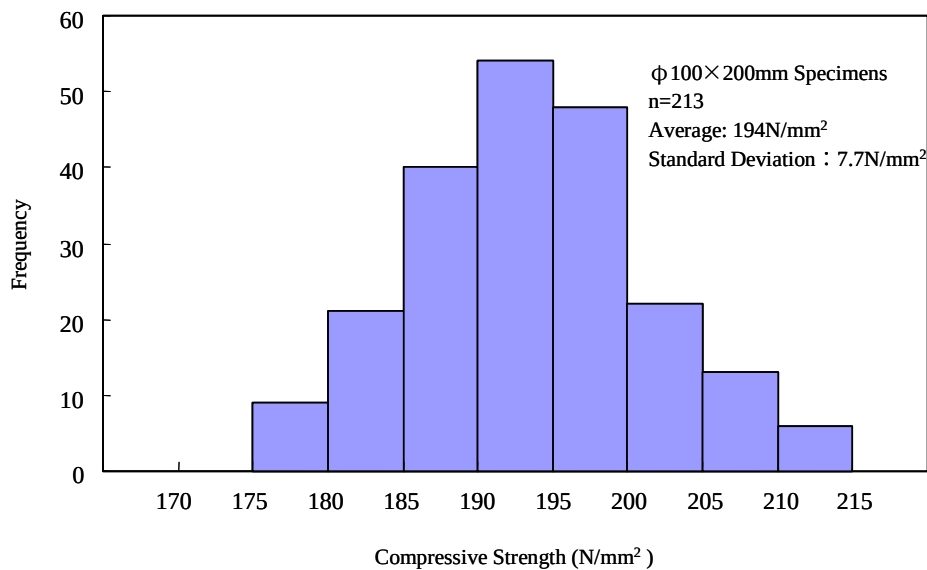


Figure C3.2.2 Frequency distribution of compression test results using ϕ 100 mm cylinders

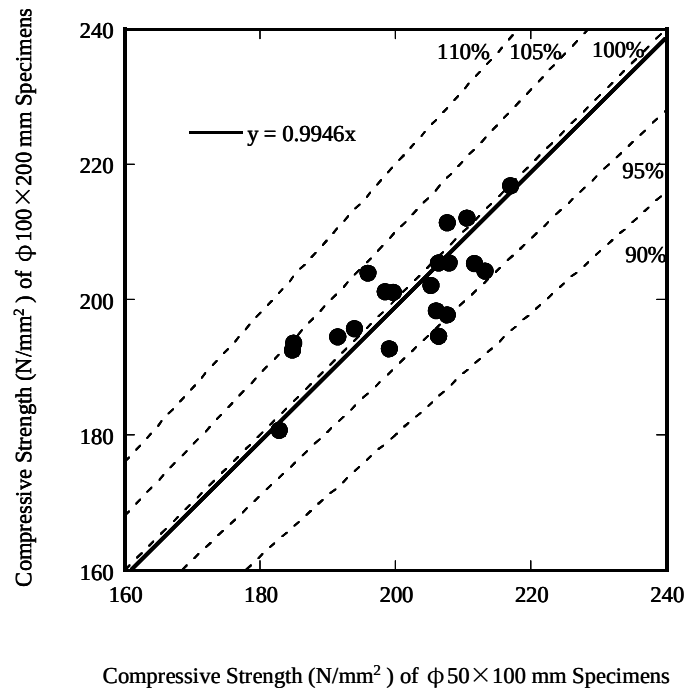


Figure C3.2.3 Comparison of compressive strength using specimens of different diameter sizes

3.2.3 First Cracking Strength

The characteristic value (f_{crk}) that signifies the first cracking strength of the UFC shall be determined by appropriate tests.

[Comments]

The UFC, which is subjected to a continually increasing uniaxial tension, initially plots out a straight line in the stress-strain curve. The straight line is where assumption of liner elasticity is applicable. However, the increasing force will cause a crack in the UFC at a point on the line, the point of elastic limit where assumption of liner elasticity is no longer applicable.

The recommendations define the first cracking strength as a stress level in the UFC associated with a point in the stress-strain curve where the assumption of liner elasticity is no longer applicable, as well as the tensile strength, which is the maximum stress developed in the UFC after the first crack has formed. The recommendations distinguish one from the other.

To obtain the first cracking strength, there are direct tensile tests, splitting-cylinder tensile tests, and flexural tensile tests. These tests have advantages and disadvantages. To obtain the first cracking strength, assuming what sort of tensile stress will be generated in the structure, a test most suitable for the situation should be chosen to make the most of the advantage. While the direct tensile test is the most versatile and generally used, special care is necessary as its

procedures are not standardized.

The splitting-cylinder test is desirable to be performed in accordance with the JIS A 1113 “Method of Test for Splitting Tensile Strength of Concrete,” to which tests for plain concrete have been applied with necessary updates and modifications. There is one thing to note, however. As shown in **Figure C3.2.4**, the specimen should be attached with strain gauges on the surfaces of both ends, perpendicular to the direction of the force, in order to continually observe the load and strain relationship. This arrangement can identify exactly when the first crack has occurred by tracking the discontinuity in data readout. The splitting-cylinder test using 100 mm diameter cylinders is a preferable method for determination of the characteristic value of the first cracking strength.

Figure C3.2.5 shows the frequency distribution of splitting-cylinder test results, performed by using 100 mm diameter cylinders of UFC (made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed).

The test results show the averaged splitting tensile strength was 11.7 N/mm² with a standard deviation of 1.3 N/mm². Assuming a normal distribution, the value that makes the risk rate 5% is 9.56 N/mm². Considering a margin of safety, the characteristic value should be set to 8.0 N/mm². The example of strain data is shown in **Figure C3.2.6**, measured in splitting-cylinder tests.

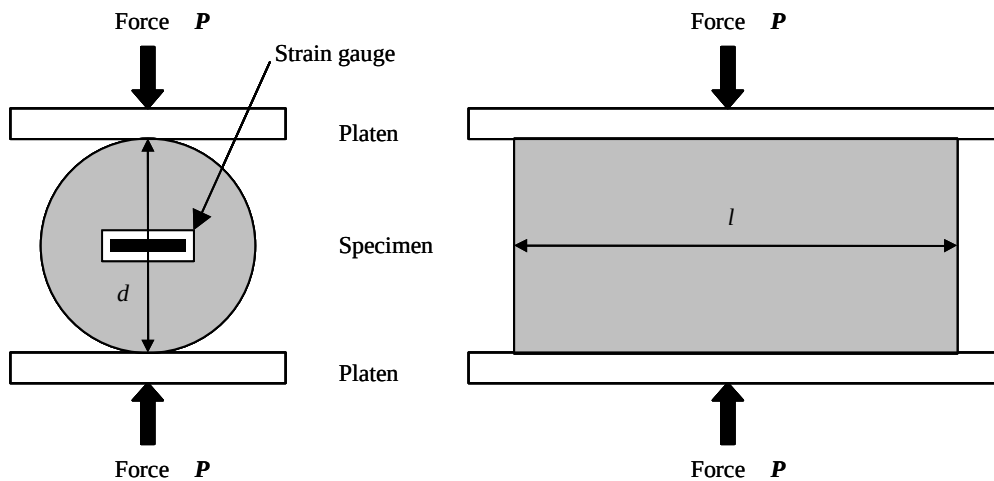


Figure C3.2.4 Example of splitting-cylinder tests using UFC

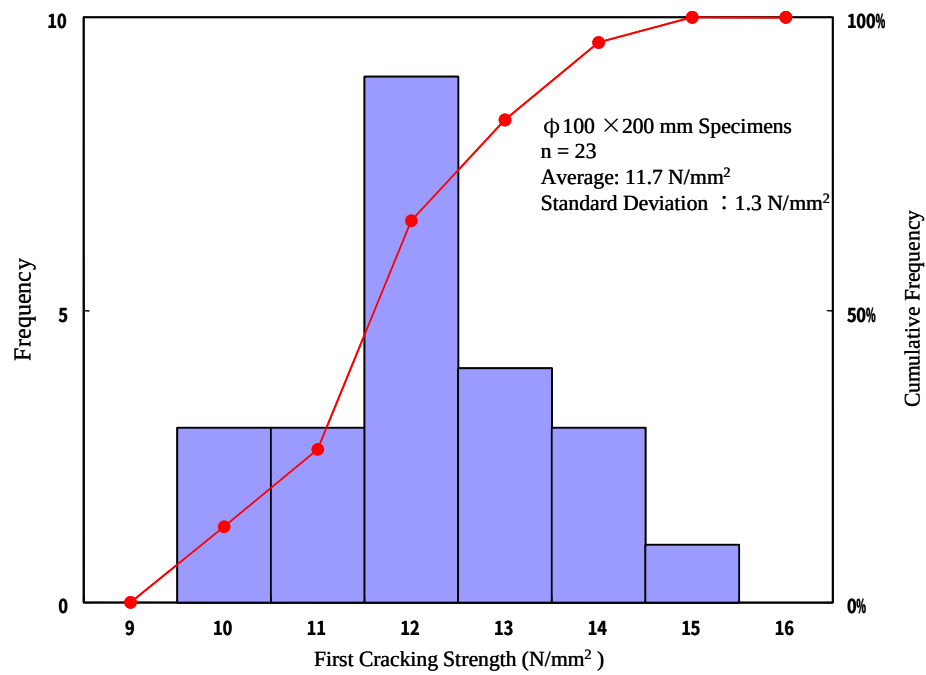


Figure C3.2.5 Frequency distribution of first cracking strength in splitting-cylinder tests using 100 mm diameter cylinders

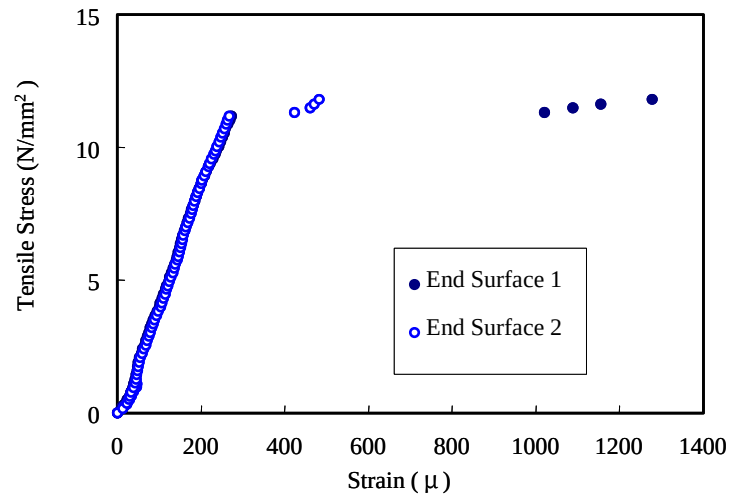


Figure C3.2.6 Example of strain measurements in splitting-cylinder

3.2.4 Tensile Strength and Tension Softening Characteristics

- (1) The characteristic value (f_{tk}) that signifies the tensile strength of the UFC and tension softening characteristics of the UFC shall be determined by appropriate tests.
- (2) For the tension-softening curve, the following idealized diagram shown in **Figure 3.2.1** can be used.

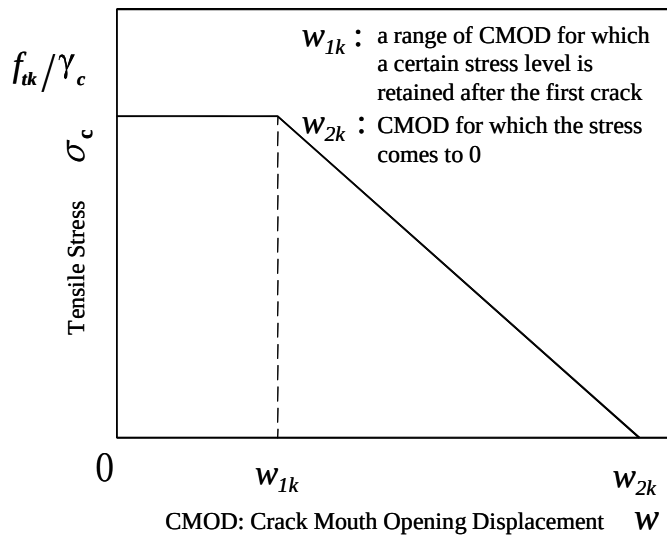


Figure 3.2.1 TSD: Tension Softening Diagram

[Comments]

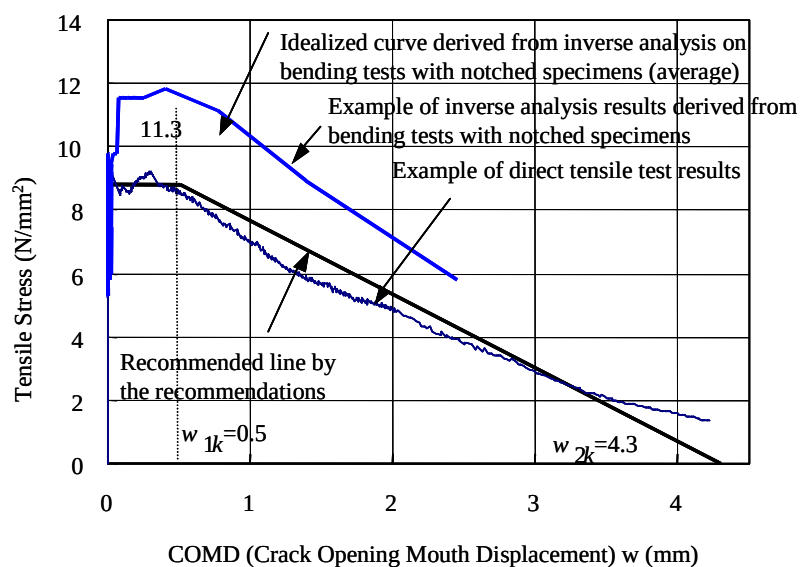
(1) The recommendations defined the first cracking strength as a stress level in the UFC associated with a point in the stress-strain curve where the assumption of linear elasticity is no longer applicable, as well as the tensile strength, which is the maximum stress developed in the UFC after the first crack has formed. The recommendations distinguish one from the other. After the crack has formed and the crack width increases, the tensile stress transferring at crack dissipates until finally a complete crack is formed in the material. The tension softening diagram (TSD) indicates this relationship of stress transfer and the crack width.

The direct tensile test would be essentially the best way to obtain the tensile strength and tension softening characteristics. There are other ways, however, available to use and effective as well. One would be the inverse analysis that is applied to flexural test results and the other is the J integration method. Each test and analysis has its own advantages and disadvantages. It is necessary to consider which one would be better suited in the actual situation. For flexural tests, there are standard test procedures such as JIS A 1106 “Method of Test for Flexural Strength of Concrete,” JSCE-G552 “Test Method for Bending Strength and Bending Toughness of Steel Fiber Reinforced Concrete,” and JCI-S-002-2003 “Method of Test for Load-Displacement Curve of Fiber

Reinforced Concrete by Use of Notched Beam.” A test method recommended by RILEM (*2) is also available.

(2) This model exhibits the direct tensile test results and the inverse analysis applied to the results of flexural strength tests both conducted with notched specimens made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed. This model, when created, also took into account the consistency with the TSD model so far used for conventional fiber reinforced concrete.

Figure C3.2.7 shows the relationships between flexural strength tests conducted using notched specimens and the TSD model. According to the inverse analysis that was applied to the flexural strength test results, there are three portions in the TSD: the portion where the stress drops immediately after the occurrence of a crack, the portion where the stress is restored by the bridging effect of steel fibers, and the portion where the stress slowly reduces to zero as the crack opening increases. Direct tensile tests do not provide precise test results without difficulties under stable conditions. However, the tension softening characteristics obtained by the direct tensile tests show almost the same tendencies with the results of inverse analysis conducted on flexural strength test results. Based on the above conditions, and considering the conformity with other test results, and for ease of use in actual situations, the recommendations decided as follows; it should be the basic assumption that the TSD model is composed of two parts. One is the stress sustaining portion, which ranges from the point the first crack, has formed to the point the stress begins to diminish, and the other is the portion where the stress decreases in a straight line.



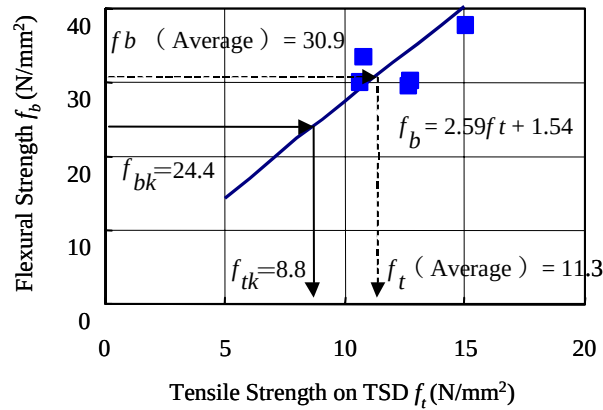
Figures C3.2.7 Calculation of TSD (Tension Softening Diagram)

Table C3.2.1 and **Figure C3.2.8** show the values derived from inverse analysis applied to the results of three-point bending tests using notched and un-notched specimens of 100 mm × 100 mm × 400 mm. **Figure C3.2.9** shows the results of three-point bending tests that used un-notched specimens made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed. With those test results, the characteristic values, $f_{tk} = 8.8$ N/mm², $w_{1k} = 0.5$ mm, and $w_{2k} = 4.3$ mm may be used for the tensile strength of the UFC. In these tests, average values obtained from material tests were used for the setting of w_{1k} and w_{2k} as they are for the simplification of TSD model. The characteristic value of flexural strength obtained from the three-point bending tests was $f_{bk} = 24.4$ N/mm² for specimens of 100 mm x 100 mm x 400 mm, and $f_{bk} = 28.9$ N/mm² for specimens of 40 mm x 40 mm x 160 mm.

Table C3.2.1 Inverse analysis on TSD

Test Cases	f_t :Tensile Strength (plateau) (N/mm ²)	w_1 :End of plateau (mm)	w_2 : Zero Stress Point (mm)	Average Tensile Strength (N/mm ²)	Flexural Sterength (Note) (N/mm ²)
1-1	14.3	0.69	4.0	15.0	38
1-2	15.4	0.47	5.3		
1-3	15.3	0.41	4.4		
2-1	12.6	0.31	3.5	12.6	29.8
2-2	11.4	0.57	4.1		
2-3	13.9	0.41	4.4		
3-1	11.5	0.46	4.5	10.6	30.2
3-2	10.9	0.40	4.7		
3-3	9.5	0.73	5.3		
4-1	11.2	0.56	3.0	10.7	33.6
4-2	11.5	0.52	4.3		
4-3	9.3	0.63	4.6		
5-1	12.5	0.56	4.3	12.7	30.5
5-2	14.1	0.47	4.1		
5-3	11.5	0.54	4.0		
Average value		0.5	4.3		

(Note: The values were derived from three-point bending tests using un-notched specimens, measuring 100 mm x 100 mm x 400 mm and blended in the same batch.)



■ : The flexural strength f_b and tensile strength f_t were derived from three-point bending tests using notched and un-notched specimens. The tensile strength f_t was attained by inverse analysis.

— : The flexural strength f_b and tensile strength f_t were derived from three-point bending tests using un-notched specimens. The relationship of f_b and f_t was attained by FEM analysis.

(Note: Specimens used in tests were 100 mm x 100 mm x 400 mm in size and those blended in the same batch.)

Figure C3.2.8 Relationship between flexural strength and tensile strength

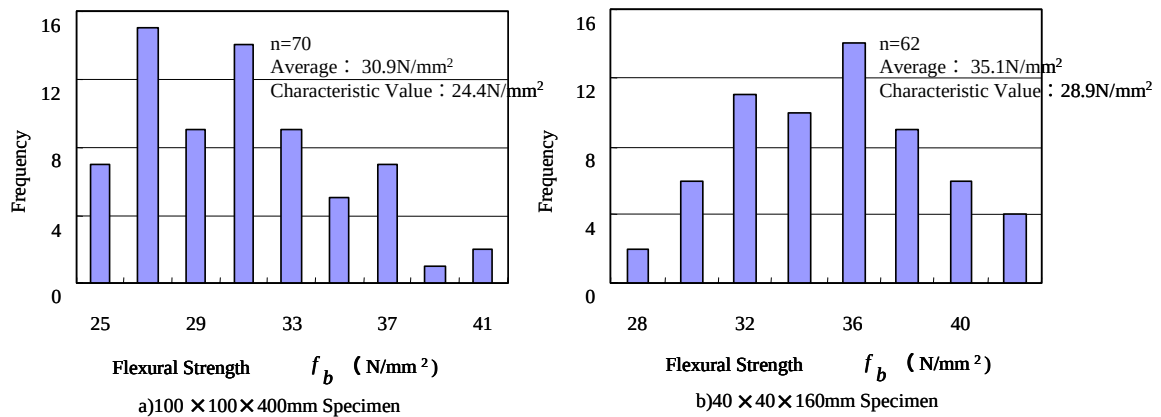


Figure C3.2.9 Flexural strength by 3-point bending tests using un-notched specimens

3.2.5 Other Types of Strength

The characteristic values of bond strength and bearing strength of the UFC shall be determined by appropriate tests.

[Comments]

The UFC demonstrates a strong bond with reinforcing bars and wires. This means, in pretensioning, the bond-development length for tendons and reinforcing steel used at joints

becomes shorter by using the UFC. Adding to this benefit, anchorage devices for tendons in post-tensioning get small. However, because of insufficient test data available so far, it is the requirement of the recommendations that the characteristic values of bond strength and bearing strength shall be determined by appropriate tests.

3.3 Stress – Strain Curve

3.3.1 Compressive Stress-Strain Curve

(1) The compressive stress-strain curve of the UFC shall take a proper form to meet the need of evaluating each limit state.

(2) The following idealized compressive stress-strain curve (**Figure 3.3.1**) may generally be used for the evaluation of ULS involved with sectional failures that may happen on a member subjected to flexural moment and/or axial compressive force. In this evaluation, Young's modulus (E_c) shall be determined in accordance with Section 3.4.

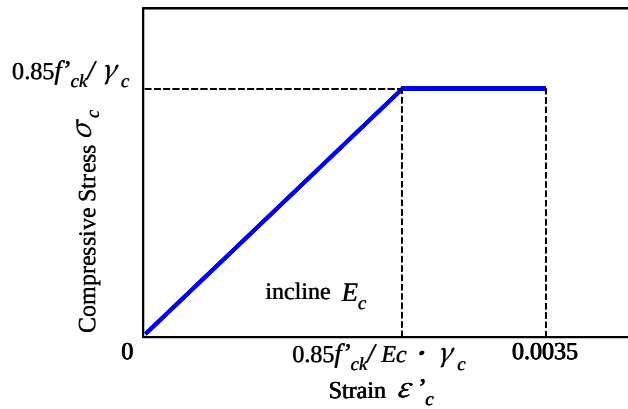


Figure 3.3.1 Compressive stress – strain curve of UFC

(3) To evaluate SLS, the compressive stress-strain diagram may be regarded as linear. Young's modulus in this evaluation may be determined in accordance with Section 3.4.

(4) To evaluate ULS, if the UFC member is subjected to biaxial or triaxial forces, effects of multi-axial forces on the compressive stress-strain curve shall be considered as required. To evaluate SLS, the UFC member may be regarded as an elastic body. In this evaluation, Young's modulus and Poisson's ratio may be determined in accordance with the description stated in Section 3.4 and Section 3.5, respectively.

(2) In generally, UFC had significantly improved ductility in the post-peak area of compressive strength, due to the fiber reinforcement. **Figure C3.3.1** shows an example of compressive stress-strain diagram of UFC using 50 mm diameter test cylinders.

Ductility in the post-peak area of the compressive strength is greatly affected by type, shape, content ratio, and other properties of fiber reinforcement. Therefore, in order to evaluate deformation, toughness or other conditions of linear members from the initial load to the ultimate state, the post-peak portion of the stress-strain curve must be set properly based on the actual behavior of the material.

To evaluate ULS accompanied with sectional failures, the curve shown in **Figure 3.3.1** may be used. The recommendations require that the characteristic value of compressive strength (f'_{ck}) be multiplied by the factor of 0.85, considering the difference of strength between test specimens and UFC members.

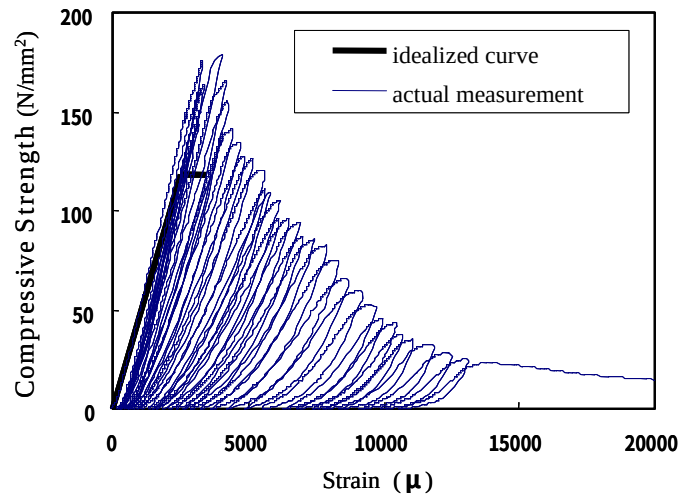


Figure C3.3.1 Example of compressive stress - strain diagram using 50mm-diameter cylinder specimens

(3) It was observed in various tests that the compressive stress-strain curve of the UFC was almost linear up until compressive strength. Therefore, the recommendations stipulate that the UFC may be regarded as an elastic body in the evaluation of SLS.

(4) The compressive stress-strain curve of the UFC shown in the **Figure 3.3.1** is based on the assumption that the acting force is uniaxial. If the acting force is biaxial or triaxial, the curve in **Figure 3.3.1** would be different. Therefore, the effects of multi-directional forces should be considered in the evaluation of ULS as required.

3.3.2 Tensile Stress-Strain Curve

- (1) The tensile stress-strain curve of the UFC shall take the proper shape to meet the need of evaluating each limit state.
- (2) The following idealized tensile stress-strain curve (**Figure 3.3.2**) may generally be used for the evaluation of ULS involved with sectional failures that may happen on a member subjected to a flexural moment and/or axial forces.

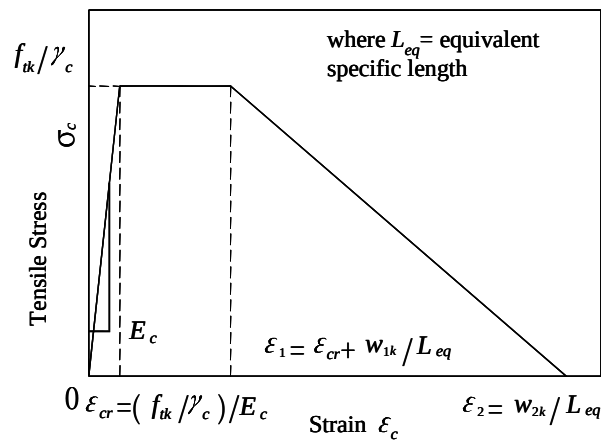


Figure 3.3.2 Tensile stress-strain curve of UFC

- (3) To evaluate SLS, the tensile stress-strain diagram may be regarded as linear. In this evaluation, the first cracking strength determined in Section 3.2.3 may be used. Young's modulus may be determined in accordance with Section 3.4.

[Comments]

(2) When tests are not performed to obtain TSD, the curve in **Figure 3.3.2** may be used as the stress-strain curve of the UFC to evaluate ULS accompanied with sectional failures. As shown in the following **Figure C3.3.2**, this stress-strain curve was attained by converting the stress-CMOD curve shown in Section 3.2.4 into a stress-strain relationship, using L_{eq} (equivalent specific length), which is equivalent to crack spacing. L_{eq} may be determined by conducting a numerical calculation in such a way that the flexural strength given by the TSD is equivalent to the flexural strength given by the stress-strain curve.

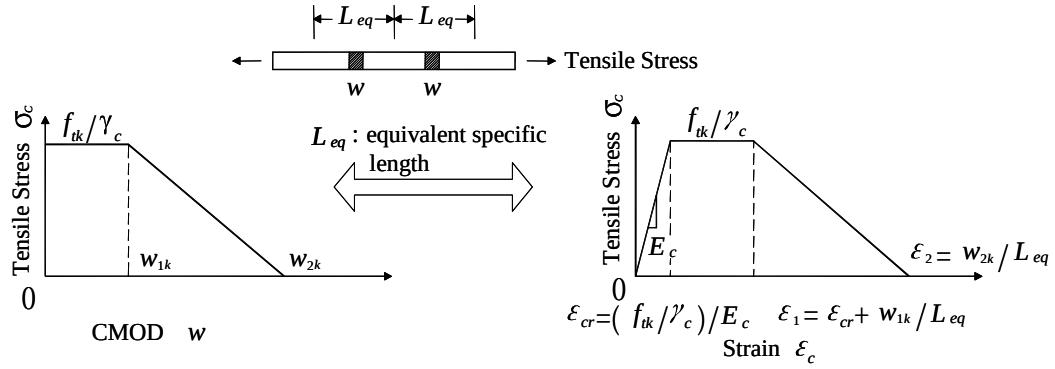


Figure C3.3.2 Relationship between TDS and tensile stress-strain

L_{eq} changes depending on height and shape of the cross section. UFC used here is made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed. For a rectangular cross section of a beam made with UFC, L_{eq} may be attained based on the following **Equation C3.3.1** and **Figure C3.3.3**. In the following equations, L_{eq} was determined in such a way that the flexural strength obtained by FEM analysis made on TSD (for rectangular specimens with different beam heights) is equivalent to the flexural strength obtained by the calculation of cross-sections using the stress-strain curve. If another method is applied, appropriate method should be used to determine the L_{eq} .

$$L_{eq} / h = 0.8 \cdot \left\{ 1 - \frac{1}{(1.05 + 6h / l_{ch})^4} \right\} \quad \text{Equation C3.3.1}$$

$$f_b = \left\{ 1 + \frac{1}{0.5 + 3.0 \cdot (h / l_{ch})^{0.7}} \right\} \cdot f_t \quad \text{Equation C3.3.2}$$

where, l_{ch} : characteristic length ($= G_F E_c / f_t^2 = 1.06 \times 10^4$ mm)

G_F : fracture energy ($= 27.12$ N/mm)

E_c : Young's modulus ($= 5.0 \times 10^4$ N/mm²)

f_t : average tensile strength ($= 11.3$ N/mm²)

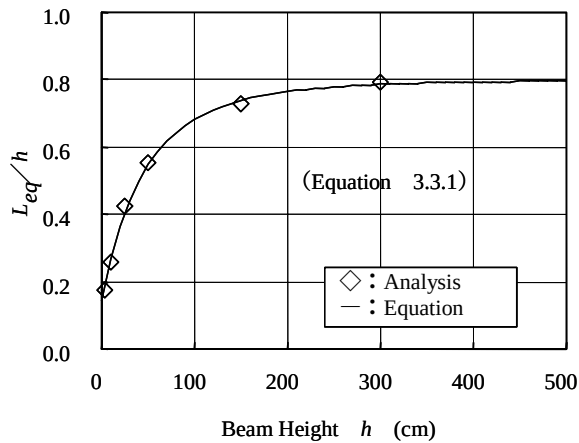


Figure C3.3.3 ELS of rectangular cross section

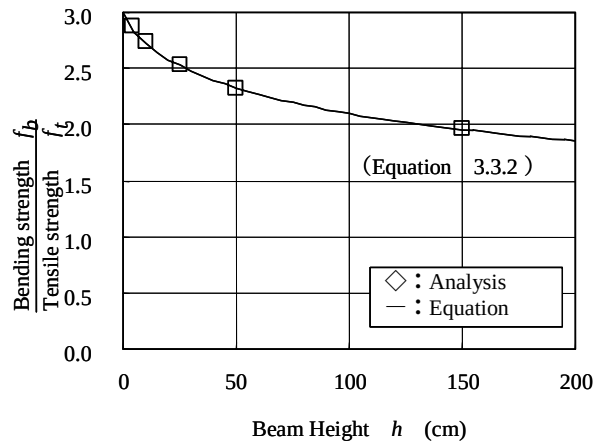


Figure C3.3.4 Flexural strength based on TSD

(3) The UFC behaves as an elastic body up to the first cracking strength. It is surmised that Young's modulus in compression is identical with that in tension within the elastic range. Therefore, the recommendations determined that the value of Young's modulus obtained by compression tests may be used for Young's modulus in tension.

3.4 Young's Modulus

(1) Young's modulus of the UFC shall be determined by appropriate tests.

(2) Young's modulus of 5.0×10^4 N/mm² can generally be used for the UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed.

[Comments]

(1) Young's modulus of UFC may be obtained in accordance with the JIS A 1149 "Method of Test for Static Modulus of Elasticity of Concrete."

(2) Past tests confirmed that Young's modulus of 5.0×10^4 N/mm² may generally be used for the UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed. It is also confirmed that, within the elastic range, both compressive and tensile stress-strain curves are almost identical.

3.5 Poisson's Ratio

Poisson's ratio for the UFC can be generally set to 0.2 within the elastic range.

3.6 Thermal Characteristics

The thermal characteristics of the UFC shall be determined based on appropriate tests and/or collected data.

[Comments]

Generally, thermal characteristics of the UFC change considerably due to water content, temperature, and other conditions. Therefore, in principle, the thermal characteristics shall be determined by appropriate tests. The following **Table C3.6.1** is the thermal characteristics of the UFC, which is made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed, obtained from past tests upon exposure to air-dry at 20°C after curing is completed.

Table C3.6.1 Heat characteristics of UFC after completion of standard heat curing

Thermal Expansion Coefficient ($\times 10^{-6}/^{\circ}\text{C}$)	13.5
Thermal Conductivity ($\text{kJ}/\text{mh}\cdot^{\circ}\text{C}$)	8.3
Thermal Diffusivity ($\times 10^{-3}\text{m}^2/\text{h}$)	3.53
Specific Heat ($\text{kJ}/\text{kg}\cdot^{\circ}\text{C}$)	0.92

3.7 Shrinkage

Shrinkage of the UFC shall be determined taking into account the quality of the materials, mix proportions, curing conditions, humidity around the structure, dimensions and shapes of the members, etc.

[Comments]

Shrinkage of the UFC is primarily autogenous shrinkage. Various factors are involved in the shrinkage, such as quality of the materials, curing conditions, etc. To determine the shrinkage strain, those factors have to be accounted for. In addition, special care is needed when to use deformed bars, because internal constraints of the UFC may cause cracks.

In case of UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm^2 , 15 mm in length, 0.2 mm in diameter, and standard heat curing employed, the following **Figure C3.7.1** was compiled based on the past test results. The figure shows the rate of shrinkage during the standard heat curing is approximately 450×10^{-6} and approximately 50×10^{-6} after completion of the heat curing. On the other hand, if heat curing is not employed, the shrinkage increases as the age progresses, quite similar to that of conventional concrete, with total shrinkage of approximately 550×10^{-6} .

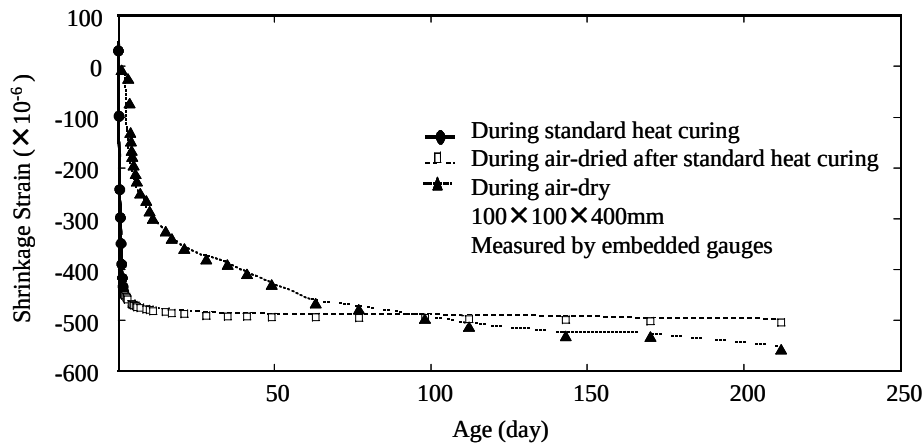


Figure C3.7.1 Shrinkage strain of UFC developed since casting into mold

If tests are not performed to calculate the shrinkage strain of the UFC, the following values shown in **Table C3.7.1** may be used for the UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm^2 , 15 mm in length, 0.2 mm in diameter, and standard heat curing employed.

Table C3.7.1 Shrinkage strain of UFC ($\times 10^{-6}$)

Condition of curing	Age of UFC				
	less than 3 days	4–7 days	28 days	3 months	1 year
Standard heat curing	50	30	0		

* The age after the start of air drying for design considerations (age after completion of heat curing).

3.8 Creep

(1) Creep strain of the UFC is generally given by the following **Equation 3.8.1**, under the assumption that creep strain is in direct proportion to elastic strain.

$$\varepsilon'_{cc} = \varphi \cdot \sigma'_{cp} / E_{ct} \quad \text{Equation 3.8.1}$$

Where, ε'_{cc} : Creep strain of UFC

φ : Creep factor

σ'_{cp} : Stress

E_{ct} : Young's modulus at age when load is applied

(2) The creep factor of the UFC shall be determined taking into account the quality of the materials, mix proportions, curing conditions, temperature and humidity around the structure, dimensions of cross sections, etc. To attain a value for creep factor in tension, the value obtained by compression tests may be used with necessary modifications, as far as the tensile stress level is below the first cracking stress.

(3) If tests are not performed, generally 0.4 may be set to the creep factor of the UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed.

[Comments]

(1) The creep strain may be assumed to be directly proportional to elastic strain in the same way as the conventional concrete as far as the stress level is below 40% of the compressive strength.

(2) Creep of the UFC is greatly affected by various factors such as quality of materials, curing conditions, etc. Therefore, the design value of creep factor shall be determined based on current and past test data and/or measurements conducted on the actual structure. Tensile stress may be generated when permanent load is applied on the UFC. However, since creep strain in tension is insignificant, the recommendations decided that the creep factor in compression may also be used for the tensile stress state as well, if only with small changes. Without heat curing, creep happens on the UFC in the same way age progresses in conventional concrete. The SETRA/AFGC stipulates 1.2 as the final creep factor in their guidelines.

(3) The following test results have been observed (**Figure C3.8.1**) regarding the relationship of the

creep factor and material age, after completion of standard heat curing. Based on this figure, it was decided that 0.4 may be used for the creep factor of the UFC made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed.

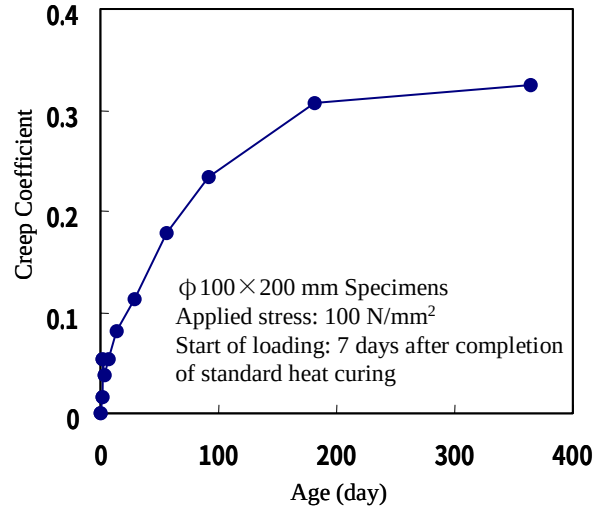


Figure C3.8.1 Creep coefficient of UFC after completion of standard heat curing

3.9 Fatigue Strength

(1) Characteristic values of fatigue strength of the UFC shall be determined by tests that consider the structure's exposure conditions.

(2) Material factor (γ_c) of the UFC is 1.3 for the fatigue limit state (FLS).

(3) The design fatigue strength (f_{rd}) for the UFC in compression and flexural compression may be attained by the following equation (**Equation 3.9.1**). The equation is focused on the relationship of stress σ_p subjected to a permanent load and fatigue life N .

$$f_{rd} = 0.85 f_d \cdot \left(1 - \frac{\sigma_p}{f_d}\right) \cdot \left(1 - \frac{\log N}{17}\right) \quad (\text{N/mm}^2) \quad \text{Equation 3.9.1}$$

where, $N \leq 2 \times 10^6$

f_d : design compressive strength of UFC, which can be attained by setting the material factor to 1.3.

(4) The design fatigue strength (f_{rd}) for the UFC in tension and flexural tension may be attained by the following equations (**Equations 3.9.2 to 3.9.4**). The equations are focused on

the relationship of stress σ_p subjected to a permanent load and fatigue life N . (Note: UFC used here is made with the standard mixed ingredients, containing 2 volume % of fiber reinforcement with a tensile strength of 2700 N/mm², 15 mm in length, 0.2 mm in diameter, and standard heat curing employed.)

If $N \leq 7.3 \times 10^4$

$$f_{rd} = f_d \cdot \left(1 - \frac{\sigma_p}{f_d}\right) \cdot \left(1 - \frac{\log N}{16}\right) \quad (\text{N/mm}^2) \quad \text{Equation 3.9.2}$$

or, if $7.3 \times 10^4 < N < 1.3 \times 10^6$

$$f_{rd} = f_d \cdot \left(1 - \frac{\sigma_p}{f_d}\right) \cdot \left(2.0 - \frac{\log N}{3.7}\right) \quad (\text{N/mm}^2) \quad \text{Equation 3.9.3}$$

or, if $N \geq 1.3 \times 10^6$

$$f_{rd} = 0.36 f_d \cdot \left(1 - \frac{\sigma_p}{f_d}\right) \quad (\text{N/mm}^2) \quad \text{Equation 3.9.4}$$

where,

f_d : design tensile strength or design flexural strength of the UFC, which may be attained by setting the material factor to 1.3.

(5) The stress σ_p of the UFC due to permanent loading shall be generally set to zero in the case of reversed cyclic loading.

[Comments]

(2) If the fatigue failure does not bring about the ultimate state of the structure, the factor γ_c can be set to less than 1.3.

(3) Neither test data nor reliable references are available so far on the design fatigue strength (f_{rd}) for the UFC in compression and flexural compression. Considering a safety margin, $K = 17$ shall be used for the design fatigue strength in compliance with the similar strength equation stated in the “Standard Specifications — Examination of Structural Performance.” In addition, as the UFC is very dense in microstructure, its compressive fatigue strength is thought to be intact, even put in underwater or constantly moist conditions.

If fatigue life N exceeds cyclic loading of 2×10^6 , in principle, the design fatigue strength shall be determined by appropriate tests due to scarcity of current knowledge on this matter. However, it is surmised that **Equation 3.9.1** provides some safety margin even when cyclic loading is beyond 2×10^6 . Therefore, this equation may be used as it is for the evaluation of design fatigue

strength, which is subjected to axial and/or flexural forces.

(4) The design fatigue strength (f_{rd}) in tension and flexural tension was determined by flexural fatigue tests both in air and water. **Figure C3.9.1** is the $S-N$ curve that exhibits the four-point bending tests with cyclic loading applied to the UFC. The test results show that ruptures were mainly caused by pullout failures of steel fibers from the matrix. There was no notable difference in the fatigue strength between tests in air and tests in water. To determine the design flexural strength f_{d} , the following **Equation C3.3.2** may be used.

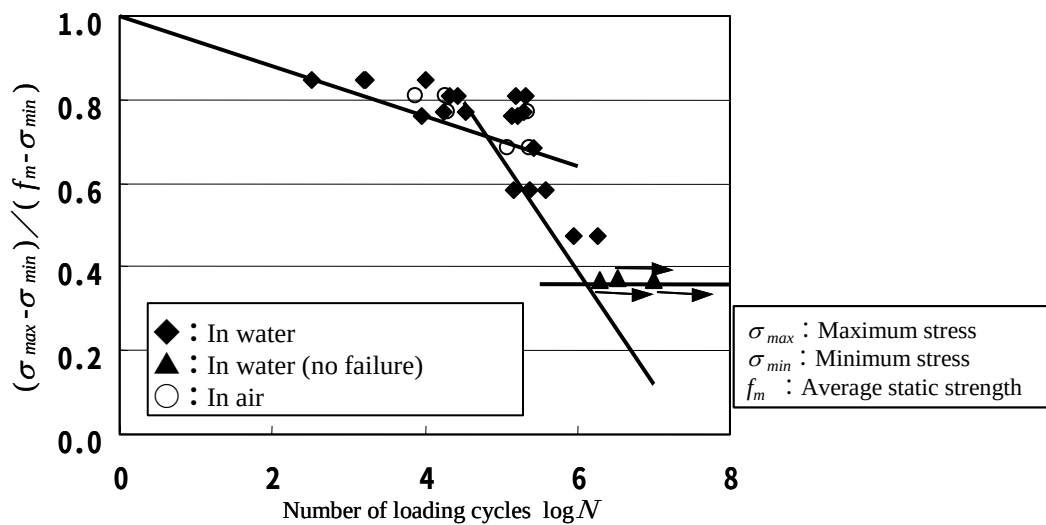


Figure C3.9.1 Results of bending fatigue tests in water and in air

(5) No data is currently available on the fatigue strength of the UFC that is subjected to alternate loading, although this sort of data is scarce for conventional concrete as well. In the recommendations, the compressive fatigue strength under alternating load is calculated as stress range repeated in only compression side, ignoring tensile stress. In the same manner, the tensile fatigue strength is calculated as stress range repeated in only tension side, ignoring compressive stress.

References

- 1) Ultra high performance fibre-reinforced concretes, BFUP Group, AFGC/SETRA, 2002.
- 2) Determination of the Fracture Energy of Mortar and Concrete by Means of Three-point Bend Tests on Notched Beams, Materials and Structures, Vol. 18, No. 106, pp.285-290, 1985.
- 3) Design guidelines for reinforced concrete column members with steel fiber, Concrete Library 97, Japan Society of Civil Engineers, 1999.