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Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Material

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Summary

This paper describes the outline of Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Material (CFRM), which was prescribed by the Japan Society of Civil Engineers (JSCE) in 1996. In order to design and construct concrete structures reinforced or prestressed with CFRM properly, a standard has to be provided, because the properties of CFRM differ greatly from those of conventional steel reinforcements or prestressing tendons. The purpose of Recommendation by JSCE is to fulfill such requirements and to focus on the precautions originated from the properties of CFRM in various aspects. It also includes Proposed Quality Standards for CFRM and Proposed Test Methods for CFRM. The former specifies the necessary items to classify currently available CFRM, and the latter specifies ten test methods to evaluate the necessary properties of CFRM.

1. Introduction

Continuous Fiber Reinforcing Materials (hereafter, CFRM) for concrete structures have been attracting a wide attention because of its several advantages such as high tensile strength, high corrosion resistance, etc. The term "continuous reinforcing materials" is Japanese terminology for FRP reinforcements or prestressing tendons used elsewhere. However, some special precautions are needed for the use of CFRM in structures properly, because the properties of CFRM differ greatly from those of conventional steel. In order to provide a standard for the use of CFRM and widen its application, Japan Society of Civil Engineers (hereafter, JSCE) carried out intensive research works under the guidance of the authors during the past 5 years, and published "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials" [1] in 1996. The Recommendation consists of Recommendation for Design, Recommendation for Construction, Proposed Quality Standards for CFRM and Proposed Test Methods for CFRM. The Recommendation for Design and Recommendation for Construction require that only the CFRM that meet Quality Standards are to be used. Whether a CFRM meets the Quality Standards or not is determined based on the results of the tests which are conducted following the Standard Test Methods.

2. Recommendation for Design

The Recommendation for Design is based on "Standard Specification for Design and Construction of Concrete Structures – Design Part" [2], which is prescribed for concrete structures in general by JSCE, and adopts the limit states design method. The concept of the limit states design method is similar to that of the model code by the European Concrete Committee. The main contents of the Recommendation for Design are design values for materials, design for ultimate limit states, design for serviceability limit states and design of prestressed concrete members.

2.1 Design Values of Materials

In this chapter, it is specified that the tensile strength of CFRM shall be determined following the equation 1.

$$f_{fd} = (m - 3 \cdot \sigma) / \gamma_{mf} \tag{1}$$

where f_{fd} is design tensile strength of CFRM, m is mean value, σ is standard deviation, γ_{mf} is material factor for CFRM and is taken as 1.15 – 1.30. The probability of breakage of CFRM is kept less than 10^{-6} by following this equation. Besides the tensile strength, strengths of curved tendons and bent portions are also specified in this chapter. These strengths have to be specified because CFRM has little plastic behavior.

2.2 Design for Ultimate Limit States

Test methods for member resistance for axial load, bending moment and shear force are specified in this chapter. As far as flexural capacity is concerned, the provisions are such that the assumptions for usual reinforced concrete shall be adopted but ultimate strain of CFRM must be used instead of the tensile strength to define the ultimate state. This is because the flexural capacity is governed by the breakage of CFRM, and strain attains the maximum value when flexural failure due to fiber rupture takes place. For shear capacity, the following equations are specified to examine the capacity. These equations are the modified ones based on traditional equations for conventional steel reinforced concrete structures, taking into account the characteristics of CFRM.

$$V_{ud} = V_{cd} + V_{sd} \tag{2}$$

where V_{ud} is ultimate shear capacity, V_{cd} is the contribution of concrete section, and V_{sd} is the contribution of shear reinforcement. V_{cd} is expressed as

$$V_{cd} = \beta_d \beta_p \beta_n f_{ct} \cdot bd / \gamma_b \tag{3}$$

$$\beta_p = \sqrt{100 p_w E_f / E_s} \tag{4}$$

where the notations of equation (3) are given in the reference [2], β_p is the term to express the effect of main reinforcement ratio $p_w = A_f / b_w d$, which is reduced by the ratio of modulus of elasticity of CFRM E_f to that of steel E_s. This is to take into account the fact that the shear capacity is lowered due to its low modulus of elasticity in comparison to that of steel. The equation to express the contribution of shear reinforcement is

$$V_{sd} = \left[A_w E_w \varepsilon_{fud} (\sin\alpha_s + \cos\alpha_s)/s_s\right] z/\gamma_b \quad (5)$$

$$\varepsilon_{fud} = \sqrt{f'_{mcd} \frac{p_w E_f}{p_{web} E_w}} \left[1 + 2\left(\frac{\sigma'_N}{f'_{mcd}}\right)\right] \quad (6)$$

The equation (5) is based on the conventional truss analogy, and the yield strength of shear reinforcement is replaced by $E_w \varepsilon_{fud}$, where ε_{fud} is calculated by equation (6), f'_{mcd} is design compressive strength of concrete allowing size effect, and σ'_N is average axial compressive stress. When the failure mode of members with CFRM is shear compression type, strain of shear reinforcement made of CFRM does not necessarily reach the ultimate one, and equation (6) is able to take into account this fact. It was shown that the above equations give lower bound values, as compared with the experimental results.

2.3 Design of Serviceability Limit States

In this chapter, methods for the examination of deflection, crack width, and so on are specified. Because CFRM is usually less corrosive, it is very difficult to specify the allowable crack width. The provisions for the allowable crack width are: allowable flexural crack width shall generally be determined based on the intended purpose of the structure, environmental conditions and member conditions; allowable crack width for aesthetic considerations may generally set to be not more than 0.5 mm, depending on the ambient environment of the structure; crack limitations and allowable crack widths for considerations of water-tightness shall be based on the Standard Specification [2]. To calculate flexural crack width, the equation specified for conventional steel reinforced concrete in the Standard Specification [2] can also be applied to the case of members reinforced with CFRM only if bond characteristics and multiple placement of CFRM are properly evaluated.

In the case of deflection, the equation for ordinary steel reinforced concrete members can also be applied to the members with CFRM. Deflections in some cases may be larger due to low modulus of elasticity and low reinforcement ratio, and in such cases the increased deflection makes shear cracking more likely. This, in turn, is considered to have some effects on deflection or displacement of the structure. The precautions in this regard are also specified.

3. Recommendation for Construction

The Recommendation for Construction is also based on the "Standard Specification for Design and Construction of Concrete Structures - Construction Part" [2] by JSCE, and consists of the chapters comprising general, materials, construction and quality control and inspection. Among them, only the contents of the first three chapters will be explained because the last chapter is not so greatly different from the case of ordinary reinforced or prestressed concrete structures.

3.1 Materials

In this chapter, qualities of the materials such as concrete, CFRM, steel reinforcement, etc. are specified. Among the provisions, less stringent provisions are specified for chloride content in concrete, because CFRM is less corrosive. However, the precautions to avoid the use of reactive aggregates are added because the alkali aggregate reaction will be exacerbated, if an excess of alkali ions co-exists with chloride ions. It is also specified that the epoxy-coated re-bar shall be a standard re-bar when steel reinforcement has to be used in conjunction with CFRM. At the same time, some provisions or recommendations are given for the use of new materials such as corrosion-proof prestressing tendons, plastic sheaths, coating materials to prevent bonding between CFRM and concrete, protection materials to protect CFRM from external or chemical damage and high-quality grout with super plasticizers.

3.2 Construction

This chapter treats handling and storage of the materials, fabrication, placement and installation, concrete works, prestressing and grouting, etc. For handling and storage of CFRM, the most important point is to avoid the deterioration of CFRM, hence the provisions for this point are specified. The situation is just same in fabrication, placement and installation, and in particular, necessary precautions to be taken are specified for curved arrangement of CFRM and bending of CFRM to make stirrups or spiral hoops, because strength of CFRM is reduced due to these treatments. As for concrete works, it is also specified that, proper care should be taken not to damage CFRM. In particular, as CFRM may be damaged by direct contact with an internal vibrator, it is recommended that an internal vibrator should be protected with a urethane covering.

3.3 Prestressing and Grouting

Taking into account the fact that CFRM exhibits greater elongation under the same prestressing force than the conventional prestressing steel, provisions are provided for the use of a jack with long stroke, or repositioning of the jack during prestressing works. At the same time, it is commented that the pull-in when anchoring CFRM may in some cases be greater than the case of prestressing steel, but the tension loss in CFRM due to set in the anchorage is less than that of prestressing steel.

4. Proposed Quality Standards for CFRM

The Quality Standards consist of the following chapters: Scope; Representation; Categories, Identification, Designations; Fiber and Fiber Bond Quality; Mechanical Properties; Nominal Diameter and Maximum Dimension; Testing; Calculation and Inspection. The specified mechanical properties of CFRM are as shown in Table 1. The first column of the table shows fiber categories, CFRM configurations and the rounded ratio by volume of axial fibers. The first symbols C, A, G and V denote carbon fiber, aramid fiber, glass fiber and vinylon fiber respectively, and the second symbols R, D, S, B, L and P denote round rod, deformed rod, strand, braid, lattice and plate respectively. The listed values of mechanical properties are the ones obtained based on the Standard Test Methods for CFRM. The primary targets of the Quality Standards are to clear what are the required properties for CFRM, what the current situation is and to suggest what type of CFRM should be developed in future, by identifying respective CFRM.

Table 1. Mechanical Properties of CFRM

Designation[1]	Ratio by Volume of Axial Fibers (%)	Guaranteed Strength[2),3)] (N/mm²)	Modulus of Elasticity (kN/mm²)	Elongation (%)	Creep Failure Strength[2)] (N/mm²)	Relaxation Rate[3)] (%)	Durability
CR65.CD65	63-65	1240	99-170	1.0-1.5		2-3	
CR50A, CD50A	49	960*	200	0.5			
CR50B, CD50B	49-52	780	190	0.4-0.5			
CS65A	64-66	980	73-210	0.5-1.5		1.04-1.06	
CS65B	64-66	790	84-170	0.5-1.4			
CL40	43	1200*	100	1.2			
C3D	60	1490*	130	1.1			
AR65, AD65	65	1720	59-60	2.9-3.1		7-14	
AS65A	60-69	1710	42-47	3.5		8.0-8.6	
AS65B	60-69	1830*	44-45	3.5			
AB65	66	1400	63-78	2.0		10	
AP65	49	1330	62	2.15		11	
AL40	43	1300*	57	2.2			
GR65, GD65	65-68	1130	37-49	2.5-2.7		1.82	
GL40	40	590	30	2.0			
GCL40A	40	530	37	1.4			
GCL40B	40	530*	37	1.4			

1) A:D<20mm, B:D≧20mm
2) Guaranteed strength and creep failure strength are guaranteed capacity and creep capacity divided by nominal area, respectively.
3) Tentative values obtained by different test methods.
4) * denotes values for only one product.
5) Blanks are due to insufficient data at this moment.

5. Proposed Test Methods for CFRM

Proposed test methods are for tensile properties, flexural tensile properties, creep failure, long-term relaxation, tensile fatigue, coefficient of thermal expansion, performance of anchorages and couplers, alkali resistance, bond strength and shear properties. Among them, the test method for tensile properties is the most fundamental one, and it specifies the methods for determination of load-displacement curve, tensile strength, tensile rigidity and Young's modulus and ultimate strain. The points of the provisions are: the length of the test piece shall be the length of the test section added to the length of the anchoring section; the length of the section shall be not less than 100 mm and not less than 40 times the nominal diameter of the CFRM; for CFRM in strand form, the length shall be more than 2 times the strand pitch as an additional condition; the number of test pieces shall not be less than five; the test temperature shall generally be within the range 5-35 degrees Celsius; the material properties of CFRM shall be assessed on the basis only of test pieces undergoing failure in the test section. The provisions for test pieces are also applied to the test methods for creep failure, long-term relaxation, tensile fatigue and alkali resistance. As for creep failure capacity, the ratio of creep failure capacity to tensile capacity at 1 million hours is determined based on the result of 1000 hours, assuming linear relationship between the load ratio and logarithm of time. The same principle is applied for the determination of long-term relaxation. In the test method for alkali resistance, it is specified that the test pieces are immersed in alkaline solution with temperature of 60 degrees Celsius and with the composition same as the pore solution found in the concrete, and the reduction in strength and change in mass after one month of immersion are determined

6. Concluding Remarks

The outline of "Recommendation for Design and Construction of Concrete Structures Using CFRM" by JSCE is introduced. Although, CFRM is not necessarily the material fully replacing the steel reinforcements or prestressing tendons, it is a very useful material for making structures highly durable against chloride attack or constructing non-magnetic structures, because of its less corrosive and magnetic properties. In particular, applications in seismic retrofitting and earth anchors are remarkably increasing in Japan. Considering these facts, it can be said that the demand for CFRM will gradually increase in the days to come. In order to design and construct structures reinforced or prestressed with CFRM properly, however, some precautions that are not necessary for ordinary reinforced concrete structures are needed, mainly because of its brittle nature and low modulus of elasticity. The Recommendation outlined in this paper throws lights to those points. In conclusion, the authors sincerely wish further development of CFRM and its widespread applications.

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References

[1] Research Committee on Continuous Fiber Reinforcing Materials (edited by Atsuhiko Machida), Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials, Concrete Engineering Series 23, Japan Society of Civil Engineers, 1997

[2] Concrete Committee, Standard Specification for Design and Construction of Concrete Structures, Part 1 (design) and Part 2 (construction), Japan Society of Civil Engineers, 1997 (in Japanese)