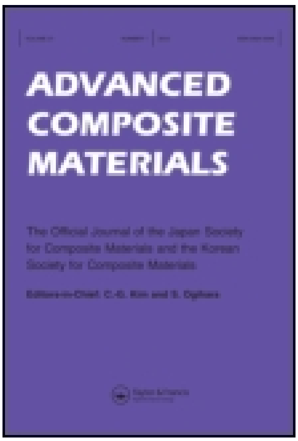

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Improvement of shear and ductility of reinforced concrete columns by wrapping of continuous fiber-reinforced polymer sheet

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Abstract—The Concrete Committee of the Japan Society of Civil Engineers (JSCE) has set up a technical committee on the retrofit of concrete structures by continuous fiber-reinforced polymer sheet (CFRP sheet). The technical committee has been working to make a recommendation for 1 1/2 years and has proposed the first draft. This paper describes some parts of the recommendation, in particular, on how to design the shear strengthening and the ductility improvement by use of CFRP sheet. In addition, discussion is extended to the proposed test methods on the tensile strength and the bond strength of CFRP sheet.

Keywords: FRP sheet; upgrading; shear; ductility; RC column.

1. INTRODUCTION

Continuous fiber-reinforced polymers (CFRPs) have been developed for more than 20 years. The first application of CFRPs to civil engineering structures was as substitutes for reinforcing steel bars, because CFRPs are not corrosive materials. Extensive research work has been conducted widely and several design guidelines have been published [1–7].

In comparison with ordinary steel reinforcing bars, CFRP bars have a high tensile strength but a relatively low modulus of elasticity. In addition, CFRPs are quite elastic up to failure and the ultimate strain capacity is 1–3%. They do not have any yield phenomenon. These material properties mean that CFRPs are less effective as substitutes for steel reinforcing bars in the seismic design of concrete structures. This is one of the reasons why CFRP bars have not been used much for concrete structures in Japan.

On the other hand, CFRP sheets became attractive for design engineers as retrofit or strengthening materials for existing RC structures after the disaster of the Great Hanshin Earthquake in 1995. The high strength, light weight, and easy handling of CFRP sheets are strongly beneficial for the retrofit or strengthening of RC structures.

Authorities in Japan, such as the Railway Technical Research Institute, the Japan Highway Public Corporation, as well as the Ministries of Construction and Transportation, have been studying the effectiveness of CFRP sheets for the retrofit or strengthening of existing RC structures. With much experimental work, they have made their own design guidelines for their specific applications with a specified type of fiber [1–5].

2. JSCE ACTIVITY

With consideration of the situation of CFRP sheet applications in Japan, the Japan Society of Civil Engineers (JSCE) decided to establish unified and more widely applicable design recommendations for CFRP sheets for the retrofit or strengthening of existing concrete structures, as well as the repair and enhancement of the durability of concrete structures.

The research committee on CFRP sheets started in April 1998 with a 2-year term. The missions of the committee were to make recommendations for the design and construction practice of CFRP sheets applied to existing RC structures for retrofit, strengthening, and enhancement of durability, and to establish standard test procedures for determining the mechanical properties of CFRP sheets, such as tensile strength, bond strength, durability, etc.

Different from previous recommendations, the JSCE recommendations are formatted and described based on the performance of RC structures with CFRP sheets. This means that the descriptions in the design part are made as how to evaluate the contribution of CFRP sheets in terms of flexure, shear, and ductility of RC members, as well as enhancement of durability.

This paper discusses mainly the evaluations of the shear and ductility contribution of CFRP sheets, and some aspects of the test methods.

3. CONTRIBUTION TO SHEAR CAPACITY

In previous guidelines, the contribution of CFRP sheet to the shear capacity of the RC member is expressed by the truss model:

$$V_u = V_c + V_s + V_f, \tag{1}$$

$$V_f = K \cdot A_f \cdot f_f \cdot z \cdot (\sin\alpha + \cos\alpha)/s_f, \tag{2}$$

where, V_u is the ultimate shear capacity of RC members with CFRP sheet, V_c is concrete contribution, V_s is the contribution of shear reinforcing bars, V_f is the contribution of CFRP sheet, K is the coefficient of effectiveness of CFRP sheet, A_f is the cross-sectional area of CFRP sheet, f_f is the tensile strength of CFRP sheet, z is the lever arm length, α is the angle of the fiber to the longitudinal direction, and $s_f = 1$, or the spacing of the CFRP strip.

Compared with steel reinforcement, CFRP (both carbon fiber and aramid fiber) is quite elastic up to failure, with less ultimate strain as shown in Fig. 1. This property does not lead to stress redistribution in the resistant mechanism, which is a typical phenomenon of resistance with steel reinforcement due to the yielding of steel. Therefore, the equation derived from the truss model should account for the non-stress redistribution of CFRP using the K factor, otherwise the contribution of CFRP sheet to the shear capacity cannot be evaluated properly (Fig. 2).

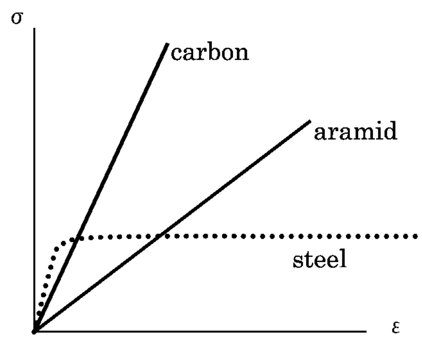

Figure 1. Stress–strain diagram of CFRP.

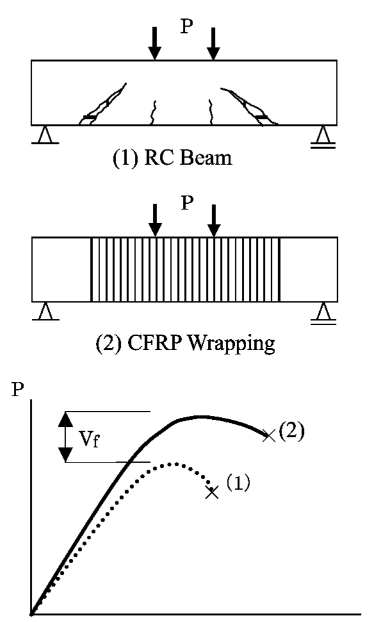

Figure 2. Contribution of CFRP sheet to the shear capacity.

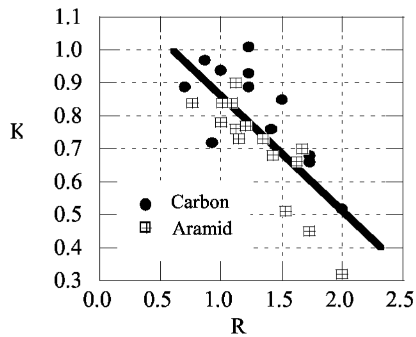

Figure 3. Correlation of K and R.

However, the problem of those guidelines lies in the fact that the value of K is determined for a specific type of fiber, regardless of the mechanical properties of the fiber; for example, 0.8 for carbon fiber sheet and 0.6 for aramid fiber sheet are recommended. Since various types of carbon fiber sheet, as well as aramid fiber sheet, have been developed which have different tensile strengths, moduli of elasticity and ultimate strains, those guidelines are limited to the specific fiber sheet.

The JSCE committee on CFRP sheet surveyed previous test results widely and re-evaluated the contribution of the sheet using the tensile strength, the modulus of elasticity, the cross-sectional area of CFRP sheet, as well as the concrete strength. After many parametric studies, the K factor is proposed in the following form:

$$0.4 \leqslant K = 1.0 - 0.3R \leqslant 0.8, \tag{3}$$

$$R = \frac{\sqrt{p_{\mathrm{f}}} \cdot f_{\mathrm{f}}}{\sqrt{f'_{\mathrm{c}} \cdot E_{\mathrm{f}}}}, \tag{4}$$

where, $p_{\mathrm{f}} = A_{\mathrm{f}}/(b_{\mathrm{w}} \cdot s_{\mathrm{f}})$, f'_{c} is the concrete strength, and E_{f} is the modulus of elasticity of CFRP sheet.

The effectiveness of the equation is shown in Fig. 3. The equation is still empirical and has a limit for application because the collected data are limited within the ranges of $d = 200$–540 mm, $a/d = 1.1$–3.6, $f'_{\mathrm{c}} = 21$–45 MPa, $f_{\mathrm{f}} = 2480$–4300 MPa, and $E_{\mathrm{f}} = 87$–252 GPa. Although the data for the equation are collected from the experimental results of columns (similar to those shown in Fig. 4), the equation could be applicable to the beams shown in Fig. 2.

4. CONTRIBUTION TO DUCTILITY

The mechanism of how CFRP sheet contributes to the ductility of RC members is much more complicated than that of how the sheet contributes to the shear capacity. Even for ordinary RC members, the ductility is still difficult to determine analytically. However, it has been observed in experimental work that RC members with a relatively higher shear capacity than flexural capacity exhibit large ductility.

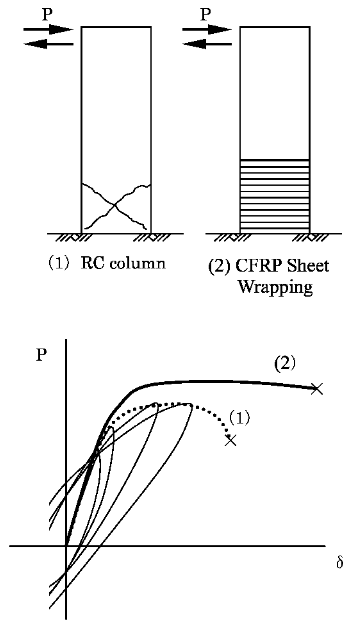

Figure 4. Contribution of the sheet to ductility.

This fact is considered in the JSCE seismic design code for concrete structures expressing that the ductility ratio is a linear function of the ratio of shear capacity to flexural capacity.

The contribution of CFRP sheet to ductility can be attributed not only to the increase of shear capacity by sheet, but also to the confinement of cracked concrete by sheet wrapping (Fig. 3). Conducting a parametric study of existing experimental data, the following equation is proposed:

$$\mu = 2.33 \cdot \frac{(0.5V_c + V_s)}{V_{mu}} \cdot \left(1 + \alpha_o \cdot \frac{\varepsilon_f \cdot p_f}{V_{mu}/(B \cdot z)}\right) + 3.29, \tag{5}$$

where μ is the ductility ratio (ratio of yield deformation to ultimate deformation), V_{mu} is the shear force at the ultimate flexural capacity, B is the width, and α_o is a coefficient (same value of Young's modulus of steel can be taken) .

The equation was examined as shown in Fig. 5, having a factor of correlation of 0.78. The equation also has a limit for application since the collected data are within the ranges of $d = 300$–800 mm, $a/d = 4.0$–5.7, $f'_c = 18$–24 MPa, $f_f = 2050$–3430 MPa, $E_f = 78$–252 GPa, and axial stress = 3.2–5.9 MPa.

In contrast with the contribution to shear capacity, the contribution of sheet to ductility depends on the existing structural performance. As mentioned before, CFRP sheet wrapping increases both the shear capacity and the confinement effect of cracked concrete. These effects should provide the member with a large deformation capacity.

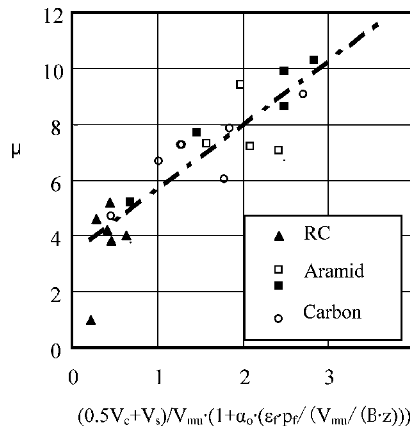

Figure 5. Correlation of μ.

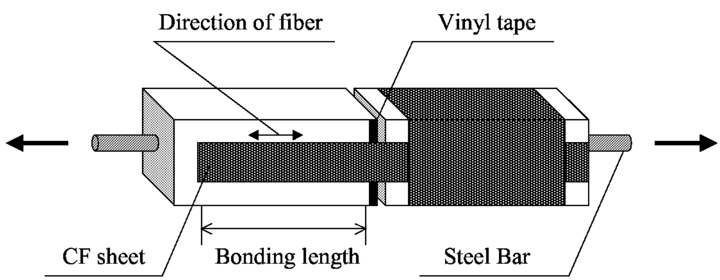

Figure 6. Test specimen for bond.

5. TEST METHODS

The Committee proposed nine test methods to determine the mechanical and durable properties of CFRP sheet. They are (1) to determine the tensile strength of sheet, (2) to determine the anchorage strength between sheets, (3) to determine the bond strength between sheet and concrete, (4) to determine the bond strength between sheet and steel plate, (5) to determine the adhesive strength between sheet and concrete, (6) to determine the tensile fatigue strength of sheet, (7) the accelerated exposure test, (8) the freeze–thaw test, and (9) to determine resistance against water, acid, and alkali. Most of the test methods are concerned with the property of sheet itself, but the bond test represents the interface strength among the sheet, adhesive material, and the surface condition of concrete. Since the bond strength between sheet and concrete is important to the contribution of sheet to the flexural and shear capacity of RC members, some aspects of the test method are discussed.

5.1. Bond strength test

The test specimen is shown in Fig. 6. Two concrete blocks ($100 \times 100 \times 300$ mm) are aligned to match the center of the cross-section. Each has a steel bar mounted at the

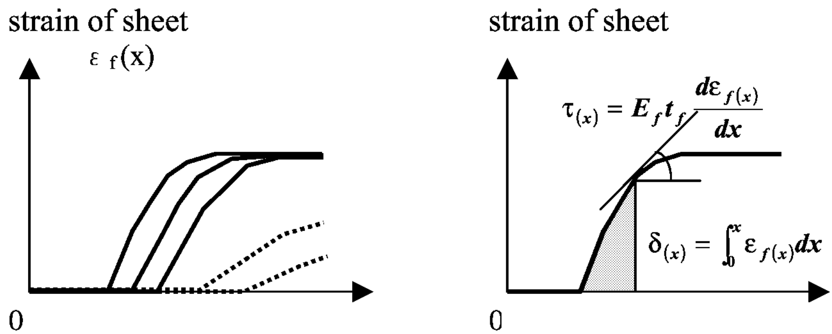

Figure 7. Strain distribution of sheet.

center of the cross-section. After alignment of two blocks, two CFRP sheets (more than 50 mm width × 400 mm length) are attached on the opposite sides. In order to obtain consistent data, sheets on one side should be anchored sufficiently. The left parts of the sheets are measured. The load is applied by pulling a steel bar at both ends. Strain gages should be attached on both surfaces of the sheet. Based on the strain distribution of the sheet as shown in Fig. 7, the bond strength is determined.

6. CONCLUDING REMARKS

Due to the deterioration of material or changes in the requirements for structures, the upgrading of existing RC structures is becoming a more and more important issue. CFRP sheets have advantageous material properties, such as a high strength, a light weight, and a high resistance to corrosion. To make the application of CFRP sheets to upgrading of structures more effective, the contribution of the sheet should be evaluated sufficiently in the performance of structures as a whole. With further understanding of the mechanism and with computational invention, the evaluation could be improved by numerical analyses.

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