JSCE RECOMMENDATIONS FOR APPLICATION OF FRP LAMINATES AND RELATED WORKS IN OTHER CODES PROVISIONS

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Introduction

It has been more than ten years since Fiber Reinforced Polymer (FRP) laminates were introduced for strengthening and retrofitting of existing concrete structures. A lot of research works have been done and some field applications have been conducted. Through international conferences on FRP, advanced knowledge on FRP materials and its applications has been exchanged and design code provisions have been brought forth in these days in several countries.

The objectives of this paper are to discuss the design concept and code provisions for FRP laminates in terms of the strengthening of flexural capacity, shear capacity and ductility of concrete members. In general, the design concept is not so different in each code because a lot of information have been exchanged and shared internationally. However, geographical and environmental condition as well as cultural background are different in each country, and then the requirements for design of concrete structures may not be the same.

In comparison of the Japanese code (JSCE code) [1] with the American code (ACI code) [2] and the European code (fib code) [3], the discussion is extended in terms of the way how to evaluate the FRP laminate contribution to improve the performance of concrete structures. Fiber materials targeted in codes are carbon fiber, aramid fiber and glass fiber. However, the JSCE code treats only carbon fiber and aramid fiber, not glass fiber because of lack of experimental results in Japan.

Flexural Strengthening

Analytical approaches to evaluate the contribution of FRP laminates to concrete structures in flexural behavior are more or less identical in three codes. All three codes adopt the traditional sectional analysis called “plane sections remain plane” for strain compatibility, and the stress strain relationships of concrete, steel and FRP laminates are used for equilibrium equations (see Figure1).

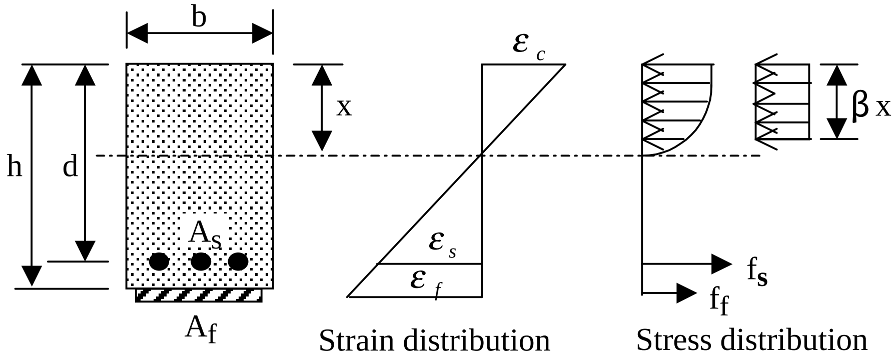

Figure 1. Analysis of cross section for flexure

With considerations of failure modes of members, a simplified method, such as a usage of stress block of concrete, is applicable. There are, however, some differences in three codes concerning with safety factors and necessary considerations in design.

JSCE code

As for safety factors, the JSCE code adopts five factors, such as a material factor (γ_m), a member factor (γ_b) , a structure factor (an importance factor) (γ_i) , a load factor (γ_f) and an analysis factor (γ_a). The values are shown in Table 1. The characteristic values are normally determined as the values of 5 % fractile based on the normal distribution of data. The flexural capacity of RC members with FRP laminates shall be calculated by the traditional theory as shown in Figure1. The code says only the general assumptions for calculation of the flexural capacity. The safety factors should be used in the following manners.

$$f_d = \frac{f_k}{\gamma_m} \qquad (1)$$

$$M_{ud} = \frac{\int \sigma \cdot x dA}{\gamma_b} \qquad (2)$$

$$\frac{\gamma_i \cdot M_d}{M_{ud}} \leq 1 \qquad (3)$$

where, f_k: characteristic strength, f_d: design strength, M_{ud}: flexural capacity, and M_d: design moment.

Table 1. Safety Factors in JSCE Code

Safety factor	Ultimate Limit State	Serviceability Limit State
Material factor (γ_m)		
Concrete	1.3	1.0
Steel	1.0 (1.05)	1.0
FRP laminates	1.2 – 1.3	1.0
Member factor (γ_b)		
Flexure	1.15	1.0
Shear	1.25	1.0
Ductility	1.3	1.0
Structure factor (γ_i)	1.0 – 1.2	1.0
Load factor (γ_f)	1.0 – 1.2	1.0
Analysis factor (γ_a)	1.0	1.0

The maximum design stress in FRP laminates is limited by Eq.4 in consideration of peeling failure starting at a cracked portion

$$\sigma_f \leq \sqrt{\frac{2G_f E_f}{n_f \cdot t_f}} \qquad (4)$$

where, σ_f: maximum design stress of FRP laminate (N/mm^2), G_f :interfacial fracture energy (N/mm^2), E_f: modulus of elasticity of FRP laminate (N/mm^2), n_f: number of plies of FR laminate, t_f:

thickness of one ply of FRP laminate.

For a serviceability limit state, three items, such as crack width, deflection and durability are specified on how to verify. In general, the verification methods developed for ordinary reinforced concrete structures are extended with proper considerations of the effects of FRP laminates. The FRP laminate can reduce a crack width in such a manner as reduction of existing steel stress and confinement of concrete surface. Crack widths after bonding of the FRP laminate can be reduced by 30% - 70% of calculated values by the JSCE code equation for RC structures. In this code 30% reduction of crack widths is recommended.

The deflection of members with FRP laminates can be calculated by the same equation as for RC structures when the flexural rigidity of members is properly evaluated as shown in Figure1. When FRP laminates cover the complete surface of concrete, intrusion of carbon dioxide, chloride ion and other substance can be prevented. There is not much data on the effect, but the code recommends 5 – 10 years of deterioration offset for single ply of FRP laminate.

ACI code

Three safety factors are introduced for evaluation of the flexural capacity of members with FRP laminates, an environmental reduction factor (C_E) for material strength (Table 2), a partial reduction factor (Ψ =0.85) for efficiency of FRP laminate and a strength reduction factor (ϕ). These factors are used in the following manner.

$$f_{fu} = C_E f^*_{fu} \tag{5}$$

$$M_n = A_s f_s \left(d - \frac{\beta x}{2} \right) + \Psi A_f f_{fu} \left(h - \frac{\beta x}{2} \right) \tag{6}$$

$$\phi M_n \geq M_u \tag{7}$$

where, f^*_{fu}: tensile strength of FRP laminate, f_{fu}: design strength of FRP laminate, M_n: nominal flexural capacity, M_u : flexural demand, others are shown in Figure1.

Table 2. Environmental Reduction Factors in ACI Code

Exposure condition	Fiber type	Environmental reduction factor, C_E
Enclosed conditioned space	Carbon/Epoxy	0.95
	Glass/Epoxy	0.75
	Aramid/Epoxy	0.85
Unenclosed of unconditioned space	Carbon/Epoxy	0.85
	Glass/Epoxy	0.65
	Aramid/Epoxy	0.75
Aggressive environment	Carbon/Epoxy	0.85
	Glass/Epoxy	0.50
	Aramid/Epoxy	0.70

The strength reduction factor (ϕ) represents the loss of ductility due to FRP laminate, and specified to be 0.9 – 0.7 as follows.

$$\phi = \begin{cases} 0.90 & \text{for} \quad \varepsilon_s \le \varepsilon_{sy} \\ 0.70 + \dfrac{0.20(\varepsilon_s - \varepsilon_{sy})}{0.005 - \varepsilon_{sy}} & \text{for} \quad \varepsilon_{sy} \le \varepsilon_s \le 0.005 \\ 0.70 & \text{for} \quad \varepsilon_s \ge 0.005 \end{cases} \qquad (8)$$

For a sustain load and a cyclic load, the code specifies the stress limit of FRP laminate as shown in Table 3.

Table 3. Stress Limit of FRP Laminate for Creep and Fatigue

Carbon fiber	Aramid fiber	Glass fiber
$0.55f_{fu}$	$0.30\ f_{fu}$	$0.20\ f_{fu}$

fib code

Safety factors for FRP laminates (γ_f) are shown in Table 4. The quality and quality control of materials are reflected in the safety factors. Other safety factors to be used are the same as specified in the Eurocode 2 (EC2), such as 1.5 for concrete strength and 1.15 for steel reinforcement. What is insisted in safety concept for the ultimate limit state is to guarantee the yielding of internal steel reinforcement so that the strengthened member will fail in a ductile manner. To attain the safety concept the minimum strain capability are introduced for FRP laminate and steel reinforcement as follows.

$$\text{FRP laminates} \qquad \varepsilon_{fu,c} \ge \begin{cases} 0.0050 - \varepsilon_o & \text{for concrete types C35/45 or lower} \\ 0.0075 - \varepsilon_0 & \text{for concrete types higher than C35/45} \end{cases} \qquad (9)$$

$$\text{Steel} \qquad \varepsilon_{su,c} \ge \begin{cases} 0.0043 & \text{for concrete types C35/45 or lower} \\ 0.0065 & \text{for concrete types higher than C35/45} \end{cases} \qquad (10)$$

In addition, the code mentions how to avoid peeling-off failure and end shear failure.

Table 4. FRP Material Safety Factors (γ_f) in fib Code

Type	prefab systems	wet lay-up systems
CFRP	1.20	1.35
AFRP	1.25	1.45
GFRP	1.30	1.50

For a serviceability limit state, it is specified how to verify the requirements for deflection, crack width and bond interface cracking.

Shear Strengthening

The shear contribution of FRP laminates is basically evaluated by the traditional truss analogy in three codes.

$$V_u = V_c + V_s + V_f \qquad (11)$$

where, V_f is the contribution of FRP laminate to the shear capacity, and is expressed in the same manner as the contribution of steel shear reinforcement. The key point lies in how much the strain of FRP laminate goes at the ultimate. Since analytical approaches are not yet developed adequately, the effective strain of FRP laminate should be determined by test results. The maximum strain at the ultimate is greatly influenced by the anchorage efficiency of laminates. For example, an RC rectangular section beam with wrapped FRP laminates can take larger shear resistance than one with side or U-shaped FRP jackets. In addition, the elasticity or rigidity of FRP laminate may influence the load carrying mechanism in shear.

JSCE code

The code treats only the case of wrapped FRP laminates. The contribution of FRP laminate is expressed in terms of elastic modulus (E_f) and the amount of laminate (ρ_f).

$$V = K \cdot \left[A_f f_{fud} (\sin\alpha_f + \cos\alpha_f) / s_f \right] \cdot z / \gamma_b \qquad (12)$$

$$0.4 \le K = 1.68 - 0.67R \le 0.8 \qquad (13)$$

$$R = (\rho_f \cdot E_f)^{1/4} \left(\frac{f_{fud}}{E_f} \right)^{2/3} \left(\frac{1}{f'_{cd}} \right)^{1/3} \qquad 0.5 \le R \le 2.0 \qquad (14)$$

where, $\rho_f = A_f/(b_w \cdot s_f)$, E_f: modulus of elasticity of FRP sheet, f_{fud}: design strength of FRP sheet, f'_{cd}: concrete strength, and γ_b : member factor (=1.25).

Eq.(13) is obtained from the regression analysis of test data as shown in Figure2.

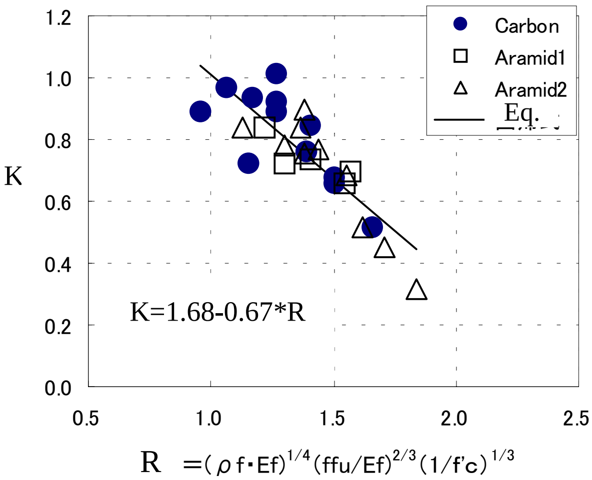

Figure 2 Relationship between K and R in JSCE Code

ACI code

The code treats the anchorage efficiency (wrapped or unwrapped) in two ways, one is a reduction factor for the shear contribution and the other is a maximum strain of FRP laminate.

Contribution of FRP laminate: $\Psi \cdot V_f$ (15)

$$\Psi = \begin{cases} 0.95 & \text{Completely wrapped element} \\ 0.85 & \text{3-sided "U-wraps" or bonded face} \end{cases}$$

$$V_f = A_{fv} f_{fe} (\sin\alpha + \cos\alpha) \cdot d_f \big/ s_f \qquad (16)$$

$$A_{fv} = 2nt_f w_f$$

$$f_{fe} = \varepsilon_{fe} \cdot E_f$$

$$\varepsilon_{fe} = \begin{cases} 0.004 & \text{for U-wraps or bonding to 2 sides} \\ k \cdot \varepsilon_{fu} \le 0.004 & \text{for completely wrapping all 4 sides} \end{cases}$$

fib code

The code specifies the maximum strain of FRP laminate for wrapped and unwrapped cases, but says that unwrapped cases shows less effective contribution, and recommends that FRP laminates should be attached to the compressive zone of RC members when full wrapping is not feasible.

$$V_{fd} = 0.9\varepsilon_{fd,e} E_{fu} \rho_f b_w d (\cot\theta + \cot\alpha) \sin\alpha \qquad (17)$$

$$\varepsilon_{fd,e} = \varepsilon_{fk,e} / \gamma_f = 0.8\varepsilon_{f,e} / \gamma_f \qquad (18)$$

$$\varepsilon_{f,e} = \begin{cases} 0.17\left(\dfrac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.30} \varepsilon_{fu} & \text{for wrapped CFRP} \\ \min\left[\begin{matrix} 0.65\left(\dfrac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.56} * 10^{-3} \\ 0.17\left(\dfrac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.30} \varepsilon_{fu} \end{matrix}\right] & \begin{matrix}\text{Side or U-shaped CFRP} \\ \text{Peeling-off} \\ \text{fracture}\end{matrix} \\ 0.048\left(\dfrac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.47} \varepsilon_{fu} & \text{for wrapped AFRP} \end{cases} \qquad (19)$$

where, $\varepsilon_{f,e}$: strain limit of FRP laminate, ε_{fu}: ultimate strain of FRP, E_{fu}: elastic modulus of FRP in the principal fiber direction, ρ_f: FRP reinforcement ratio, b_w: web width, d: effective depth, θ: angle of diagonal crack, α: angle of principal fiber orientation, f_{cm}: concrete strength.

The strain limit of FRP laminate is obtained from the regression analysis of test data as shown in Figure 3.

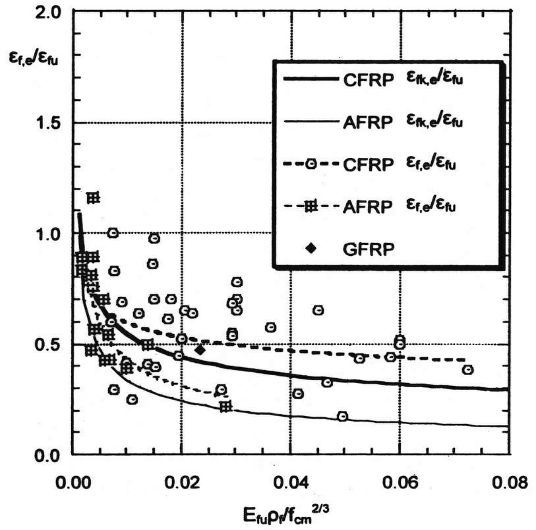

Figure 3 Nominal FRP Strain Limit in fib Code

The code extends the shear provisions to the torsional strengthening taking α =90 only for the case of full wrapping by FRP laminates.

Ductility Improvement

Wrapping by FRP laminates can improve not only the shear resistance of existing RC members but also confinement of concrete resulting in enlargement of deformation capacity. A large deflection capacity gives high resistance to RC structures against accidental loads. The fib code describes the confinement effects of concrete in the forms of stress-strain relationships. The JSCE code indicates directly how to calculate the improvement of deformation (or deflection) of RC members by FRP laminate wrapping.

JSCE code

In order to evaluate the improvement of deformation capacity, a ductility ratio (μ) is introduced. It represents the ratio of the ultimate deformation to the yield deformation of members. In the conventional seismic design, larger ductility ratio RC structures have, larger seismic actions they can resist against. The basic concept on ductility improvement lies in that the ratio of the shear capacity to the flexural capacity dominates the ductility of member. The code provides the equation as follows.

$$\mu_{fd} = \left[\frac{1.16(0.5V_c + V_s)}{V_{mu}} \cdot \left\{ 1 + \alpha_o \cdot \frac{\varepsilon_{fu}\rho_f}{V_{mu}/(B \cdot z)} \right\} + 3.58 \right] \Big/ \gamma_{bf} \leq 10 \qquad (20)$$

where, μ_{fd} : ductility ratio (ratio of yield deformation to ultimate deformation), V_c : concrete contribution, V_s : steel reinforcement contribution, V_{mu} : shear force at the ultimate flexural capacity, B: width, α_0 : coefficient (same value of Young's modulus of steel can be taken), ε_{fu} : ultimate strain of FRP, ρ_f : ratio of FRP (= $A_f/(s_f \cdot B)$), γ_{bf} : member factor (=1.3) .

Eq.20 is obtained by the regression analysis of test data as shown in Figure 4.

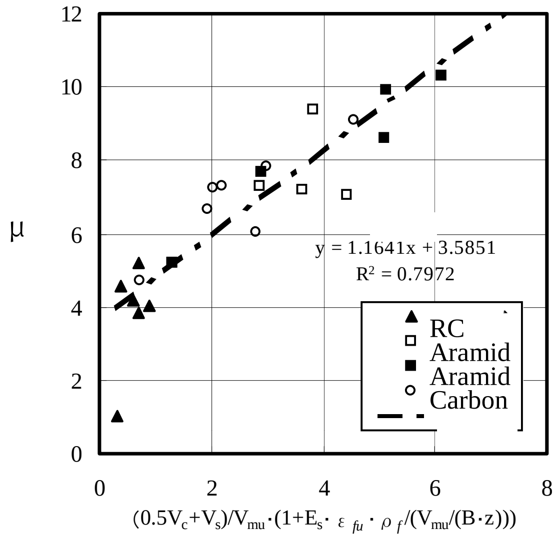

Figure 4　Ductility Ratio in JSCE Code

Concluding Remarks

Comparing steel reinforcement FRP laminates are elastic up to failure and have low elastic rigidity. In addition, they are strong in tension but quite vulnerable against shearing force. These material properties influence the contribution to flexure and shear strengthening as well as ductility improvement of concrete members.

In three code provisions, JSCE, ACI and fib, the basic concept for shear strengthening design by FRP laminates in flexure and shear is almost identical. The safety factors, however, have some differences because of differences in materials and in construction practice as well as in job experience.

Strengthening contribution of FRP laminates has become clear step by step. The next problems to solve are durability of FRP laminate itself and the contribution of FRP laminate to improve the durability of concrete structures by wrapping the surface of concrete.

References

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