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Current trends and future issues of code for upgrading concrete structures with use of FRP in Japan

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ABSTRACT: The subcommittee on investigation research of design method for upgrading concrete structures with use of FRP at committee on Hybrid structures in Japan Society of Civil Engineers worked on research for total approximately four years from June, 2010 to May, 2014. During the first term for two years, the subcommittee pointed out the issues of existing design method by upgrading FRP material. Based on that studies, the information to help rationalization of the design method was provided in next second term for two years. This report outlines the subcommittee report on "Current trend and future issue for upgrading concrete structures with use of FRP at committee on Hybrid structure" (In Japanese).

1 INTRODUCTION

For technologies for reinforcing reinforced concrete structures by FRP sheets, guideline documents have existed since 1996 (RTRI 1996a, NEXCO 2014, and RTRI 1996b). After that, Japan Society of Civil Engineers (JSCE) published a guideline by combining these guideline documents and findings derived from research results (JSCE 2000). Since then, the use of new reinforcing materials such as FRP plates and grids, which are not covered by the guideline, has increased. However, the current situation is no guideline document has been compiled after the guideline was published by JSCE in 2000. On the other hand, in other countries such as the US and EU, guidelines have been set up for reinforcement by FRP sheets and plates, etc.

A revision of the guideline by JSCE in 2000 is expected to be made in the future, and it is expected that this revision work will require documents to overcome various issues. Against this backdrop and purpose, the "*Subcommittee on investigation research of design method for upgrading concrete structures (H209)*" was set up inside the JSCE Committee on Hybrid Structures. This study committee carried out research activities for approximately four years in total, from June, 2010 through May, 2014. It carried out a research study contributing to the rationalization of the reinforcement design of concrete structures mainly using FRP materials. The emphasis of the study was especially on the impacts of bonding, fatigue, and environmental effects. This article will describe an overview of the study.

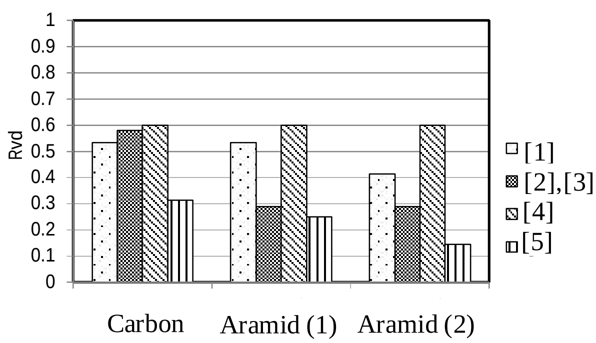
2 CURRENT SITUATION OF REINFORCEMENT DESIGN OF CONCRETE STRUCTURES USING FRP MATERIALS

2.1 *FRP Sheets*

Regarding the calculation of flexural proof stress (ultimate strength), the guidelines specify that it be calculated based on conventional flexural theory for reinforced concrete components. On the other hand, for debonding of FRP sheets, there are two types of methods: one specifies the necessary anchorage length in order that the debonding does not determine the flexural proof stress, and another calculates the flexural proof stress assuming debonding failure as shown in Equation 1.

$$\sigma_f \leq \sqrt{\frac{2G_f E_f}{n_f \cdot t_f}} \tag{1}$$

For the calculation of shear proof stress, the guidelines specify the method to accumulate the shear force loaded on the FRP. However, there are differences in the values specified for setting the shear reinforcement efficiency and for reduction of effective strain, etc., and this has resulted in differences in the evaluations of shear proof stress. The formula to calculate the shear force loaded on the FRP is as shown in Equation 2, and a comparative example of the calculated reduction rates of the shear forces loaded on the FRP sheets in the standards (for single layer reinforcement) is as shown in Figure 1.



Note : [1] JSCE, [2] [3] RTRI, [4] NEXCO, [5] ACI

Figure 1. Comparative example of the calculated reduction rates of the shear forces loaded on the FRP sheets.

$$V_{fd} = K \cdot \left[A_f \cdot f_{fud} \left(\sin \alpha_f + \cos \alpha_f \right) / S_f \right] \cdot Z / \gamma_b \tag{2}$$

Regarding the toughness rate, there is consistency among the guidelines that it be evaluated according to the function of the shear margin, but are different in the effects of structures before reinforcement and in the types of reinforcing materials, etc.

As described above, while the basic ideas for the technical standards in the calculations of stress and rigidity are the same in the guidelines, they are different in ideas on debonding, which has a large impact on the performance and details of the reinforcement efficiency, etc. In order to consolidate the guidelines, these points need to be sorted out.

2.2 *FRP Plates and FRP Grids*

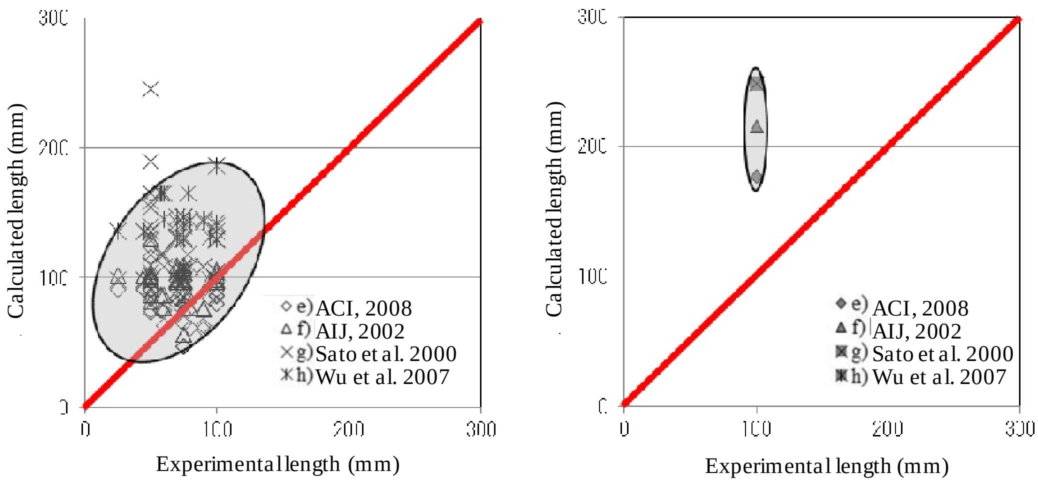
Design standardization on FRP plates and FRP grids has not been achieved yet. As demands for efficiency such as simplified construction work and shorter construction periods are expected to further increase in the future, the desired direction is to move forward to codify the FRP plate and FRP grid construction methods as technical standards in the same way as the FRP sheet construction method.

3 EVALUATION OF MODEL EQUATIONS ON ADHERENCE AND ANCHORAGE USING FRP SHEETS AND FRP PLATES

3.1 *Issue Extraction on Model Equations for Effective Bond Length and Necessary Anchorage Length*

The guidelines and the documents specify model equations that have been formularized for calculating the necessary anchorage length and the effective bond length for using FRP sheets and FRP plates (ACI 2008, AIJ 2002, Sato et al. 2000 and Wu et al. 2007). This section describes the evaluation performed reflecting the existing simple shearing test results in model equations for the effective bond length.

Graphs comparing experimental values and calculated values for the effective bond length are as shown in Figure 2. In the case of FRP sheets, the calculated values obtained from the model formulas e) through h) are similar to the experimental values (ACI 2008, AIJ 2002, Sato et al. 2000 and Wu et al. 2007). This shows that values that are close to the experimental values for effective bond length can be calculated from these model equations. Comparing the model equations reveals that the values obtained by dividing the calculated values by the experimental values increase in the order e) < f) < g) < h). However, the results clearly show that in the model equations e) and f), there are cases where the minimum value falls far below 1.00. On the other hand, in the case of FRP plates, no correlation can be found between the calculated values and the experimental values, and the values are scattered compared to the results with FRP sheets.



(a) FRP sheet (b) FRP plate

Figure 2. Comparing experimental values and calculated values for the effective bond length.

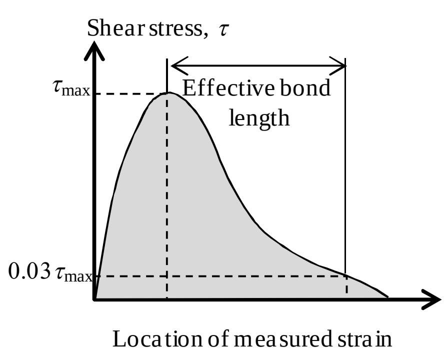


Figure 3. An example of effective bond length.

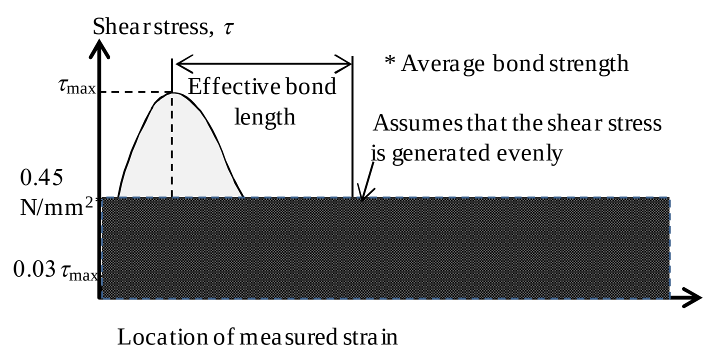


Figure 4. An example of effective bond length and average bond strength.

3.2 *Issues with the Necessary Anchorage Length Model Formulas Based on the Concept of Average Bond Strength*

As shown in Figure 3, for the actual shear stress distribution, the shear stress becomes a maximum at the anchorage end, and the farther the position is from the anchorage end, the smaller the shear stress tends to be. This is finite. However, the concept of the necessary anchorage length, unlike the actual shear stress distribution, assumes that the shear stress is generated evenly as shown in Figure 4. Therefore, the shear stress is not assumed to be finite, and the necessary anchorage length can be calculated even when tensile stress which cannot be fully anchored is generated. If the shear stress that is generated at the anchorage end is too large to fully anchor, the use of a steel plate, etc., can be combined for anchorage at the end. Also in this case, the necessary anchorage length can be calculated based on the concept of the average bond strength. In this case, as the necessary anchorage length that is longer than the actual effective bond length is calculated, the average bond strength becomes smaller. From the above, in the case of reinforcement using FRP sheets and plates, when calculating the required anchorage length, or when considering the need for combined use of steel plates, etc., for the end anchorage, it is necessary to consider values calculated by model formulas for calculating effective bond length.

4 INVESTIGATION OF FATIGUE REINFORCEMENT PERFORMED ON RC FLAT SLAB BY BONDING FRP SHEETS AND FRP PLATES

4.1 *Evaluation of Reinforcing Effects of FRP Sheets on RC Flat Slab Reinforcement*

In past experiments and researches, systematic evaluation of the lifetime increase rate was attempted focusing on the reinforcement amount. The results suggest that an excessive increase in reinforcement amount can decrease the reinforcing effect, and that when evaluating the reinforcing effect, properties such as the load-bearing capacity of the base flat slab needs to be considered (Kobayashi et al. 2005).

Therefore, attempts were made to construct equations based on a mechanism to improve fatigue resistance of the RC flat slab by FRP sheet reinforcement.

The following three types of reinforcing effects of FRP sheets were considered:

α_n: Reinforcing effect associated with the shift of the neutral axis

α_q: Reinforcing effect generated by improvement in the degree of anisotropy of the floorboard

α_c: Reinforcing effect generated by restraint of cracking

As a result of considering the above three reinforcing effects, Equation 3 can be considered, where α_f stands for the lifetime increase rate of the reinforced flat slab.

$$\alpha_f = \alpha_n \cdot \alpha_q \cdot \alpha_c \tag{3}$$

Figure 5 shows the relationship between the number of runs obtained by dividing the converted number of failures through experiment by the calculated value for the lifetime increase rate, α_f, and P_0/P_{sx} as the S-N relation of FRP sheet-reinforced flat slab. The result shows that the equivalent number of runs of the reinforced flat slab lies almost along the S-N line, where the lifetime increase rate has been considered.

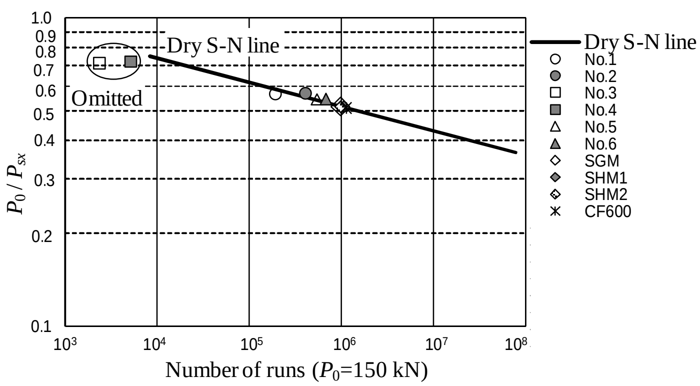


Figure 5. The relationship between the number of runs and P_0/P_{sx} as the S-N relation of FRP sheet-reinforced flat slab.

Table 1. The lifetime increase rates obtained from experiments and numerical calculations.

	Experiment		Numerical calculation		
	A, B	C	A	**B**	C
S3, S4a	40	88	38	24	18
S4b	20	24	20	13	4

4.2 *Evaluation of Reinforcing Effects of FRP Plates on RC Flat Slab Reinforcement*

Past researches suggest the following three methods to evaluate the reinforcing effects of FRP plates in reinforced flat slab. A comparative study was done by calculating the fatigue lifetimes in these evaluation methods using the experiment test specimens specified in the documents.

A; Evaluation using the lifetime increase rate, α_f

B; Evaluation using P'_{sxi}, considering debonding failure proof stress
C; Evaluation based on material damage to compression zone concrete

The lifetime increase rates obtained from experiments and numerical calculations are as shown in Table 1. The results show that method A, i.e., evaluation using the lifetime increase rate, α_f, has high consistency in experiments and numerical calculations for evaluating the lifetime rates achieved with reinforcement.

4.3 *Issues and Prospects in Fatigue Design*

In fatigue design of RC flat slab reinforced by the adhesion of FRP sheets or FRP plates, several methods have been suggested for lifetime extension effects by the use of FRP reinforcing materials. However, currently, the reinforcing mechanisms have not yet been revealed. Among these methods, for a method using the lifetime increase rate, the fatigue life of the flat slab can be evaluated with a relatively high degree of accuracy against past experimental test results, with a dynamic model using the physical properties of FRP sheets and FRP plates, which suggests the possibility that this method may be applied to reinforcement design.

Another finding from past experiments is fatigue debonding identified in the case where, when the applied load is large, repeated runnings of the wheel load gradually extend the debonding area of the FRP reinforcing material. There is also a report saying that placing CFRP plates, which have thickness in the board and high tensile toughness per unit width, in a discrete way, increases the bond stress generated between the concrete and the CFRP reinforcing material, and thus accelerates debonding. Therefore, mechanisms for reinforcing RC flat slab with FRP sheets and FRP plates against fatigue need to be revealed. It is also considered necessary to study the generation limit of fatigue debonding caused by the repeated bond stress generated at the boundary between the FRP reinforcing material and the concrete, the fatigue debonding growth rate, and the effects of fatigue debonding on the fatigue resistance of the flat slab, by considering the properties of FRP reinforcing materials such as toughness and widths.

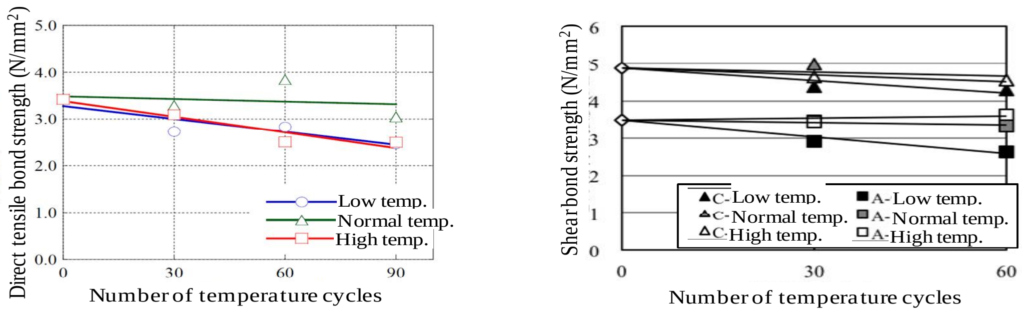
5 STUDY ON THE IMPACT OF ENVIRONMENTAL EFFECTS ON ANCHORAGE AND BONDING OF FRP SHEETS

5.1 *Temperature Dependence*

The temperature-dependent expansion and contraction of FRP sheets, which have different linear expansion coefficients compared to concrete, are expected not to follow those of concrete. In past studies concrete to which FRP sheets were adhered was exposed to a fixed temperature and temperature change for a certain period of time to evaluate the direct tensile adhesive strength and the shear bond strength (Koda et al 2011, Koda et al. 2012). Figure 6 shows the relationships between the direct tensile bond strength/shear bond strength and the number of temperature cycles under temperature change. These diagrams show that the strength tends to decrease under repeated temperature changes between low and high temperatures. The result suggests the possibility that the decrease in the bond strength is caused by 1) bond strength decrease in the epoxy resin at a fixed high temperature, and 2) the accumulated reciprocity of strain near the bonding interface, which results from the difference in linear expansion coefficient between the sheets and the concrete under temperature change.

5.2 *Effects of Freezing Damage Environment Including Anti-Freezing Agents*

In addition to the base material concrete degradation caused by freeze-thaw effects and bond strengths depending on the type of FRP sheet, evaluation was performed on bond performance under exposure to sprayed anti-freezing agent based on the direct tensile bond test and the bending bond test (Kamiharako et al. 2006, Kamiharako et al. 2007). Figure 7 shows the direct tensile bond strength in a freezing damage environment. This diagram shows that the bond strength, which decreases under the impact of freeze-thaw effects of the base material concrete, resulted from the change in failure modes due to the degradation of the base material. The other finding was that the direct tensile bond strength decreased by approximately 20% to 45% due to changes in (the speed of) freeze-thaw temperatures under exposure to sprayed anti-freezing agent. It was shown that under exposure to sprayed anti-freezing agent, a slow temperature change causes damage to the base material concrete, and thus, decreases the bond performance.



(a) Direct tensile bond test (b) Shear bond test

Figure 6. The relationships between the direct tensile bond strength/shear bond strength and the number of temperature cycles under temperature change.

The results of the above studies suggested the possibility that the environmental temperature affects the adhesive and bond performance of FRP sheets, and especially, the low-temperature history indicates that attention needs to be paid to this kind of decrease in performance.

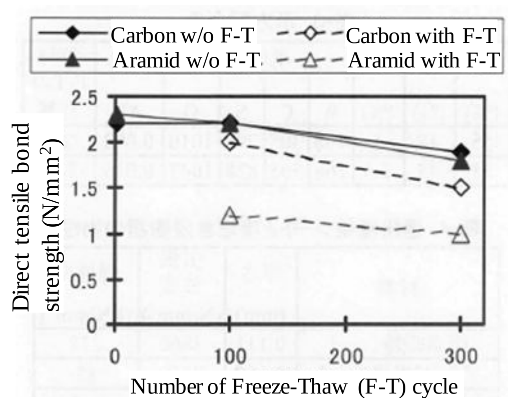


Figure 7. The direct tensile bond strength in a freezing damage environment.

6 CONCLUSIONS

Based on the above studies, the following suggestions can been made on a reinforcement design method with the use of new FRP materials:

6.1 *Issues that Need Improvement in Current Reinforcement Design Methods*

For design of bending and shear reinforcement with the use of FRP sheets, the current design methods need to be reviewed. Regarding bending reinforcement design, the guideline suggests a design formula to utilize the interfacial failure energy G_f (JSCE 2000). This is considered to require verification by experimental results, etc. Regarding shear reinforcement, it is considered that the shear reinforcement efficiency, K, needs to be reevaluated. Additionally, the same applies also to toughness reinforcement design. In many of the guideline documents, design formulas are regression formulas for experimental results. Therefore, it is considered necessary to reevaluate these formulas.

The current situation is that construction methods to reinforce reinforced concrete structures with the use of FRP plates or FRP grids do not have design standards. It is desired that regarding FRP plates, standards be set up promptly based on the accumulation of experimental results by using the findings obtained from them.

6.2 *Issues with Evaluation Formulas For Adherence and Anchorage of FRP Sheets and Plates*

Figure 2 shows that there are cases where the calculated values for effective bond length proposed so far can far exceed the effective bond lengths obtained through simple shear tests, both for FRP sheets and plates. When determining the anchorage length considering an excessively calculated effective bond length, the length may fail to be ensured on the actual components. In such cases, mechanical anchorage may need to be performed in some way. As the current design guideline documents do not cover this, it is considered that a new reinforcement design method should incorporate it.

6.3 *Design to Reinforce Against Fatigue using FRP Sheets and Plates*

Currently, the accumulated cases of wheel load running tests on FRP material-reinforced flat slab are not sufficient, because of the fact that only a limited number of institutions can perform experiments on wheel loads that are the same as actual traffic loads, and due to issues of costs and effort spent on the experiments. However, Figure 5 shows that it is possible to forecast the remaining life with a certain degree of accuracy by making improvements to the existing evaluation formula. This diagram shows that multiplying the remaining lifetime by a correction factor or a lifetime increase factor provides a high accuracy of S-N line. Therefore, it is considered necessary to establish design standards for measuring remaining lifetimes against fatigue with reference to this method.

6.4 *Toward Consideration of Environmental Effects in Reinforcement Design*

Chapter 5 clarified that the accelerating test had already verified that, primarily, the temperature load affecting FRP sheet-reinforced concrete material does not damage FRP sheets, but that it degrades the boundary between the sheet and the concrete, and the concrete as the base material, as shown in Figure 6. As shown in these diagrams, repeated temperature cycles gradually reduce the bond strength. However, no studies were conducted on how this kind of decrease in bond strength affects the structural performance of the components. Therefore, based on investigations of the components, discussion is needed on how much the effects of temperature load should be reflected in reinforcement design.

As a method to reflect the effects of temperature load, multiplying stress and distortion applied to the design by a reduction factor, as specified in the standard by ACI, can be considered (ACI 2008). However, without considering investigations of the components, rational reduction factors may not be obtained. It is desired to accumulate experiments and analysis samples in the future in order to properly consider the impact of environmental effects on FRP material-reinforced components in reinforcement design.

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