

LATEST ACHIEVEMENT IN TECHNOLOGY AND RESEARCH OF RETROFITTING CONCRETE STRUCTURES

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Abstract

Major retrofitting methods for concrete structures, such as external bonding, jacketing (or wrapping) and overlaying, are characterized with interface (or bonding) between an existing concrete surface and the retrofitting material. The mechanism of retrofitted members is essentially the same in the sense that it depends much on the interface constitutive model. Therefore, those methods can be dealt with in the same manner that is to provide an interface model for predicting the member behavior.

In this paper, which summarizes the report of JCI TC-014A "Committee on Retrofitting Technology for Concrete Structures", latest information on the interface mechanical properties and the interface models for external bonding and overlaying methods with various retrofitting materials is presented. Some numerical calculations, which disclose the interface mechanism, are also introduced.

Behaviors of the retrofitted members are introduced in relation to the interface mechanical property. In addition some new technologies in external bonding and jacketing are presented briefly. Lastly a new direction for the development of retrofitting material and method to achieve an optimum desired performance of the retrofitted member behavior is presented for discussion.

Keywords: retrofit, interface, bond, external bonding, jacketing, overlaying

1. Introduction

External bonding, jacketing (or wrapping) and overlaying are considered major retrofitting methods for concrete structures. Retrofitting materials used in these methods include reinforced concrete, prestressed concrete, other concrete materials, steel plate, FRP sheet, FRP plate and FRP grid. Bond properties between these materials and the existing structures and their mechanical properties significantly influence the mechanical properties of retrofitted structures. Despite numerous studies in the past, methods to accurately evaluate the mechanical properties such as ultimate strength, deformation and stiffness of retrofitted members have yet been developed. This is because the stress transferred mechanism namely slip and debonding at the bonding interface has not been fully clarified and also because there are various retrofitting materials with various mechanical properties. JCI set up a Technical Committee on Retrofitting Technology for Concrete Structures in 2001 to clarify the stress transfer mechanism at bonding interface and the mechanical properties of the retrofitted members. At the end of its 2-year term, the Committee is to (i) provide useful information needed to develop a more rational retrofitting design, and (ii) propose optimum retrofitting materials and retrofitting design methods. The next chapter summarizes the Committee Report [1].

2. Outline of Committee Report

The Committee Report consists of 6 chapters. Chapter 1 is the introduction. Chapter 2 describes general classification of retrofitting methods and the retrofitting methods discussed in this committee report. Chapter 3 clarifies microscopic stress transfer mechanism at bonding interface, while Chapter 4 presents methods to predict numerically macroscopic bond properties based on the microscopic mechanism clarified in Chapter 3. Chapter 5 describes properties of retrofitted members, relating them to the bond properties. Based on the findings in Chapters 3 to 5, Chapter 6 presents the optimum microscopic bond properties and retrofitting material properties for macroscopic bond properties and member properties after retrofitting. The following sections, 2.1 to 2.4 briefly present the contents of Chapters 3 to 6.

2.1 Local Bond Properties in Various Retrofitting Methods

It is common among various retrofitting methods that retrofitting materials share forces acting on a concrete member, which is to be retrofitted. It is important to clarify the mechanism of how the retrofitting materials share the forces to accurately evaluate the retrofitting effects and develop rational retrofitting design methods.

As shown in Fig.1 researches on retrofitting technology in the past can be classified into those for “element level” and for “member level”. In the element level research, experiments were conducted with specimens prepared in such a way that mechanical behavior at bonding interface between retrofitting materials and concrete could be observed. In the member level research, properties in flexural and shear of retrofitted members were investigated using specimens with a configuration similar to the real ones. Simulations of retrofitted members were conducted by using the finite element methods or the like.

In the Committee Report retrofitting methods are classified into overlaying, FRP sheet external bonding, steel plate external bonding, FRP plate/grid external bonding and FRP spraying. The element level research on each method is summarized with respect to the following 3 points and latest data are presented:

- 1) Retrofitting materials at bonding interface
- 2) Local bond properties at interface and investigation of the factors
- 3) Problems remaining to be solved

The materials for each retrofitting method are listed, and the properties of bonding interface between these materials are examined separately as “macroscopic properties” and “microscopic properties” (see Fig.1). The former is a maximum load obtained by pullout bond tests and an average bond strength that is the maximum load divided by bonding area, while the latter is the local bond properties at a point, e.g. relationship between local bond stress τ and slip s and interfacial fracture energy G_f . Since these local bond properties can be directly applied to the simulation of member level behaviors by numerical analysis such as finite element analysis, extensive researches are currently going on. In order to investigate uniquely the local bond properties regardless retrofitting materials, the following two points are considered; (i) classification of bond property according to direction of forces acting on interface, and (ii) factors for the bond property.

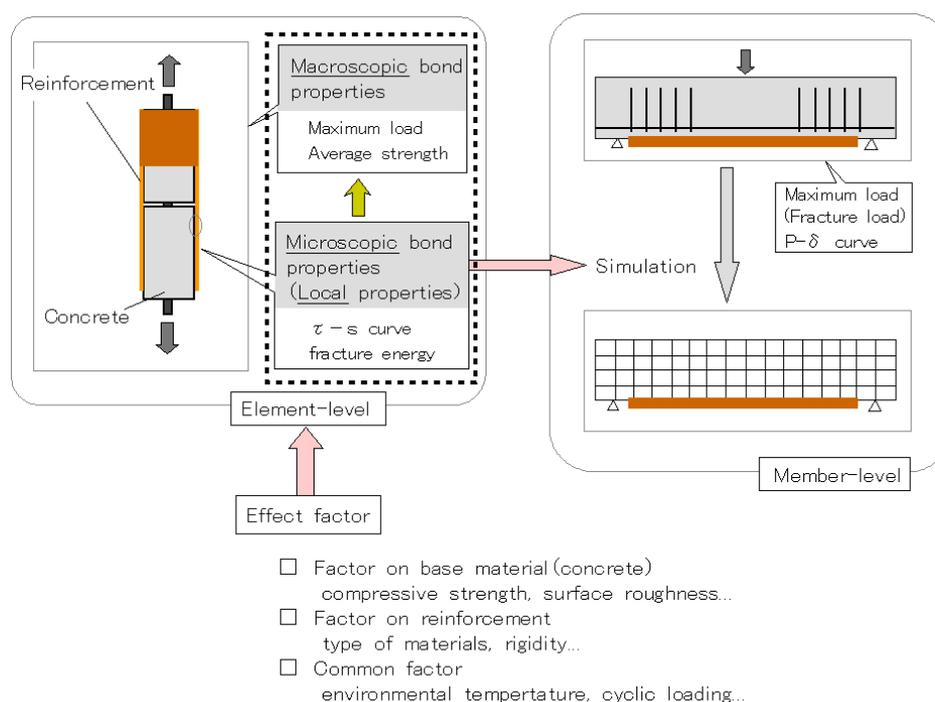


Fig.1 Bond property in element and member levels

(1) Classification of bond property according to force direction

Interface bond types are classified as shown in Fig.2 according to the Adhesion Handbook compiled by The Adhesion Society of Japan [2]. The first type is “shear bond” in which forces act on the interface in parallel. The second type is “cleavage bond” in which forces act at an end of the interface to open it, and the last type is “tensile bond” created by forces acting uniformly in the direction normal to interface. Mouth opening type or Mode I in fracture mechanics corresponds with shear bond, while in-plane shear type or Mode II with T-type cleavage bond. The Committee Report summarizes the state-of-the-art for each of these three bond types.

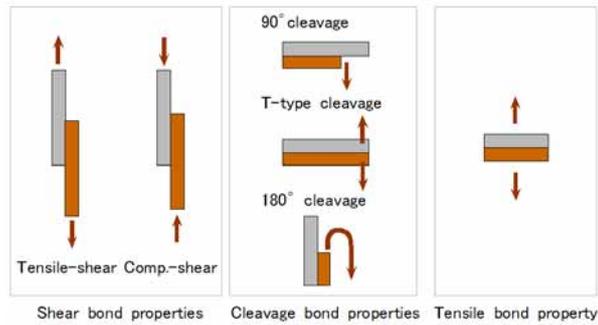


Fig.2 Classification of bond property [2]

(2) Factors for bond property

As shown in Fig.3 mechanical and environmental factors for the bond property are listed for each retrofitting method. The mechanical factors include mechanical properties of retrofitting materials and concrete, other factors for failure criteria, adhesive forces at bonding interface and WBL (Weak Boundary Layer). The mechanical properties of retrofitting materials and concrete are elastic modulus/stiffness of retrofitting materials and concrete strength. Loading rate, member size and their combined effects are the other factors for failure criteria. There are two types of adhesive forces; macro and micro adhesive forces. It is considered that the combined adhesive forces act on the concrete-retrofitting material interface. The macro adhesive forces are called anchor effect which is created by roughness of the concrete surface. WBL, which is among the mechanical factors, are laitance and defect at concrete surface caused by poor construction. The environmental factors are related to environmental conditions. A retrofitting method, which is suitable to achieve the best bond property under effects of the mechanical factors, may not be the best for the environmental factors. The environmental factors are related to physical and chemical properties of retrofitting materials.

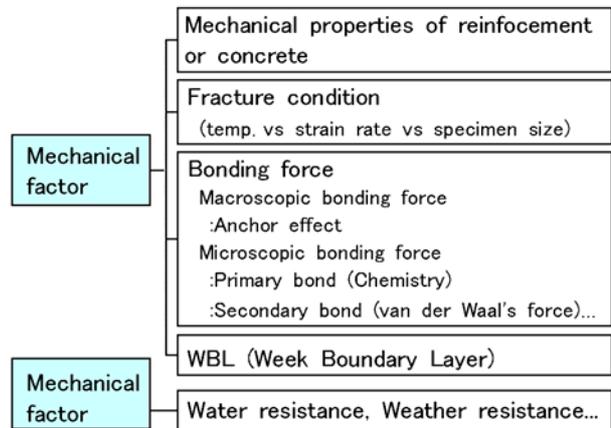


Fig.3 Factors for bond property

(3) Summary of each retrofitting method

Below are the local bond property and the remaining problems to be solved for each retrofitting method:

Overlaying method

Previous studies on interface bond are mostly with qualitative approach, which present concrete surface roughness, wet and dry condition, and direction of joint as the factors. As one of the studies with quantitative approach, the study on peeling in shear at bonding interface of PCM (Polymer Cement Mortar) overlaying at member bottom is introduced. It is expected that a more accurate design for overlaying method can be developed by conducting more studies with quantitative approach.

FRP sheet external bonding method

Extensive researches after the Great Hanshin-Awaji Earthquake in 1995 enhance the reliability and safety of external bonding method with FRP sheet significantly despite the fact that it is a rather new method. Factors investigated in the previous studies with element level experiments are shown. Proposed formula for average bond strength and local bond stress and slip relationship are compared. The remaining problems are clarification of (i) thermal stress mechanism, (ii) deterioration of bonding interface due to blockage of water seepage, and (iii) fracture and durability of interface with new adhesives.

Steel plate external bonding method

Bonding width, length, concrete strength, cyclic loading, and concrete surface condition are explained as the factors. The remaining problems are clarification of interfacial fracture energy and effects of anchor which are used for positioning of the steel plate. Researches with quantitative approach are necessary to develop a rational design method.

FRP plate/grid external bonding method and FRP spraying method

There are not many studies on local bond property in FRP plate/grid external bonding method and FRP

spraying method since they were introduced rather recently. There is an experimental study on macro bond property with single-plane or double-plane shear tests, in which micro bond property is examined indirectly through the macro bond property. It is necessary to quantify the local bond property based on further studies and studies on FRP sheet.

2.2 Simulation of stress transfer in element level by using local bond property

Possibility of predicting macro bond property through simulation of element level behavior by numerical analysis with micro bond property as input data is investigated in the following two cases:

(1) FRP sheet external bonding method

The shear bond and cleavage bond are investigated. Figure 4 shows different local bond stress and slip relationships of concrete surfaces with different surface treatments, which were obtained by double shear planes tests. It is shown that the sheet strain distribution and the maximum pullout force can be predicted accurately.

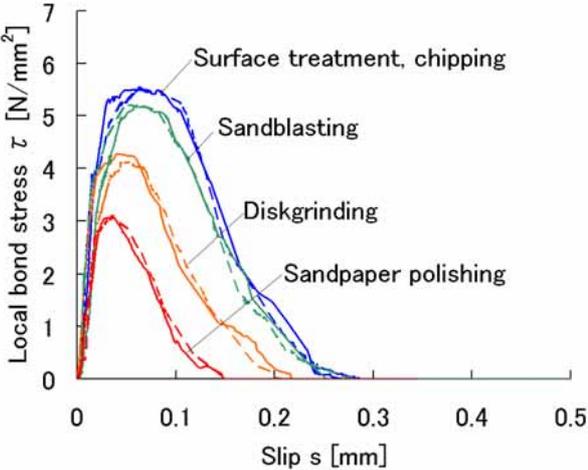


Fig.4 Local bond property

(2) Steel plate external bonding method

Stress analysis with consideration of shear deformation of adhesive layer and numerical analysis with FEM are conducted. The stress analysis can predict measured bond stresses reasonably except those at the plate end. Underestimation of the stresses at the plate end is considered due to the fact that the assumption of uniformly distributed stress in a cross section is not true near the plate end.

2.3 Member property in each retrofitting method

Latest research development on FRP external bonding, steel plate external bonding and concrete overlaying methods are presented with emphasis on clarification of influences of micro bond properties on the member properties after retrofitting.

(1) FRP sheet external bonding method

Tension stiffness of member retrofitted with FRP sheet

In the past, tension stiffness of member retrofitted with FRP sheet was not thoroughly studied the tension stiffness effects and crack spacing prediction are therefore investigated. Figure 5 illustrates the tension stiffness curves (or average concrete stress curves), which are obtained by numerical analysis, of reinforced concrete with and without FRP sheet (RC and RCC). After yielding of steel reinforcement the tension stiffness increases as the FRP sheet (CFS) amount decreases. The crack spacing formula presented is a modified version of CEB-FIP formula. In the formula the local stress and slip relationship is considered.

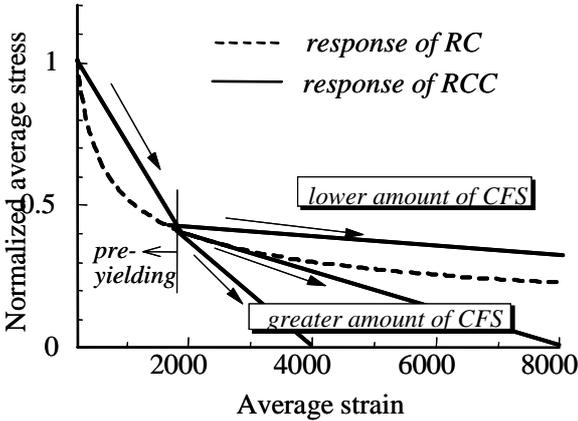


Fig.5 Tension stiffness

Flexural property of member retrofitted with FRP sheet

A finite element analytical method for members retrofitted with FRP sheet in flexure and its results are presented. Based on the analytical results a simplified design method for flexural retrofitting by FRP sheet and design examples is investigated.

Evaluation of shear retrofitting effects by FRP sheet

The same reinforced concrete member with FRP sheet as shear reinforcement is analyzed using three methods; with the modified compression field theory, the finite element method and a macro model. In the analyses where the local bond stress and slip relationship at sheet-concrete interface is applied, the ultimate shear capacities differ between the cases with and without the bond. Interfacial fracture energy affects the shear behavior significantly.

Recent development of retrofitting methods with continuous fiber (or FRP)

Debonding of externally bonded sheet prevents members from developing full structural performances. New methods to overcome this shortcoming are being developed. One of them is prestressed FRP

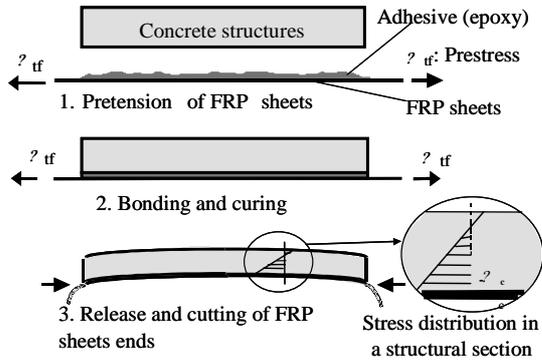


Fig.6 External bonding with prestressed FRP sheet

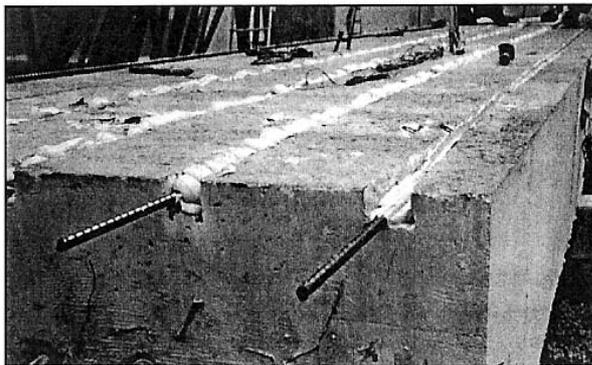


Fig.8 Near Surface Mounted FRP

sheet/plate external bonding method (see Fig.6). Like prestressing steel in prestressed concrete, the prestressing utilizes the material strength more efficiently. Enhancement of the yield load as well as crack width control can be easily achieved.

Retrofitting of column with wing walls by FRP sheet was recently proposed, however its shear resisting mechanism has yet been clarified. A prediction method of the shear capacity with consideration of sheet delamination is introduced. In this method a column with wing walls is replaced by an equivalent rectangular column (see Fig.7).

Carbon FRP plates have been used as externally bonded flexural reinforcement for beams in Japan recently. Its anchorage and fatigue properties are introduced for practical design.

Near surface mounted FRP, which is embedded in groove near the surface and bonded by adhesive resin, is being developed in USA and Switzerland (see Fig.8) [3]. NSM FRP has a much better bond strength than sheet, so that debonding failure can be controlled fully.

The surface treatment before execution, which creates grooves, is necessary for part of the surface, while sheet external bonding requires pre-treatment of the entire surface. The stress transfer mechanism, however, is still being investigated, after which the rational design method will be developed.

Researches to improve the bond property of sheet-concrete interface are being conducted. The methods for improvement are (i) increase surface roughness by sandblasting and water jet, (ii) application of soft adhesive resin. There are some practical applications with those methods.

(2) Steel plate external bonding method

Retrofitted member in flexure

A typical failure mode is out-plane peeling at plate end in the case of a short bonded length for steel plate (see Fig.9). The out-plane peeling is different from the in-plane peeling which often happens in the case of sheet and typical for externally bonded materials, such as steel and FRP plates, whose out-plane flexural stiffness is rather large. Deterioration of bond due to flexural cracking increases the

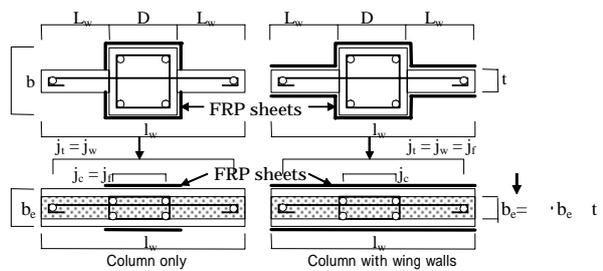


Fig.7 Modeling of column with wing walls

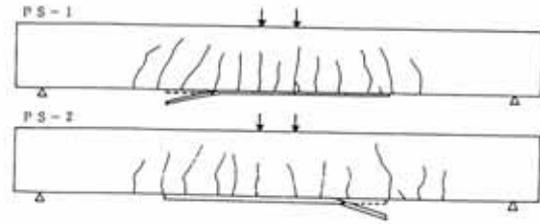


Fig.9 Out-plane peeling of steel plate

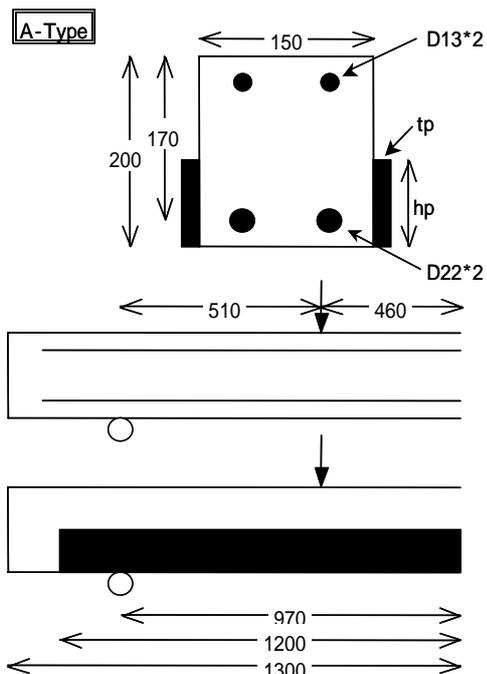


Fig.10 Shear strengthening by steel plate

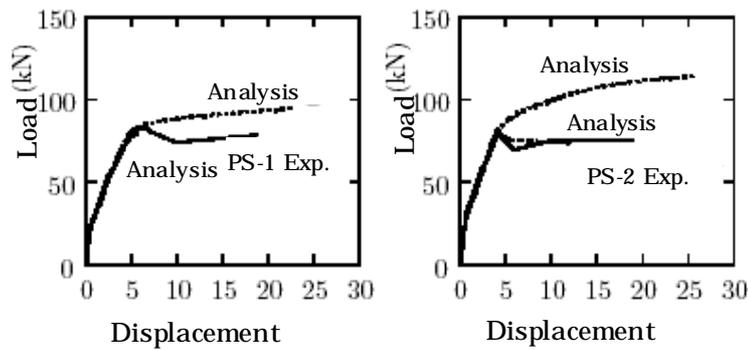


Fig.11 Example of FE analytical results

bond stresses near the plate end and leads to this failure.

Retrofitted member in shear

A study on shear reinforcement by steel plates externally bonded on both sides of beam (see Fig.10) discloses that shear failure is caused by out-of-plane deformation of the steel plates and that the steel plate height affects the shear reinforcement efficiency [4].

Performance evaluation of retrofitted member by FEM

Non-linear FE analysis is conducted for two cases; (i) no peeling of steel plate and (ii) consideration of peeling of steel plate, the latter of which can predict experimental results with a good accuracy (see Fig.11).

(3) Concrete overlaying method

Retrofitting methods by spraying polymer cement mortar (PCM) and highly ductile mortar at the bottom surface of slabs are being developed for shrinkage crack control.

Interface bonding property between the overlaid concrete and the existing member concrete has yet been clarified. Some numerical analyses, in which bi-linear or cut-off types of bond stress and slip curves are applied for bond link element, are introduced. It is expected that further data collection of the bond property can improve the accuracy of the numerical analysis.

2.4 Optimization of retrofitting material and its effect

(1) Micro bond property to optimize macro bond property

Macro bond properties such as the maximum pullout force and corresponding slip depend on micro bond properties. The macro bond properties are calculated with different values of interfacial fracture energy and sheet stiffness (product of elastic modulus and thickness), which is a factor to determine the value of the fracture energy. Figure 12 illustrates a model of the analysis. Relationships between interfacial fracture energy and maximum pullout force and between interfacial fracture energy and slip at the maximum force shown in Fig.13 indicate that the macro bond strength (or pullout force) increases with the interfacial fracture energy. In some cases effective bond length increases with fracture energy. Therefore, bond length should be longer than the effective bond length. It can be seen that the slip at the maximum pullout force is in proportion to the root square of the fracture energy. This is because the local bond stress and slip relationship are assumed to be similar as shown in Fig.14. With this assumption the effective bond length does not change as the fracture energy changes. Figure 15 shows the relationships between sheet stiffness and maximum pullout force and between sheet stiffness and slip at the maximum force under the condition of constant interfacial fracture energy. The macro bond strength increases with the sheet stiffness, however the slip at the maximum force does not change.

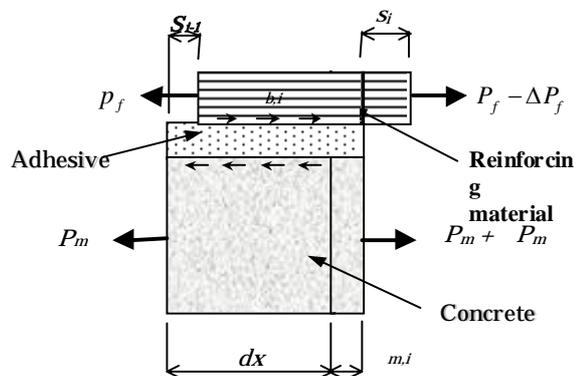
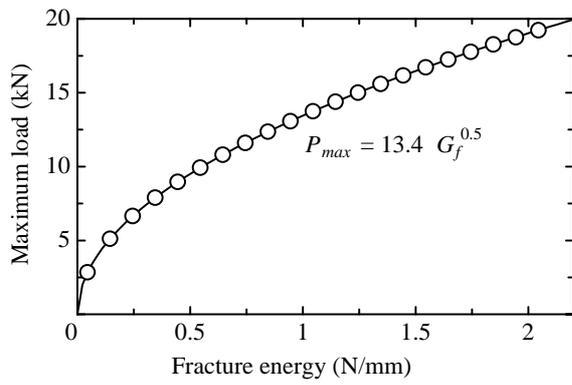


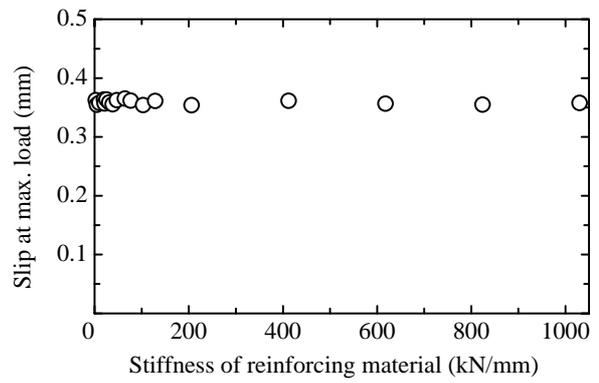
Fig.12 Model for analysis

(2) Micro bond property and mechanical property of retrofitting material to optimize mechanical property of member

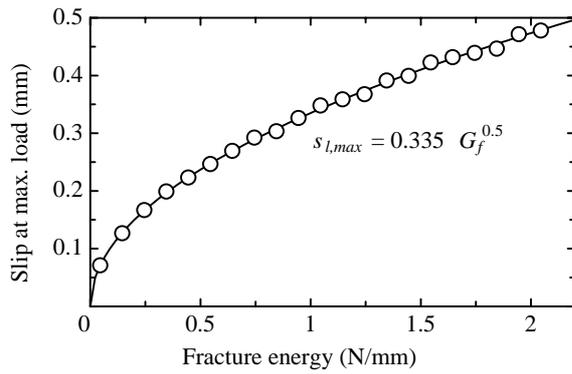
Analysis on shear capacity of retrofitted member, which is similar to the one in (1), is introduced [5]. Table 1 shows the calculation condition, while Fig.16 indicates the relationships between interfacial fracture energy and the shear force carried by sheet for different sheet thickness t_f . In the case of



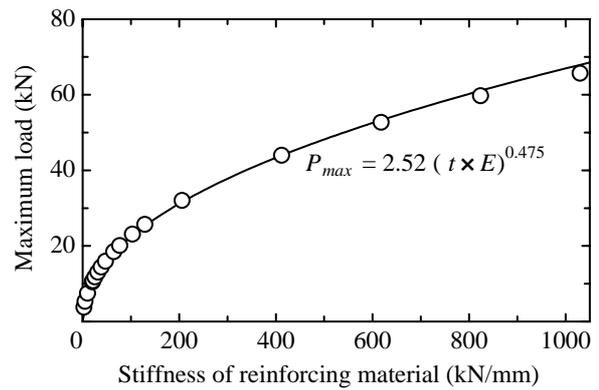
(a) Maximum pullout force



(a) Maximum pullout force



(b) Slip at maximum pullout force



(b) Slip at maximum pullout force

Fig.13 Relationships between interfacial fracture energy and macro bond properties

Fig.15 Relationship between FRP stiffness and macro bond properties

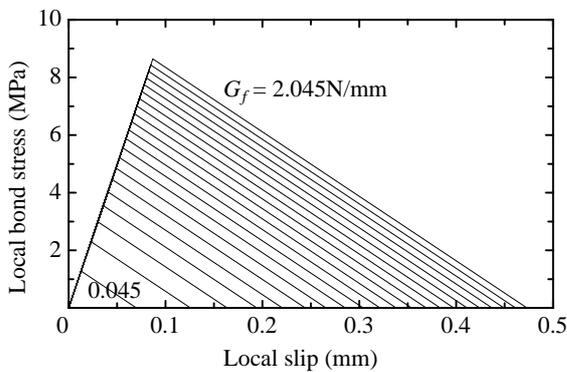


Fig.14 Local bond stress and slip relationship

small thickness (or stiffness) the shear capacity decreases as the fracture energy increases because sheet fracture happens before sheet debonding and this fracture happens sooner with larger fracture energy. In the case of large stiffness the shear capacity increases as the fracture energy increases. Consequently there is the optimum combination of fracture energy and sheet amount (thickness or stiffness) to achieve the high shear capacity.

3. Concluding Remarks

In the Committee Report external bonding,

Table 1 Condition for calculation

Whole depth (mm)	350
Effective depth (mm)	300
Compressive failure strain (μ)	2500
Sheet thickness t_f (mm)	0.05 ~ 0.6
Elastic modulus of the sheet (GPa)	240
Tensile strength of the sheet (MPa)	3000
Shear stress t_c (MPa)	0.94 ~ 60
Slip δ_c (mm)	0.2

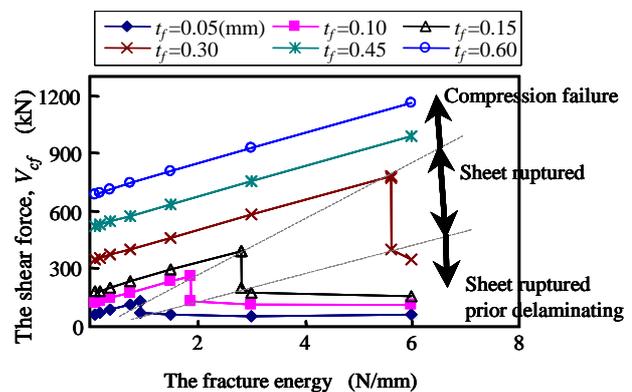


Fig.16 Relationship between interfacial fracture energy and shear force carried by FRP sheet

jacketing and overlaying methods, which have been treated separately, are investigated in the same concept with respect to their interfacial bonding property. The classification according to the types of peeling phenomena (or bond property) is applied instead of types of retrofitting methods. It shows that the macro bond property and the retrofitted member property can be simulated by numerical analysis with modeling of micro bond properties. As a result, it presents the micro bond properties and mechanical properties of retrofitting materials to optimize macro bond properties and member properties after retrofitting.

It is hoped that the findings presented in the Committee Report will help improve the current retrofitting technology and develop rational verification methods for the performances of retrofitted structures. The current report focuses on upgrading of mechanical properties by retrofitting, upgrading of other properties such as durability will be dealt with in our future work.

The Committee Report is also available in English. The report is compiled with papers presented at the JCI International Symposium [1].

Acknowledgments

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References

- [1] Technical Committee on Retrofitting Technology for Concrete Structures (JCI TC-014A): *International Symposium on Latest Achievement of Technology and Research on Retrofitting Concrete Structures, Proceedings and Technical Report of JCI Technical Committee*, Japan Concrete Institute (JCI), JCI-C59E, July 2003.
- [2] The Adhesion Society of Japan: *The Adhesion Handbook*, Third Edition, Nihon Kogyo Shimbun-sha, 1996 (in Japanese).
- [3] Rizkalla, S. and Hassan, T.: Various FRP Strengthening Techniques for Retrofitting Concrete Structures, *FRP Composites in Civil Engineering*, Vol.2, pp.1033-1040, Dec. 2001.
- [4] Adhikary, B. B. and Mutsuyoshi, H.: Nonlinear FEM Model and Design Formula for Externally Bonded Steel Plates for Shear Enhancement of RC Beams , *Proceedings of the Japan Concrete Institute* , Vol.23 , No.1 , 2001.
- [5] Shimbo, T., Shimomura, T., Maruyama, K. and Kamiharako, A.: Sensitivity Analysis on Shear Capacity of Continuous Fiber Reinforced Concrete, *Proceedings of the Japan Concrete Institute*, Vol.22, No.3, pp.313-318, 2000 (in Japanese).