Committee Report : JCI- TC092A

Technical Committee on Bond Models and their Applications for Numerical Analyses

Hiroshi SHIMA, Toshiyuki KANAKUBO, Yuichi UCHIDA, Ken WATANABE

Abstract

The objective of the Committee was to understand bond behavior on a microscopic scale, and thus to review the information relating to bond behavior, and to make a proposal for using the information specifically through determination of a bond constitutive law which is practical in FEM. This paper reports the activities and describes part of the study results of individual working groups: Basic WG (to review and to introduce various topics relating to bond problems); WG2 (to study the FEM constitutive law; performing meso-scale FE analysis to determine τ-s relationship); and WG3 (FEM member WG; performing FE analysis of members' experiments using several τ-s relationships).

Keywords: Bond constitutive law, Basic bond equation, Literature survey, FEM, RBSM, Bond splitting, Meso-scale

1. Introduction

Brittle fractures of reinforced concrete members include bond fracture and anchorage fracture. The full understanding of bond and anchorage fractures is, however, very difficult owing to the interactions of microscopic stress transmission, the constitutive law of each material, linked fractures at the macroscopic level, etc. In recent years, Finite Element Method (FEM) has become a useful tool to determine the behavior of reinforced concrete members. FEM is, however, significantly affected by the model of bond behavior, specifically the preconditions in a bond-softening region considerably affect the accuracy of the solution. The Committee carried out research activities (FY2009 to FY2010) aiming to grasp the bond behavior on a microscopic scale, thus to review the information relating to bond behavior and to make a proposal for using the information specifically through determination of the bond constitutive law in FEM aimed at its practical application. **Table 1** lists the members of the Committee.

The activities of the Committee proceeded in roughly two stages. In the first stage, the research of each member was introduced, aiming at recognition of bond

Table 1: Committee Members

Chairman	Hiroshi SHIMA	Kochi University of Technology
WG1 (Basic)		
○	Toshiyuki KANAKUBO *1	University of Tsukuba
	Keiichi IIZUKA	Tokyo Electric Power Services Co., Ltd.
	Tetsuzo KAKU	Nihon Fukushi University
	Kenji KABAYAMA	Shibaura Institute of Technology
	Goro KONDO	Chiba University
	Yuichi SATO *2	Kyoto University
	Yuya TAKASE	Tobishima Corporation
	Yukihiro TANIMURA	Railway Technical Research Institute
	Yasutaka NOMA	Hazama Corporation: Jan. 2011 -
	Takeju MATSUKA	Hazama Corporation: - Dec. 2010
	Akira YASOJIMA *1	University of Tsukuba
WG2 (FEM constitutive law)		
○	Yuichi UCHIDA	Gifu University
	Hikaru NAKAMURA	Nagoya University
WG3 (FEM members)		
○	Ken WATANABE	Railway Technical Research Institute
	Takashi KASHIWAZAKI	Chiba University
	Yousok KIM	University of Tokyo
	Shigehiko SAITO	University of Yamanashi
	Kazuki TAJIMA	Nihon University
	Takeshi MAKI	Saitama University
	Tadatomo WATANABE	Hokubu Consultant Co., Ltd.

Persons marked by ○ are managers of the WG.

*1 Also in WG4 (General Affairs).

*2 Also in WG3 (FEM members).

issues by all the members of the Committee and of different points to emphasize depending on differences in their respective special fields (civil and architecture), and aiming at information exchange relating to the latest research on bond problems.
The introduction covered a wide spectrum, including the result of RBSM analysis using a detailed model of the node shape of deformed reinforcing bars, the bond splitting fracture of reinforced concrete members under an anti-symmetric bending moment, and the FEM analysis of the bond splitting fracture.

The keywords discussed in the information exchange and largely accepted by the members of the Committee include "bond constitutive law" and "relationship between bond stress and slip during fracture". Although the term "bond constitutive law" is still not familiar even in the concrete engineering field, the Committee members have commonly used the term as an expression of the relationship between the bond stress τ (shear stress) and the relative slip s (shear deformation) between reinforcement and surrounding concrete, or further the relationship with the strain of reinforcement in some cases. The term "relationship between bond stress and slip" is a bond constitutive law applied to the case of cracks in peripheral concrete and of making bond stress decrease at an early stage. The correlation between the state of stress of peripheral concrete and the bond constitutive law has become a keyword in the Committee's activity.

The second stage was the organization of working groups (WGs) to implement the detailed activities of the Committee based on the discussions given in the introduction to members' research. The discussions led to the following four working groups.

- WG1: Basic WG (WG to review and to introduce various topics relating to bond problems)
- WG2: WG to study the FEM constitutive law (WG to conduct FEM meso-scale analysis to determine the τ-s relationship)
- WG3: FEM member WG (WG to conduct FE analysis of members’ experiments using the τ-s relation
- WG4: General Affairs WG

Chapters **2** to **4** of the paper describe a summary of the activities of WG1 to WG3.

2. Review of bond problems, and bond in the literature and cases of damage

2.1 Review of information on bond problems and literature in the field

(1) History of basic equations of bond

Experiments to validate the bond and anchor strength of reinforced concrete began in Europe and the U.S. as early as the beginning of the 20th century. However, establishing a theoretical quantitative equation satisfying bond slip and material deformation, and expressing a balance between bond stress and intersection forces, did not show steady progress. The reasons for the difficulty in establishing a theoretical equation are presumably the troublesome computation, the difficulty in experimental verification, and the limited applications of the research results.

Presently the basic equation governing bond behavior is a differential equation of second order, represented by Eq.(1) (hereinafter referred to as the “basic bond equation”).

$$\frac{d^2s}{dx^2} = \frac{4}{d_b}\left(\frac{1}{\rho_s E_s} + \frac{1}{E_c}\right)\tau \quad (1)$$

where, E_s is the elastic modulus of a reinforcing bar, E_c is the elastic modulus of concrete, d_b is the diameter of the reinforcing bar, and ρ_s is the ratio of reinforcement.

Table 2 summarizes the development of research on the basic bond equation. The history began in the early 20th century. However, verification of accuracy and of practical applicability based on experiments began in the 1950s. Arnovljević and Bufler derived a differential equation for the stress of a reinforcement, and Fukuda derived an equation for the bond stress. Rehm provided an equation correlating the differential equation of second order for s with τ, given in Eq.(1). Although the same can be said for any differential equation for any variable, the use of the τ-s equation proposed by Rehm might enhance adoption of the τ-s relationship as a simulative constitutive law.

(2) Rearrangement of basic bond equation

This section reviews the basic bond equation. The position in the axial direction of reinforcement in a reinforced concrete is adopted as an independent variable x. There are eight unknowns in analyzing the bond problem: force applied to the reinforcing bar and to the concrete, ($P_b(x)$ and $P_c(x)$); stress ($\sigma_b(x)$ and $\sigma_c(x)$); strain ($\varepsilon_b(x)$ and $\varepsilon_c(x)$), bond stress ($\tau_b(x)$), and slippage ($s(x)$). The constants are the elastic modulus of the reinforcing bar and of concrete, (E_b, E_c, $n=E_b/E_c$), and the cross sectional area (A_b, A_c, $p=A_b/A_c$), and perimeter of the reinforcing bar (φ_b). There are four conditions (seven equations) for the unknowns to be satisfied.

(i) Material constitutive law

$$\sigma_b(x) = E_b \cdot \varepsilon_b(x), \quad \sigma_c(x) = E_c \cdot \varepsilon_c(x)$$

(ii) Stress definition

$$\sigma_b(x) = P_b(x)/A_b, \quad \sigma_c(x) = P_c(x)/A_c$$

(iii) Equivalent condition of force

$$\frac{dP_b(x)}{dx} = \tau_b(x) \cdot \phi_b, \quad \frac{dP_c(x)}{dx} = -\tau_b(x) \cdot \phi_b$$

(iv) Definition of slippage (Equation of deformation compatibility condition)

$$s(x) = \int_{x_0}^{x} \varepsilon_b(x)\,dx - \int_{x_0}^{x} \varepsilon_c(x)\,dx + s_0 \quad (2)$$

where, s_0 is the slippage at $x = x_0$.

Table 2: Development of bond basic equation

Year	Researcher	Outline of research
1909	Ivan Arnovljević	**Derivation of a differential equation of second order** which dominates shear slip on a joint interface for steel plates joined together by welding or by riveting.
1933	Takeo Fukuda	**Application of the differential equation** of Arnovljević to the RC bond problem. Trial calculation based on the assumption of linearity.
1958	Hans Bufler	Calculation based on the assumption of linearity. **Comparison with bond stress experimental values.**
1961	Gallus Rehm	Modeling the *τ-s* relationship by a square root equation under an assumption of linearity. **Providing a differential equation for the slip *s*.**
1967	Hiroshi Muguruma and Shiro Morita	**Calculation based on a non-linearity assumption.**
1975	Shiro Morita and Tetsuzo Sumi	**A *τ-s* history model under repeated loading.**

Eq.(2) is differentiated with respect to x to derive Eq.(3).

$$\frac{ds(x)}{dx} = \varepsilon_b(x) - \varepsilon_c(x) \tag{3}$$

Further Eq.(3) is differentiated with respect to x to derive Eq.(4).

$$\frac{d^2 s(x)}{dx^2} = \frac{d\varepsilon_b(x)}{dx} - \frac{d\varepsilon_c(x)}{dx} = \tau_b(x) \cdot \phi_b \cdot \frac{1}{A_b \cdot E_b} + \tau_b(x) \cdot \phi_b \cdot \frac{1}{A_c \cdot E_c} \tag{4}$$

Thus Eq.(5) is obtained.

$$\frac{d^2 s(x)}{dx^2} = \frac{1 + n \cdot p}{A_b \cdot E_b} \cdot \tau_b(x) \cdot \phi_b \tag{5}$$

The eighth conditional equation can be an arbitrary one. If, for example, Eq.(6) is adopted,

$$\tau_b(x) = f(s(x)) \tag{6}$$

then Eq.(5) becomes a differential equation of $s(x)$, which is convenient. Eq.(6) is, however, difficult to solve mathematically. Eq.(6) is what is called the "bond constitutive law".

Alternatively, for example, if Eq.(7) is applied,

$$\tau_b(x) = f(s(x),\ \varepsilon_b(x)) \tag{7}$$

if the relationship of Eq.(2) is used, then Eq.(6) holds. Unless, however, the boundary conditions (x_0 and s_0) in Eq.(2) are determined, Eq.(7) cannot be determined. If (x_0 and s_0) are known (such as in a pull-out condition for the case of sufficiently long bond length), $\varepsilon_b(x)$ can change $\tau_0(x)$.

(3) Literature survey on bond behavior and bond constitutive law

There are many papers related to bond behavior and bond constitutive law. Regarding these, the Committee focused on bond constitutive law and surveyed the following journals.

(i) Journal of Japan Society of Civil Engineers
(ii) Journal of Architectural Institute of Japan
(iii) Proceedings of Japan Concrete Institute
(iv) Journal of Japan Concrete Institute
(v) Overseas literature
(vi) International conference relating to bond (Bond in Concrete)

<u>Regarding (i) and (ii):</u>

Various *τ-s* relationships were proposed under different loading conditions and different fracture modes. After the papers given in **Table 2** were published, Shima et al. derived a *τ-s* relationship as a function of related parameters based on a pull-out test without bond splitting fracture, and verified that the *τ-s* relationship can also describe the bond characteristics after steel yielded. Kanakubo et al. proposed a *τ-s* relationship for bond splitting fracture and investigated the bond splitting fracture strength.

<u>Regarding (iii):</u>

There are different experimental studies on the *τ-s* relationship. **Table 3** gives an outline of the literature.

<u>Regarding (v):</u>

The trend of bond research was surveyed through literature in the U.S. and German-language area during the period from the end of the 19th century to the beginning of the 21st century. 328 papers appearing in seven journals published in the U.S., Germany and Austria were covered as listed in **Table 4**. In principle, papers that discussing the *τ-s* relationship were selected. The survey results are summarized below.

- At almost the same time as the invention of RC at the end of the 19th century, the bond problem was recognized. The world’s first guideline of RC design in 1904 described a method of calculating the bond stress on a bent member and the allowable bond stress.
- Bond experiments were reportedly conducted as early as at the end of the 19th century. By the 1910s, basic bond test methods were established, including the pullout bond test, tensile bond test, and the measuring method for the slip of main reinforcing bar of a bent beam.
- Slightly after the above experiments, a test method for a cantilever beam was developed in 1940. In the initial period of the research, the method was applied to validate the anchoring of a bent main reinforcing bar.

- The bond research was encouraged whenever a new type of reinforcement was introduced, such as the deformed reinforcing bar, the high strength reinforcing bar, the epoxy-coated reinforcing bar and the use of FRP.
- In early stage, the bond research was limited to the bent main reinforcing bars of a beam and to their lap joints. It was extended to the tension-stiffening of flat plate from the 1970s, and to the joints and columns from the 1980s.
- From the 1970s, the study of bond splitting fracture was started, and a resistance mechanism model applying ring tension was proposed.
- Bond analysis using a differential equation first appeared in 1933. However, the analytical study on bond problems began to receive much attentions only after 1961, when Rehm's work was published.
- The FEM for RC structures began with the research of Ngo et al. in 1967, and the modeling of bonds using bond-link elements is first proposed by this work.

2.2 Review of guidelines, standards, and textbooks related to bond

Aiming at a review of bond information which appeared in guidelines and standards for bond inside and outside Japan, a survey was undertaken on the following standards. The subjects emphasized were whether the τ-s relationship was presented or described, and whether the evaluation of cracks and anchors took the bond performance (strength) into account.

- Standard Specification of Concrete [Design Part], Japan Society of Civil Engineers (2007)
- Standard and Description of Calculation of Reinforced Concrete Structures, Architectural Institute of Japan (2010)
- CEB-fip Model Code (1990, 2010)

The CEB-fip Model Code (2010) added the pullout state of a reinforcing bar to the conventional τ-s model and determined parameters in the concrete splitting state, thus allowing the model to perform better.

Table 3: Literature survey in Annual Journal of Japan Concrete Institute

Author	Object of study	Method of study	Major results
Okamura et al. (1983)	Grasp of local *τ-s* relationship.	Test of repeated pullout bond with parameters of anchor length and concrete strength.	An analytical model is provided, with constitutive elements of a reinforcing bar and concrete at the interface layer.
Morita, Fujii et al. (1984)	Observation of the *τ-s* relationship when a pillar suffers a bond splitting fracture.	Test on a short pillar under repeated loading in alternate positive and negative directions.	The current findings on bond are applicable also to a pillar member.
Fujii, Sumi, Nagatomo et al. (1999, 2001)	Bond characteristics at side-split type bond fracture.	A simplified specimen is provided. Pullout bond test with parameters of reinforcing bar diameter and anchor length.	The *τ-s* curve converges to a single shape departing from the loading edge.
Nagatomo et al. (2004)	Simulation of side-split type bond fracture.	Numerical analysis by the incremental method using a one-dimensional spring model.	The proposed model shows good agreement with the test result.
Shima et al. (1991)	The *τ-s* relationship in case of corrosion of a reinforcing bar.	Pull-out test with parameters of corrosion rate of reinforcing bar, covering depth, and presence/absence of reinforcing bar.	With the progress of corrosion, the maximum bond stress linearly decreases, and the decrease rate significantly increases with increase in the covering depth.
Shima et al. (1991)	Adoption of CFCC (Carbon Fiber Composite Cable) instead of reinforcing bar.	Pull-off test with parameters of anchor length and concrete strength.	No effect of concrete strength appears. The effect of the difference in anchor length on the *τ-s* relationship is small.
Shima et al. (1993)	Effect of loading speed on the *τ-s* relationship.	Pull-out test while varying the loading speed from the quasi-static state to the impact-loading state.	The degree of maximum bond stress has a linear correlation with the logarithm of loading speed.
Kanakubo et al. (1996, 1997)	Grasping the *τ-s* relationship in a RC member with bond splitting fracture.	Pull-out test with a slit formed in the concrete portion.	The bond splitting fracture strength is evaluated by the distance from the center of the main reinforcing bar to the slit, the ratio of the main reinforcing bar diameter, and the concrete splitting strength.
Kanakubo, Yasojima et al. (2000, 2004)	Bond performance of the main reinforcing bar under lateral restriction.	Pull-out test with parameters of lateral restriction force, etc.	The maximum bond stress increases with the gradient of the restriction stress and with concrete strength.
Ono et al. (1992, 1993)	Investigation of variations of the *τ-s* relationship with time.	Sustained loading test for a tensile bond specimen.	A *τ-s* relationship model under sustained loading is provided. The distribution of the degree of strain and the changes of slippage in the edge part with time can be analytically grasped.
Ono et al. (2007, 2008, 2009)	Grasping the *τ-s* relationship between a fine deformed reinforcing bar and concrete.	Pullout bond test and tensile bond test with parameters of reinforcing bar diameter, node shape, concrete strength, covering depth, and anchor length.	The *τ-s* relationship is bilinearly approximated. A model equation is provided using the test parameters.
Ichinose et al. (2000, 2001)	Effect of dimensions on bond splitting fracture.	Two-dimensional stress analysis by FEM, and pull-out test with lateral reinforcing bars.	The dimensional effect affects the maximum bond stress.
Kondo et al. (2005)	The local *τ-s* relationship under sustained loading.	Sustained loading test for a specimen having a short bond region, and pull-out test for the specimen after the sustained loading test.	The relationship between the slip speed and the bond stress rate is formulated.
Kondo et al. (2008)	Effect of loading speed.	Pull-out test with varying slip speed for the pull-out type and the bond splitting fracture type.	The effect of loading speed on maximum bond stress is larger in the bond splitting fracture type.
Saito, Higai et al. (2005)	Grasping the *τ-s* relationship in the case of short covering depth.	Tensile bond test with parameters of covering depth and reinforcing bar diameter.	A *τ-s* model applicable also to the case of short covering depth is formulated.

Table 4: Overseas literature surveyed

Abbreviation	Name of journal	Period	Outline	Number of papers
ACI	Journal of American Concrete Institute	1905-1986	Journal of American Concrete Institute	101
	Structural Journal of ACI	1987-2010	Structural Journal of ACI	
ASCE	Transactions of the American Society of Civil Engineers	1872-1940	Transactions of the American Society of Civil Engineers	104
	Proceedings ASCE, Structural Division	1939-1982	Proceedings ASCE, Structural Division	
	Journal of Structural Engineering, ASCE	1983-2010	Journal of Structural Engineering, ASCE	
BE	Beton und Eisen	1905-1942	Technical journal of German RC engineering; gathering papers, construction reports, and various topics.	47
	Beton- und Stahlbetonbau	1943-1945 1950-1982		
BI	Bauingenieur	1920-1996	Technical journal of German civil engineering; gathering papers, construction reports, and various topics.	5
DAfStb	Deutscher Ausschuss für Eisenbeton	1911-1938	Technical papers of German RC engineering; a single issue contains a single paper of several tens of pages to several hundreds of pages, or contains a few papers.	39
	Deutscher Ausschuss für Stahlbeton	1938-2005		
ZAI	Zeitschrift für Architektur und Ingenieurwesen	1901-1906	General German engineering journal; containing papers and topics about machinery, shipbuilding, electrical equipment, civil engineering, and architectural design.	3
ZÖ	Zeitschrift des Österreichischen Ingenieur- und Architekten-Vereins	1859-1910	Journal of Engineering and Architecture of Austria; containing papers and topics about machinery, shipbuilding, electrical equipment, civil engineering, and architectural design.	20
	Other			9

Also, textbooks on reinforced concrete structures were surveyed to review the descriptions of bond in the textbooks. These textbooks describe bond stress and variables affecting bond behavior. These descriptions were summarized in the book "reinforced concrete structures" by Dr. Kosaka and Dr. Morita.

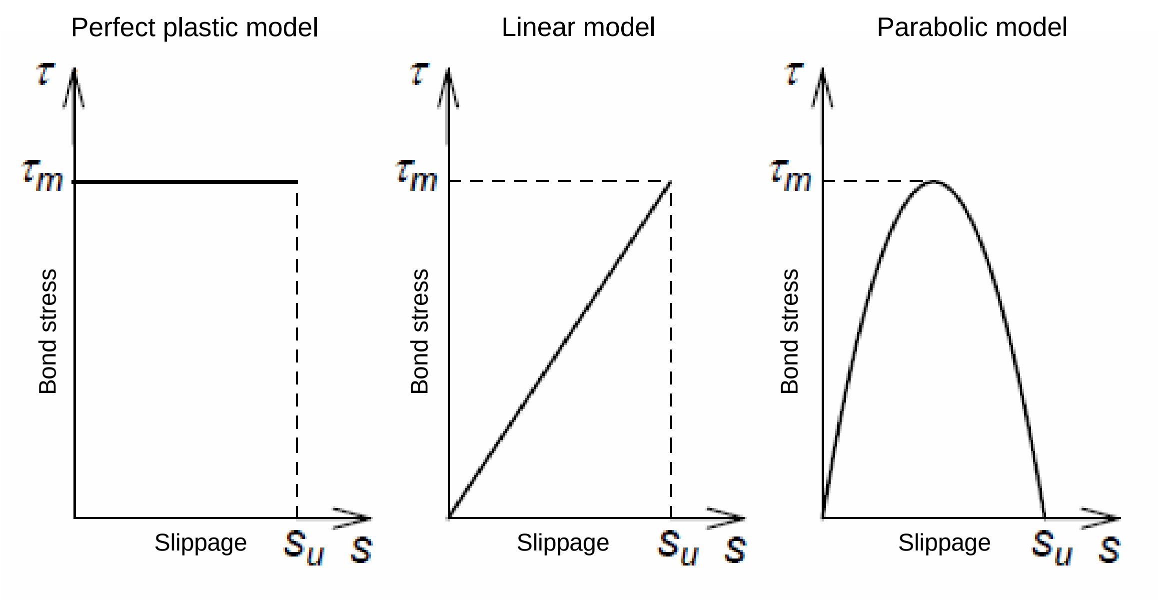


Fig. 1: *τ-s* models deriving a theoretical solution

2.3 Sensitivity analysis by theoretical solution

Presently, the τ-s relationship which can perfectly solve Eq.(5) mathematically is represented by the perfect plastic model, the linear model, and the parabolic model, as illustrated in **Fig. 1**. For each of these models, a theoretical solution and a sensitivity analysis of parameters for a tensile bond specimen and a pullout bond specimen were conducted. **Fig. 2** shows examples of the analysis. In the tensile bond specimen, the linear model and the parabolic model gave similar distributions of bond stress and of tensile force. When the local bond strength, the bond rigidity and the ultimate slip varied, the region where the bond stress occurred significantly varied in all the models. It was also confirmed that the cross sectional area of the specimen and the elastic modulus of concrete did not affect the respective distributions.

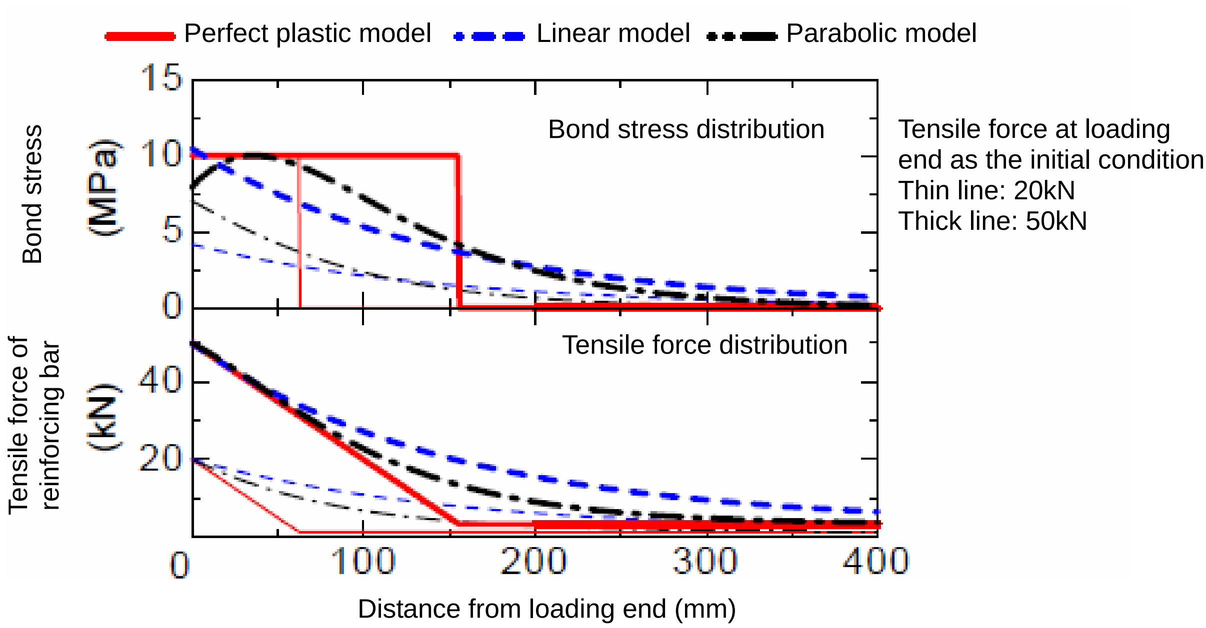


Fig. 2: Examples of sensitivity analysis

2.4 Examples of actual damaged structures

Among the disaster cases of structures in the Southern Hyogo Earthquake, a survey was carried out on bond failure. The survey showed some cases of bond splitting fracture along the main reinforcing bar in beams and columns (**Photo 1**), of separation of cover concrete on columns using a round reinforcing bar, and of bond cracks accompanied by shear fracture, etc.

Photo 1: Examples of bond splitting fractures

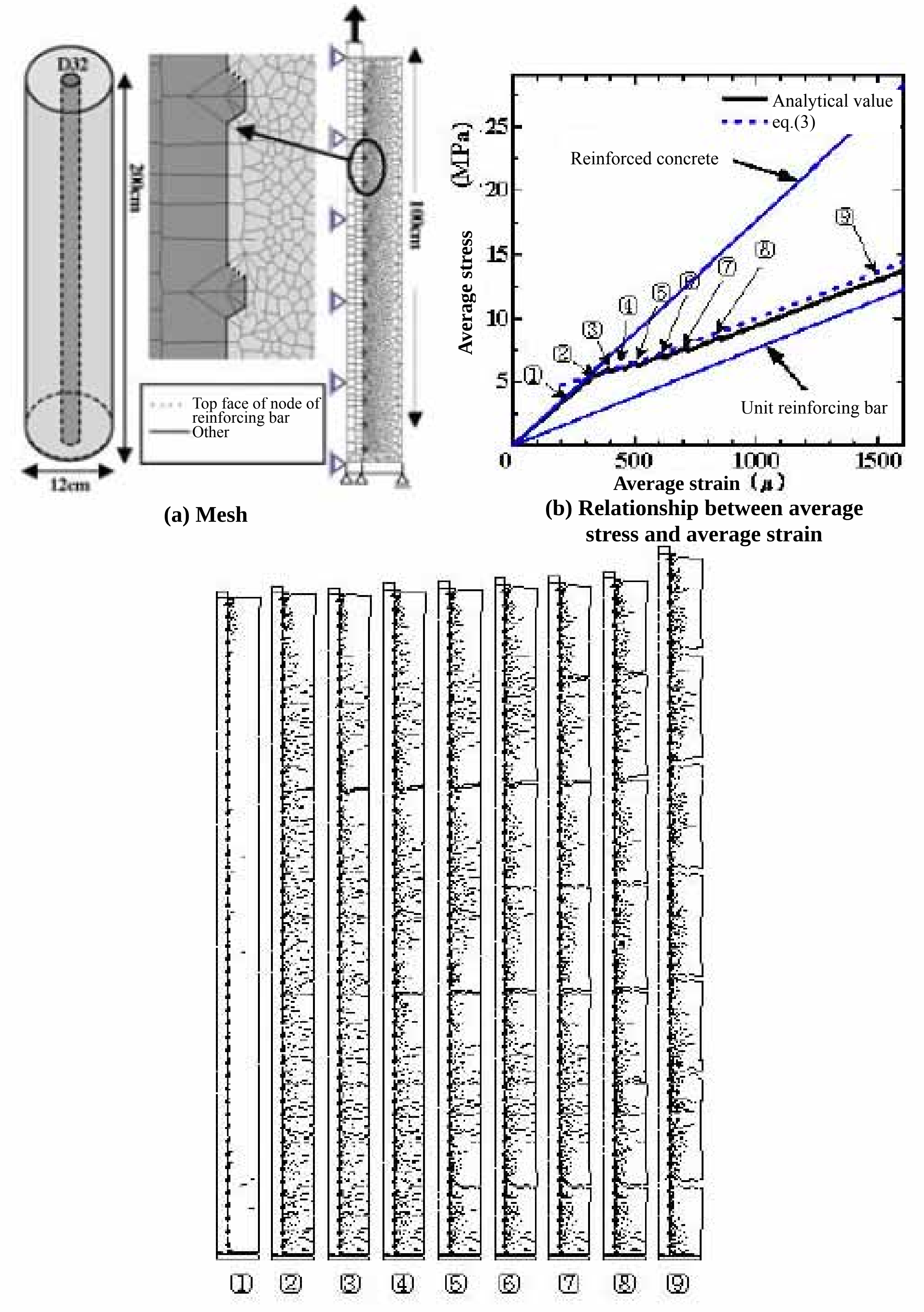
3. Analysis of bond behavior using micromodel

Studies began as early as the 1980s to determine the bond behavior through direct modeling of the mechanical interface locking between the ribs of a reinforcing bar and concrete, which is the essence of the bond between a deformed reinforcing bar and concrete.[1),2),3)] According to the analysis, the *τ-s* relationship is not regarded as a constitutive law, and the bond phenomenon is reproduced as a result of the propagation of fracture of concrete peripheral to the reinforcing bar, such as the internal cracks occurring from the front end of a rib and the plasticizing of concrete at the front side of the rib. Consequently, it is expected that the analytical results give a macroscopic bond model.

For the analysis of a specimen or a member modeled to the size of the ribs of a reinforcing bar, the scale of the problem to be solved becomes large so that a large computational capacity is required. Recently, problems of several tens of thousands of degrees of freedom can be computed at a practical level, and several analyses have already been reported. Examples of analysis by RBSM and FEM are described below.

3.1 Examples of RBSM analysis

Rigid body - spring model (RBSM) is a model which can directly express the crack phenomena of opening and shear, and is an analysis method suitable for analyzing fracture phenomena accompanied by the propagation of cracks. Muto et al.[4)] conducted analysis of a tensile bond specimen with a circular cross section, as illustrated in **Fig. 3 (a)**, by modeling to the size of the rib of a reinforcing bar. **Fig. 3 (b)** shows the relationship between the average stress and the average strain on the entire member. The analysis result agreed well with the values derived from the conventional empirical equation. **Fig. 3 (c)** shows the analysis result for crack propagation. Also, the ultimate crack distance (macroscopic cracks penetrating the cross section) agreed well with that derived from the conventional empirical equation. Since modeling to the size of the rib of a reinforcing bar allows us to reproduce most of the macroscopic bond behavior of a deformed reinforcing bar, it is expected that it will become possible to evaluate the bond mechanism numerically.



(a) Mesh

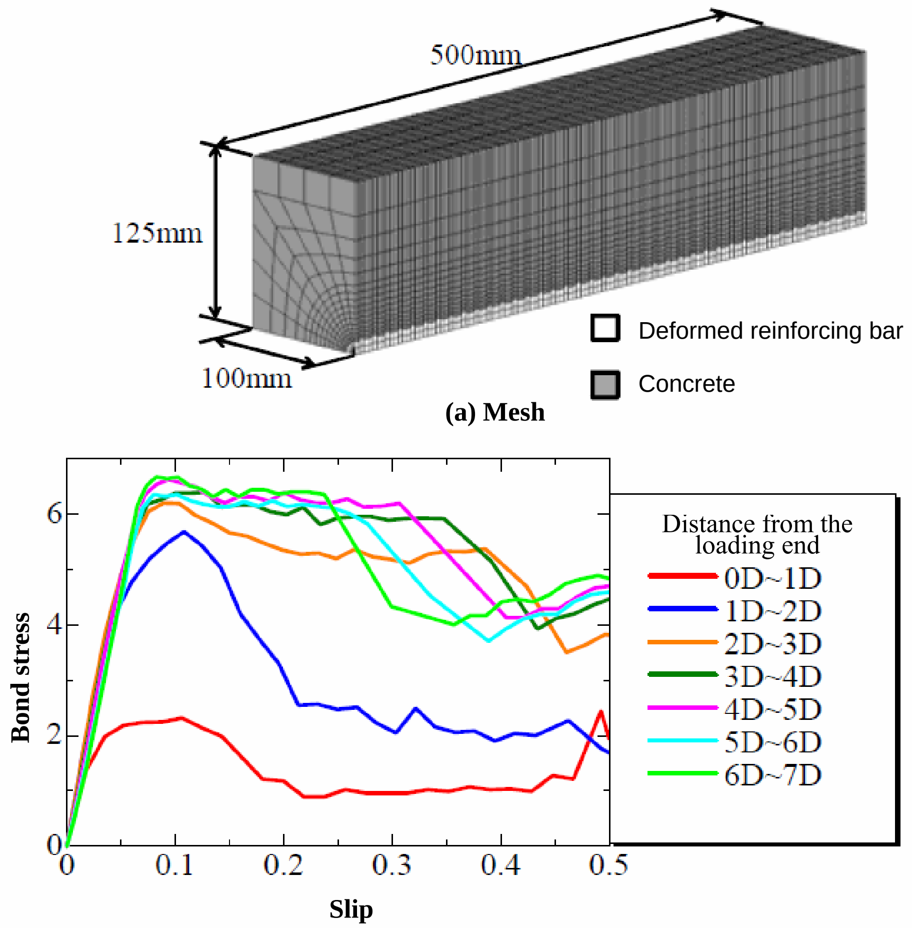
(b) Relationship between average stress and average strain

(c) Propagation of cracks

Fig. 3: Analysis of tensile bond specimen by RBSM[4)]

3.2 Examples of FEM analysis

Fig. 4 (a) illustrates a finite element model of a tensile bond specimen having a cross section of 200 mm x 250 mm with a reinforcing bar of D19 in diameter. **Fig. 4 (b)** shows the *τ*-*s* relationship at points located at different distances from the loading end determined from the strain distribution in the reinforcing bar. **Fig. 4 (b)** shows that the *τ*-*s* relationship differs at different locations of the reinforcing bar, and the maximum bond stress decreases with the decrease in the distance from the loading end. The phenomenon qualitatively agrees with existing experimental and analytical results[1).]



(b) Relationship between local bond stress and slip

Fig. 4: Analysis of tensile bond specimen by FEM

3.3 Issues of analysis by micro-scale model

Micro-scale analysis is expected to be useful in determining of the bond mechanism. At present, however, the following issues need to be considered.

(1) Material characteristics at microscopic level

The adequacy of applying material characteristics obtained from the macroscopic behavior of the specimen to the characteristics of elements at several millimeter order; and the uncertainty of the presence and effect of a brittle layer near the surface of the reinforcing bar.[5)]

(2) Verification of analysis result

The lack of a verification method for analysis results, and lack of experimental data for the verification because the fracture phenomenon occurs inside the specimen.

(3) Capacity of pre-post processor and of computer

The necessity of a highly functional pre-post processor because of the complex shape, and necessity of a large capacity computer because of the very large degree of freedom in the 3-D problems.

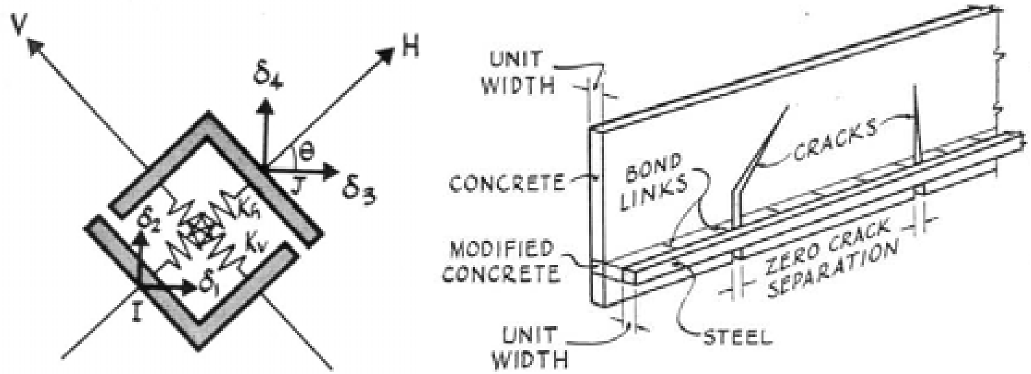
4. Bond in FE analysis of RC member

An objective of the Committee is to solve the load-deformation relationship in RC members with bond splitting fracture based on the stress transmission mechanism. To confirm the role of the bond model, the members of the Committee used their respective analysis tools to perform a trial analysis of a benchmark specimen. This section describes the results of the trial analysis on an RC member, together with the history of analyses.

4.1 History of modeling of bond action

(1) Bond link model

On applying FE analysis to RC structures, the most important issue is the modeling of cracks and the bond action. Actually, the paper of Ngo and Scordelis[6)] which is known to be the first application of FE analysis to RC structures dealt with the modeling. The modeling of bond action provided in the paper is the bond link model. **Fig. 5** illustrates the concept of the bond link model.



(a) Linkage element **(b) Analytical model**

Fig. 5: Bond link model of Ngo and Scordelis

After the introduction of the bond link model, research proceeded on horizontal spring (H axis) and vertical spring (V axis) characteristics which express the bond slip behavior. Muguruma, Morita et al.[7)] proposed a rigidity equation based on various parameters of a reinforcing bar for modeling as a linear spring. Nilson[8)] applied the nonlinear τ-s relationship to a horizontal spring based on the result of the existing tensile bond test, and further modified the characteristics applied depending on the distance from the crack. After the study of Nilson which applied the nonlinear τ-s relationship to the bond link model, studies of modeling of bond action using the bond link model have been concentrated into the following two subjects.

(1) Proposal of τ-s relationship model capable of representing the phenomena.

(2) Verification of bond link model.

For (1), typical expressions are the Morita equation[7)], Nilson equation[8)], and CEB-fip model code[9)]. As historical models, the Morita and Sumi model[10)], and Tassio et al. model[11)], are presented.

For (2), Kokusho et al.[12)] performed FE analysis using a bond link model dealing with pull-out test of the reinforcing bar, and pointed out that the strain state is underestimated in a range from the surface of the reinforcing bar to the depth of double the diameter of the bar. Labib et al.[13)] investigated the vertical spring characteristics of linkage elements and pointed out that the vertical spring characteristics are important to represent the bond phenomena of a deformed reinforcing bar. Morita et al.[14)] pointed out that the τ-s relationship applied to the bond link model is substantially independent from the τ-s relationship obtained from experiments, and they gave the difference in the definition of slippage as a proof.

(2) Cases of modeling of various bond actions

Regarding the modeling of bond action in FE analysis, various methods have been introduced other than that of the bond link model. For example, Rainhardt et al.[3)] provided a slip layer near the reinforcing bar (**Fig. 6**) to simulate the stress state and the crack state in the surrounding concrete. Other methods include that based on fracture dynamics, that expressing stress transmission between concrete and the reinforcing bar, and that which performs an analysis by precisely reproducing the rib shape of the deformed reinforcing bar. In recent years, Ichinose et al.[15)] gave a simulation of bond splitting fracture using deformed reinforcing bars (**Fig. 7**). In addition, a method of expressing the bond-slip by a tension stiffening model which treats the reinforcing bar and concrete integrally, rather than separately, was utilized.

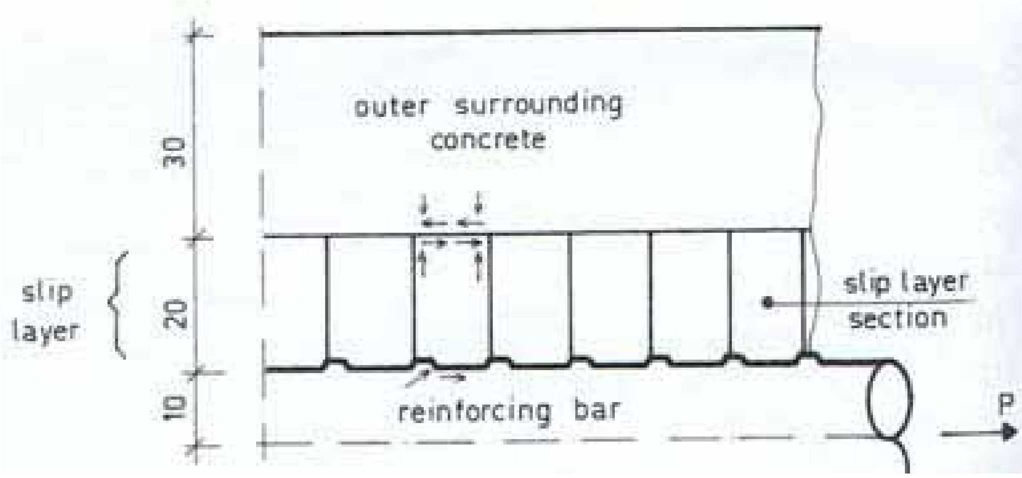


Fig. 6: Slip layer model by Reinhardt et al.

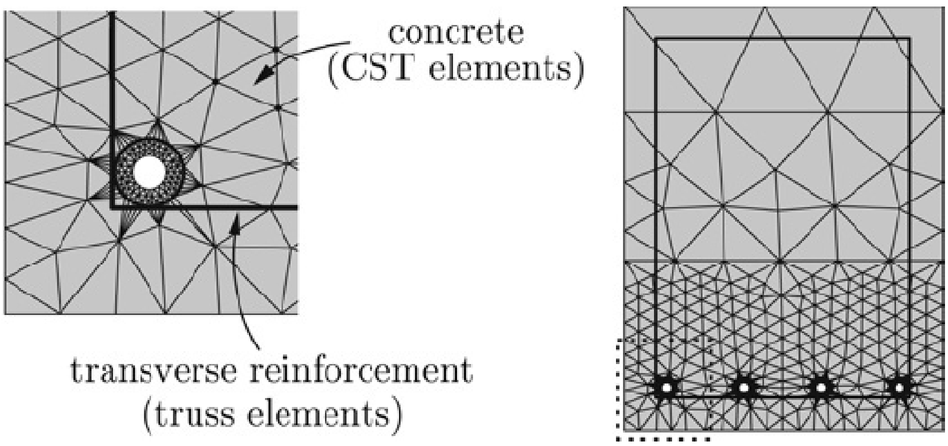


Fig. 7: Mesh on beam section

4.2 Analysis of uniaxial tensile test of RC member

A uniaxial tensile test of RC member is a basic experimental method when investigating the bond characteristics between a reinforcing bar and concrete. This section describes the effect of bond modeling on the analysis result through the analysis of a uniaxial tensile test using nonlinear numerical analysis.

(1) Analysis by the smeared crack model (FEM)[16)]

The specimen to be analyzed was a square pillar (2700 mm in member length, 200 mm x 150 mm in section size) illustrated in **Fig. 8**, with one deformed reinforcing bar D19 being placed at the center of the cross section[17)]. The analysis was two-dimensional and adopted two kinds of models: a model of smeared cracks - smeared reinforcing bars (Code: WCOMD);

and a model of smeared cracks - discrete reinforcing bars (Code: DIANA). In the model of smeared cracks - smeared reinforcing bars, the bond between the reinforcing bar and the concrete is not directly modeled, and the considered parameters include the bond parameter C[18] in the tensile softening characteristic applied to the concrete under tensile stress, and the effect of bond on the relationship between average stress and average strain in the reinforcing bar. On the other hand, in the model of smeared cracks - discrete reinforcing bars, the reinforcing bars are discretized and modeled by beam elements, and the interface joint elements between the reinforcing bar and the concrete take the bond stress - slip model[19] into account.

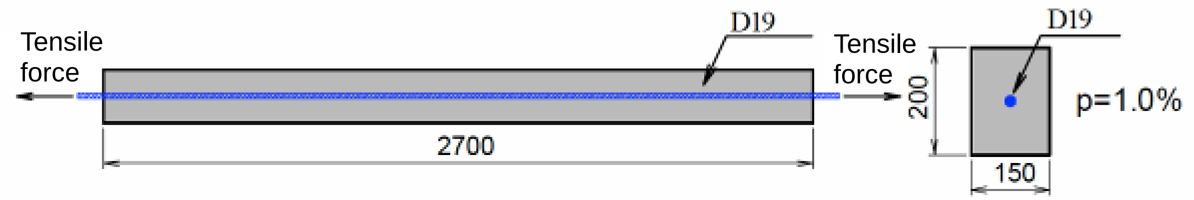


Fig. 8: Uniaxial tensile test specimen

Fig. 9 shows the load-displacement relationship when the bond parameter C (standard C is 0.4) is varied in the analysis of the smeared cracks - smeared reinforcing bars model. The bond parameter C represents the magnitude of bearing stress of concrete under bond, and significantly affects the analytical result.

Fig. 10 shows the analysis result of the smeared cracks - discrete reinforcing bars model. When analysis is performed with discrete reinforcing bars and introducing the τ-s relationship, the characteristic of concrete under tensile stress should exhibit tension softening model. The analysis result, however, underestimated the experimental result. On the other hand, the analysis result using tension stiffening model showed a relatively good agreement with the experimental result. A presumed reason for the good agreement is that, when the smeared crack model is applied to the concrete elements, the cracks do not segregate but tend to be smeared, thus the bond model does not work effectively.

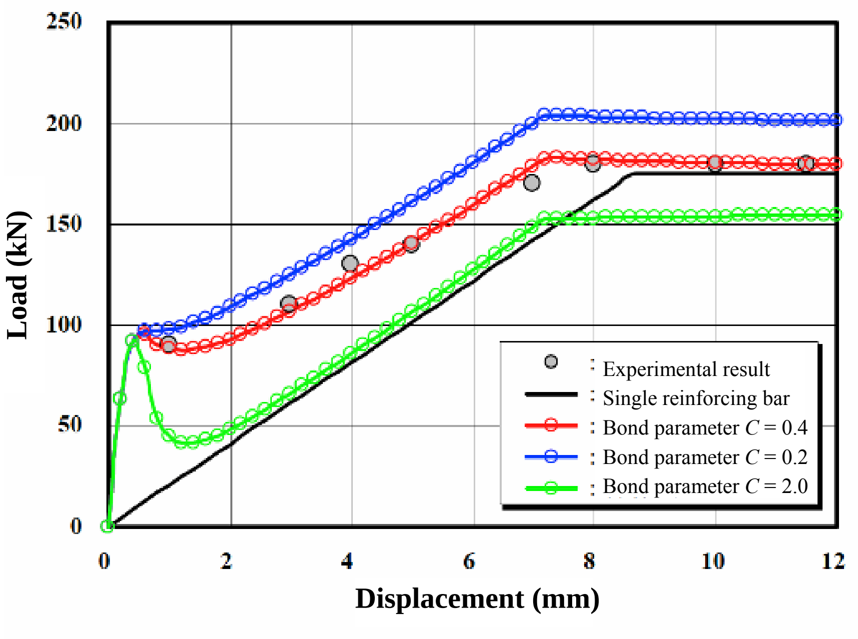


Fig. 9: Relationship between load and displacement (Smeared cracks - smeared reinforcing bar model)

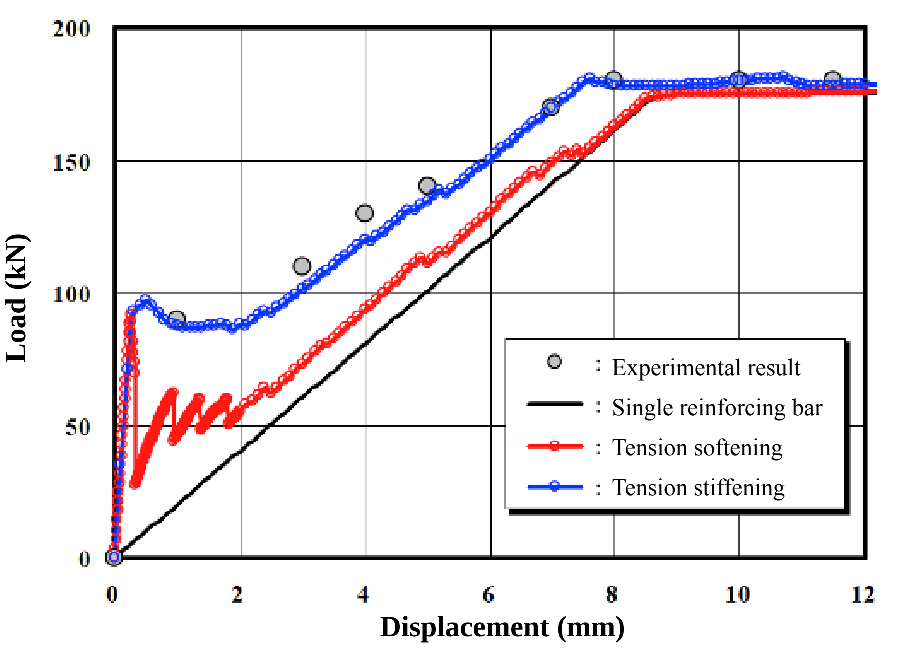


Fig. 10: Relationship between load and displacement (Smeared cracks - discrete reinforcing bar model)

If an object in which the bond effect cannot be neglected is analyzed using the nonlinear finite element method, it is necessary to pay attention to the combination of material models, and to ensure that the bond effect can be adequately evaluated.

(2) Analysis by discrete type analysis model (RBSM)

A uniaxial tensile test of RC member was analyzed by a rigid body - spring model[20] (RBSM) as a discrete type analysis method. **Fig. 11** illustrates the analysis model. The reinforcing bars are discretized and modeled by the beam elements, and a link element is positioned between the reinforcing element and the concrete element to introduce the *τ-s* relationship.

Fig. 12 shows the load-elongation relationship obtained from the analysis and **Fig. 13** shows the cracks. As shown in **Fig. 12**, in the initial stage of loading, the member showed the initial stiffness gradually decreasing stiffness as cracks appeared, and finally approached the behavior of a single reinforcing bar. According to the analysis, the stress becomes dispersed, although slightly, because the concrete is divided into elements having random shapes of an arbitrary polygon, thus resulting in the successive appearance of cracks.

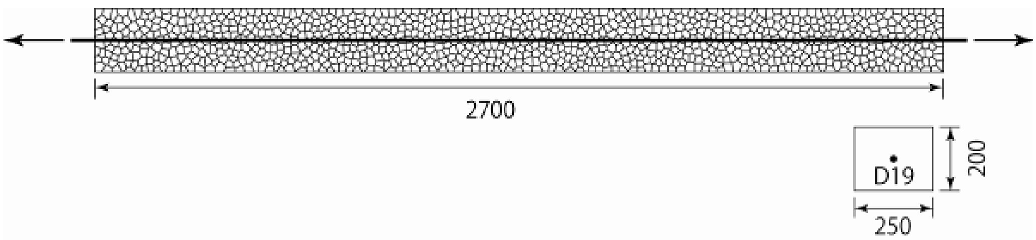


Fig. 11: Analytical model

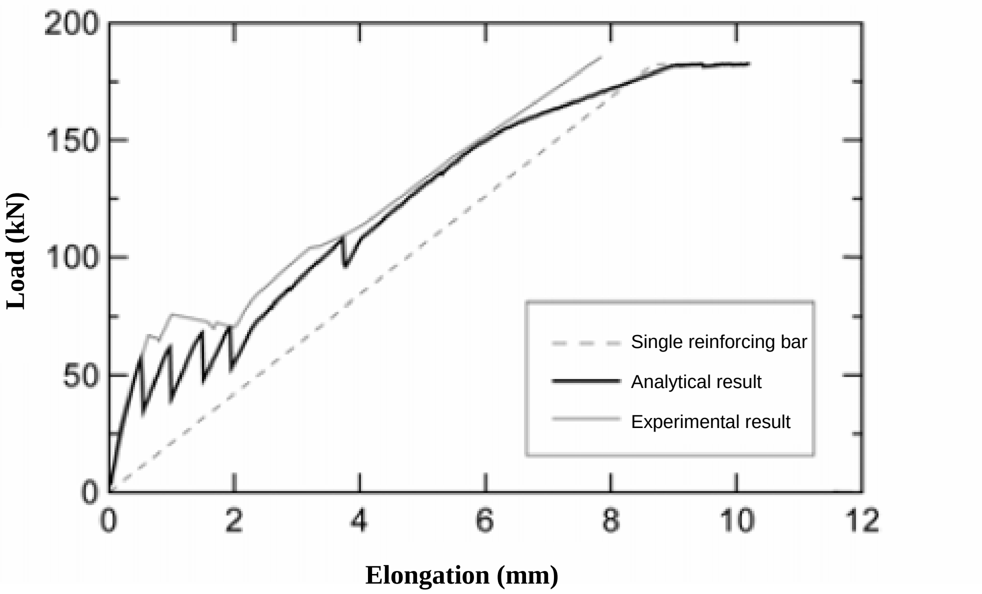


Fig. 12: Load-elongation relationship

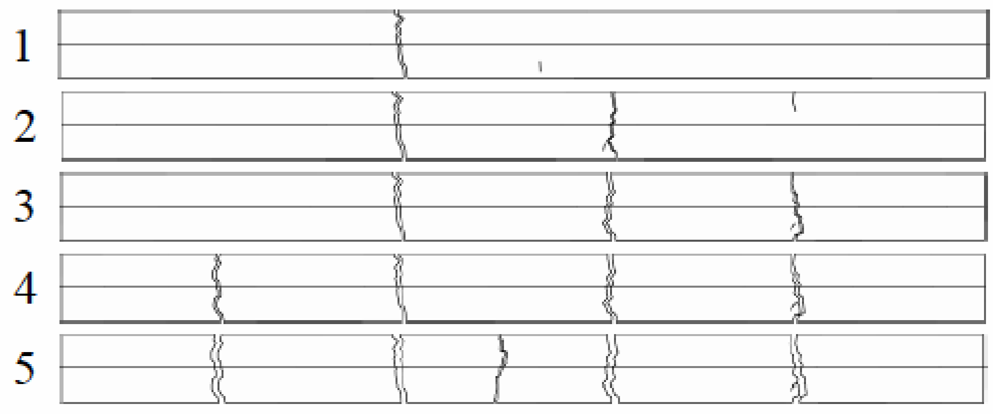


Fig. 13: Crack shapes

When analysis is performed by the ordinary finite element method, there is a uniform stress field inside the member, which is known to generate cracks in the entire region of the member. In that case, to reproduce the successive propagation of cracks requires an analysis model which expresses non-uniformity, such as by providing randomly-distributed tensile strength.

4.3 Analysis of loading test of RC member

FE analysis is applied to a specimen[21)] of RC beam with a small shear span ratio (a/d) under anti-symmetric bending.

(1) Analysis by smeared cracks

The analysis used the commercially available FEM software DIANA, and adopted the model of smeared cracks - discrete reinforcing bars. The model applied to the concrete was the fixed-angle crack model in which a shear stress - shear strain relationship is used considering compatibility with the loading experiment. The nonlinear constitutive law for the concrete is the Thorenfeldt model and the Hordijk model, which considered the fracture energy. To express the interaction between the concrete and the longitudinal reinforcing bars, a trial analysis was performed under the condition that the bond characteristic is assumed as perfect bond, using the τ-s curve proposed by Shima et al. and Suga et al[22)].

Fig. 14 shows examples of the analysis results. In the analysis for DB408, many diagonal cracks occurred at the center of the beam. Since the yield of the shear reinforcing bar is observed in the peak state, the analysis presumably could pursue the fracture state similar to the experiment. On the other hand, for DB608 and DB808, bending shear cracks and cracks along the longitudinal direction of the reinforcing bar occurred. However, many diagonal cracks are observed at the center of the beams, showing a crack pattern different from that observed in the experiment.

(2) Analysis by FEM Code (FINAL)

This section describes the result of FE analysis applied to a benchmark specimen, using the *τ-s* model of Morita and Fujii to the 4-node bond link elements, and forcefully generating bond splitting cracks. The Morita and Fujii model[23)] is a multipoint polyline *τ-s* curve expressing the bond behavior which accompanies splitting, with the feature of quantifying the bond strength and slip during splitting based on many experimental results. On the other hand, the model adopts a linear gradient of 0.01 N/mm^2 until reaching the bond strength, thus giving a somewhat rough assumption as the *τ-s* curve for FEM.

In FEM, the simplest method for expressing the deterioration of bond is to insert the bond link element between the reinforcing bar element and the concrete element, and the method has been widely adopted in research and in actual design. An issue of the method is that the deteriorating bond phenomenon which actually propagates around the reinforcing bar over a fairly wide range is modeled by integrating the phenomenon into dimensionless joint elements. Actually the current commercial FEM cannot correctly reproduce the damage of cover concrete and the propagation of splitting cracks. On this point, the Committee has developed a user subroutine to apply the Morita and Fujii *τ-s* curve to the joint elements, thus forcefully generating cracks in the adjacent concrete, and has applied the subroutine to FINAL, a commercially available software.

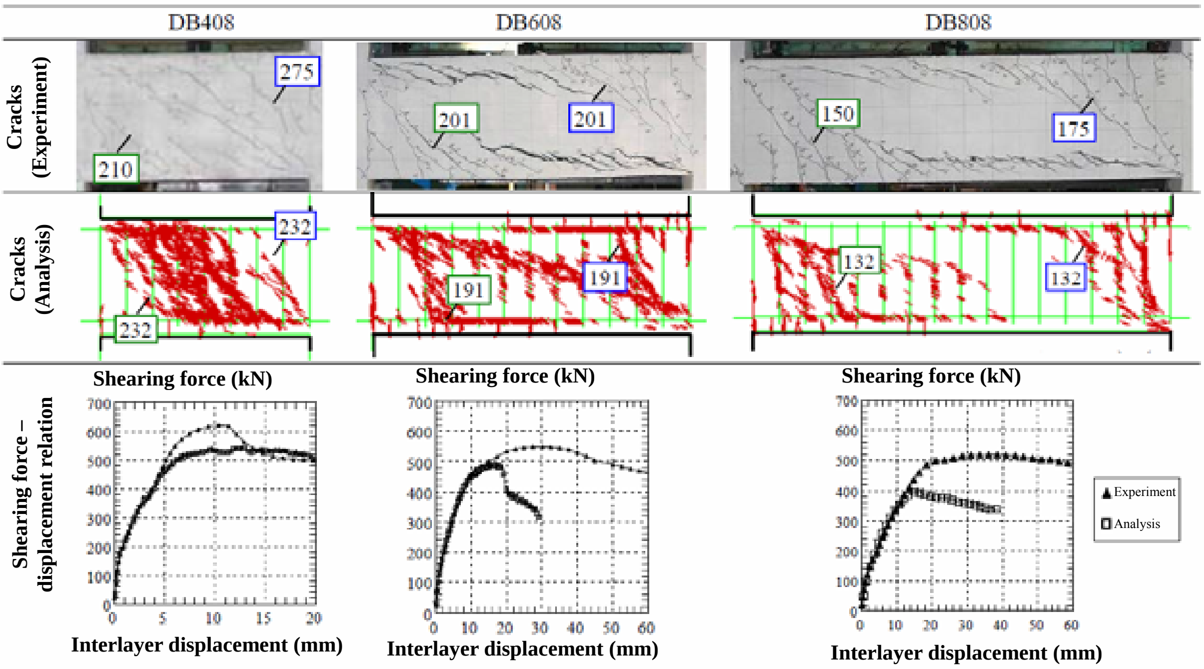


Fig. 14: Examples of analysis results using the smeared cracks - discrete reinforcing bar model

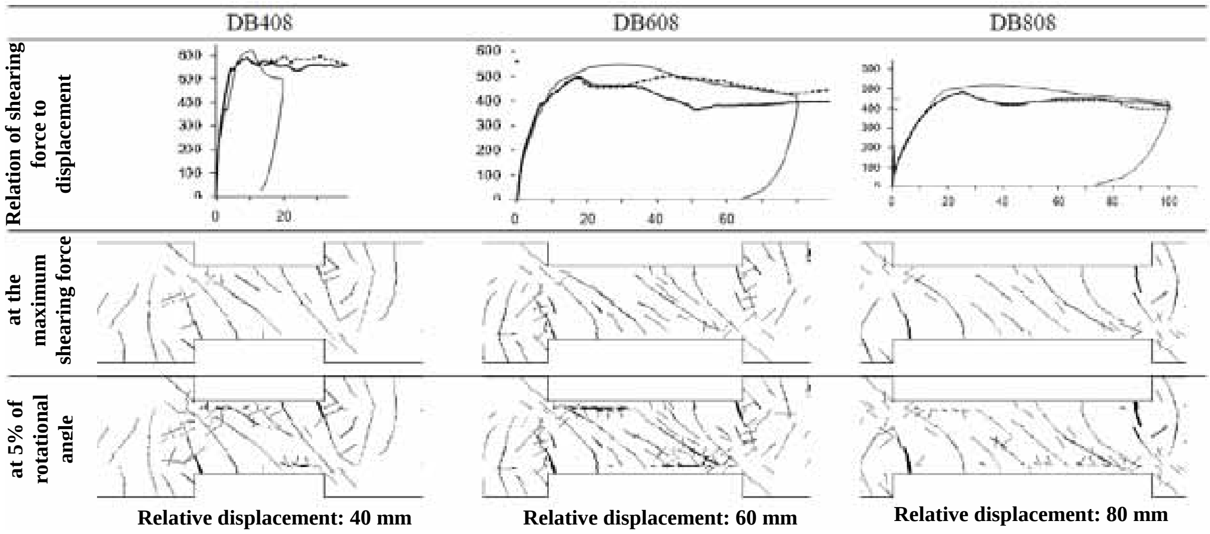


Fig. 15: Examples of analysis results using FEM Code (FINAL)

Fig. 15 shows the analysis of the shear force – displacement relationship (the thin line is experimental values, the thick line is an analysis without splitting cracks, and the chain line is analysis values with splitting cracks), and the crack pattern. Since splitting cracks appear after reaching the maximum load, the behavior before reaching the maximum load is the same in all cases, giving differences after the peak. However, the difference in the relationship of shear force to displacement is not so significant. Regarding cracks at the maximum strength, the experiment showed a region free from cracks near the center of the span. In the analysis, however, cracks are generated over the entire span. The direct cause of overestimation of the shear strain in the reinforcing bar is the generation of cracks in the center region of the span in the analysis, while the center region does not substantially suffer cracking in the test.

In the experiment, before growing the shear cracks over the entire region of the span, splitting cracks were presumably generated along the main reinforcing bar, thus a region of no cracks remained. The objective of forcefully introducing splitting cracks in the analysis was to reproduce the above phenomenon. As illustrated in **Fig. 15**, however, many shear cracks have already formed at the maximum load, and the effect of suppressing shear cracks by forcefully introducing splitting cracks was not observed.

5. Conclusion

We discussed the main activities of three working groups of the Committee. Please refer to the Committee Report for details. The chair of the Committee would like to express his gratitude deeply for the great works of the committee members and JCI staffs. The main discussions and results of the Committee will also be reported in the coming international symposium, Bond in Concrete 2012, which will be held in June, 2012.

References

1) Kokusho, S., Hayashi, S. and Yoshida, H.: Study on Bond between Deformed Bar and Concrete, Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, pp.1513-1514, 1981

2) Ingarffea, A.R. et.al.: Fracture Mechanic of Bond in Reinforced Concrete, ASCE Structural Division, Vol.110, No.4, pp.871-890, 1984

3) Reinhardt, H.W. et.al.: Prediction of Bond between Steel and Concrete by Numerical Analysis, Material and Structures, Vol.17, No.100, pp.311-320, 1984

4) Muto, S., Nakamura, H., Tanabe, T., Srisoros, W. and Lee, S.H.: Analysis of Bond Characteristics Between Concrete and Deformed Bar by Meso-Scale Analysis, Journal of Applied Mechanic, JSCE, Vol. 7, No. 2, pp. 767-774, 2004

5) Salem, H.M. and Maekawa, K.: Pre- and Post yield Finite Element Method Simulation of Bond of Ribbed Reinforcing Bars, ASCE, J. Struct. Eng., Vol.130, pp.671-680, 2004

6) Ngo, D. and Scordelis, A.C.: Finite Element Analysis of Reinforced Concrete Beams, ACI Journal, No.64, pp.152-163, 1967.3

7) Mugrauma, H., Morita, S., and Tomita, K.: Stress Distribution in Reinforced Concrete Beams with Flexural Cracks, Transactions of the Architectural Institute of Japan, No. 200, pp.27-34, 1972

8) Nilson, A. H.: Nonlinear Analysis of Reinforced Concrete by the Finite Element Method, ACI Journal, No.65, pp.757-766, 1968.9

9) CEB-fip Model Code, July, 1991

10) Morita, S. and Kaku, T.: Bond-Slip Relationship under Repeated Loading. Transactions of the

Architectural Institute of Japan, No. 229, pp.15-24, 1975

11) Tassios, T.P. and Yannopoulos, P.J. : Analytical Studies on Reinforced Concrete Members Under Cyclic Loading Based on Bond Stress-Slip Relationships, ACI Journal, May-June, pp.206-216, 1981

12) Kuromasa, S., Takiguti, T., Hayashi, S., and Yamanaka, H.: Fundamental Study of Bond Between Deformed Steel bar and Concrete (Part 3), Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, pp.1155-1156, 1974

13) Labib, F. and Edwards, A.D.: An Analytical Investigation of Cracking in Concrete and Eccentric Reinforced Concrete Tension Members, Proc. Institute of Civil Engineers, Part2, Vol.65, pp.53-70, 1978.3

14) Morita, S. and Fujii, S.: State of the Art of Bond Modeling in Finite Element Analyses, Technical Papers of Colloquium on Finite Element Analyses of Reinforced Concrete Structures, pp.35-42, 1984

15) Ogura, N., et.al. : Analysis of Bond Splitting Failure of Deformed Bars within Structural Concrete, Engineering Structures, Vol.30, pp.428-435, 2008

16) Sekisita, Y., Kawaguchi, K., Kobayashi, R., and Miyamoto, S.: Effect of Models inUni-axial Tensile Behavior Analysis of RC Members by Distributed Crack FEM Model, Summaries of Technical Papers of Annual Meeting, Japan Society of Civil Engineers, pp.1143-1144, 2010

17) Tamai, S., Shima, H., Izumo, J., and Okamura, H.: Average Stress-Strain Relationships of Steel in Uniaxial Tension Member in Post-Yield Range, Journal of Japan Society of Civil Engineers, No. 378, Vol.6, pp.239-248, 1987

18) Okamura, H. and Maekawa, K.: Nonlinear Analyses and Constitutive Laws of Reinforced Concrete, Gihodo Shuppan, Tokyo, 1990

19) Shima, H., Chou, L., and Okamura, H.: Bond-Slip-Strain Relationship of Deformed Bars Embedded in Massive Concrete, Journal of Japan Society of Civil Engineers, No. 378, Vol. 6, pp.165-174, 1987

20) Saito, S. and Hikosaka, H.: Numerical Analyses of Reinforced Concrete Structures using Spring Networks with Random Geometry, Journal of Japan Society of Civil Engineers, No.627/V-44, pp.289-303, 1999.8

21) Watanabe, K., Tadokoro, T., Tanimura, Y. and Kurokawa, H.: Effects of The Shear Span Ratio on The Failure Mode of RC Deep Beams under The Anti-Symmetry Moment, Proceedings of the Japan Concrete Institute, Vol.29, No.3, pp.691-696, 2007

22) Suga, M., Nakamura, H., Higai, T, and Saito, S.: Effect of Bond Properties on The Mechanical Behavior of RC Beam, Proceedings of the Japan Concrete Institute, Vol.23, No.3, pp.295-300, 2001

23) Goto, S., Morita, S., Fujii, S., Tokuno, M., and Fukui, K.: Influence of Lateral Reinforcement on Bond Splitting Failure Modes. Annual Reports of Architectural Institute of Japan, Kinki Branch, Vol. 21, 197-200, 1981