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BOND BEHAVIOR SIMULATION USING RBSM WITH BEAM ELEMENT AND VORONOI MESH

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Abstract: This study proposed a numerical model based on 3D RBSM to realistically simulate bond behavior of deformed rebar in concrete. In this model, rebar was modelled by beam element subjected to local bond model through link element and concrete was modelled by rigid particles using a Voronoi mesh with random geometry. The proposed model could automatically simulate the effect of cover thickness on bond stress slip relationship and cracking behavior from rebar. It was confirmed that the model is a suitable alternative of 3D modelling of deformed rebar with rib to simulate bond behavior, while providing a low-cost numerical tool along with less time consumption.

1 INTRODUCTION

Through various pullout experimental studies, it has been confirmed that bond behavior of deformed bar in concrete is significantly dominated by the rib geometry of rebar than chemical adhesion and friction [1]. Due to the interlocking mechanism, the bearing stress produce crushing of the concrete in front of the rib element of rebar along with the propagation of internal cracks from the boundary of rib. Formation of these internal cracks from the ribs surface has been thoroughly investigated in the study of Goto [2] and widely termed as Goto-cracks.

Thus, in analytical study, it has been considered important to model a 3D rebar shape with the rib element to realistically simulate the local behavior near to the ribs and generate a characteristic bond stress slip behavior [3, 4, 5]. However, detail modelling of 3D rebar shape is a tedious and time-consuming task. Furthermore, the computational cost to simulate the real-size structural members, modelled with the rib element of 3D rebar is highly expensive. Hence, a beam element incorporated with bond model by link element, in general, is used to simulate the bond behavior of deformed rebar in RC members, when Finite Element Analysis is used. However, the model alone can’t simulate several effects related to bond behavior such as effects of cover thickness, stirrups and cracks along rebar. The effects are usually introduced in bond stress slip relationship as parameters [1, 6] and defined functions are used in FEA without simulating internal crack propagation from the rib surface.

In this study, it is revealed that a Voronoi mesh technique with random geometry to model concrete and a simple one-dimensional beam element incorporated with local bond model through link element can well simulate the effect of cover thickness on the bond and internal cracking behavior. Then, the suitable local bond models are verified. The proposed numerical model is an alternative of 3D rebar with rib element to simulate bond behavior, while providing a low-cost analytical tool along with less time consumption. It is confirmed that this model can be an efficient and economical tool for the structural evaluation, considering local bond effect which influences on cracking space, crack width, member stiffness and so on.

2 NUMERICAL ANALYSIS MODEL

2.1 3D-RBSM

In 3D-RBSM, concrete is modeled as an assemblage of rigid particle interconnected by springs at their boundary surfaces as shown in Figure 1. Since crack propagation is affected by mesh design, a random geometry is generated by Voronoi tessellation to reduce mesh bias dependency on the development of potential cracks [7].

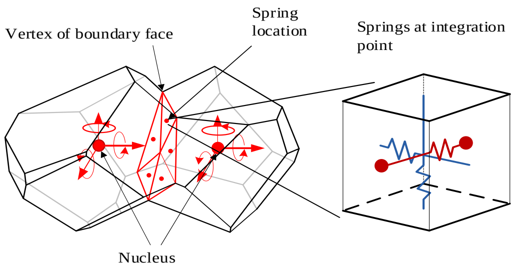


Figure 1: Concrete model

2.2 Concrete material model

The constitutive models for tension and compression of normal springs and for shear springs used in 3-D RBSM for monotonic loading analysis are constructed by uniaxial relationships between stress and strain, as shown in Figures 2-6. The details of the models and the relevant model parameters have been described and verified in the research conducted by Yamamoto et al. [8].

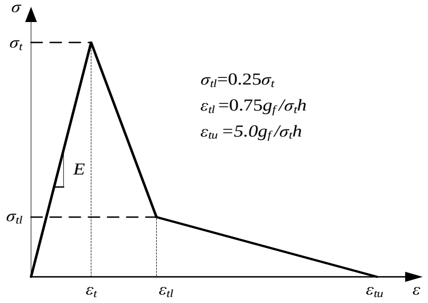


Figure 2: Tensile model of normal spring

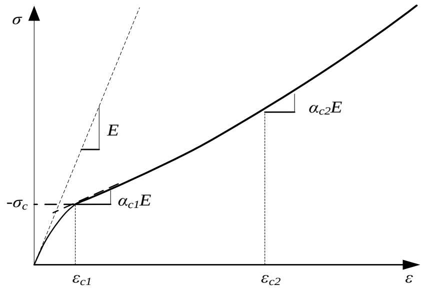


Figure 3: Compression model of normal spring

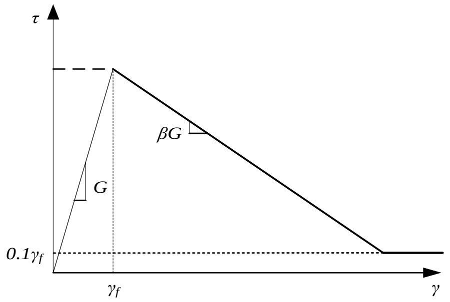


Figure 4: Shear spring model

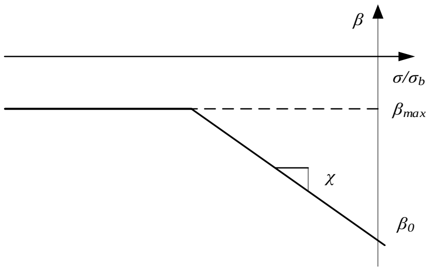


Figure 5: Softening coefficient for shear spring

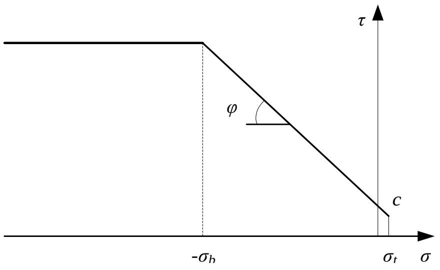


Figure 6: Mohr-coulomb criteria

2.3 Reinforcement material model

Steel reinforcement is modelled as a series of regular beam elements [7] as shown in Figure 7. In this model, the reinforcement can be freely arranged within the member, regardless of the mesh design of concrete [9]. At each beam node, two translational and one rotational degrees of freedom are defined by means of the springs. The reinforcement is attached to the concrete particles by zero-size link elements, which is attached between the beam node and the particle computational point to provide a load transfer mechanism between materials. The space of link element is near rigid particle size of concrete. Each link element consists of two springs, one spring in tangential and other in normal direction to the axis of reinforcement. Tangential spring is used to represent the shear stress transfer from ribs part, in an attempt to simulate the bond between concrete and rebar. In the model, the non-linear bond stress-slip relationship is introduced. Normal spring is assigned very large stiffness to prevent displacement in this direction [7].

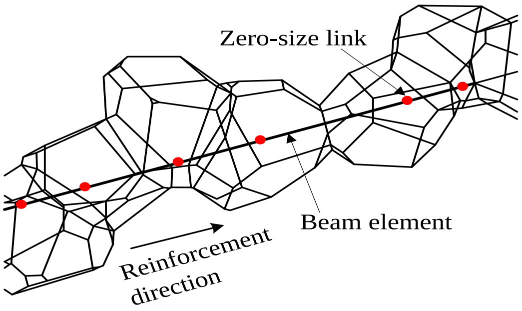


Figure 7: Reinforcement model

3 SIMULATION OF BOND BEHAVIOR WITH BEAM ELEMENT

3.1 Local bond stress slip models

Crack development is strongly dependent upon the bond interaction between concrete and reinforcement of link element. Figure 8 shows the several local bond stress-slip models for structural analysis.

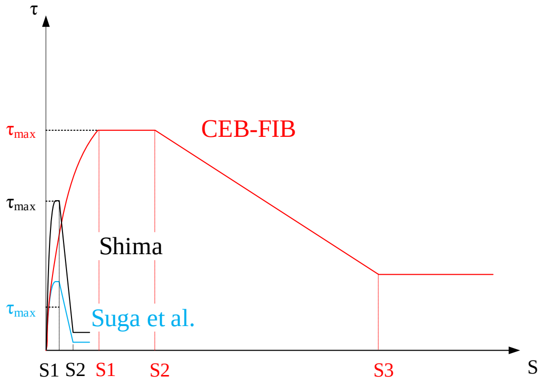


Figure 8: Renowned local bond stress-slip models

Black line shows Shima model [10], which was based upon the experimental outcomes of rebar embedded in a massive concrete specimen. Blue line shows the model proposed by Suga et al. [11] which have been used to simulate several structural members in 3D-RBSM and FEM by Authors [5, 11]. Basically, the model was proposed by modifying Shima model considering a strength reduction factor of 0.4 for the structural analysis of RC members with smaller cover thickness than massive concrete. For the case of Shima and Suga model, constitutive equations of bond stress dependent upon slip, can be seen in Equation 1.

$$
\begin{array}{ll}
\tau_{max} = \alpha \times 0.9 \times f'c^{2/3} & \\
\tau = \tau_{max}\,(1-\exp(-40(s/D))) & s_1 \geq s \geq 0 \\
\tau = \tau_{max}/(s_1-s_2)\,(s-s_1) + \tau_{max} & s_2 \geq s \geq s_1 \\
\tau = 0.10 \times \tau_{max} & s \geq s_2 \\
\alpha = 1 \text{ for Shima Model} & \\
\alpha = 0.4 \text{ for Suga Model} &
\end{array}
\tag{1}
$$

Where, τ: bond stress (MPa), $f'c$: compressive strength (MPa), s: slip (mm), D: diameter of rebar (mm), s_1: 0.2 mm and s_2: 0.4 mm.

Also, in Figure 8, red line shows the renowned CEB-FIP local bond stress-slip model [1]. The model has higher local bond stress limitation based upon pullout failure, as compared to Shima and Suga model. Also, for CEB-FIP model, loading stiffness as well as post peak behavior is softer than Shima and Suga model. The constitutive laws of CEB-FIP model are shown in Equation 2.

$$\tau_{max} = 2.5\times f'c^{0.5}$$

$$\begin{array}{ll} \tau = \tau_{max}\,(s/s_1)^{0.4} & s_1\geq s\geq 0 \\ \tau = \tau_{max} & s_2\geq s\geq s_1 \\ \tau = \tau_{max} - (\tau_{max}\text{-}0.4\ \tau_{max})\ (s\text{-}s_2)/(s_3\text{-}s_2) & s_3\geq s\geq s_2 \\ \tau = 0.4\times\tau_{max} & s\geq s_3 \end{array} \qquad (2)$$

Where, s_1: 1.0 mm, s_2: 2.0mm, s_3: clear spacing between bar lugs.

3.2 Influence of local bond model to simulate effect of cover thickness on global bond behavior

Outcomes of effect of several local bond models are validated by simulating two end pullout experiments performed by Iizuka et al. [6]. In his experiment, a two-end pullout test was performed on a deformed rebar embedded in a cube specimen of 150mm. The schematic diagram of two end pullout test can be seen in Figure 9. In this test, a rebar embedded inside the specimen at desired cover thickness is subjected to two end loading. A strain gauge is installed on rebar at half of embedment length to measure the strain in order to calculate the average bond stress. While transducers (LVDTs) are used at both end of the rebar to measure the average slip.

To evaluate several local bond models, three specimens with cover thickness of 10mm (C10), 30mm (C30) and 50mm (C50) are selected [8]. Rebar diameter is 19mm. A mesh size of 10mm is throughout used to simulate the test specimens. The numerical model of 10mm concrete cover specimen is shown in Figure 10.

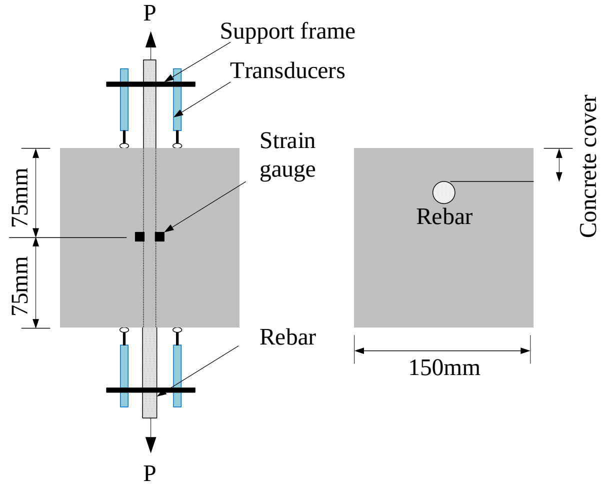


Figure 9: Schematic diagram of two end pullout test

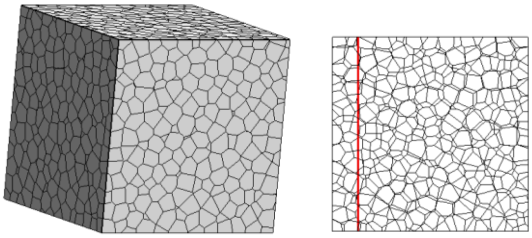
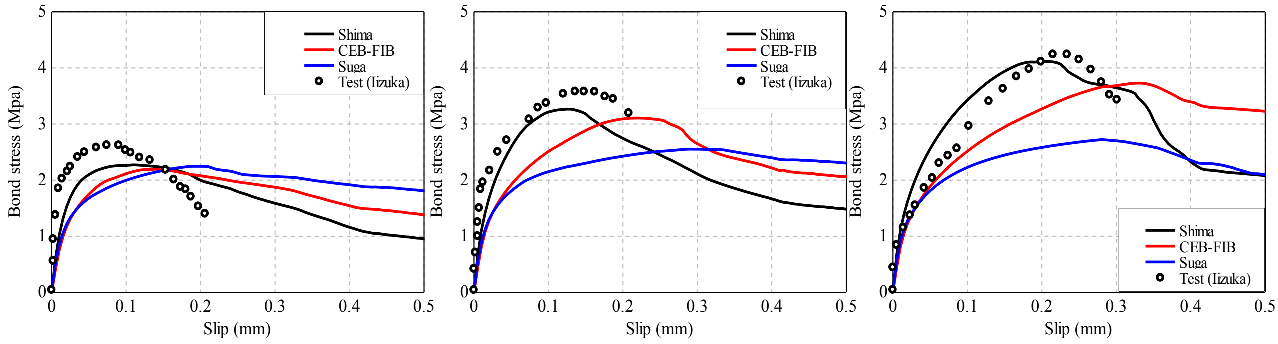


Figure 10: Numerical model (Mesh-10mm)

Figure 11 shows the influence of local bond models on the global bond stress-slip behavior based on comparison with experiments for cover thickness of 10mm (C10), 30mm (C30) and 50mm (C50). Black, red and blue lines represent results for Shima, CEB-FIP and Suga model, respectively. While circle marks represent the experimental results.

For the small cover thickness i.e. 10mm, all three models can reasonably predict the



a. C10 **b.** C30 **c.** C50

Figure 11: Influence of local bond model on global bond stress-slip behavior

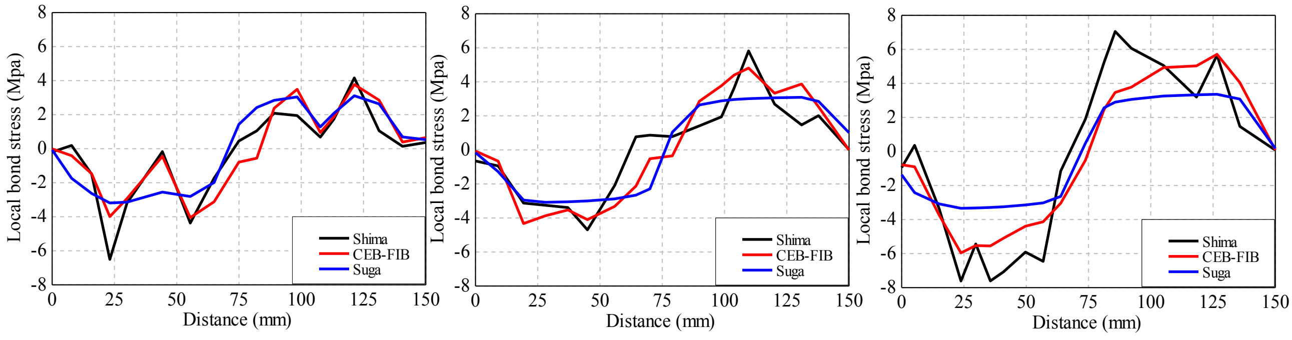
average bond stress as observed in experiments. This indicates that for case of thin cover thickness, local bond strength is not so important factor for global bond behavior. In case of cover thickness of 30mm and 50mm, Suga model underestimates the experimentally observed bond stress-slip behavior due to the reduced local bond stress (0.4 times of Shima). It is noted that this range of cover thickness (30 and 50mm) is practically observed in structural members. On contrary, for the case of Shima and CEB-FIP model, both can reasonably estimate the increasing average bond stress of experiments with increasing cover thickness. Regarding pre-peak behavior, Shima model shows more similar behavior in comparison to experiments than CEB-FIP model due to higher stiffness of local bond model. Shima model well matches with the experimental results in terms of stiffness, peak bond stress as well as the slip at the peak bond stress.

In Figure 12, the distribution of local bond stress along the rebar length is shown at 0.30mm slip. While Figure 13 shows the deformation and the internal cracking pattern for CEB-FIP, Shima and Suga models for all three cases of cover thickness at 0.30mm slip. In several experiments, it has been mentioned that with an increase in cover thickness, internal cracks do not propagate to the surface of specimen. Based on this behavior, all three local bond models can clearly show influence of increase in cover thickness on internal and surface cracking behavior, although the local bond models do not include the parameter of cover thickness. For the case of 10mm cover thickness, internal cracking, deformational behavior and local bond stress distribution is quite similar for all three models. However, for Suga model, intensity of internal and surface cracks is lower than Shima and CEB-FIP model, due to which the local bond stress-slip stiffness behavior is softer in comparison to experiments. The lower bond stress influences to crack propagation length due to the limitation of stress transfer from rebar.

For 30mm and 50mm cover thickness case, a constant and even distribution of local bond stress is observed in Figure 12 for Suga model because of limitation of peak bond stress (0.4 times of Shima). On contrary, the higher bond stress of Shima and CEB-FIP models promote uneven distribution of local bond stress and internal cracks proceed towards the boundary of specimen. However, due to mild stiffness of CEB-FIP local bond model, intensity of internal cracking at same slip level is lower as compared to Shima model. Based upon these observations, it is concluded that Shima model is a better tool to evaluate the effect of change in confinement on overall bond behavior. So, in following sections all the analytical results with beam element are based upon Shima model.

3.3 An economical and efficient alternative of meso-scale 3D rebar model

To take into account the increased bearing stress due to ring tension effect of conical cracks propagation from the rib surface of a deformed rebar, several researchers have emphasized to model the rib formation in numerical analysis [3, 4, 5]. Ikuma et al. [5] considered meso-scale model of actual rib



a. C10 **b.** C30 **c.** C50

Figure 12: Local bond stress distribution at 0.30mm slip

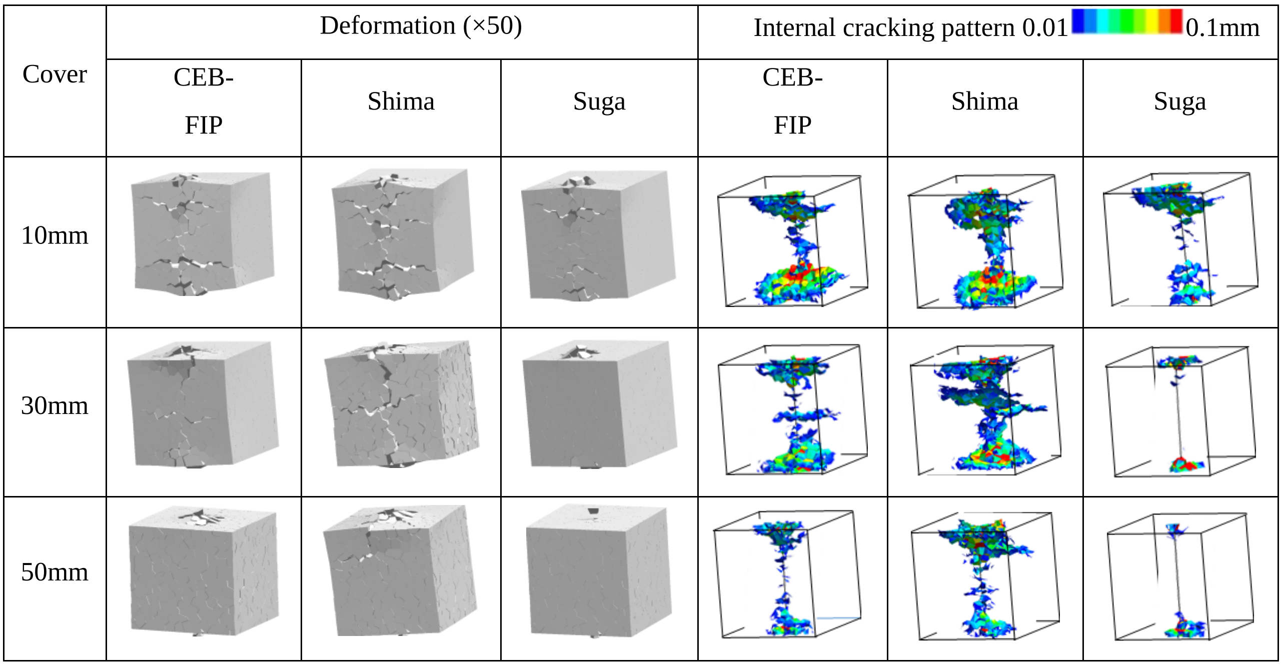
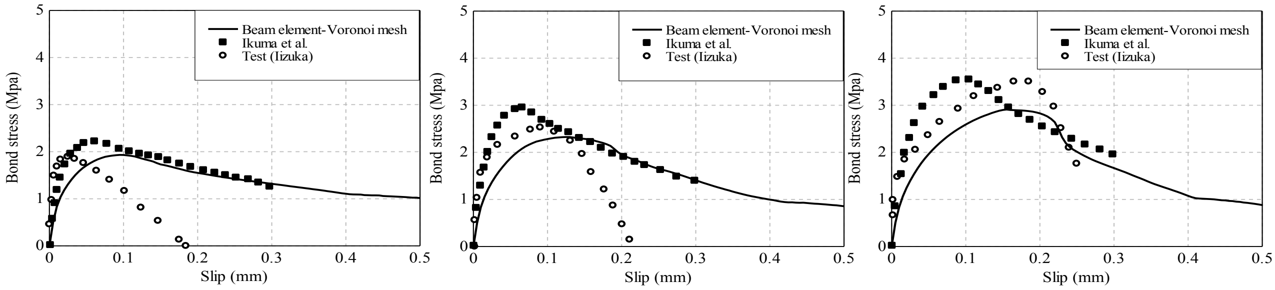


Figure 13: Influence of local bond model on deformation and internal cracking behavior (slip=0.30mm)

element of deformed rebar to evaluate the bond behavior under the influence of increasing cover thickness by 3D-RBSM. However, it was shown in previous section that proposed model, which is based on a simple beam element model with combination of Voronoi mesh, can also simulate conical cracks propagation from the rib surface.

To build comparison, three test specimens with cover thickness of 10mm (C10), 30mm (C30) and 50mm (C50) are used [6]. Diameter of rebar is 25mm, different from previous section. Figure 14 presents the bond stress-slip comparison between beam element and 3D-rebar model with Voronoi mesh [5], along with test results. It shows that a beam element with Voronoi mesh can well estimate the peak bond stress in comparison to meso-scale 3D rebar model. In comparison to experiments, beam element model well correlates with the pre-peak stiffness behavior and the slip at peak bond stress, for the case of nominal cover thickness of 30 and 50mm as well as rebar diameter of 25mm

Internal cracking pattern and deformational behavior comparison between beam element and 3D-rebar model are shown in Figure 15 for the case of 30mm cover thickness specimen. By using a beam element rebar model, similar internal cracking pattern, cracks at rebar interface and deformational behavior can be generated as analyzed results of a meso-scale 3D rebar model. In Figure 16, the characteristic conical crack formation of ribbed rebar observed in research work of Goto et al. [2] is shown. In his experiment on bond mechanism of deformed rebar, it was found that, internal cracks have a great influence on the bond mechanism between steel and concrete. The internal cracks at 60-



a. C10 **b.** C30 **c.** C50

Figure 14: Influence of rebar model on bond stress-slip behavior

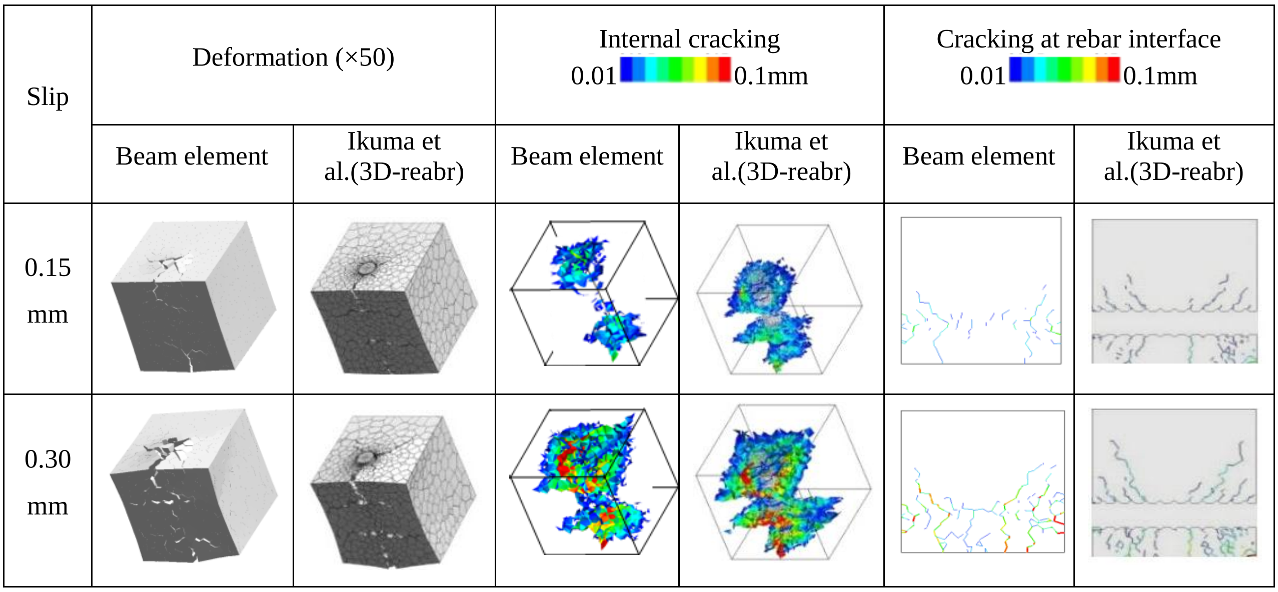


Figure 15: Influence of rebar model on internal cracking and deformation behavior (C30)

degree angle produces ring tension effect and increase the bond stress for deformed rebar structures. It is evident that the proposed model has inherited ability to generate the internal conical cracks at the interface of the rebar, similar to the observation of Goto as well as 3D rebar model. Due to which a ring tension effect can be generated and with a simple model of beam element in combination of Voronoi mesh, reasonable bond stress-slip behavior is observed in comparison to experiments and meso scale 3D-rebar model.

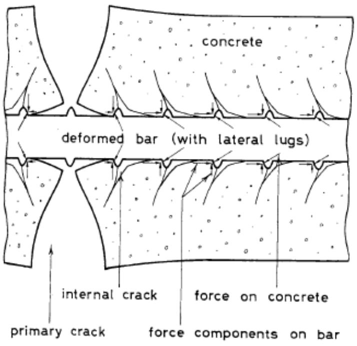


Figure 16: Goto internal cracks

4 CONCLUSIONS

Based upon the outcomes of proposed numerical model to model concrete as a Voronoi mesh with random geometry, rebar as a simple beam element and local nonlinear bond stress-slip behavior, the following conclusions are drawn:

1. Proposed numerical model can automatically simulate the effect of cover thickness on global bond stress-slip relationship and cracking behavior from rebar such as Goto crack. Due to which, complicated parametric functional dependency of bond on cover thickness, as in FEA, is not required to be modelled.
2. Shima model is suitable local bond stress-slip model to combine with the proposed method. The features are that the bond strength is larger than Suga model and stiffness is larger than CEB-FIP model. It will be desirable to make more reasonable model to simulate all behavior related bond such as splitting crack due to bond stress, bond behavior in massive concrete, stress and strain distribution of rebar in cracked RC member, in future study.
3. The Voronoi mesh probably contributes the propagation of conical cracks from the ribbed surface of deformed rebar promoting to the ring tension phenomena observed in RC structures. The role of random geometry mesh will be discussed in detail in a future study.
4. The proposed model is a suitable alternative of 3D modelling of rebar with rib of deformed bar to simulate bond behavior, while providing a low-cost analytical tool along with less time consumption.

REFERENCES

[1] CEB-FIP, 1999. Structural concrete-textbook on behavior, design and performance, updated knowledge of the CEB-FIP model code 1990, Vol. 1. Sprint-Druck, Stuttgart, Germany.

[2] Goto, Y., 1971. Cracks formed in concrete around deformed tension bars. *ACI Structural Journal*, **68(4):**244-251

[3] Kurumutani, M., Anzo H., Kobayashi K. and Okazaki S., 2017. Damage model for simulating chloride concentration in reinforced concrete with internal cracks. *Cement and Concrete Composites,* **84:**62-73.

[4] Eddy, L., Matsumoto, K. and Nagai, K., 2016. Effect of perpendicular beams on failure of beam-column joints with mechanical anchorages by 3D RBSM. *Journal of Asian Concrete Federation,* **2(1):**55-66.

[5] Ikuma, K., Yamamoto, Y., Nakamura, H. and Miura, T., 2018. Mesoscale simulation of bond behavior of deformed rebar based on coupled RBSM-FEM method. *Proceedings of JCI annual convention,* **40(2):**541-546. (In Japanese).

[6] Iizuka, K., Higai T., Saito, S. and Takahashi, R., 2011. Bond stress-slip-strain relationship of deformed bars including the effect of concrete cover thickness. *Journal of JSCE,* **67(2):**280-296. (In Japanese).

[7] Yamamoto, Y., Nakamura, H., Kuroda, I. and Furuya, N., 2014. Crack propagation analysis of reinforced concrete wall under cyclic loading using RBSM. *European Journal of Environmental and Civil Engineering,* **18 (7):**780-792.

[8] Yamamoto, Y., Nakamura, H., Kuroda, I. and Furuya, N., 2008. Analysis of compression failure of concrete by Three-Dimensional Rigid Body Spring Model. *Journal of JSCE,* **64(4):**612–630. (In Japanese).

[9] Bolander, J.E. and Hong, G.S., 2002. Rigid-Body-Spring Networks modeling of prestressed concrete members. *ACI Structural Journal,* **99(5):**595-604.

[10] Shima, H., Chuo LL. and Okamura H., 1987. Micro and macro models for bond in reinforced concrete. *Journal of the Faculty of Engineering, the University of Tokyo,* **XXXIX (2):**133-194

[11] Suga, M., Nakamura, H., Higai, T. and Saito, S., 2001. Effect of bond properties on the mechanical behavior of R.C. beam. *Proceedings of Japan Concrete Institute,* **23(3):**295-300. (In Japanese).