From rebar detailing to structure:

Meso-scale simulation of reinforced concrete using Rigid Body Spring Method

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- Modeling of RBSM
  - ✓ RBSM for Structural Analysis Model
  - ✓ Bond Simulation with Meso-scale Behavior
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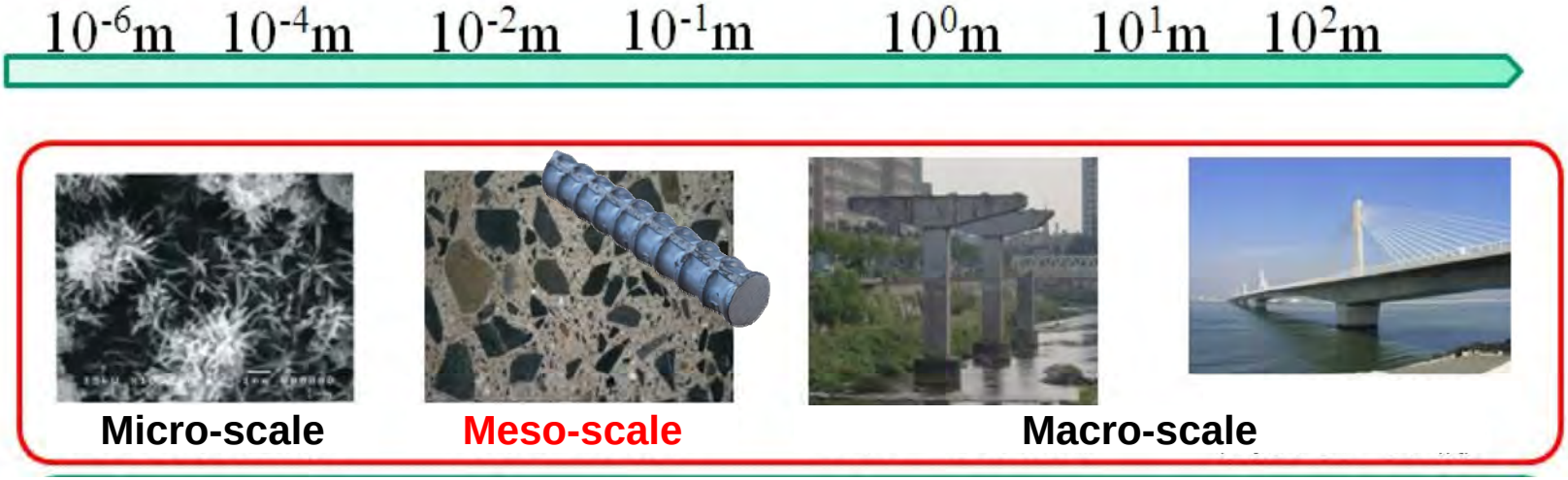
  - ✓ Clarification of Role of Rebar Detailing
  - ✓ Understanding Shear Failure Mechanism
  - ✓ Application to Shear Failure of Fiber Reinforced Concrete
- Conclusion

Motivation of Utilization of Meso-scale Simulation

What is meso-scale of concrete structures?

- ✓ micro-scale : cement hydrates (Crystal scale)
- ✓ macro-scale : beams, columns, bridges (members and structures scale)
- ✓ meso-scale : Concrete (aggregates scale)
  Reinforcing bars (lug and rib scale)
  Crack(crack width scale)

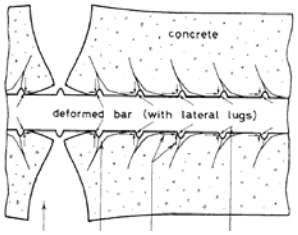


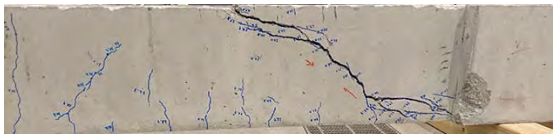
Motivation of Utilization of Meso-scale Simulation

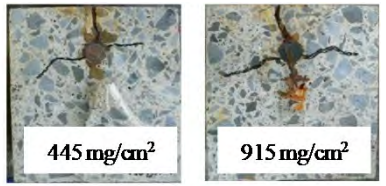
Why meso-scale is important for concrete structures?

Because many failure mechanisms originate at this scale:

- ✓ Crack initiation around aggregates and rebar
- ✓ Crack propagation from aggregate and rebar
- ✓ Bond failure and slip
- ✓ Compression failure
- ✓ Shear failure
- ✓ Chloride ingress pathways
- ✓ Corrosion-induced cracking





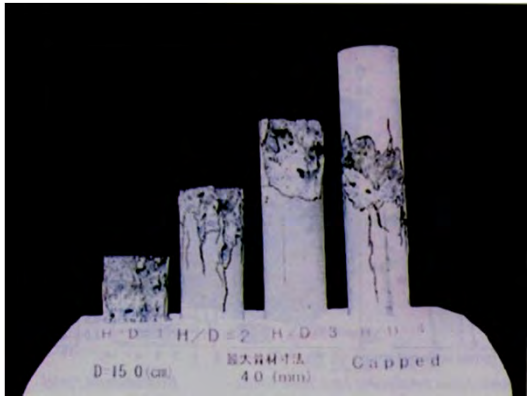


Meso-scale models reveal how structural damage starts and evolves.

Motivation of Utilization of Meso-scale Simulation

What can be understood from meso-scale simulation?

- ✓ **Safety of concrete structure**
  - ☐ **Realistic localization fracture behavior such as damage level and damage zone**

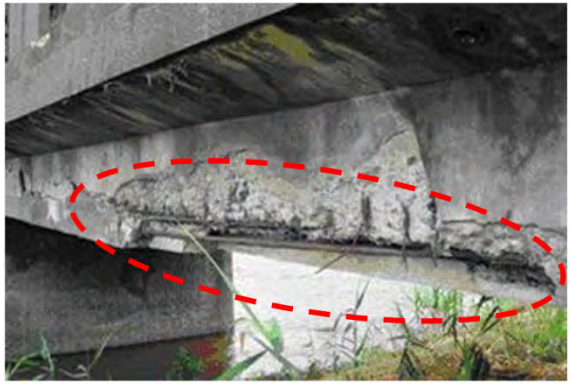


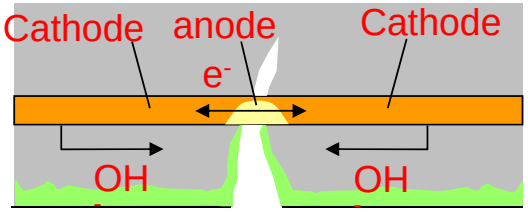
Motivation of Utilization of Meso-scale Simulation

What can be understood from meso-scale simulation?

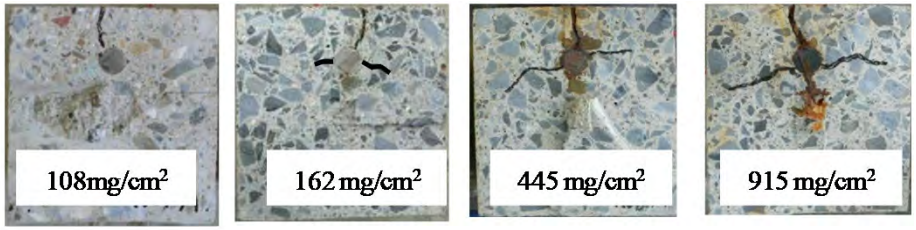
✓ Durability of concrete structure

- ☐ Deterioration occur around rebar and coarse aggregate at meso-scale.
- ☐ Good durability assessment requires realistic cracking behavior such as crack width and crack propagation.





Pitting corrosion at crack position



Motivation of Utilization of Meso-scale Simulation

What can be understood from meso-scale simulation?

✓ Reinforcement Detailing

- Reinforcement detailing is most essential regulation in the design and construction of concrete structures.
- Bond is related to meso-scale behavior near rebar and it is bone of concrete structural design to understand basic mechanism and to improve reinforcement arrangement.

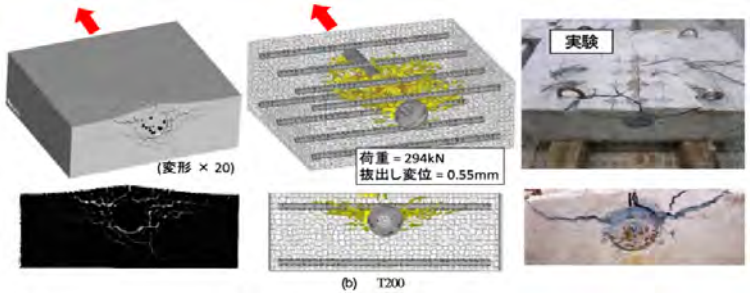
performance of concrete structures

workability and productivity of construction work

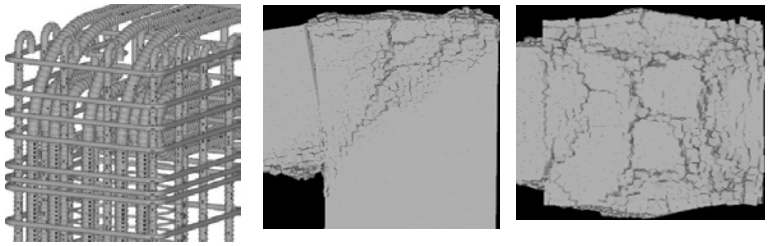
Motivation of Utilization of Meso-scale Simulation

How to use meso-scale simulation?

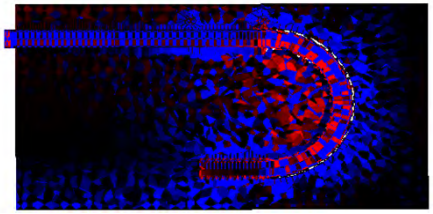
In current JSCE specification, the application of meso-scale analysis that the rebar is modeled precisely, is recommended to evaluate structural details performance.

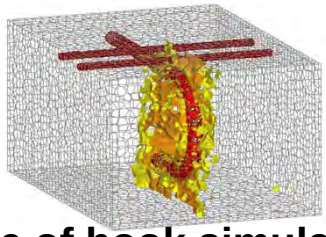


Example of mechanical anchor simulation

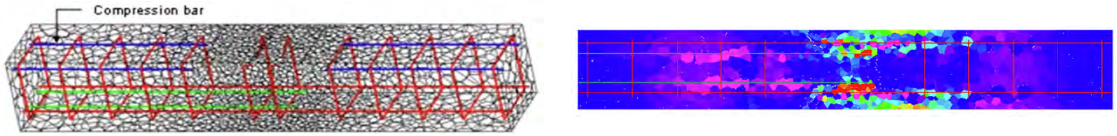


Example of member joint simulation





Example of hook simulation



Example of lap splice simulation

In near future

Use meso-scale analysis to verify the performance of reinforcement detailing

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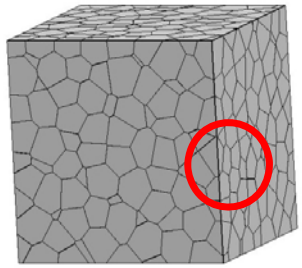
Numerical Method - 3D-Rigid Body Spring Method – Concept and Modelling of RBSM

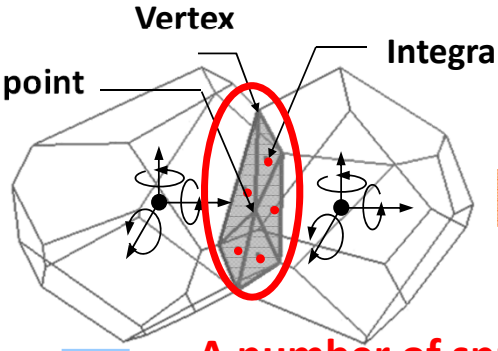
Concrete Element

RBSM is one of **discrete element method** to simulate structural behavior by springs between **Rigid Bodies**.

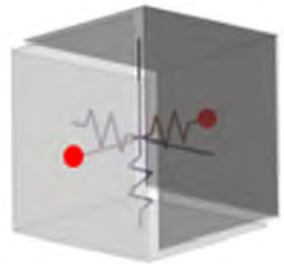


Analytical model is divided by 3-D **Voronoi** particles

For reduction of elements dependency



A number of springs are set in boundary of each surface of Rigid Body



One integral point has two kinds of springs (normal/shear)

Cracks are expressed by the failure of springs and cracking behavior can be shown directly.

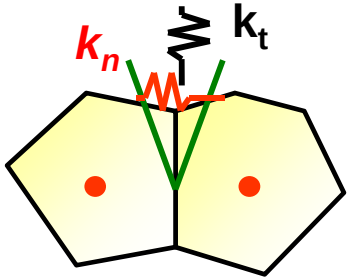
Element size is usually assumed about 10 to 30mm as same as aggregate size in meso-scale.

(Yamamoto et al., J. of JSCE, 2008)

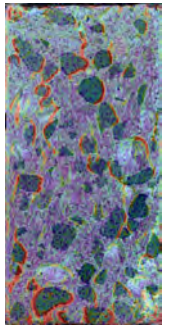
Numerical Method - 3D-Rigid Body Spring Method – Concept and Modelling of RBSM

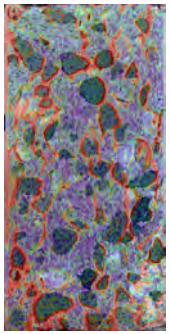
Concrete Material Model

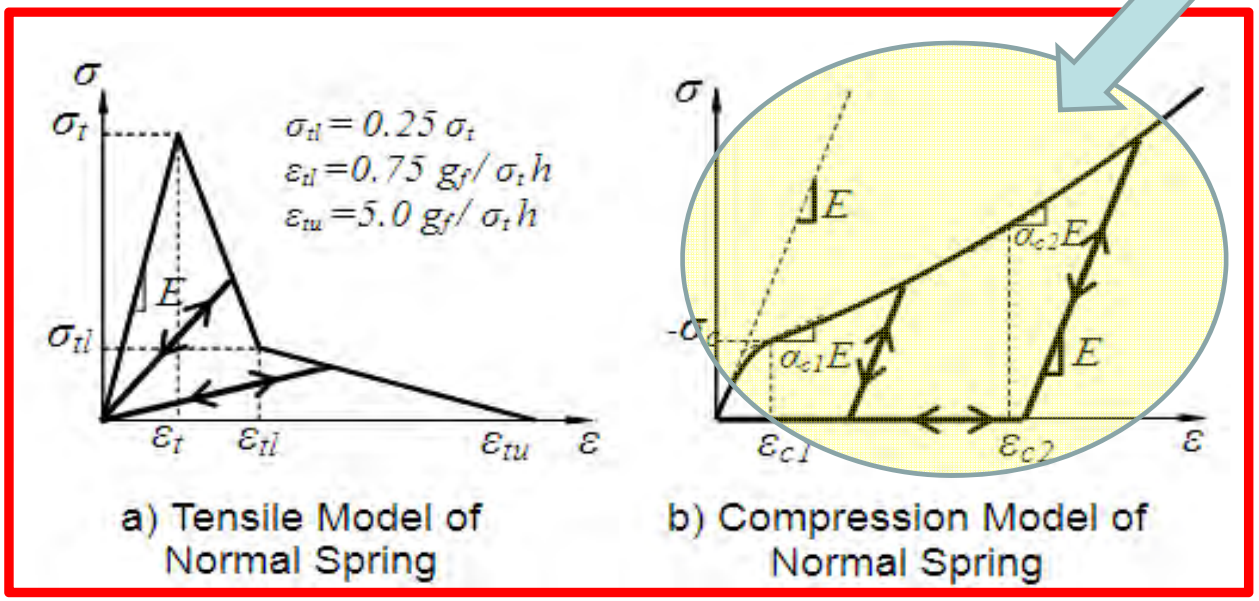
Normal spring



no softening part is modeled in compression







Concrete Models (Yamamoto et al. 2008)

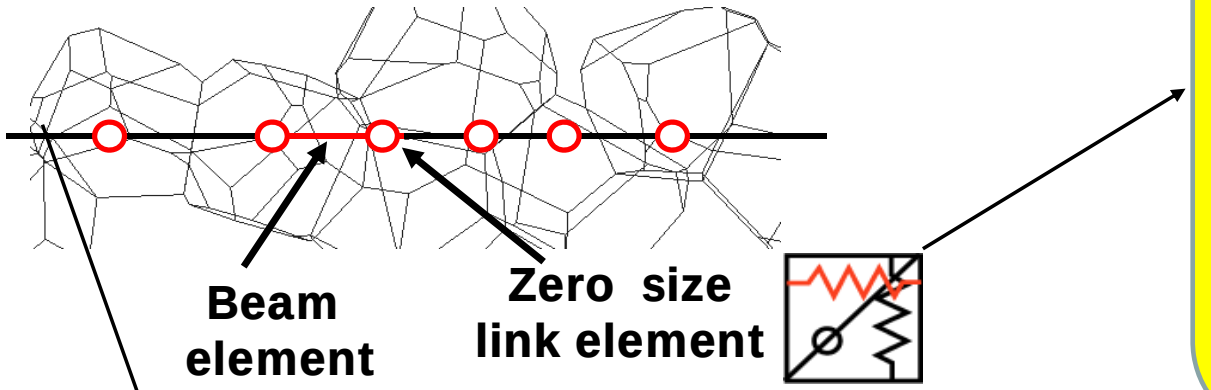
- Compression failure is not compression failure of concrete.
- Compression failure is accumulation of failure of tensile and shear failure.

✓ **Meso-scale model should be different with Macro-scale model.**

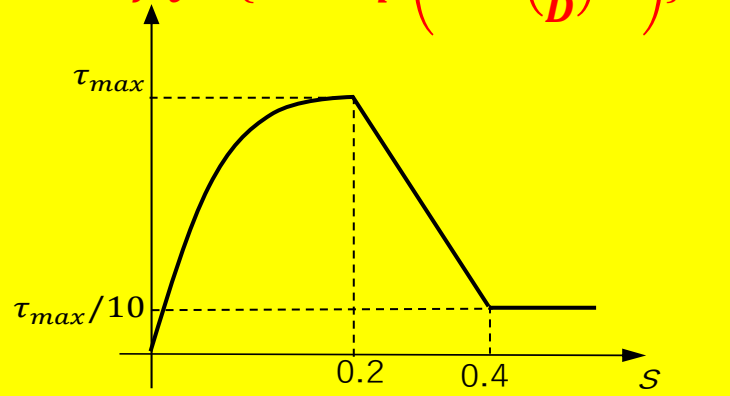
✓ **How to define meso-scale behavior.**

Numerical Method - 3D-Rigid Body Spring Method – Concept and Modelling of RBSM

Reinforcement and Bond Model

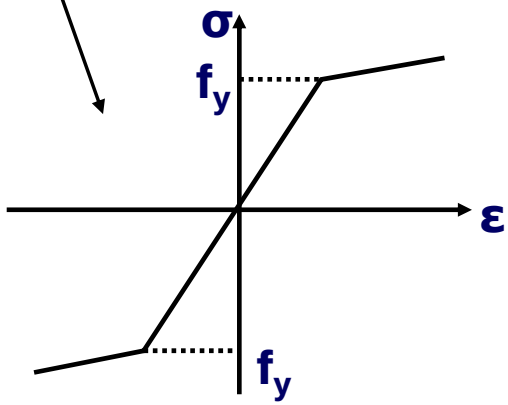


$$\tau = 0.9 f'_c{}^{2/3}\{1 - exp\left(-40\left(\frac{s}{D}\right)^{0.5}\right)\}$$



Bond stress-slip model

A simple bond slip model only for tangential direction is applied under any conditions.



Stress strain relationship

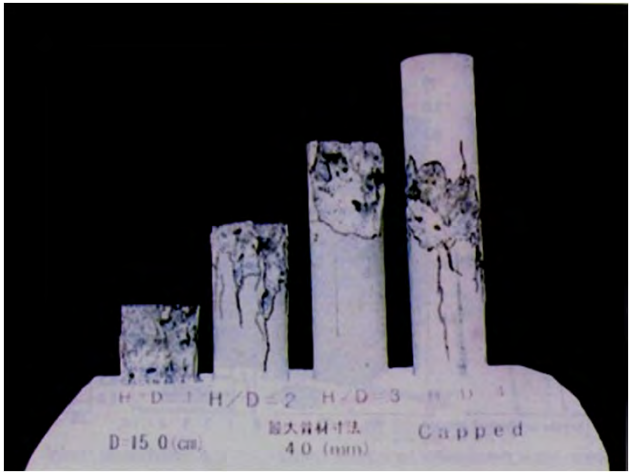
Reinforcement : beam element

beam nodes : attach to the concrete particles through zero-size link element

stress strain relationship : bi-linear model.

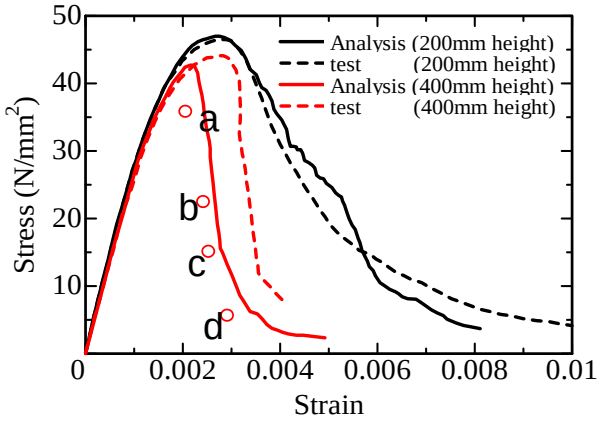
Bond property: introduced into the shear spring of linked element

Numerical Method - 3D-Rigid Body Spring Method –
Uniaxial Compression Behavior

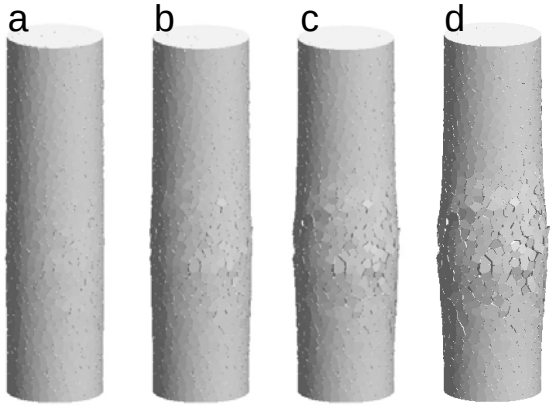


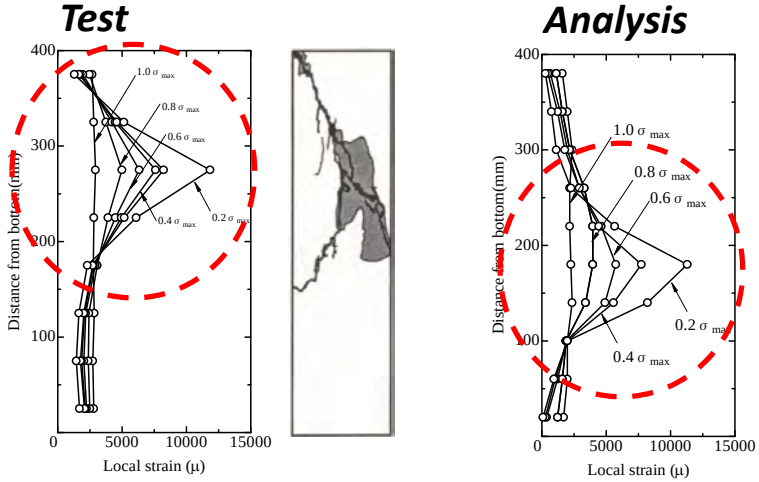
Localization behavior of compression failure

(Nakamura et al., ASCE, 2001)
Compressive fracture energy



Stress-Strain relationship





Strain distribution along the height and deformation

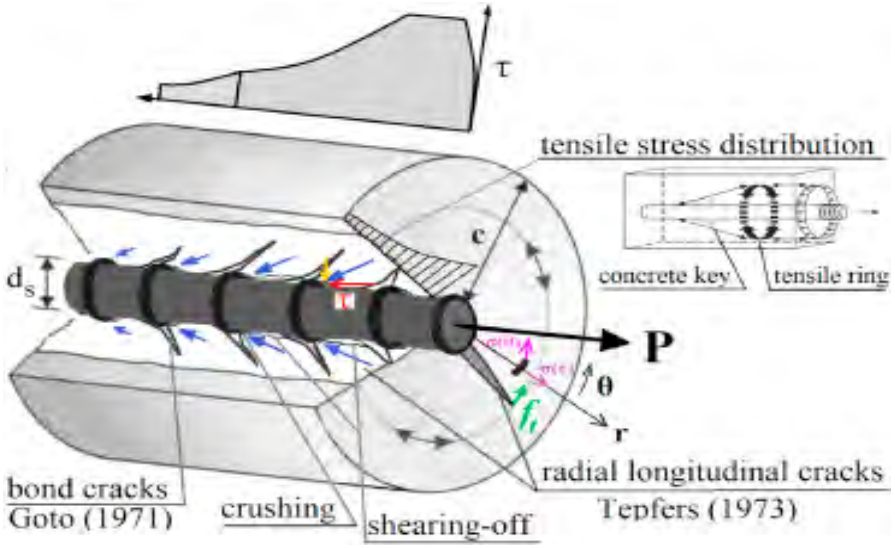
(Yamamoto et al., J. of JSCE, 2008)

Localized compression failure behavior under compression force was successfully simulated by RBSM

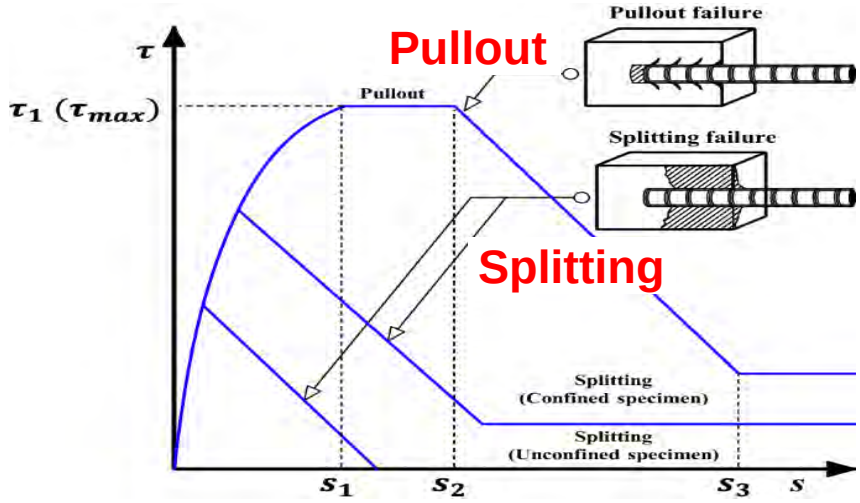
Simulation of Bond Behavior of Deformed Rebar

Importance of bond simulation

Bond simulation is key point of meso-scale simulation.



Bond mechanism



Bond-slip model

Bond performance is combination of meso-scale behaviors near rebar and confinement effect around rebar.

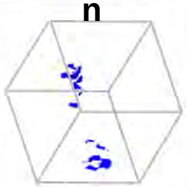
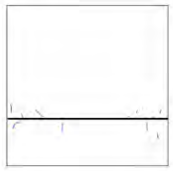
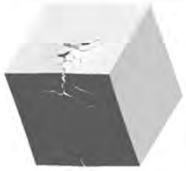
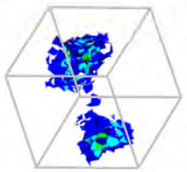
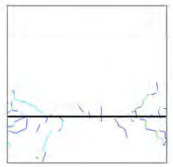
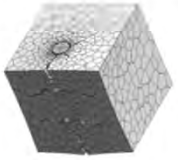
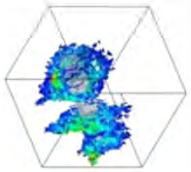
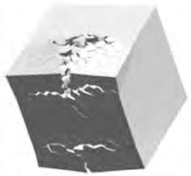
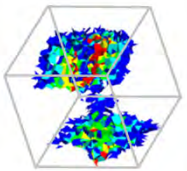
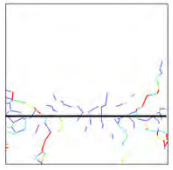
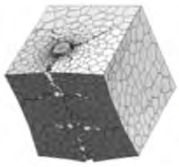
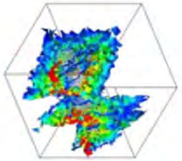
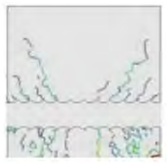
Bond failure modes are defined by pullout and splitting failure Mode.

- **Macro-scale models require numerous models and parameters.**
- **Meso-scale models enable the simulation of bond behavior using simpler models and fewer parameters.**

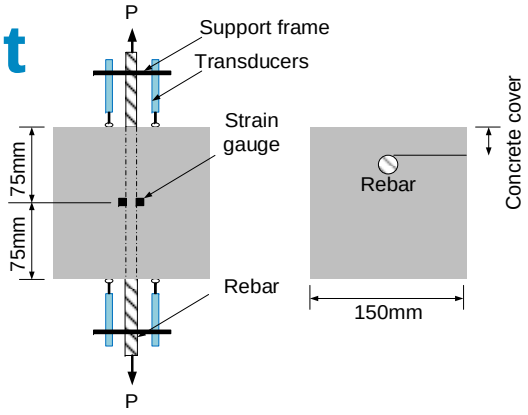
Simulation of Bond Behavior of Deformed Rebar

Internal crack pattern of RBSM with beam element and 3D model

Internal Crack Pattern of Two Ends Pull Out Test

	Beam Element			3D Model		
	C=30mm			C=30mm		
Slip (mm)	Deformation	3D Crack Distribution	Crack at Center	Deformation	3D Crack Distribution	Crack at Center
0.05						
0.15						
0.30						

Internal crack pattern



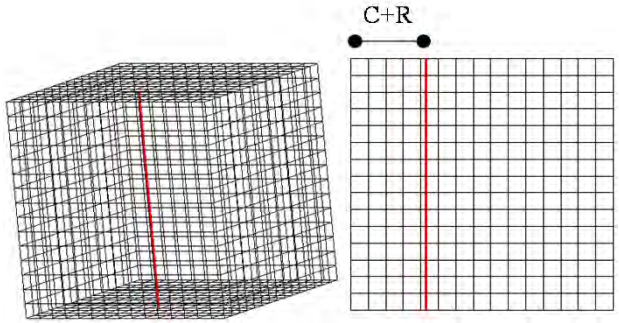
- ✓ Inclined internal cracks develop from lug for both models.
- ✓ Beam element model can appear same bond crack behavior as 3D rebar model.
- ✓ No modeling of 3D rebar shape, beam element in RBSM can simulate successfully similar internal crack formation from lug.

(CCC, 2020)

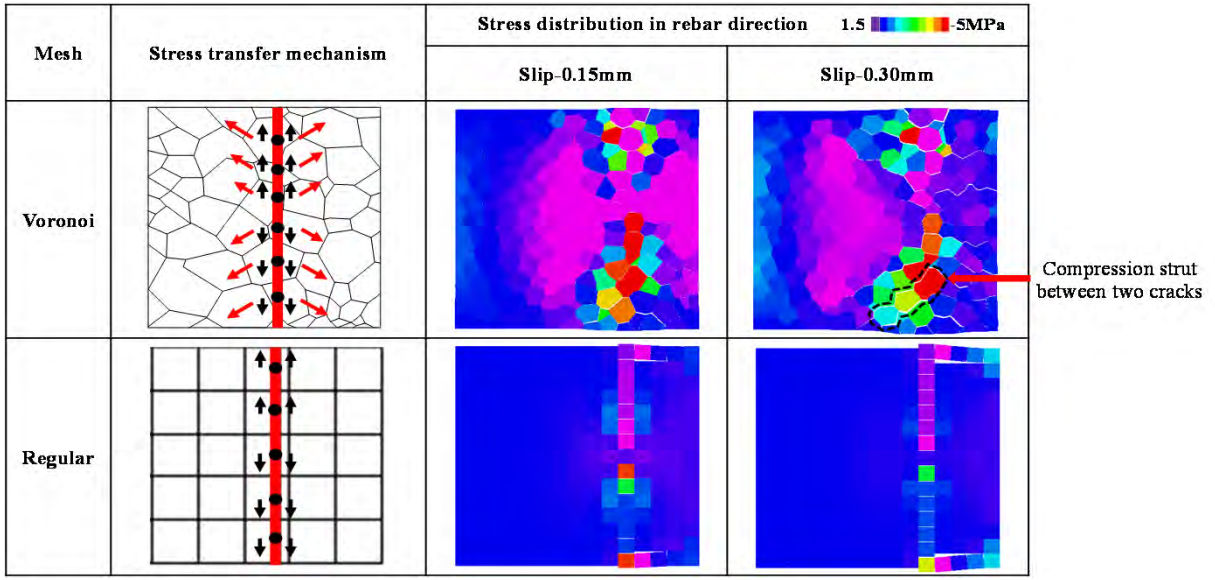
Simulation of Bond Behavior of Deformed Rebar

Key point of beam element model

Why can this simple beam model simulate internal cracking behavior ?



Simulation by regular mesh arrangement



Effect on Stress Transfer Mechanism (CCC, 2020)

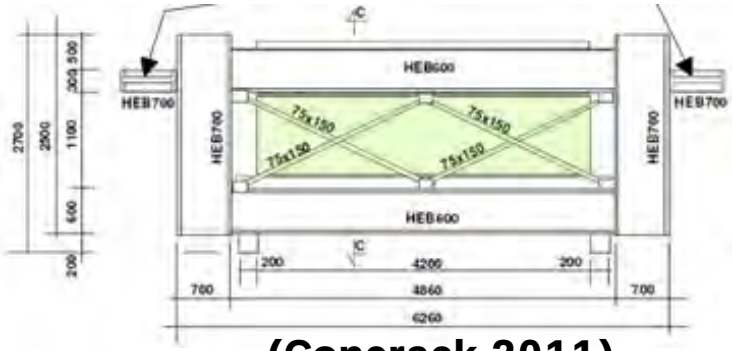
- ✓ Key aspect is random mesh modeling.
- ✓ Model only bond stress along the rebar.
- ✓ Stress is transmitted to arbitrary direction by random shape.
- ✓ Random shape worked as similar with lug and rib of deformed rebar.

Combination of Voronoi element and beam element is key for meso-scale analysis of bond.

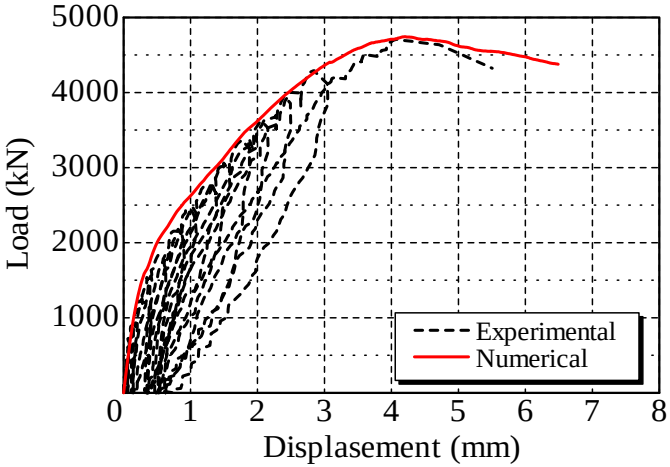
Numerical Method - 3D-Rigid Body Spring Method –
Simulation results of member level to confirm performance of RBSM

Cyclic Shear Wall Test

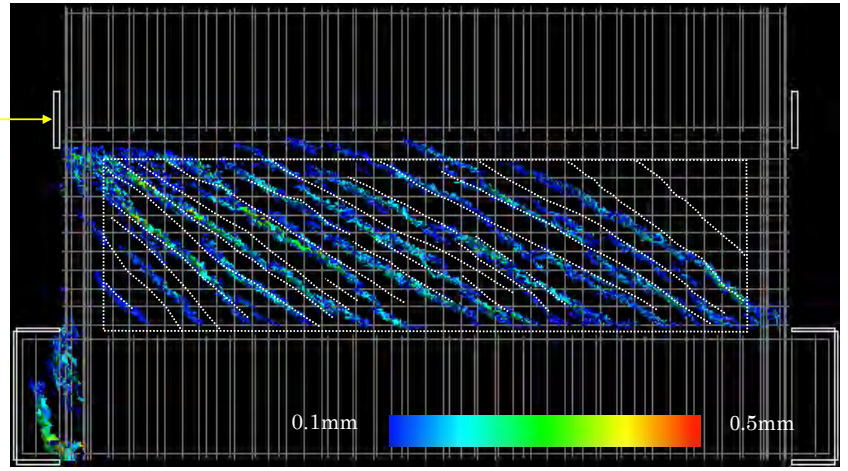
The test were conducted by the national French project "CEOS.fr"(2011). The tests aim to evaluate current cracking assessment method by the blind benchmark



(Concrack 2011)



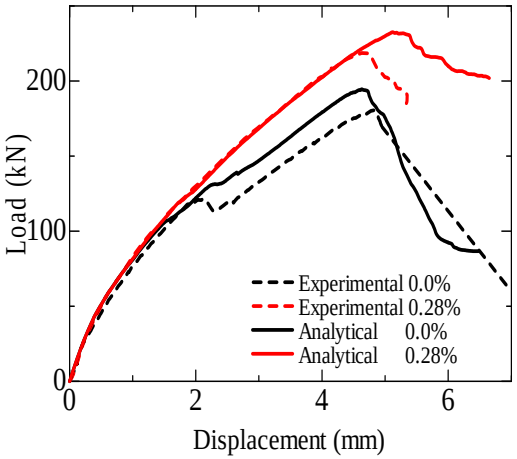
Load Displacement relationship

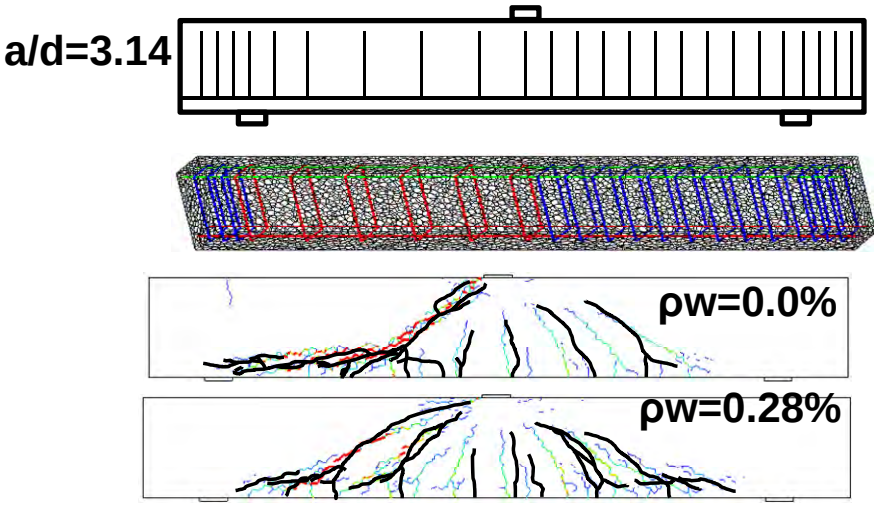


Crack pattern at 4200kN

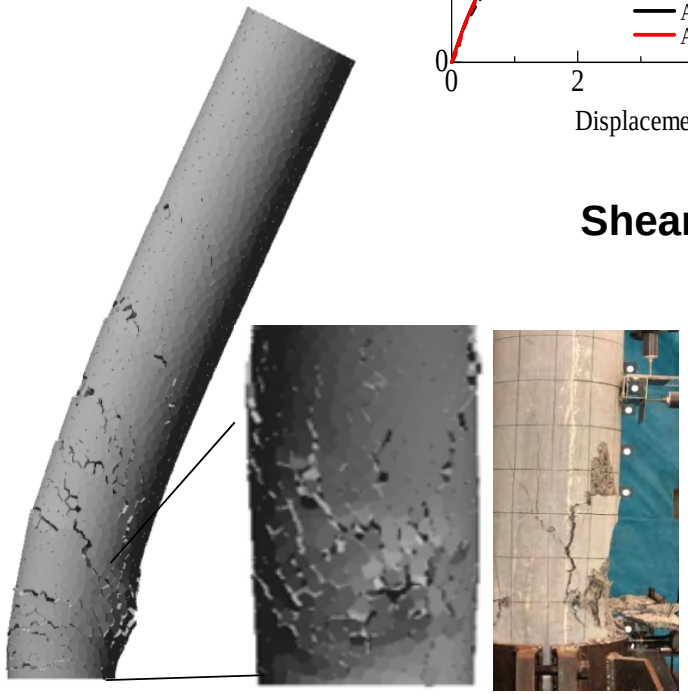
✓ The bond model plays an appropriate role, and the combination of the discrete model and the bond model has proven effective in accurately evaluating crack patterns.

Numerical Method - 3D-Rigid Body Spring Method –
Simulation results of member level to confirm performance of RBSM





Shear failure of RC beam (analysis before test)(2018,ACT)



Flexural failure of PHC pile

Dynamic torsion behavior of RC building

International benchmark SMART 2013

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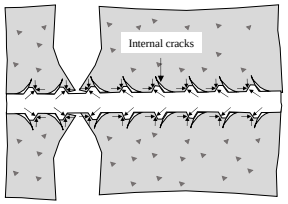
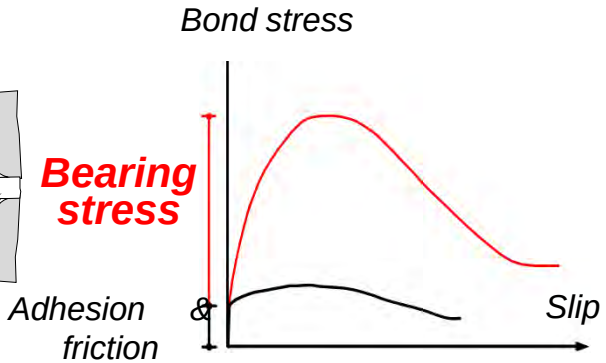
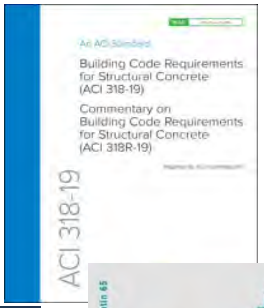
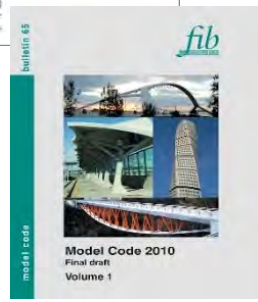
Motivation of Reinforcement Detaining Simulation



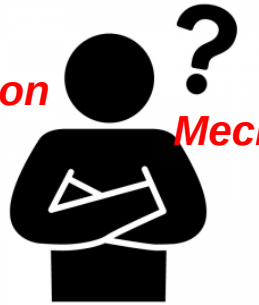


Codes: Empirical Formulae





Crack Propagation Mechanism

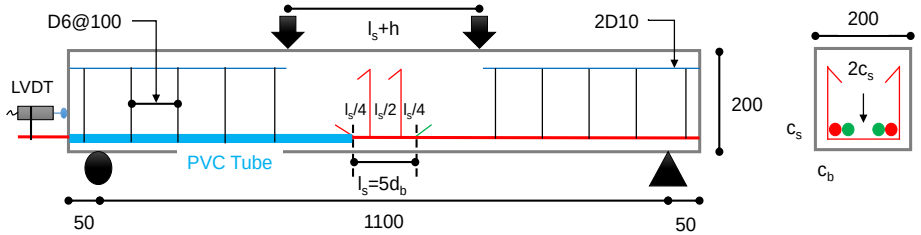


Many researchers have carried out detailed investigation of various parameters on the effect of rebar detailing.

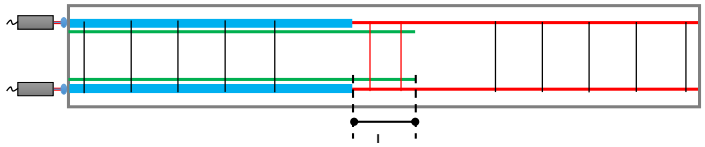
- ✓ Most rebar detailing, such as hooks and lap splices, were specified several decades ago based on experimental studies and the mechanism such as internal crack propagation and stress transmission has not been clarified.
- ✓ **Meso-scale simulation will provide the mechanism and important knowledge to revise design code.**

Numerical Evaluation of Beam Behavior with Lap Splices

Meso-scale simulation of lap splices

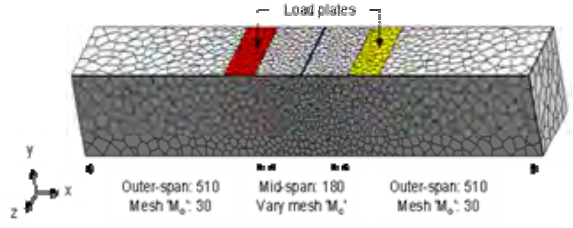


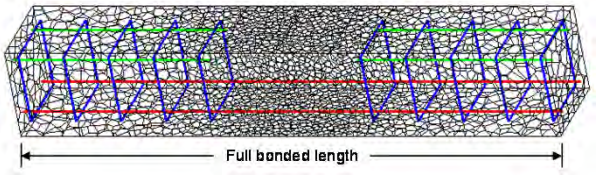
a. Side view.

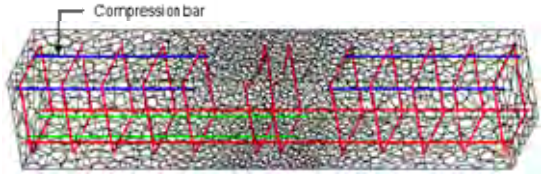


c. Bottom view.

B.S. Hamad, S. Najjar, (2002)

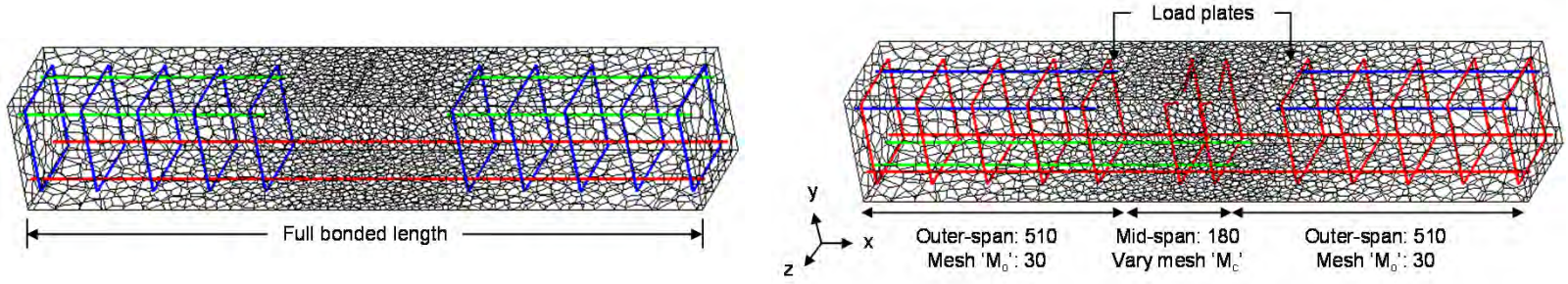


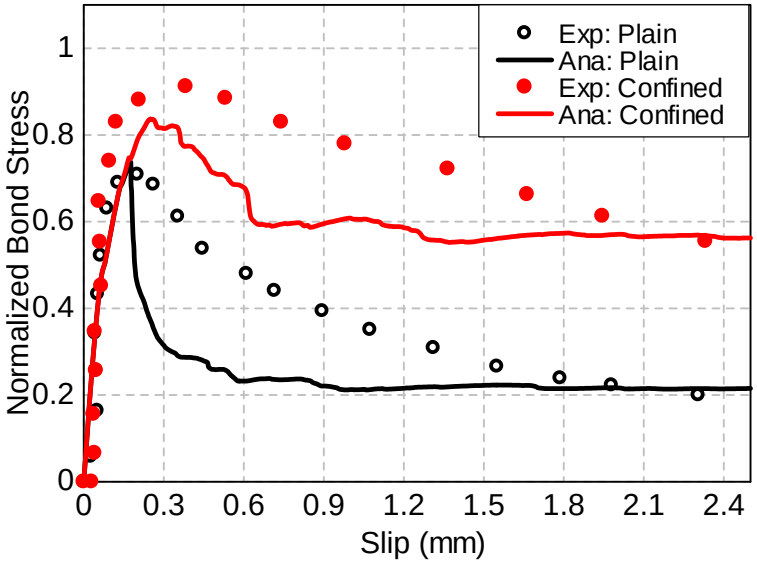




- ✓ **Outline of the test specimen**
  Parameters: stirrup confinement with and without stirrup case.
- ✓ **Numerical modeling**
  Mesh size in the mid-span: about 7 to 13 mm to produce cracking inner and outer splice rebars.
- ✓ **Important finding in test**
  Spalling of cover concrete at lap splices part.

Effect of Stirrup at Lap Splices





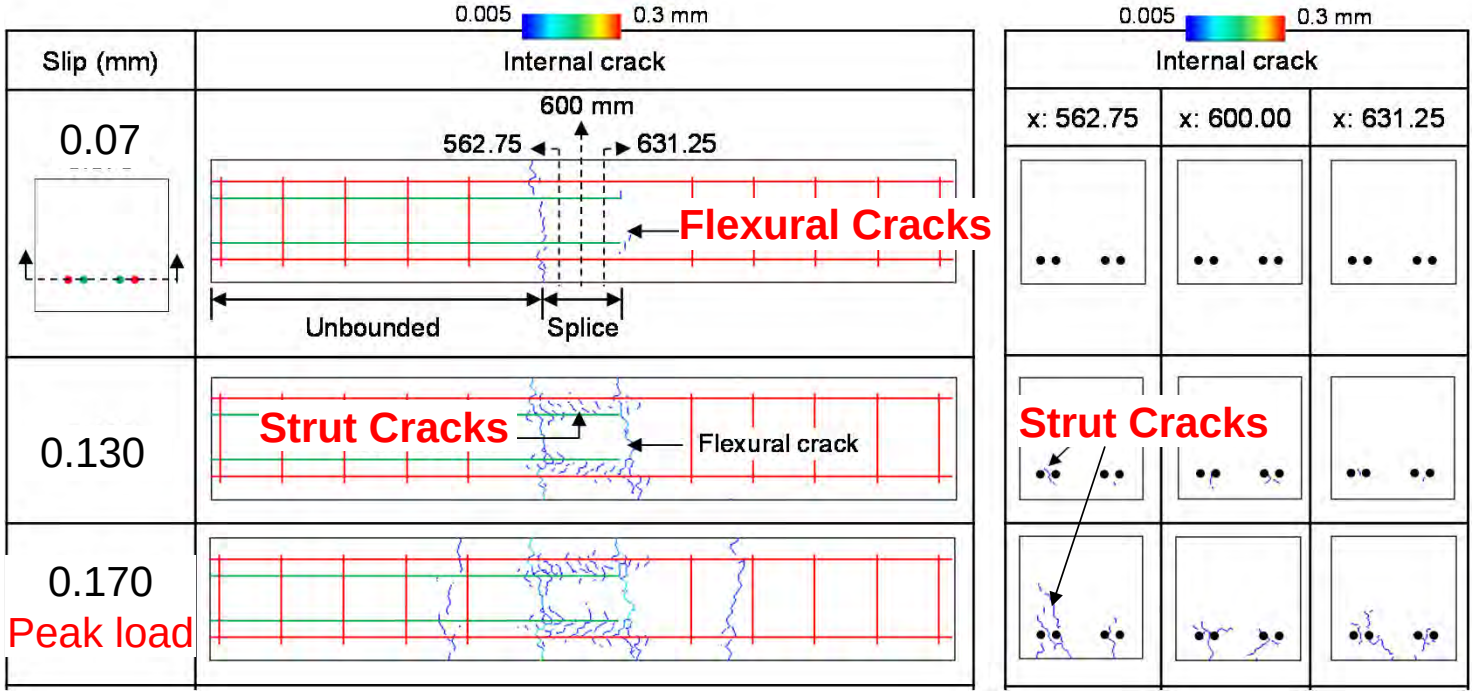
Usman Farooq, Engineering Structures(2022)

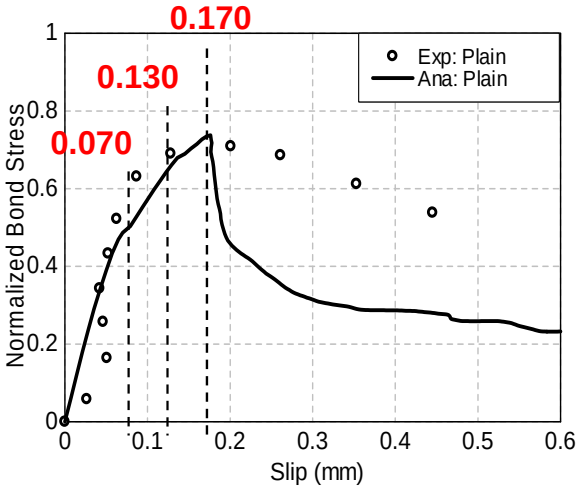
Comparison of bond stress and slip relationship obtained from test and analysis.

Numerical model simulated well both behavior with and without stirrup cases.

Effect of Stirrup at Lap Splices

Crack distribution of specimen without stirrup before peak

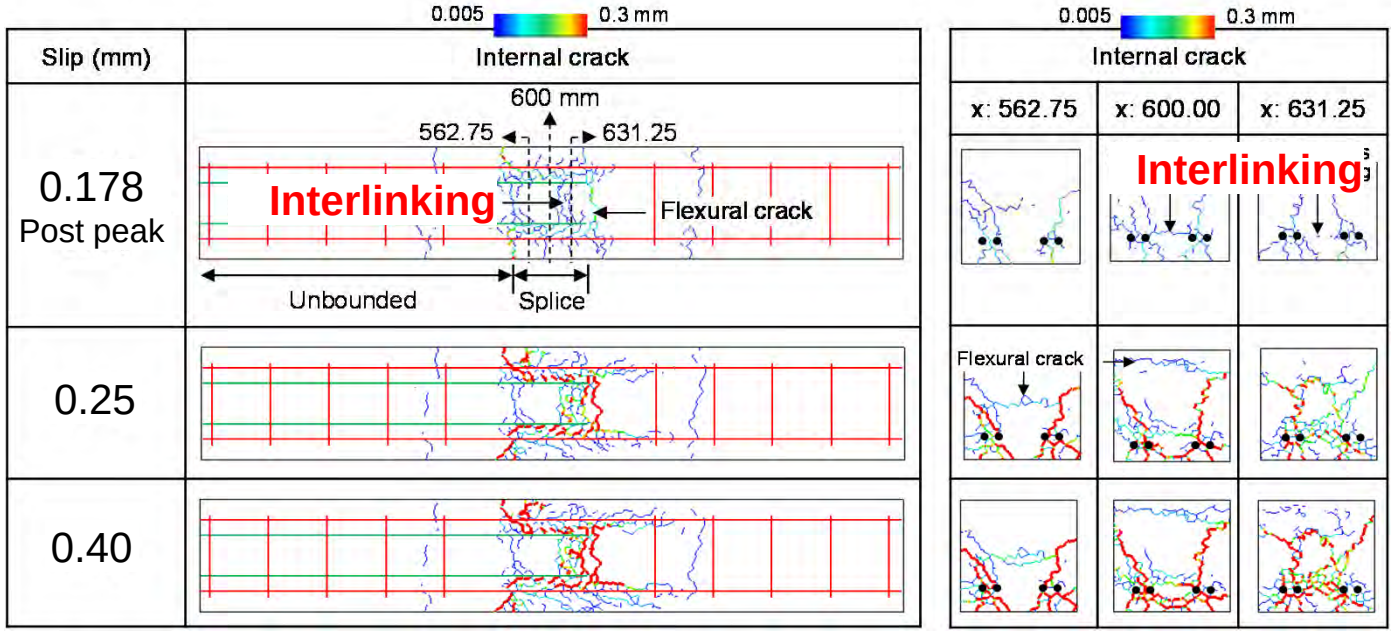


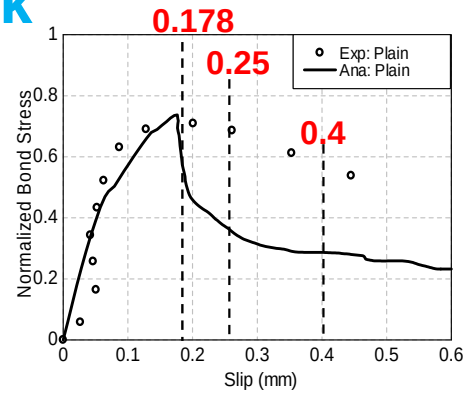


- ✓Dominant formation of flexural cracks at first.
- ✓Strut cracks initiate in-between individual splice bars.
- ✓At peak load, strut cracks propagate to side and bottom direction.

Effect of Stirrup at Lap Splices

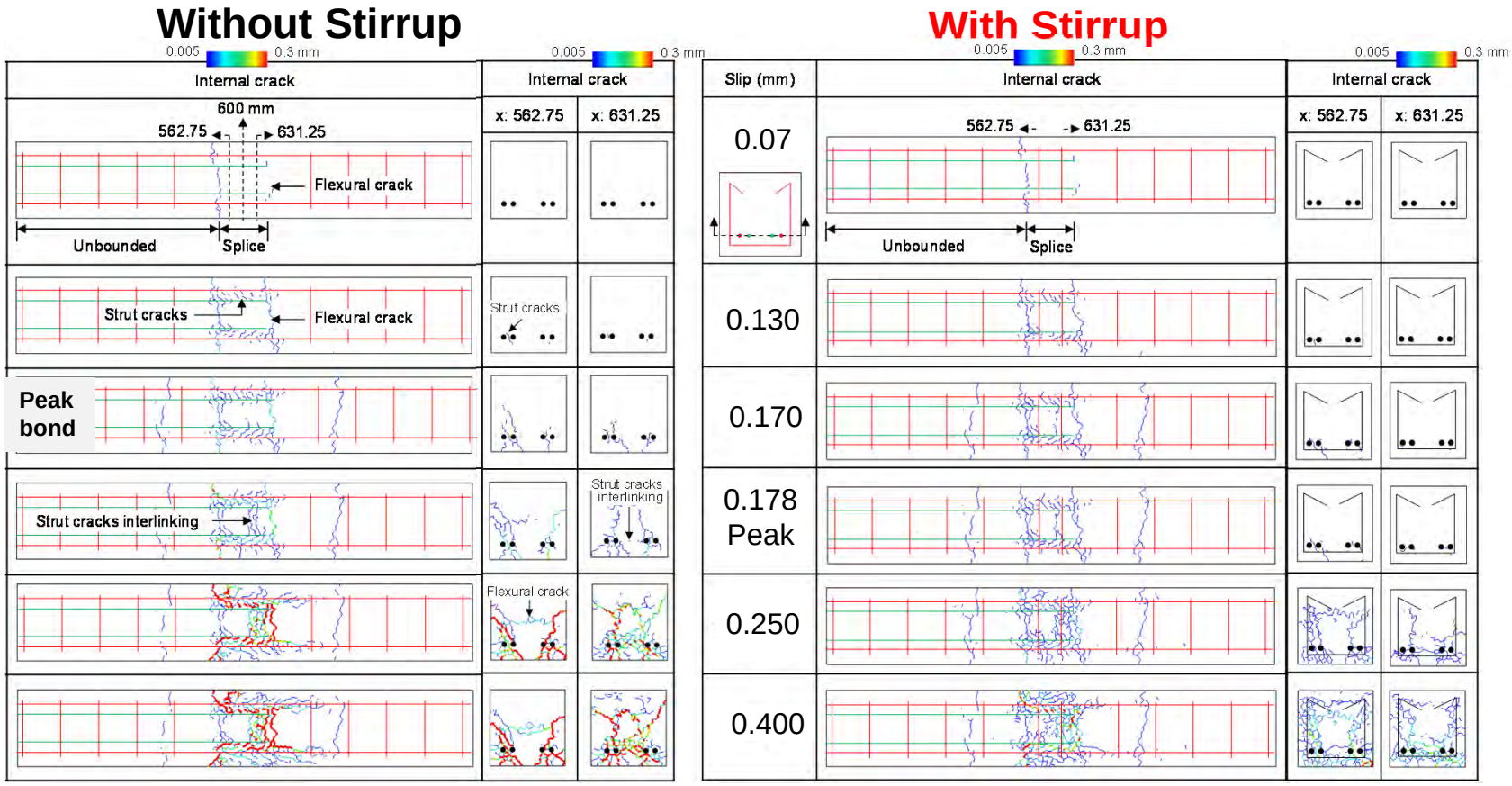
Crack distribution of specimen without stirrup after peak





- ✓ Strut cracks appeared at the side surfaces and opened.
- ✓ Failure of unconfined splices initiates with bottom cover splitting due to strut crack formation, followed by interlinking of strut cracks between pair of lap splices.
- ✓ **Meso-scale analysis can show crack propagation and failure behavior clearly.**

Effect of Stirrup at Lap Splices



Effect of stirrup at lap splice :

- ✓ Stirrup confinement reduces the bottom splitting, strut cracking, and changes the angle of crack formation.
- ✓ Stirrup confinement maximizes the cross-sectional capacity to support the stresses and increases the bond capacity.

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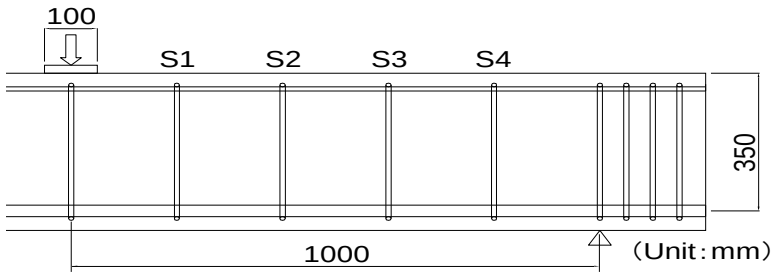
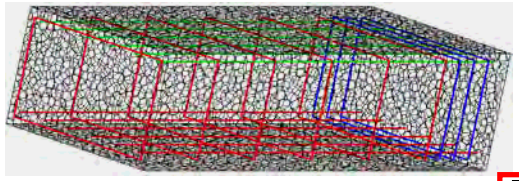
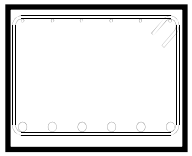
Understanding Shear Failure Mechanism by Meso-Scale

What do we get from detail discussion of meso-scale simulation results?

a/d : 2.86

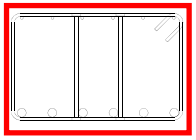






Case 1

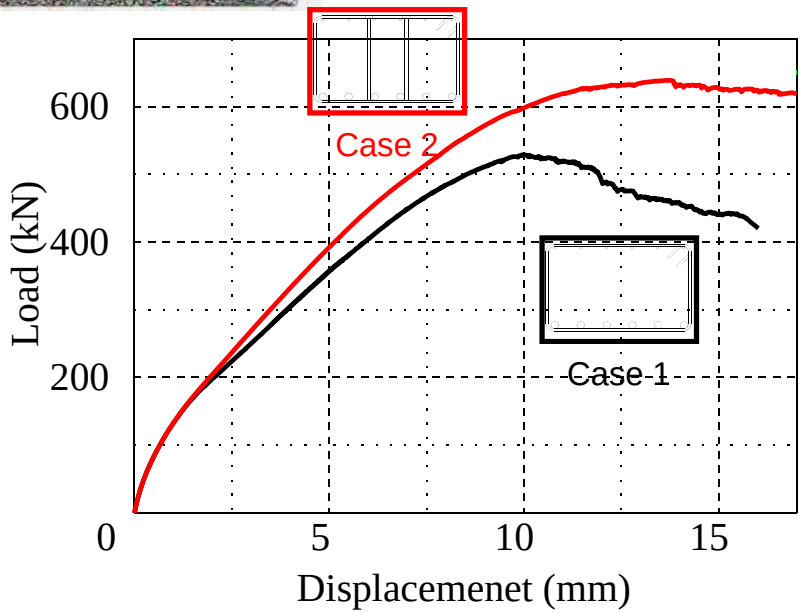
Closed stirrup case
(large leg space)
(2*As)



Case 2

Closed stirrup and
2 vertical stirrup case
(small leg space)
(4*0.5As)

Same stirrup ratio



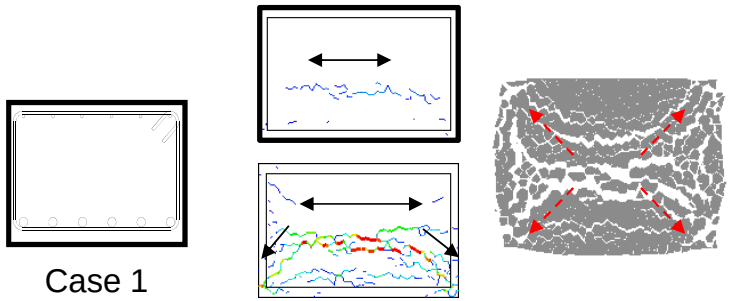
Load displacement relationship

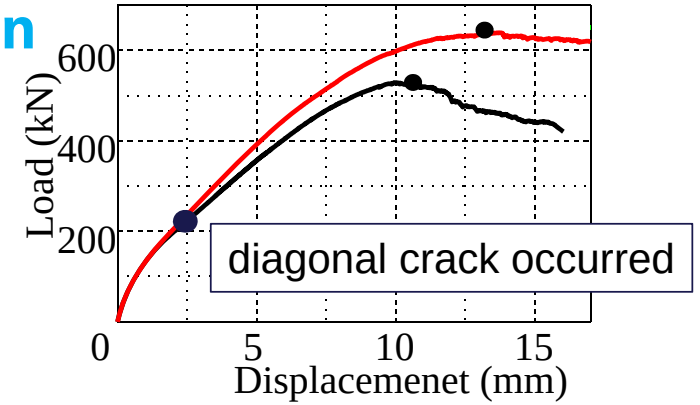
- ✓ **Design shear capacity are same for same stirrup ratio.**
- ✓ **Simulated load displacement relationship are quite different.**

Why difference occur?

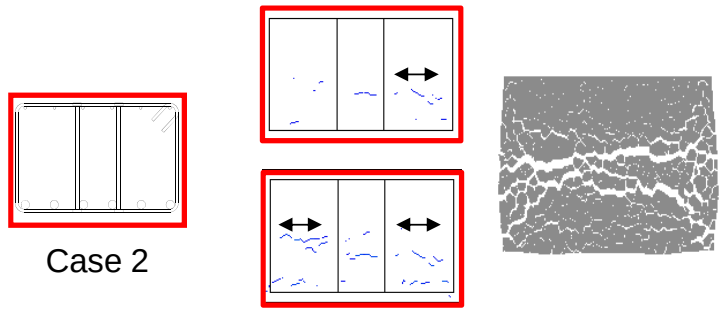
Understanding Shear Failure Mechanism by Meso-Scale

Difference from internal crack in cross section





Behavior in cross section



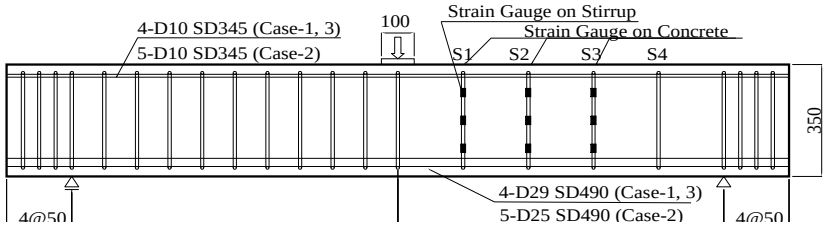
- Crack initiate at center and propagate horizontally after diagonal crack occur.
- Crack propagate diagonally to corner near peak load.
- Cross section expand in width direction

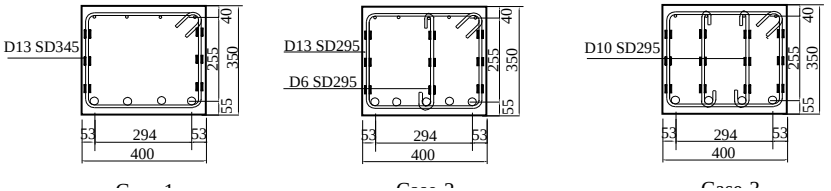
- Crack propagate horizontally in the cross section
- Crack can not propagate diagonally in small space
- Cross section did not expand in width direction

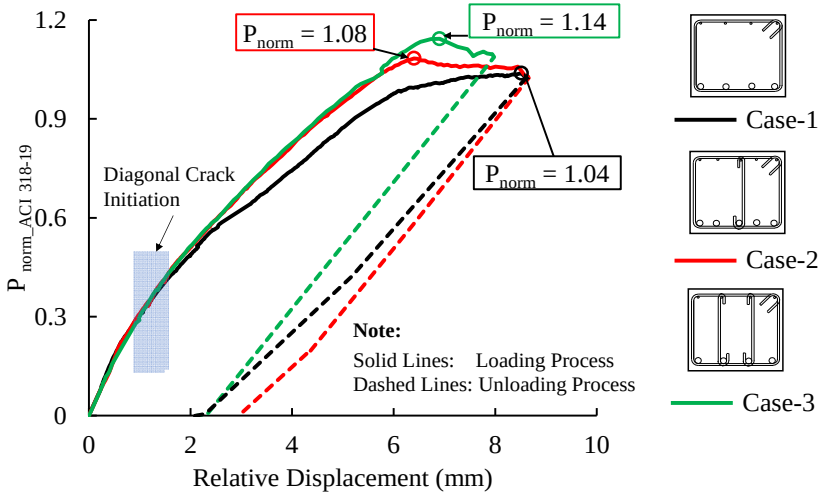
Detail observation of numerical results of meso-scale analysis will give us the possibility to get new knowledge to structural research field.

What are impacts to structural research ?

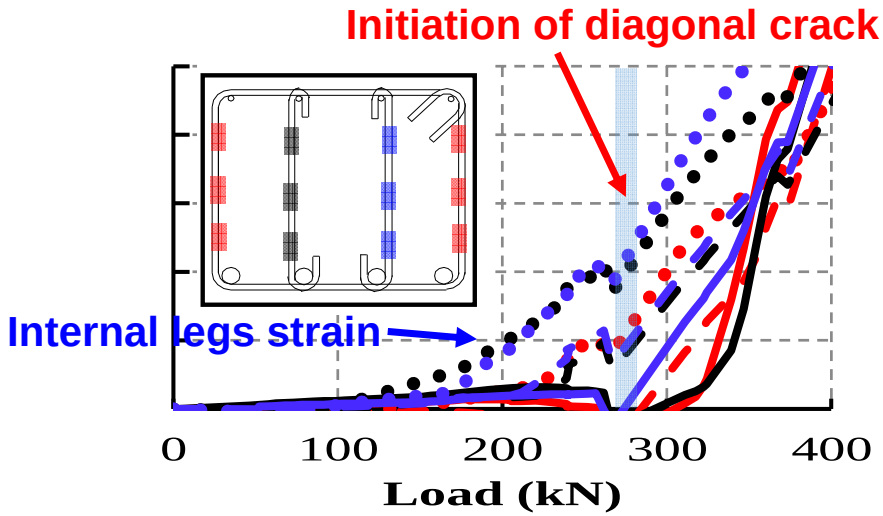
Numerical findings were confirmed by experiment after simulation







(Muhammad et al., Developments in the Built Environment, 2024)



Stirrup strain development

Internal leg strain increase before the initiation of diagonal cracking.

When we discuss the results of mesoscale analysis, it is important to conduct experiments that can explain the suimulated results.

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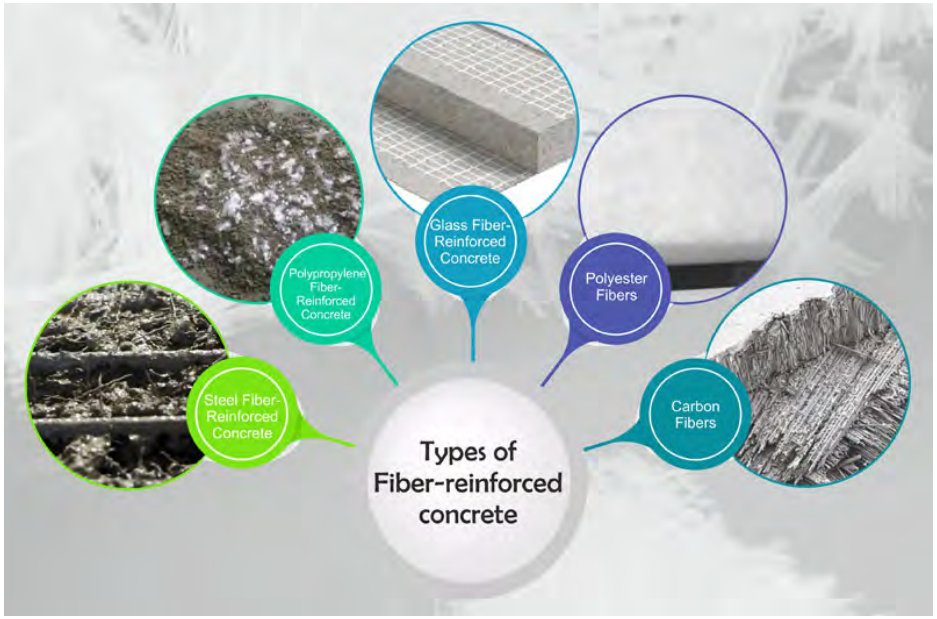
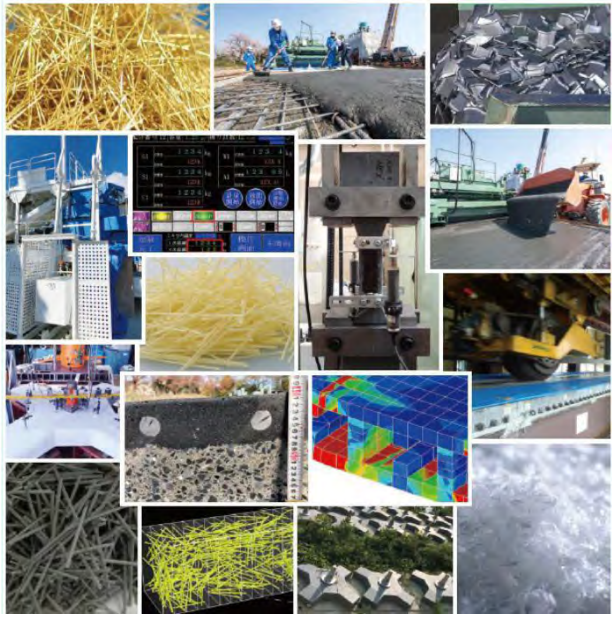
Research Background and Motivation

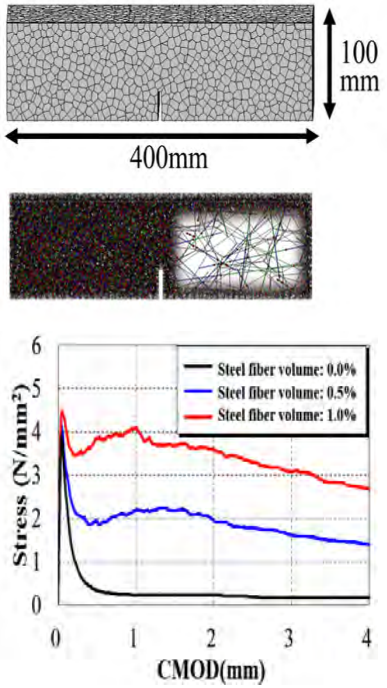
FRCC(Fiber Reinforced Cementitious Composites)

✓**Attractive behavior such as high tensile strength and reduction of cracking.**



https://constrofacilitator.com/fiber-reinforced-concrete-advantages-types-and-applications/

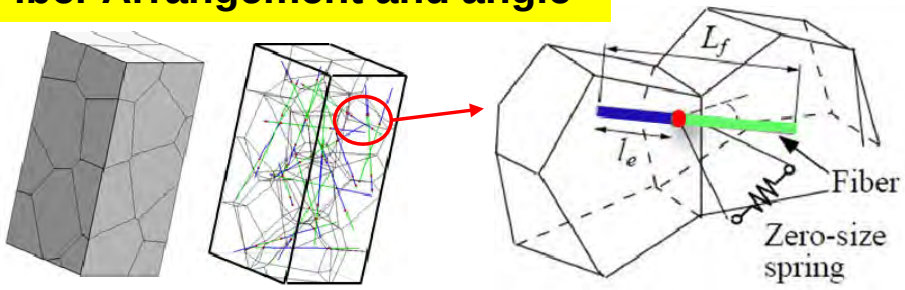




- ✓ **Behaviors vary fiber type, fiber distribution and matrix properties.**
- ✓ **Meso-scale simulation is useful to consider these parameters.**

Outline of Steel Fibers Modeling

Fiber Arrangement and angle



- ✓ **Steel fibers are modeled by discrete short fibers , which are arranged inside the Voronoi mesh to arbitrary direction.**
- ✓ **A zero-size virtual spring is placed where fiber crosses the boundary of two Voronoi cells, and the force transfer by fibers act on the spring.**

Crack Bridging Constitutive Model of Steel Fiber with Hook End

After Cracking | Local Bond-Slip Model

Bond Stress

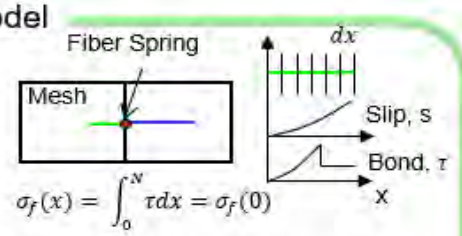
$$\tau(s) = \begin{cases} \tau_a \left(\frac{s}{s_1}\right)^{\alpha} & ;if\ s \le s_1 \\ \tau_f & ;if\ s > s_1 \end{cases}$$

τ_a, τ_f, s_1, l_e, Slip

Bond kinematics

$$\tau_a = \left(\frac{E_m}{E_f}\right)^{\alpha 1} \sqrt{f'_c} \qquad \tau_f = \beta\sqrt{f'_c}$$

Fiber Spring



$$\sigma_f(x) = \int_0^N \tau dx = \sigma_f(0)$$

E_m = Elastic Modulus of Matrix
E_f = Elastic Modulus of Fiber
f'_c = Compressive Strength of Matrix

Hook End Effects (P_h)

$$N_{sp} = \begin{cases} 1000s - 720s^2;\ s \le 0.6\ mm \\ 2.24s^5 - 35s^4 + 201.6s^3 - 500s^2 + 445s + 172;\ 0.6\ mm < s \le 5.5\ mm \\ 70 - 1.57s;\ s > 5.5\ mm \end{cases}$$

$$N_{norm} = nH\sqrt{\frac{f'_c f_y}{E_f}} \qquad H = \mu\rho\theta$$

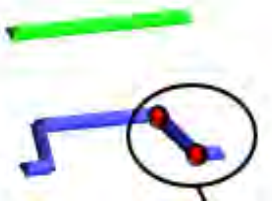
n = Number of hinges

Hook End fiber

- ✓ **The fiber pullout load is considered by combining the local bond-slip model of the straight section with the mechanical hook action at the hook end.**

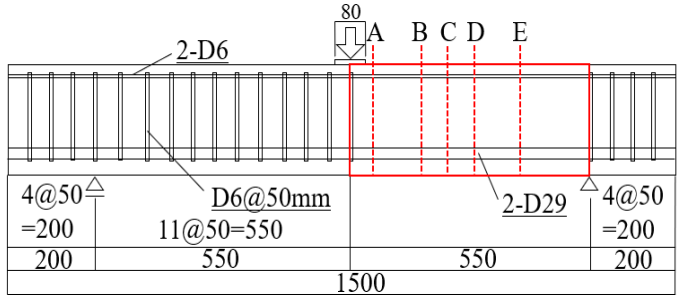
Smooth steel fiber
$(P(0) = P_s)$

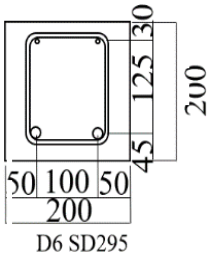
Hook end steel fiber
$(P(0) = P_s + P_h)$



Simulation of SFRC Beam Failed in Shear

Shear failure test of SFRC beam



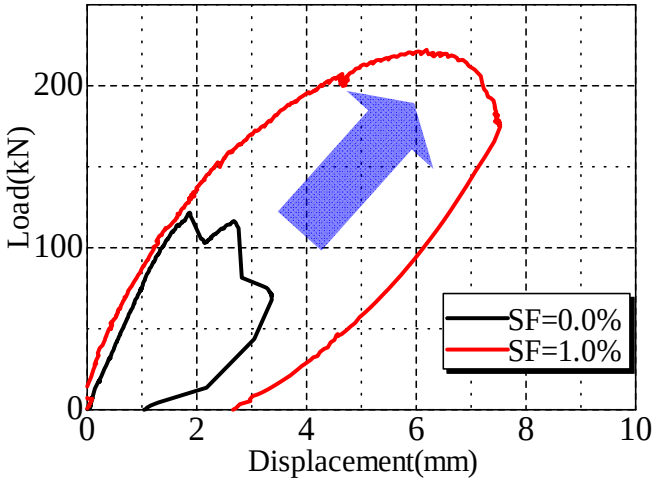


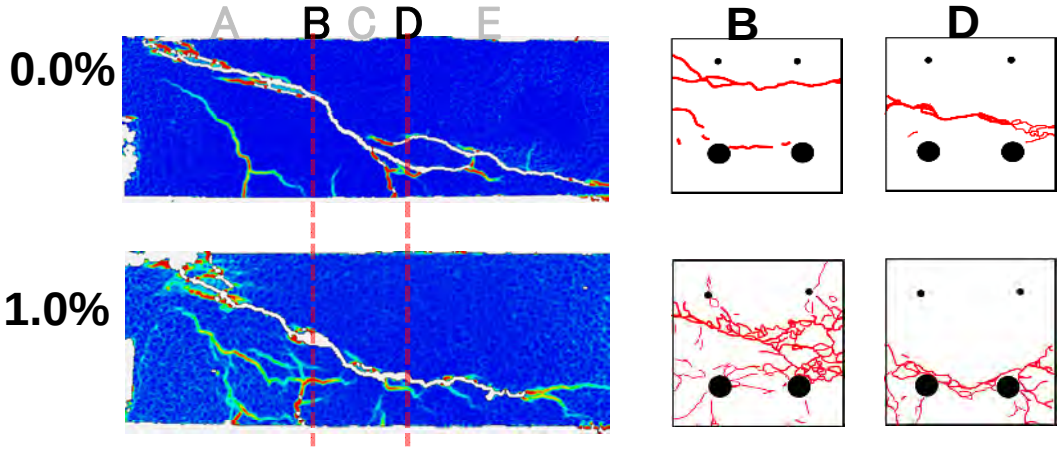
a/d=3.55

f'c=36(N/mm²)

SF(Hooked)= 0.0%, 1.0%

Dimension of tested beam.





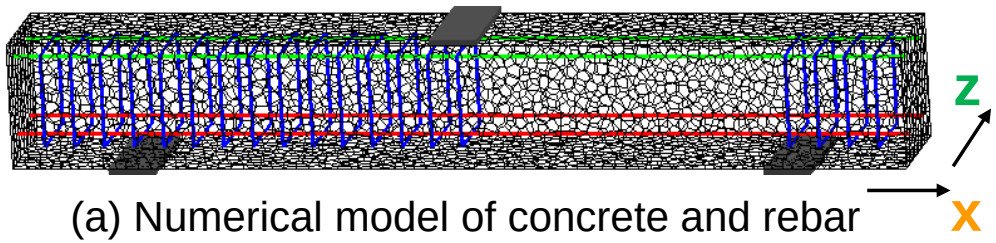
Cracks at Side Surface and in Cross Section

A clear increase in shear strength by using SFRC.

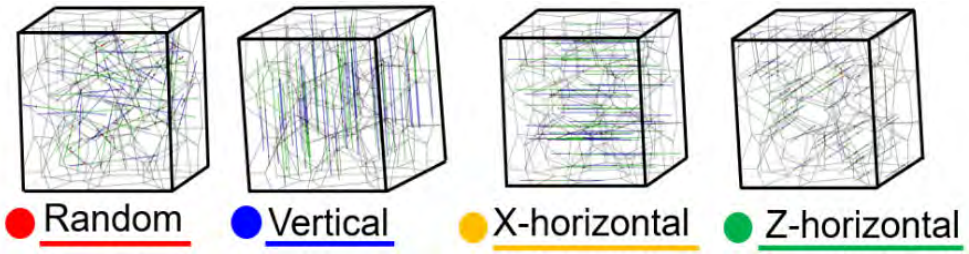
Not only cracks on the surface but also cracks in cross section obvious disperse.

Simulation of SFRC Beam Failed in Shear

Numerical Model and Results –Load Displacement Relationship

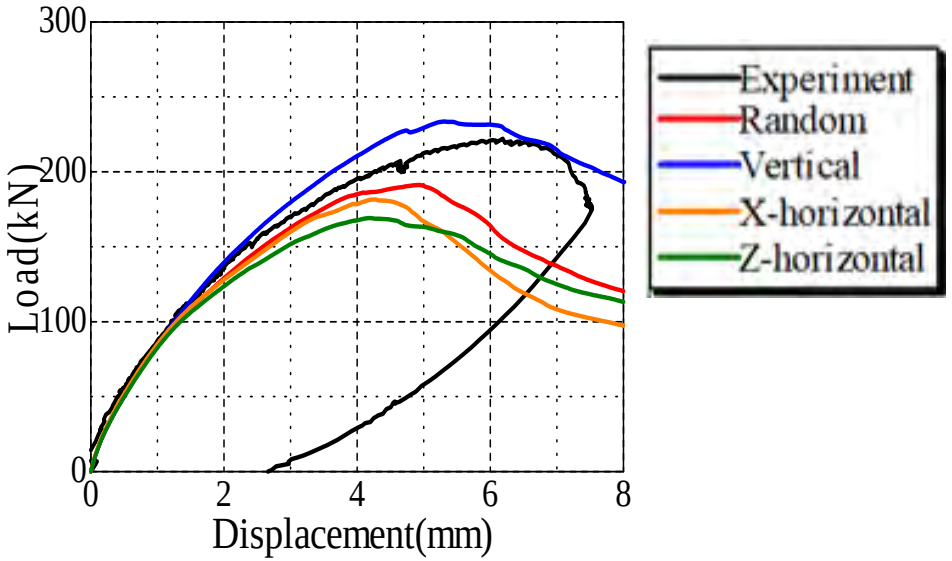


(a) Numerical model of concrete and rebar



(b) Fiber orientations

Numerical model of tested specimen.

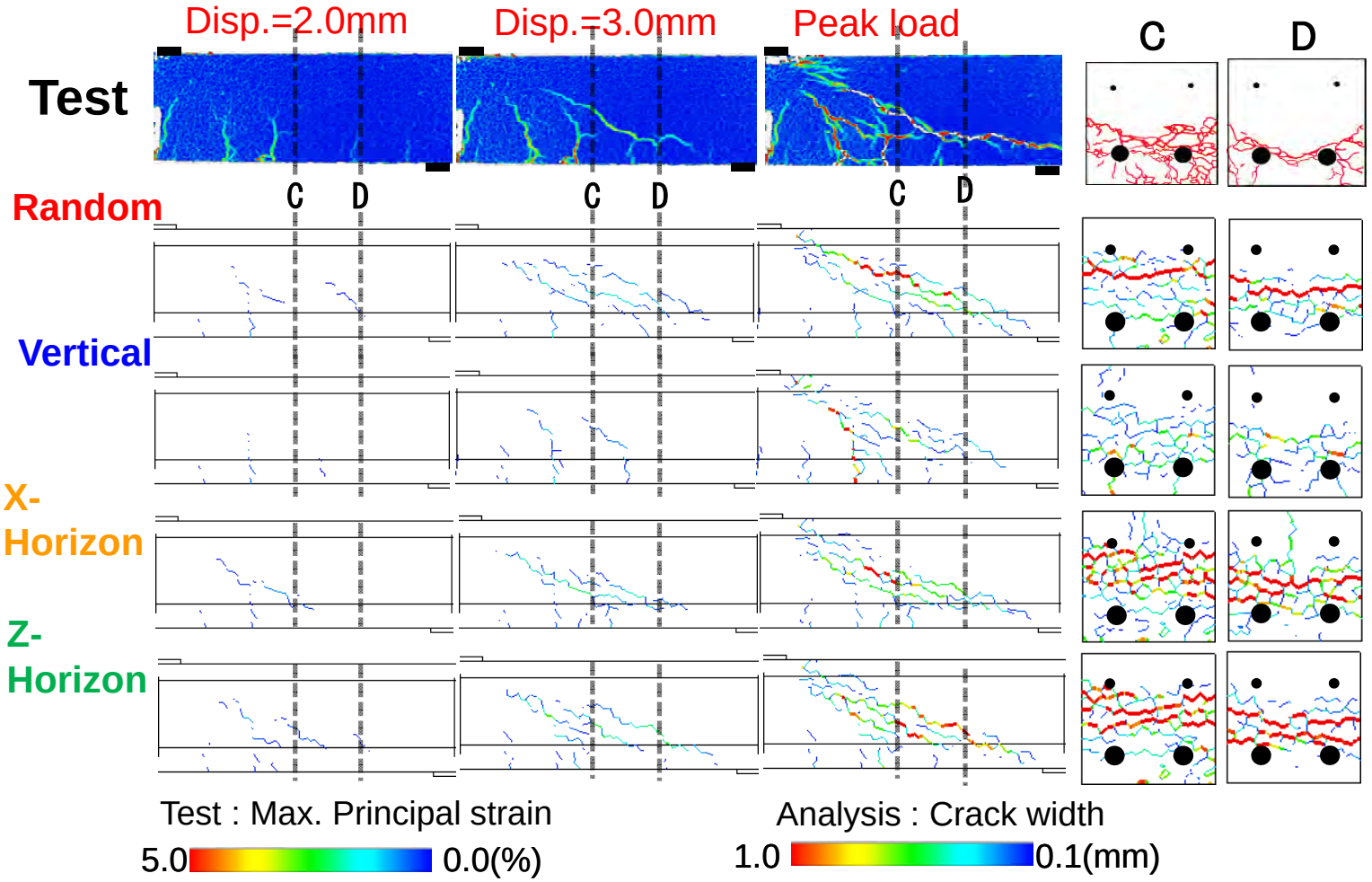


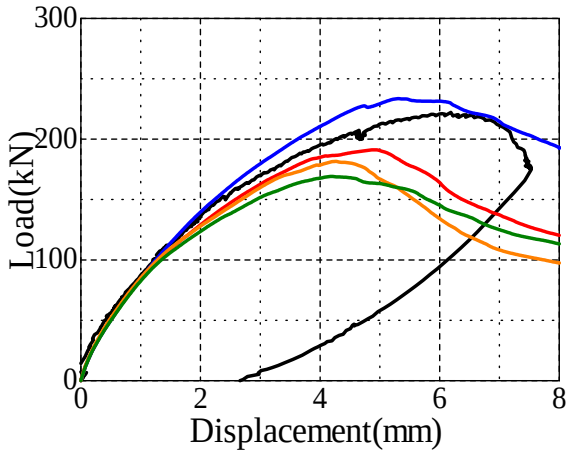
Comparison of load displacement relationship.

The load-displacement relationship showed a tendency for the load to be larger for the vertical orientation than for the other orientations, and closer to the experimental value.

Simulation of SFRC Beam Failed in Shear

Numerical Results – Cracking Behavior -





The fiber orientation affects the initiation of diagonal cracks, crack propagation, crack dispersion, and ultimately the dominant crack location for both surface and internal cracks.

The analysis to consider fiber orientation at meso scale is important and it is useful to evaluate FRC behavior.

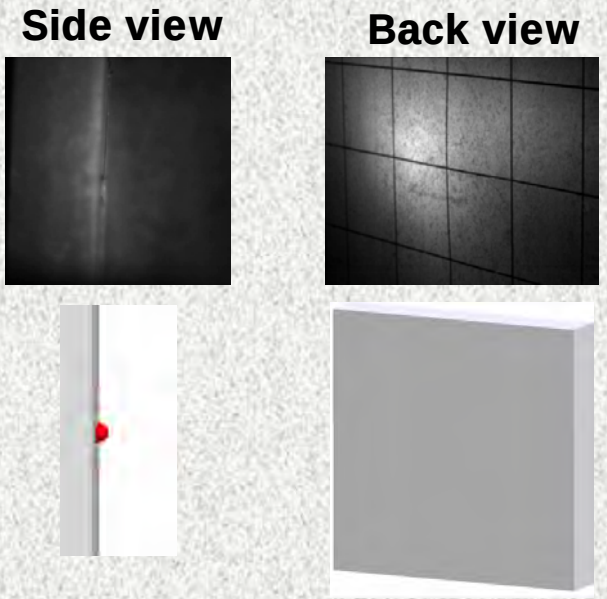
CONTENTS

- Motivation of Discrete Model(RBSM)
- Modeling of RBSM
  - ✓ RBSM for Structural Analysis Model
  - ✓ Bond simulation with meso-scale behavior
  - ✓ Application to structural analysis
- Impacts to Structural Research
  - ✓ Understanding Shear Failure Mechanism
  - ✓ Clarification of Role of Rebar Detailing
  - ✓ Application to Shear Failure of Fiber Reinforced Concrete
- Conclusion

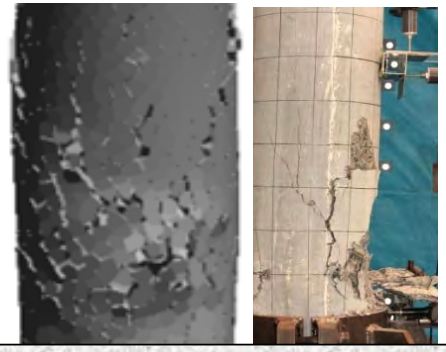
What Can We See Through Crack?

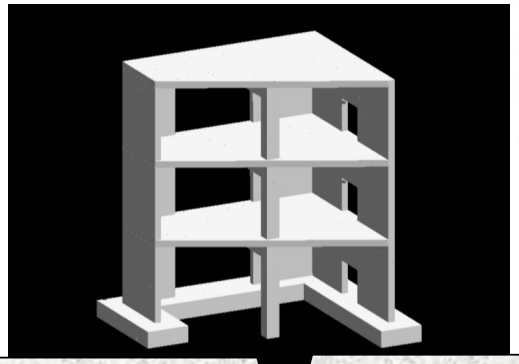
What are lessons from damage due to big earthquake?

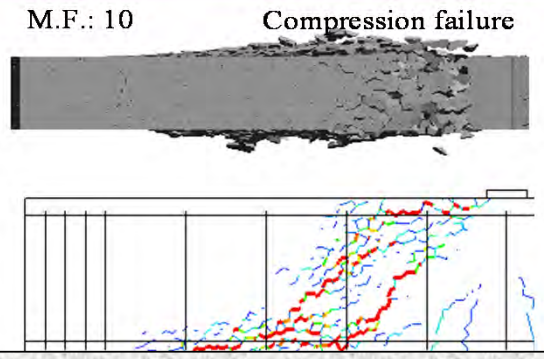
- Ultimate Behavior : not only design stage but also collapse (Crack separation)
- Damage evaluation for rapid restoration(Crack accumulation)
- Evaluation of excessive action such as collision and fire (Dynamic crack propagation)



What can we see through simulated crack?







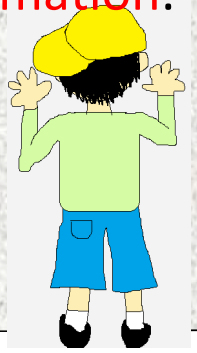
What are lessons
from advancement of simulation method

- What is merit of meso-scale simulation than classical F.E.M.
- How to verify accuracy and reasonableness of simulation results?
- How to use many information obtained from simulation results?

- What do we get from simulation results?
- What are impacts to structural research?

What can we see through meso-scale simulation

- Meso-scale simulation can provide realistic behavior of concrete structures based on fundamental mechanical behavior related to minor and major crack initiation and propagation.
- The application of the model are increasing for several problems and the utilization will increase with increase of computer performance.
- Both the advancement of numerical and experimental technique are important. Numerical and experimental technique should be advanced together.
- Especially, numerical side should require to experimental side based on the knowledge obtained from many information.



Thank you for your kind attention

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