Numerical Evaluation on Performance Improvement of Concrete Members Using Steel Fibers

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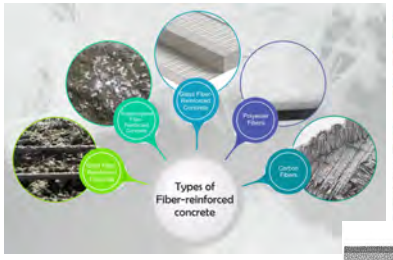
- Research Background and Motivation
- Simulation Method -Rigid Body Spring Method-
- Modeling of SFRC in RBSM
- Simulation of Bond behavior in SFRC
- Simulation of SFRC Beam Failed in Shear
  - ✓ Effect of fiber orientation
  - ✓ Clarification of Shear Resistance Mechanism of SFRC
- Conclusion

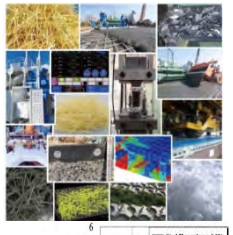
Research Background and Motivation

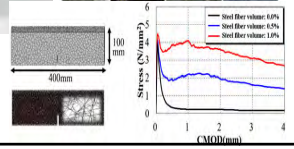
FRCC(Fiber Reinforced Cementitious Composites)

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



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

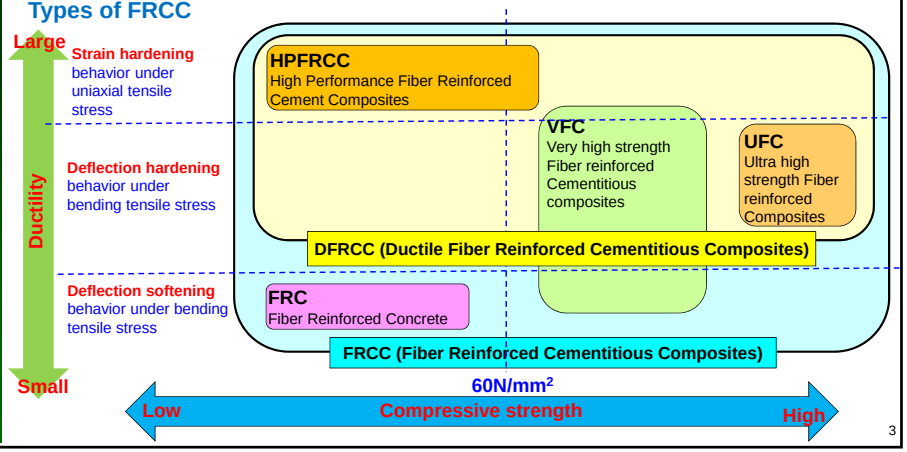




- ✓ Many researchers have been developed the numerical modeling not only FRCC itself but also application to concrete structures.
- ✓ In the situation, detail investigation of structural level is important topic and in particularly, application to concrete member to enhance the performance both serviceability and safety is most attractive use of FRCC.

Research Background and Motivation

Types of FRCC



Research Background and Motivation

JSCE Recommendation

1983	Recommendations for Design and Construction of **Steel Fiber Reinforced Concrete** (**SFRC**)	Steel fiber, Vol.=0.5-2.0%
1999	Recommendations for Design of Reinforced concrete column with **Steel Fiber Reinforced Concrete** (**RSF Column**)	Steel fiber, Vol.=1.0-1.5%
2004	Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete (**UFC**)	Steel fiber, Vol.>2.0%
2007	Recommendations for Design and Construction of **High Performance** Fiber Reinforced Cementitious Composites with Multiple Fine Cracks (**HPFRCC**)	Organic Fiber (PVA, PE, etc)
2024	Recommendations for Design and Construction of **Very High Strength** Fiber Reinforced Cementitious Composites (**VFC**)	Organic Fiber, Inorganic fiber



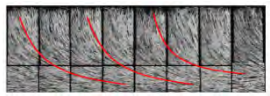
Recommendation were published for each material properties.

Research Background and Motivation

There are many things to consider when we use FRCC.

- **There are many types of FRCC**
  - ✓ **Various strength matrixes (Mortar, Concrete)**
  - ✓ **Various type of fibers**
    (Material(Inorganic and Organic), Strength, Fiber shape, length, diameter)
- **Structural performance is affected by the fiber orientation.**
  - ✓ **The orientation coefficient is considered in the design (determined experimentally).**





X-ray CT images
Fiber orientation is strongly influenced by fluid behavior of matrix.

- **Material properties are determined experimentally, and the performance of the members is also determined experimentally.**
- **Structural details such as reinforcement arrangement and anchorage performance are confirmed experimentally.**

It is difficult to standardize many types of FRCC uniformly.

Research Background and Motivation

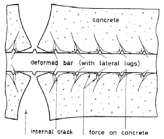
When various types of FRCC are utilized, it is required that all various properties are confirmed experimentally.

A numerical method capable to model various types of FRCC and to evaluate the various properties is desired.

The analysis have to be able to appropriately:

- ✓ **Evaluate cracking (Smeared crack or Discrete crack)**
  - **Discrete Element Method**
- ✓ **Consider variations of fiber type and shape**
- ✓ **Consider fiber orientation**
  - **Modeling each individual fiber**
- ✓ **Evaluate interaction with rebar (bond and anchoring performance)**
  - **Simulation internal cracks from lug**





Internal crack/ Goto crack

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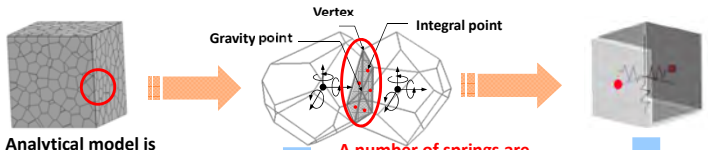
Numerical Method - 3D-Rigid Body Spring Method – Concept and Modelling of RBSM

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

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

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

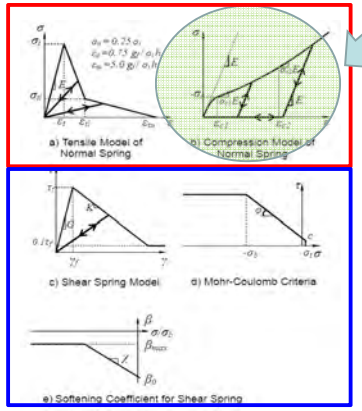
RBSM can be positioned as a model that can directly evaluate the cracking behavior of FRCC.

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

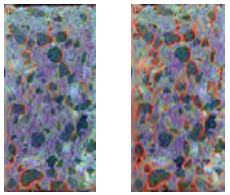
Concrete Material Model

Normal spring k_n k_t

Shear spring k_n k_t



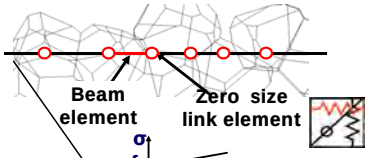
no softening part is modeled in compression

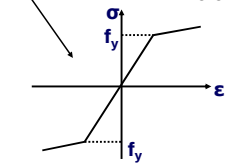


- The feature of the model is that no softening part is modeled in compression.
- Compression failure is not compression failure of concrete. It is accumulation of failure of tensile and shear failure.

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

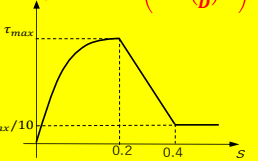
Reinforcement and Bond Model





Stress strain relationship

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



Bond stress-slip model

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

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

Since bond model is same for normal concrete and FRCC, differences in bond characteristics between among materials are represented by accurately evaluating the change of confinement effect due to cracking around the rebar.

Simulation of Bond Behavior of Deformed Rebar

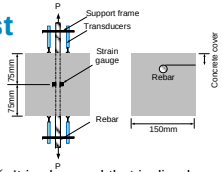
Internal crack pattern of RBSM with beam element and 3D model

Internal Crack Pattern of Two Ends Pull Out Test

Beam Element | 3D Model

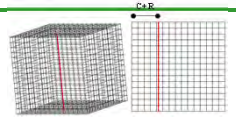
Slip (mm)	C=30mm Deformation	C=30mm 3D Crack Distribution	C=30mm Crack at Center	C=30mm Deformation	C=30mm 3D Crack Distribution	C=30mm Crack at Center
0.05						
0.15						
0.30						

(CCC, 2020) Internal crack pattern

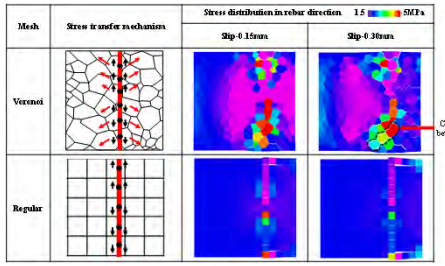


- ✓ It is observed that inclined internal cracks develop from lug for both models.
- ✓ Beam element model can appear same bond crack behavior as 3D rebar model.
- ✓ Combination of Voronoi element and beam element can simulate similar internal crack formation from lug.
- ✓ This is important requirement for appropriate evaluation of interaction of rebar.

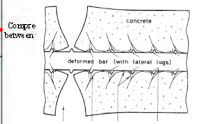
Simulation of Bond Behavior of Deformed Rebar
Key point of beam element model



Simulation by regular mesh arrangement



Effect on Stress Transfer Mechanism

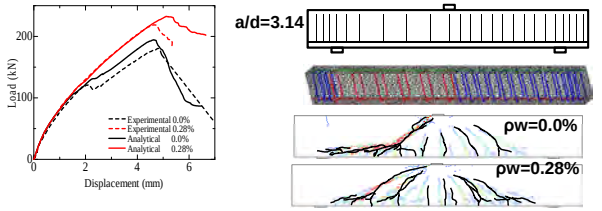


Internal Crack（Goto et al.）

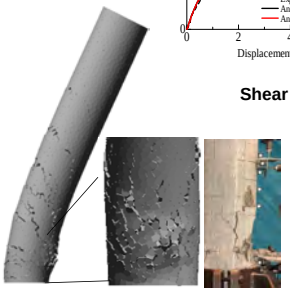
(CCC, 2020)

- ✓ Why can this simple model simulate internal cracking behavior similar with 3D rebar model with lug.
- ✓ Key aspect is random mesh modeling. I modeled only bond stress along the rebar. But the stress is transmitted to arbitrary direction by random shape. The random shape worked as similar with lug and rib of deformed rebar.

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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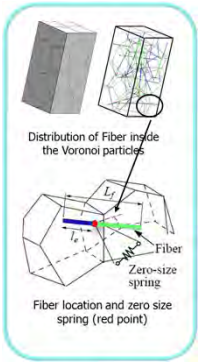
Constitutive Model of Steel Fiber
Short Fiber Model –Smooth and Hooked-End Fiber

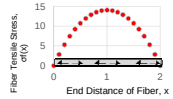


Pre-Cracking | Axial Tensile Stress

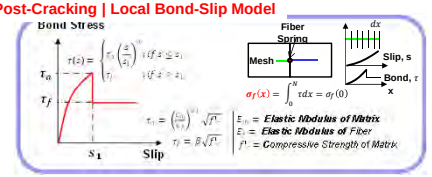
$$\sigma_f(x) = E_f \varepsilon_m \left\{ \frac{1 - \cosh\left(\beta\left(\frac{l}{2} - x\right)\right)}{\cosh\left(\frac{\beta l}{2}\right)} \right\}$$

$\sigma_f(x)$ = Fiber tensile stress (MPa),
E_f = Fiber elastic modulus (MPa),
ε_m = Matrix strain,
l = Embedment length (mm),
x = Distance from the end of fiber (mm), and
β = Constant determined by several factors (and set to 1.0 in this study).

Prior to matrix cracking, axial stiffness of the fiber spring is determined using shear lag theory (Cox, 1952)



Post-Cracking | Local Bond-Slip Model

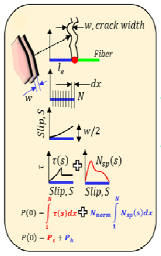


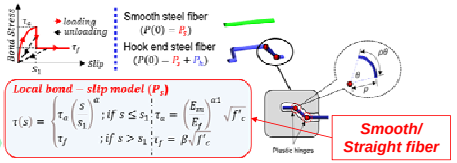
(CCC, 2023)

- ✓ Individual fiber was modeled by discrete short fiber, which was arranged inside the Voronoi particles to arbitrary direction.
- ✓ A discrete constitutive model for SFRC was utilized in this study.
- ✓ A virtual bridging force of all fibers is applied by zero size element at fiber location.
- ✓ The elastic tensile stress along the length of the fiber is estimated during the pre-cracking stage.
- ✓ In the post-cracking stage, the fiber bridging force is estimated.

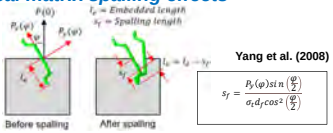
Constitutive Model of Steel Fiber

Crack bridging part





Local matrix spalling effects



Yang et al. (2008)

$$s_f = \frac{P_f(\varphi)\sin\left(\frac{\varphi}{2}\right)}{\sigma_t d_f \cos^2\left(\frac{\varphi}{2}\right)}$$



- ✓ fiber-bridging force is calculated by estimating the local bond stress and incorporating the hook end effects based on the local slip.
- ✓ The local bond stress is estimated using the proposed local bond-slip model. The hook-end effects are incorporated by employing the pullout slip function.
- ✓ The estimated bridging force is decomposed into axial and shear components, then local matrix spalling effect is considered.

(CCC, 2023)

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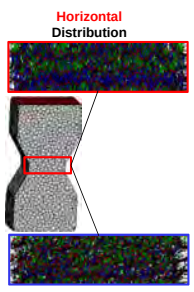
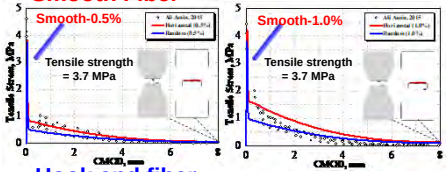
Application of Developed Steel Fiber Model

Direct Tensile Test

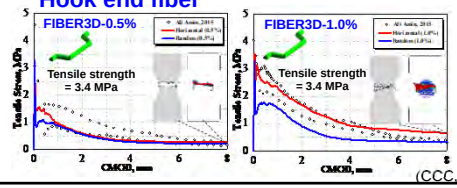
fiber type(smooth and hook end fiber), fiber volume and fiber orientation



Smooth Fiber



Hook end fiber

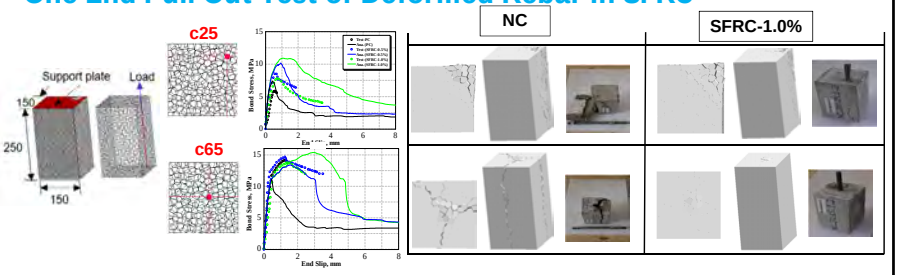


- ✓ Smooth steel fiber shows gradual softening with the effects of local bond stress.
- ✓ Hook end fiber shows additional hardening with the effects of mechanical hook action.
- ✓ Effect of fiber type, fiber volume and fiber orientation are simulated reasonably.

(CCC, 2023)

Application of Developed Steel Fiber Model

One End Pull Out Test of Deformed Rebar in SFRC

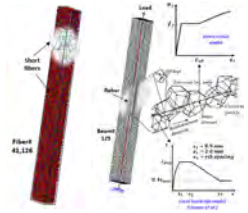


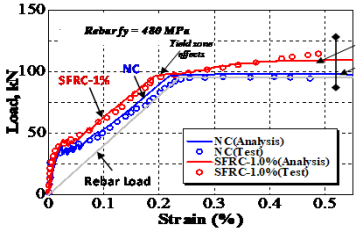
- ☐ Cover thickness and fiber volume are considered as parameters.
- ☐ The macro bond behavior from normal concrete to SFRC with different cover thickness could reproduce the experimental observation.
- ✓ **In the analysis, a simple local bond slip model was used. Improvement of bond behavior come from increase of confinement effect to restrain crack opening by fiber in SFRC.**

Application of Developed Steel Fiber Model

Tension Stiffening Behavior of SFRC

Beam element model

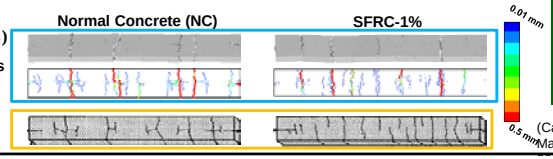




Validation of tension stiffening analysis.

- ✓ The tension stiffening capacity of SFRC was found to increase from the cracking stage to the post-yield region compared to normal concrete. Especially, the contribution after yielding for hardening behavior is clearly simulated.
- ✓ In the cracking behavior, fiber contribute to reduce splitting cracks along rebar and to increase cross sectional cracks and micro cracks. Bond performance was maintained due to restraint splitting cracks.
- ✓ This confirmation serves as an essential validation step for scale up to apply to RC beams with SFRC.

Cracking behavior (strain=0.55%)



(Case Studies in Construction Materials,

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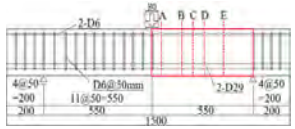
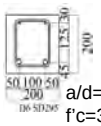
Simulation of SFRC Beam Failed in Shear

Shear failure test of SFRC beam

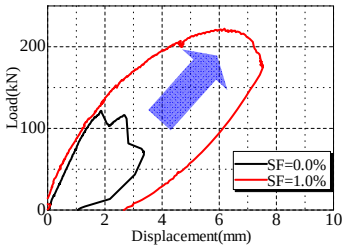


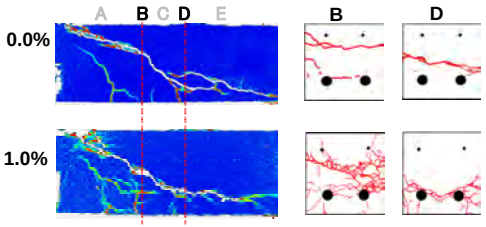
Dimension of tested beam.



a/d=3.55
f'c=36(N/mm²)
SF(Hooked)= 0.0%, 1.0%

- ✓ During the loading, the cracks on the sides were measured by DICM, and after the experiment, the specimen was cut to check for cracks in the cross section.
- ✓ A clear increase in shear strength was confirmed by using SFRC. Furthermore, not only the cracks on the surface but also the cracks in the cross section showed obvious disperse distribution.

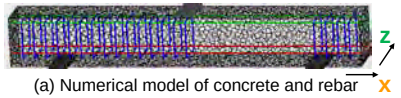




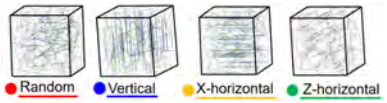
Cracks at Side Surface and in Cross Section

Simulation of SFRC Beam Failed in Shear

Numerical Model and Results –Load Displacement Relationship

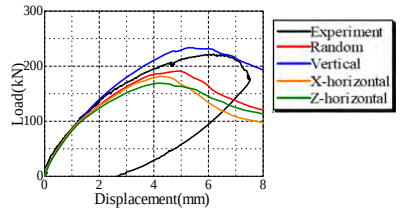


(a) Numerical model of concrete and rebar



(b) Fiber orientations

Numerical model of tested specimen.

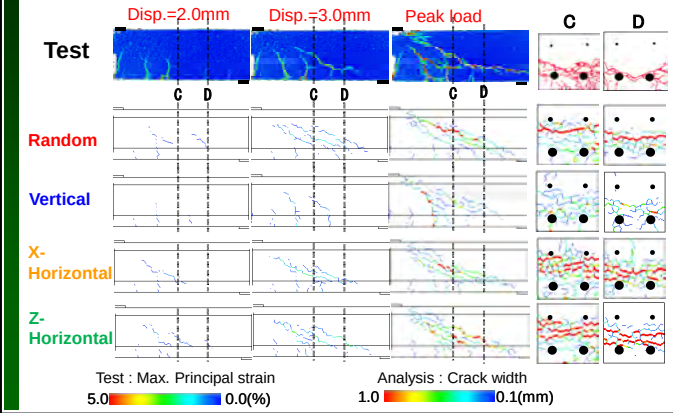


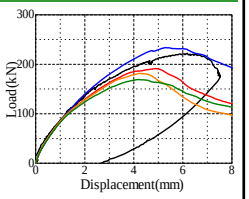
Comparison of load displacement relationship.

- ✓ 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.

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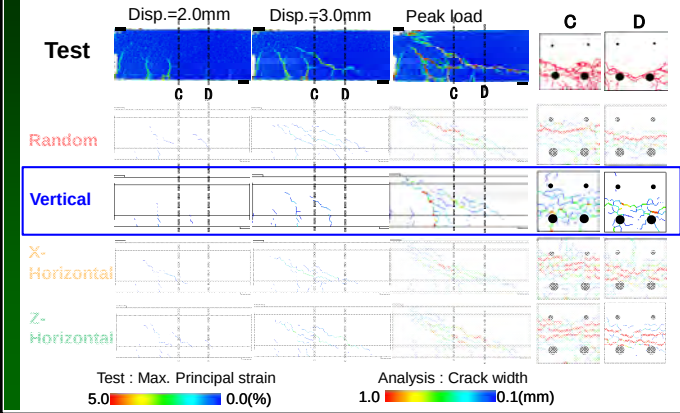

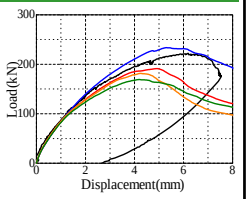

- ✓ The simulated cracking behavior showed that the vertical orientation was closer to the experimental results as well as load displacement relationship.
- ✓ It is important to validate the applicability not only load displacement relationship but also detail cracking behavior.

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- Research Background and Motivation
- Simulation Method -Rigid Body Spring Method-
- Modeling of SFRC in RBSM
- Simulation of Bond behavior in SFRC
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  - ✓ Effect of fiber orientation
  - ✓ Clarification of Shear Resistance Mechanism of SFRC
- Conclusion

Research Background and Motivation

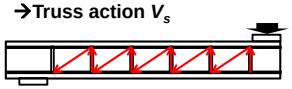
Understanding strengthening mechanism is important for effective use of SFRC

Shear Resistance Mechanism of RC member

Beam action

- Concrete contribution
- Stirrup contribution

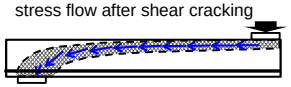
→Truss action V_s



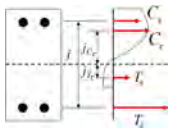
Arch action

- Concrete contribution

Induced by arch-shape compressive stress flow after shear cracking



The effect of fiber has been usually assumed as same as stirrup contribution in design, but the shear resistance mechanism should be clarified from numerical side



Beam $Vt=(\frac{dT}{dx}+\frac{dCs}{dx})\times\frac{j}{2}+\frac{dCc}{dx}\times jc$

Arch $Va=Cc\times\frac{djc}{dx}$

Beam and arch action can be calculated by using information of the internal forces for arbitrary beam segment (*dx*=50mm).

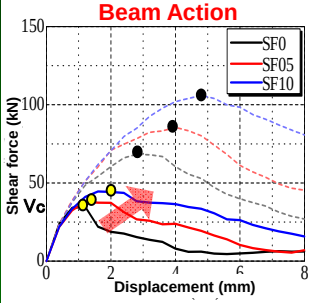
Shear Resistance Mechanism of SFRC member

Simulation of Fiber Content Effect

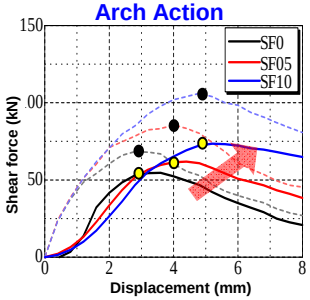
SF= 0.0%, 0.5%, 1.0% (Random Orientation)

f'c was assumed 36(N/mm²), different with test specimen.

Beam Action



Arch Action

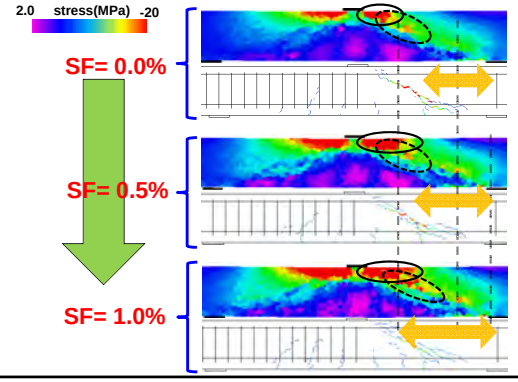


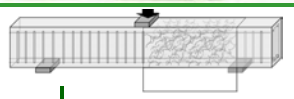
- ✓ In the case without fibers, the beam action decreased after the formation of diagonal cracks, while the arch action increased up to the point of shear capacity.
- ✓ With increasing fiber volume, the reduction in beam action after diagonal cracking became more gradual. This clearly demonstrates the contribution of fibers. The behavior is similar with the case that stirrup ratio is increased.
- ✓ Arch action also increased with higher fiber volumes. In particular, arch action significantly increased as displacement increase..
- ✓ Fibers contribute to enhancing beam action similarly to stirrups, and also play a role in increasing arch action.

Shear Resistance Mechanism of SFRC member

Simulation of Fiber Content Effect

Axial stress distribution at maximum load





- ✓ It is observed that horizontal upper chord of compression stress and the diagonal compression stress strut were developed with the increase of fiber volume.
- ✓ The horizontal upper chord of compression stress proves the development of beam action, and the diagonal compression stress strut proves the development of arch action.
- ✓ Same conclusion was obtained from the observation of stress distribution that fiber contributes to both beam action and arch action as shear resistance.

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CONCUSIONS

- ❑ FRCC is attractive material, but its use requires several experiments due to problems such as fiber orientation. If various types of FRCC can be evaluated using numerical analysis, the utilization of FRCC is expected to advance further.
- ❑ The proposed FRCC model, when combined with RBSM, can accurately evaluate the bond and anchorage performance of FRCC, as well as the behavior of SFRC beams failed in shear. In particular, it can accurately simulate not only the load-displacement relationship but also local crack behavior.
- ❑ Fiber reinforcement contributes to both beam action and arch action as shear resistance. Understanding the resistance mechanism through numerical analysis will provide ideas for more effective use of FRCC.