Cracking Propagation Simulation of Concrete due to Rebar Corrosion

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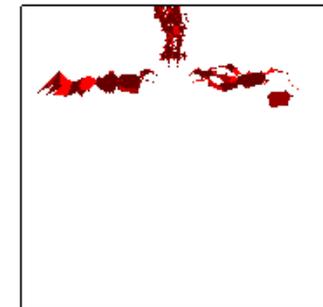
Minoru KUNIEDA *Asoc. Prof., Nagoya University*

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➢ **Fundamental view of corrosion crack propagation with single rebar specimen.**
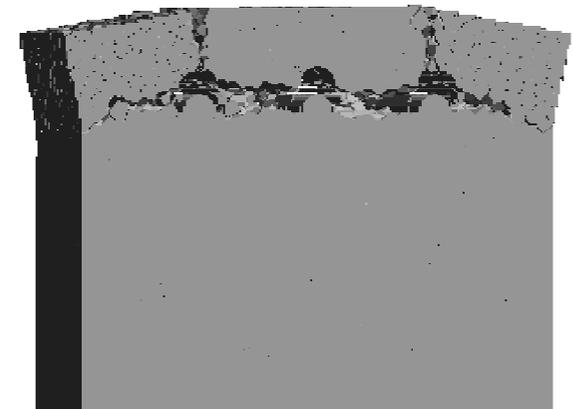**-Test results**
-Numerical results

➢ **Corrosion of multi rebars**

-Applicability of numerical method

➢ **Effect of rebar spacing**

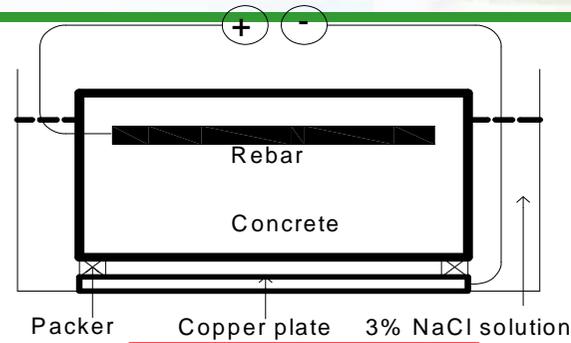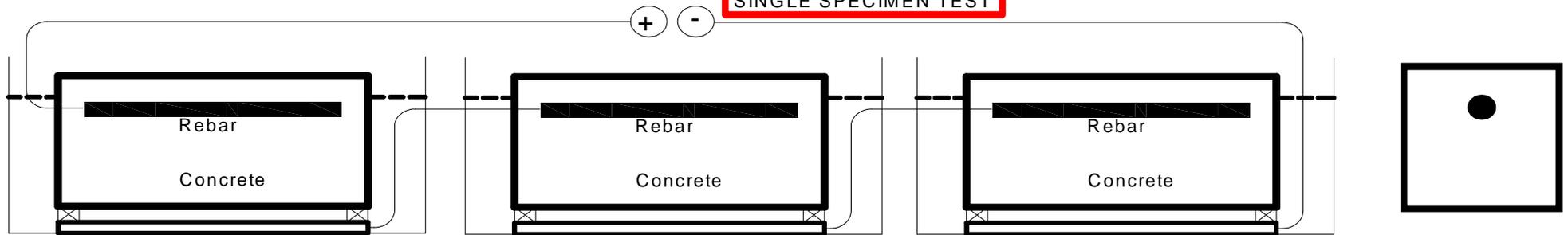**-Crack propagation behavior**
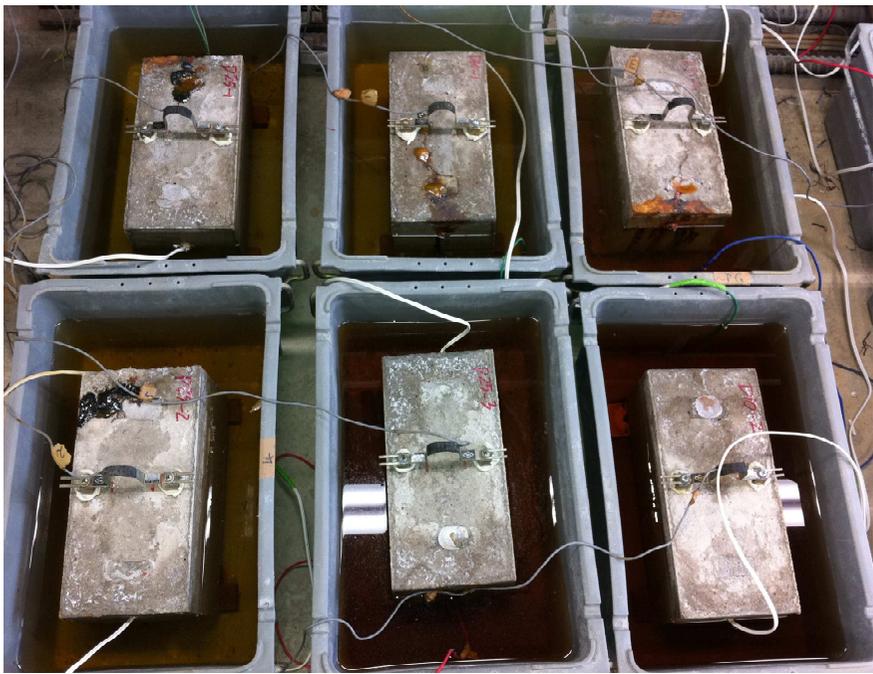
➢ **Conclusion**

Electric corrosion test

Rebar

Concrete

Packer   Copper plate   3% NaCl solution

SINGLE SPECIMEN TEST

Specimen with Single rebar
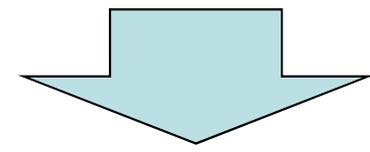
Rebar

Concrete

Rebar

Concrete

Rebar

Concrete

MULTI SPECIMEN TEST

The purpose is to evaluate relationship between surface crack width and internal crack propagation.

surface crack :observable information
internal crack : damage information

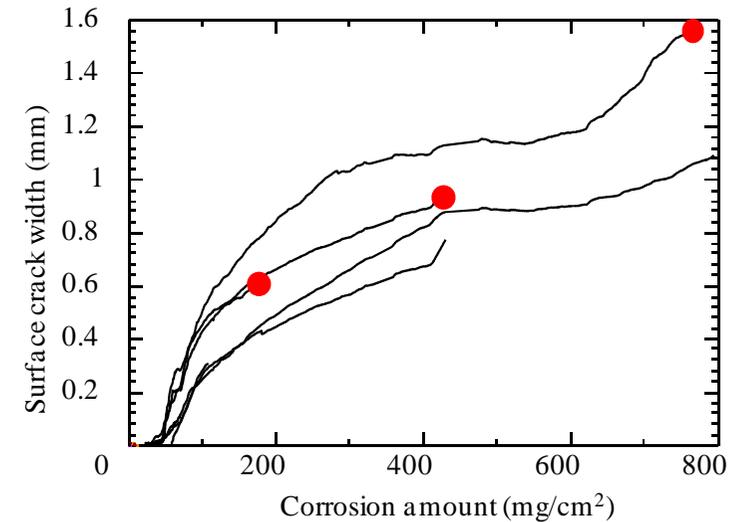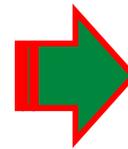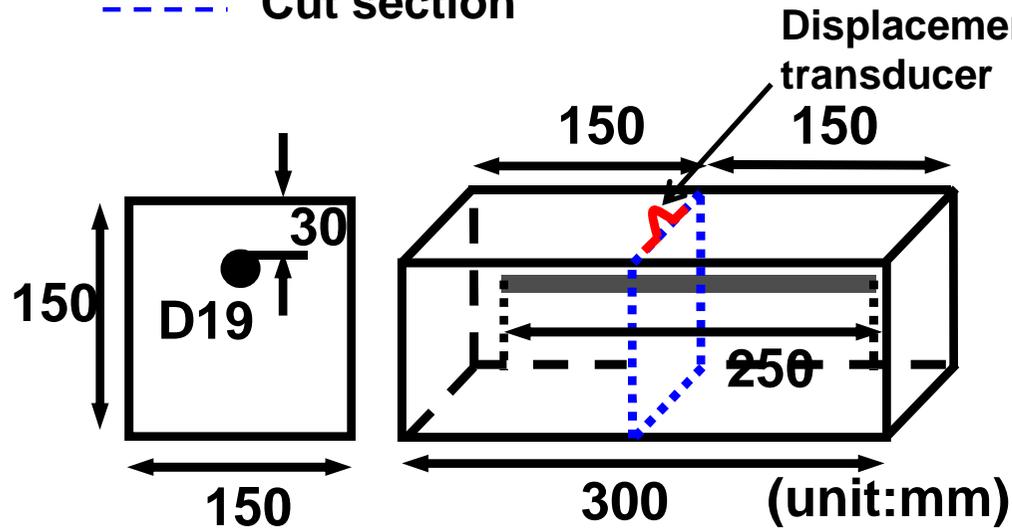**important for maintenance process to achieve sustainable concrete structures**

Test procedure

— Measurement of surface crack width

- - - - Cut section

Displacement transducer

150 150

30

150 D19

150 250 300 (unit:mm)

Surface crack width propagation

Measurement of surface deformation

Laser meter

Measuring lines

Specimen

85 90

Observation/ measurement of internal crack

Observation of corroded section

Test results

Surface crack width (mm) vs Corrosion amount (mg/cm²)

Surface crack propagation

150, 150, D19, 30

Lateral crack length(mm) vs Corrosion amount (mg/cm²)
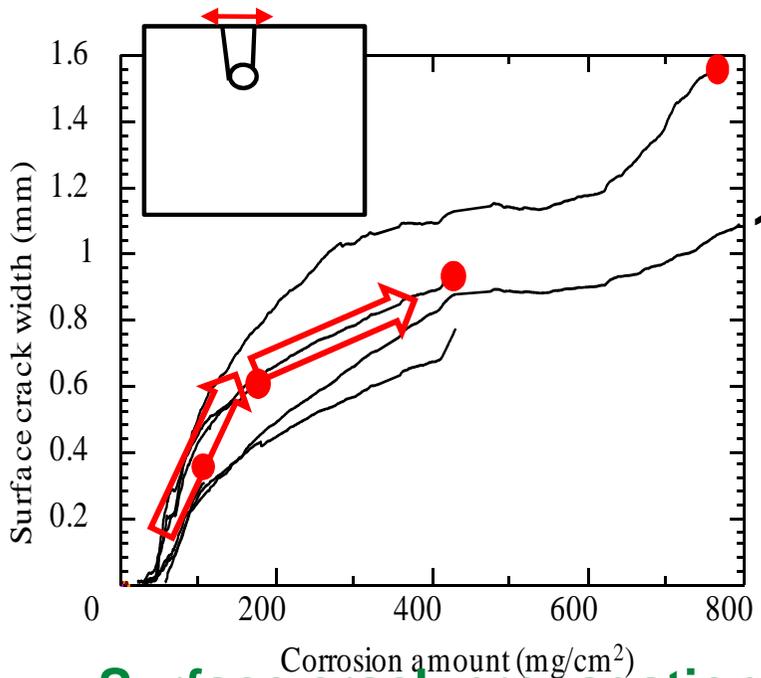
Internal crack propagation
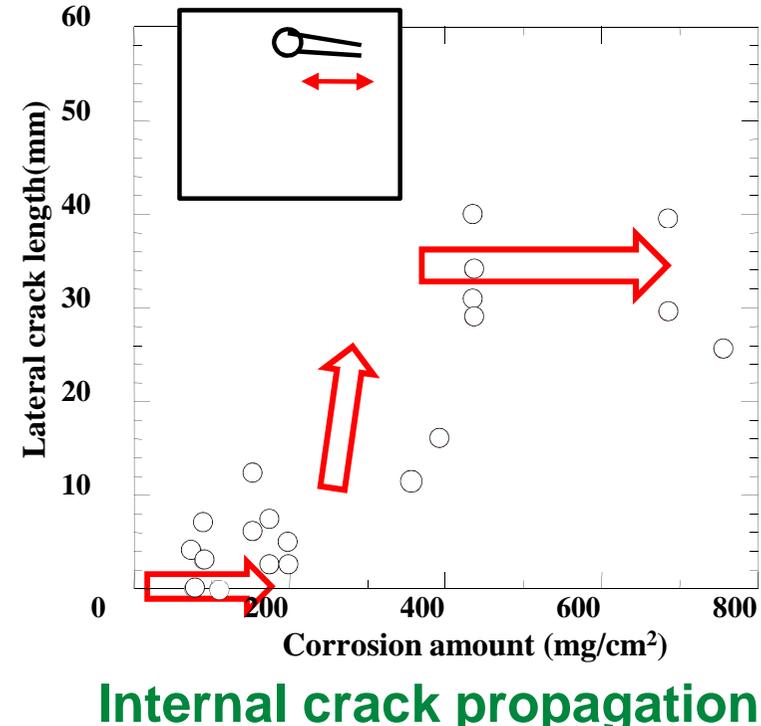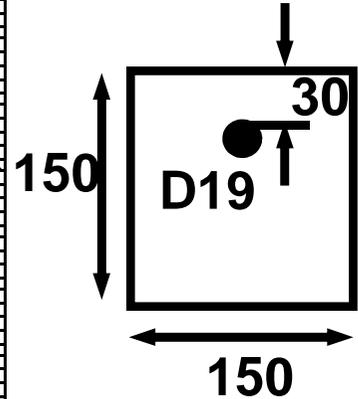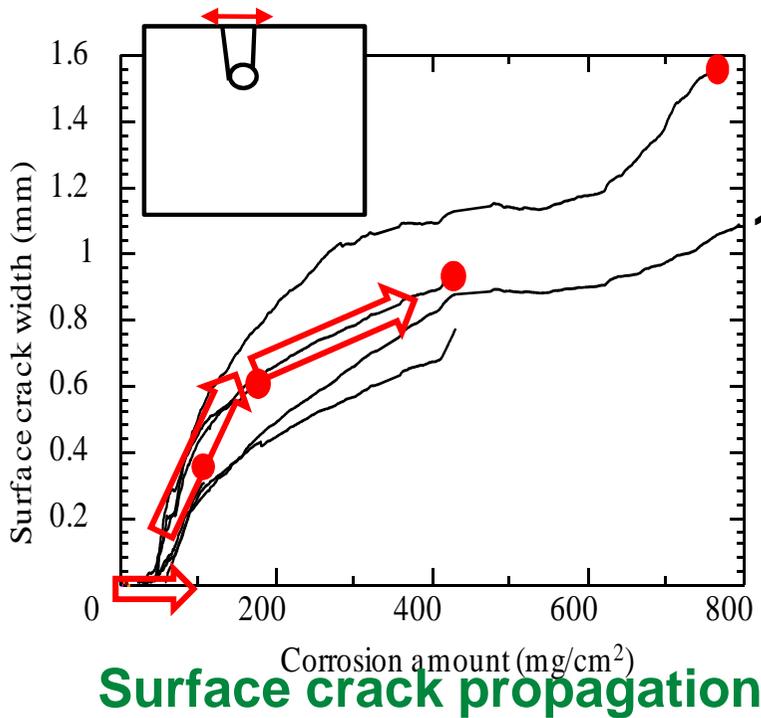
□Surface crack occur some corrosion amount.
□Surface crack width increase rapidly.
  Internal crack does not propagate in the stage.
□Speed of surface crack propagation become slow.
  Internal crack length increase rapidly.
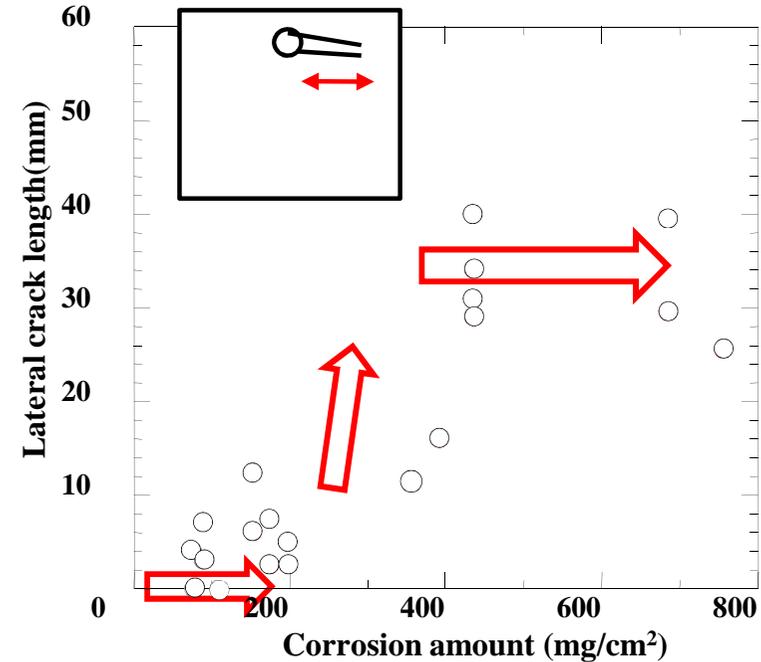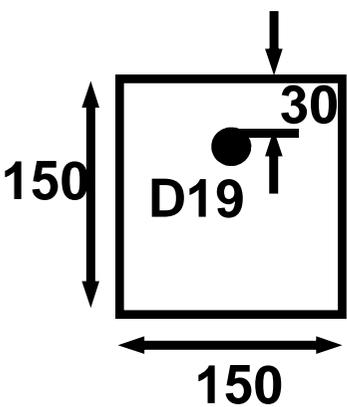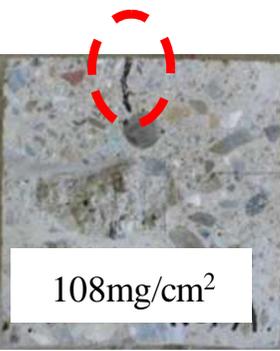□Internal crack length converge a value.

Test results

Surface crack propagation

Internal crack propagation

Surface crack pattern

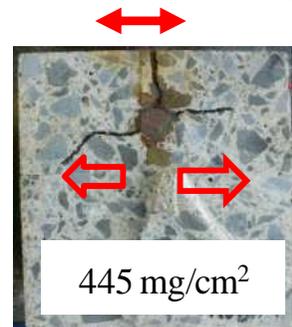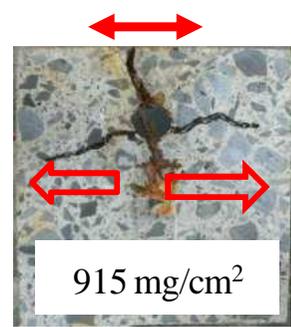|			
108mg/cm²	162 mg/cm²	445 mg/cm²	915 mg/cm²
Surface crack width: 0.35mm	Surface crack width: 0.54mm	Surface crack width: 0.94mm	Surface crack width:1.52mm

Internal crack pattern

Rigid Body Spring method

Zero springs

Triangle center point
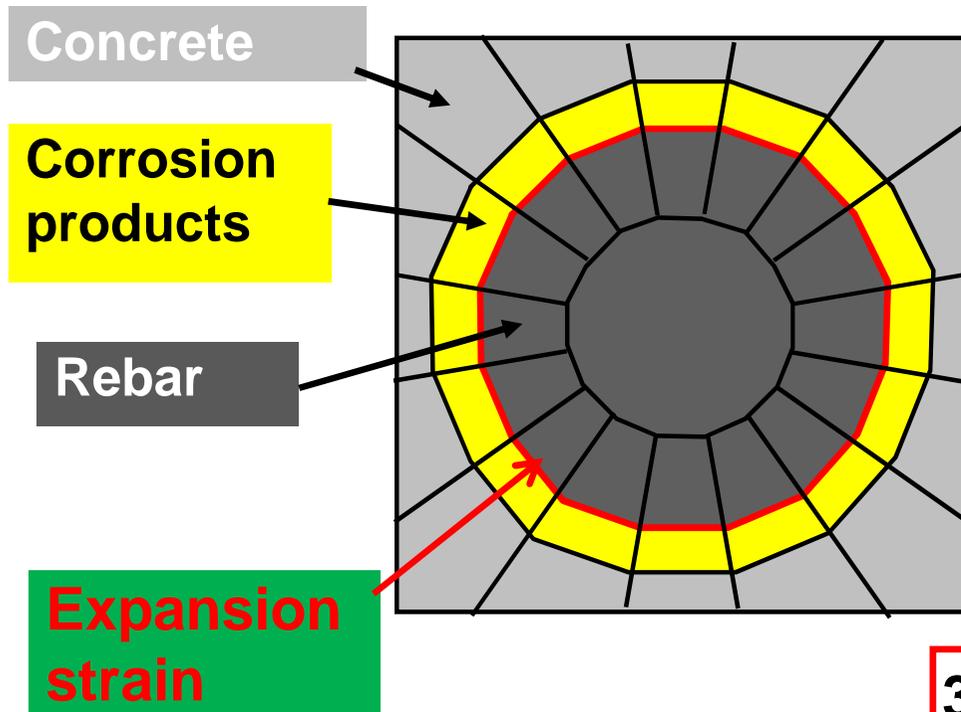
Nuclear
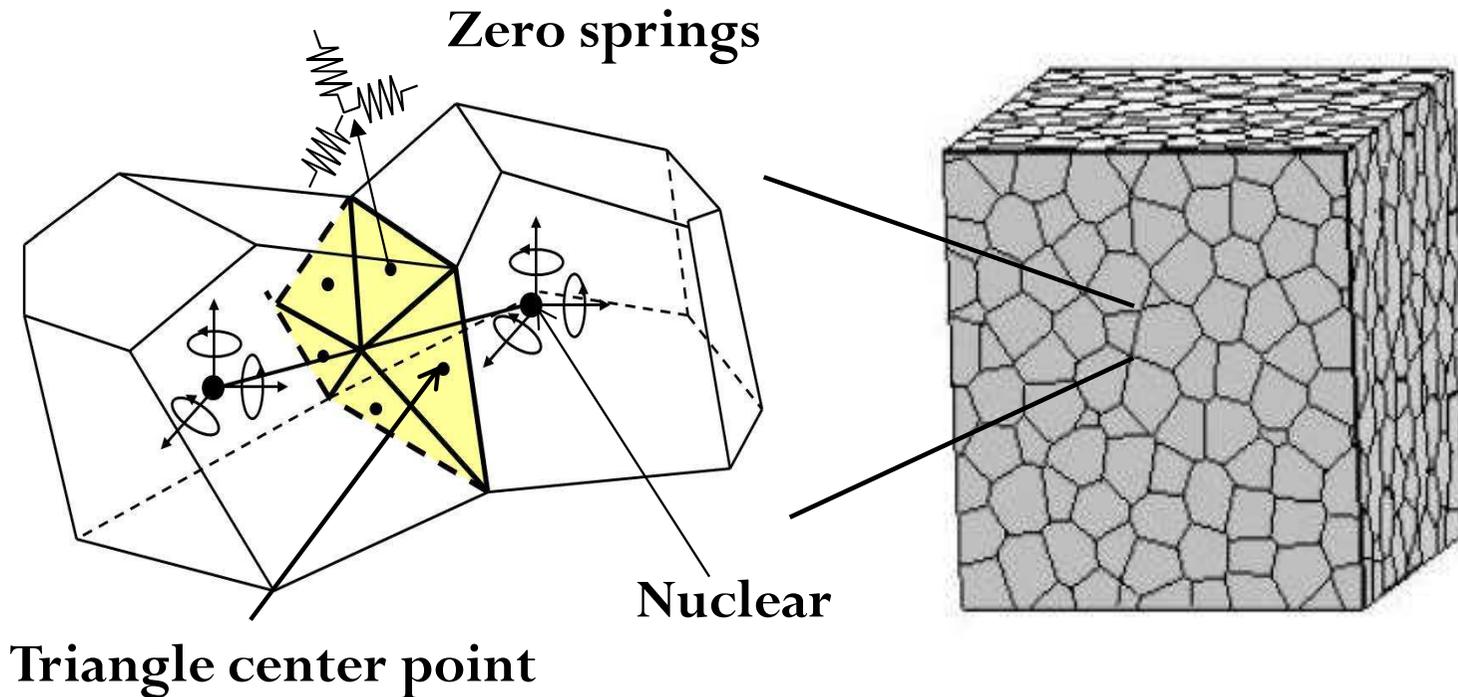
Corrosion crack propagation is simulated using rigid body spring method with Voronoi diagram.
Rigid body spring method is one of discrete element method to obtain cracking behavior directly.

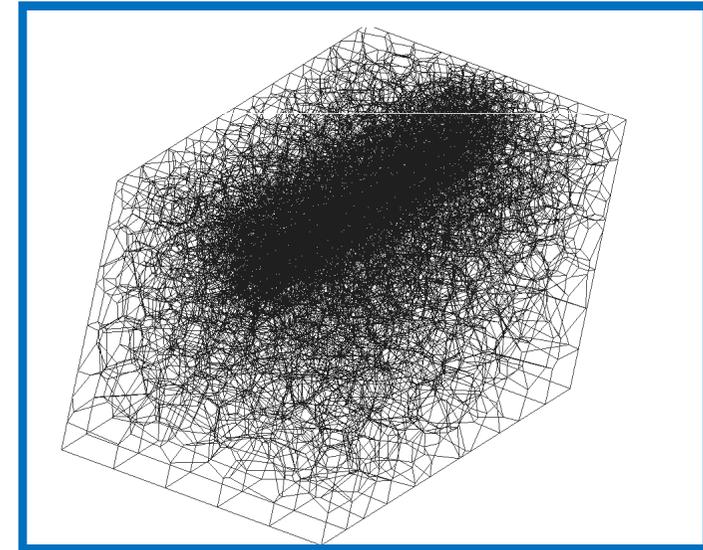## Corrosion model

Concrete

Corrosion products

Rebar

Expansion strain

Corrosion model

3D model of a single rebar specimen

The deformation of the rebar radius due to rebar corrosion is modeled by using the three-phase material model including rebar, corrosion products and concrete.
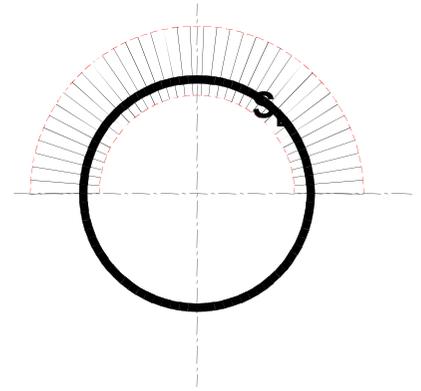
Other corrosion models
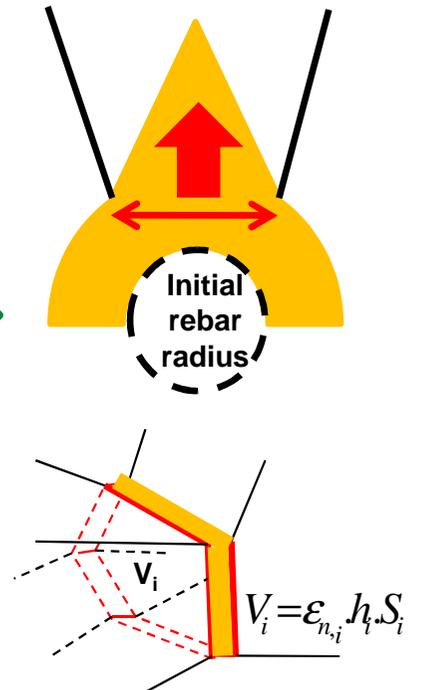
Local corrosion model

Rebar corroded section

Rebar is locally corroded on its section. This phenomenon is considered by local corrosion expansion model.

Penetration of corrosion products

Corrosion products

Top surface

Section through center of rebar

Initial rebar radius

$$V_i = \varepsilon_{n,i} h_i S_i$$
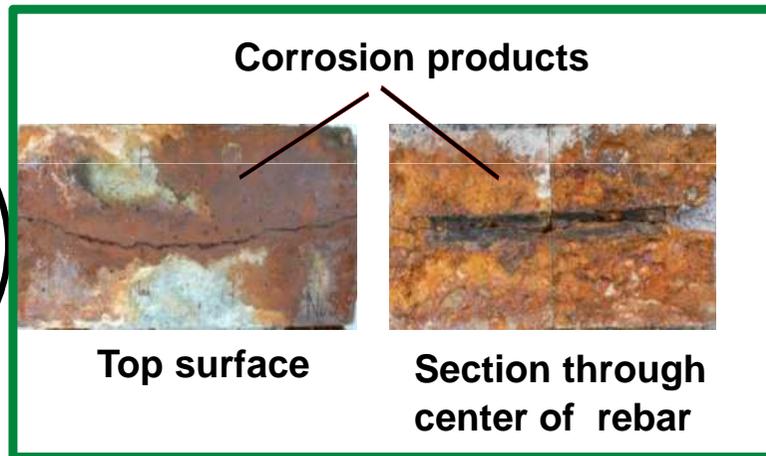
Corrosion products penetrate into cracks. This phenomenon is considered by reduction of corrosion expansion considering crack volume for corrosion product penetration.

Comparison between numerical and test results

108mg/cm^2
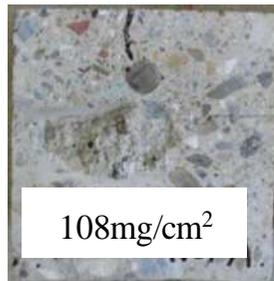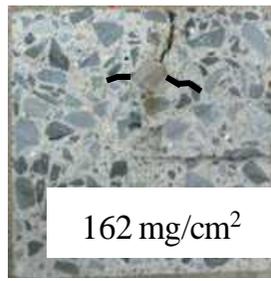Surface crack width: 0.35mm

162 mg/cm^2
Surface crack width: 0.54mm
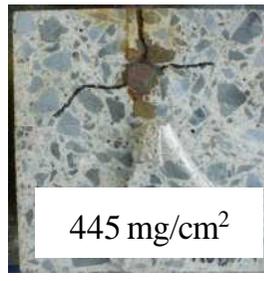
445 mg/cm^2
Surface crack width: 0.94mm
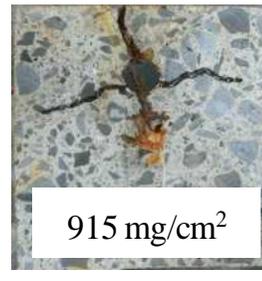
915 mg/cm^2
Surface crack width:1.52mm

Internal crack pattern
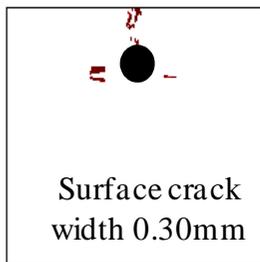

Surface crack width 0.30mm
90 mg/cm^2
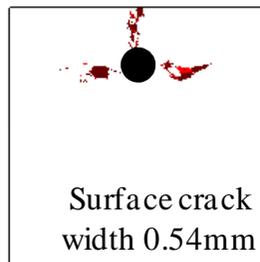
Surface crack width 0.54mm
220 mg/cm^2
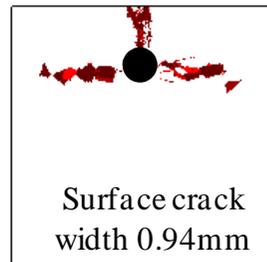
Surface crack width 0.94mm
400 mg/cm^2
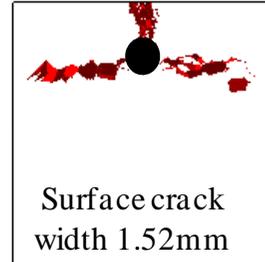
Surface crack width 1.52mm
600 mg/cm^2

Internal crack patterns
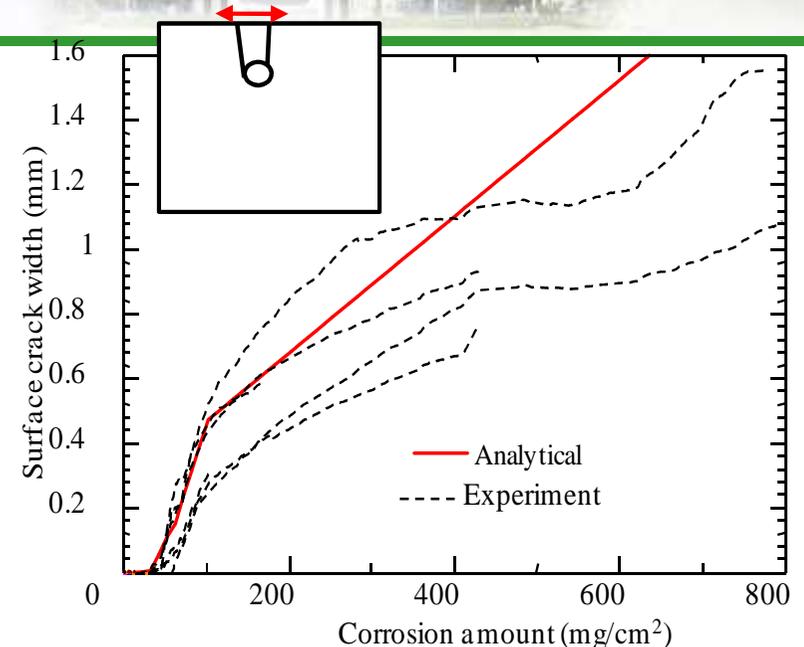
Surface crack width propagation
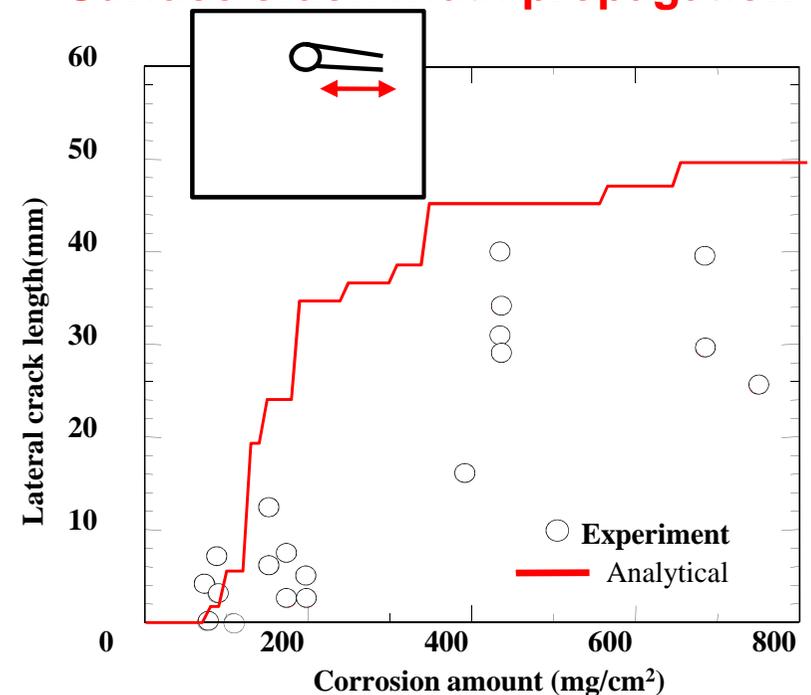
Internal crack length propagation

Effect of specimen width obtained from numerical model

Surface crack propagation

Internal crack propagation

W150

W600
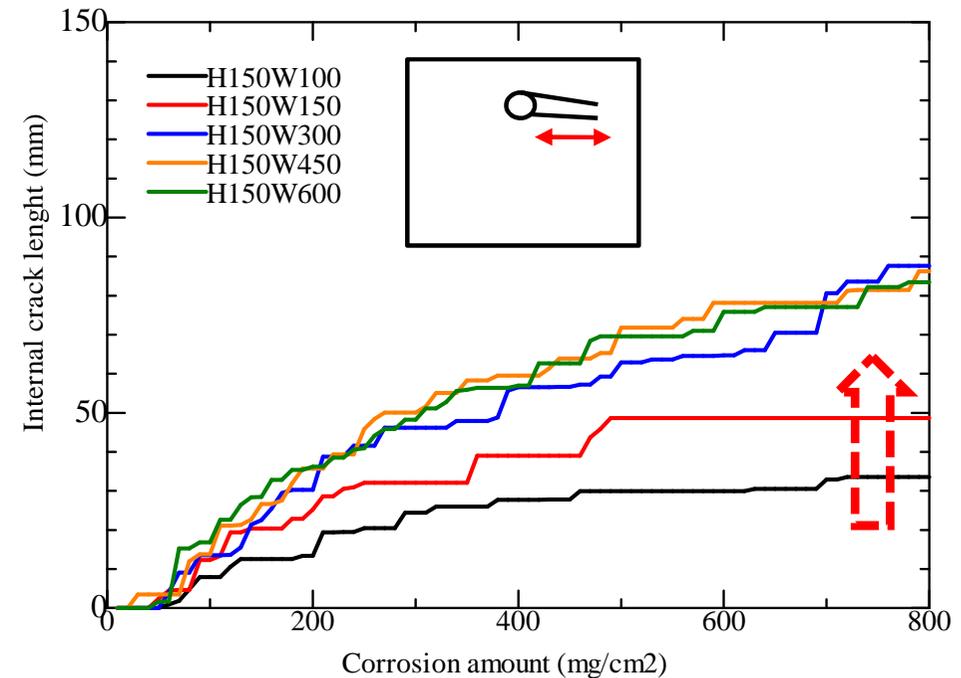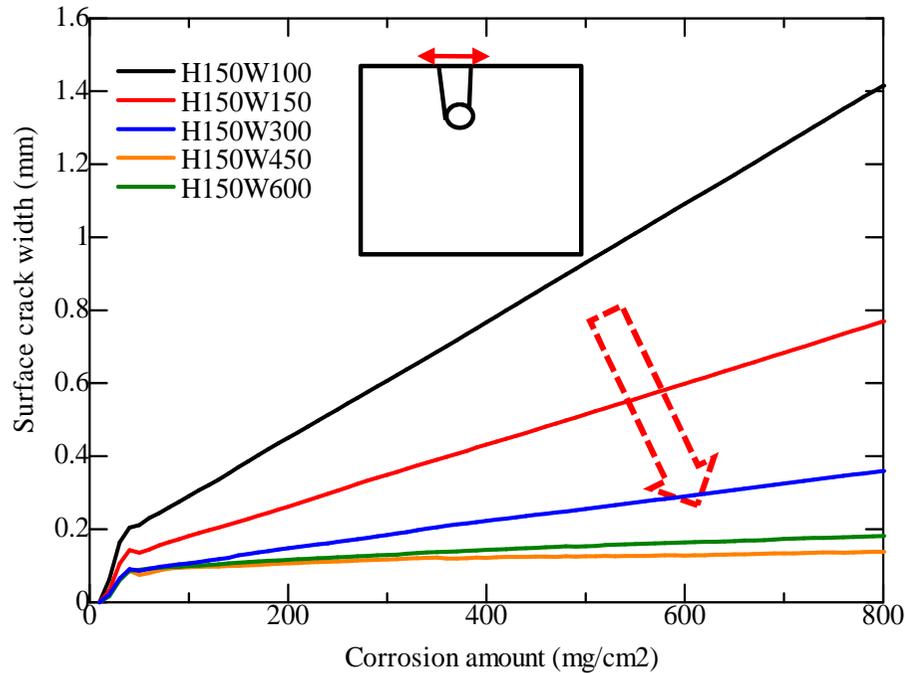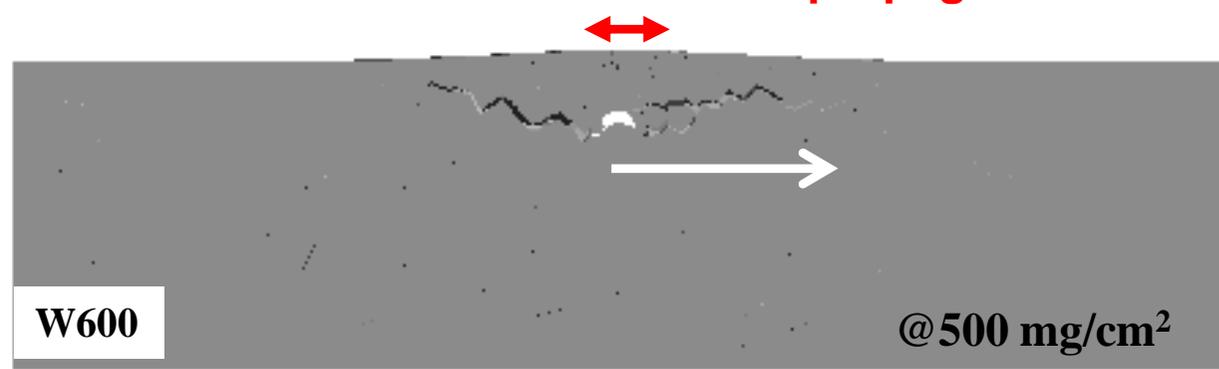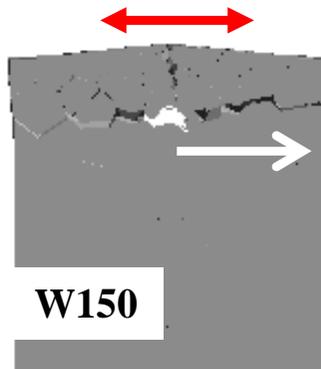
@500 mg/cm²

When the specimen width become larger, surface crack width become smaller and internal crack length become longer.
For wider size specimen, surface crack is not dominant, but internal crack propagate.

Effect of specimen width can be understood by the surface deformation.
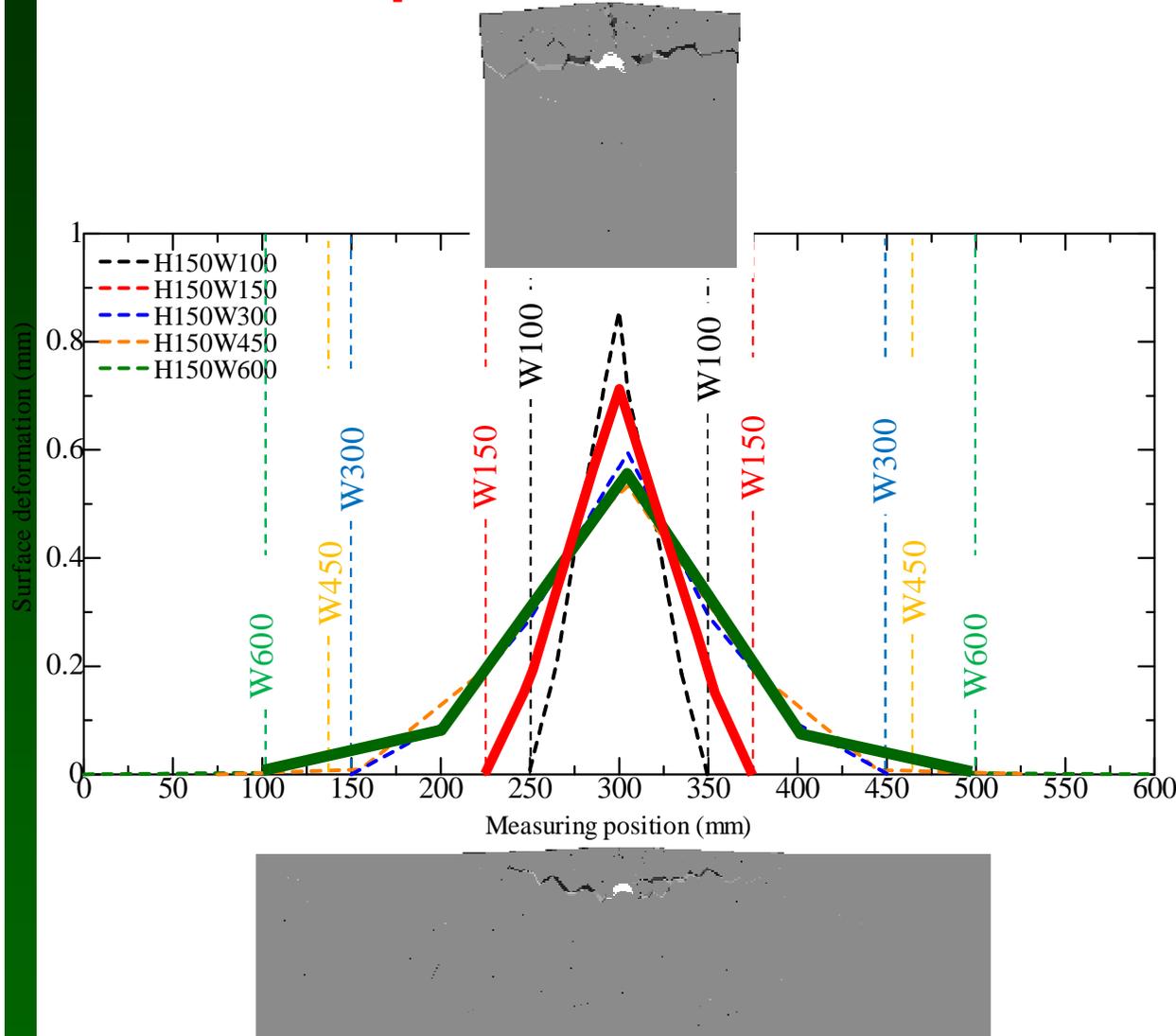
The surface deformation is influenced by width.

For smaller specimen, all area deform and deformation become larger. Since the gradient of deformation corresponds to stain, surface crack width become bigger for smaller width specimen.

For larger width specimen, surface deformation area become wide and constant but the value become small. Therefore, surface crack does not develop.

Crack propagation is strongly influenced by boundary condition and we have to consider the boundary condition as structural problem to evaluate crack propagation.

Rebar spacing is also boundary condition.

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➢ **Fundamental view of corrosion crack propagation with single rebar specimen.**
   -Test results
   -Numerical results
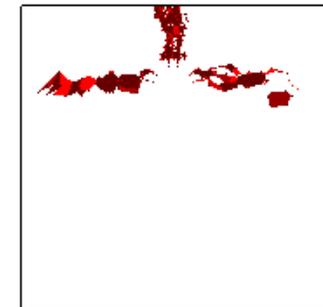
➢ **Corrosion of multi rebars**

   -Applicability of numerical method

➢ **Effect of rebar spacing**

   -Crack propagation behavior

➢ **Conclusion**
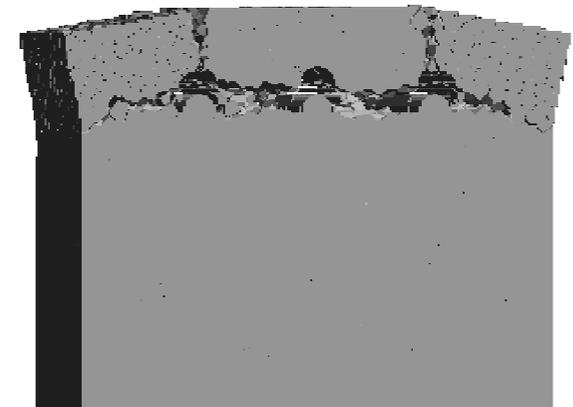
The applicability of numerical method to multi rebar specimen is confirmed for two specimens.

Unit in mm

L M R

160

200

40

60 60 60 60

240

2100

a) Section

b) Side view
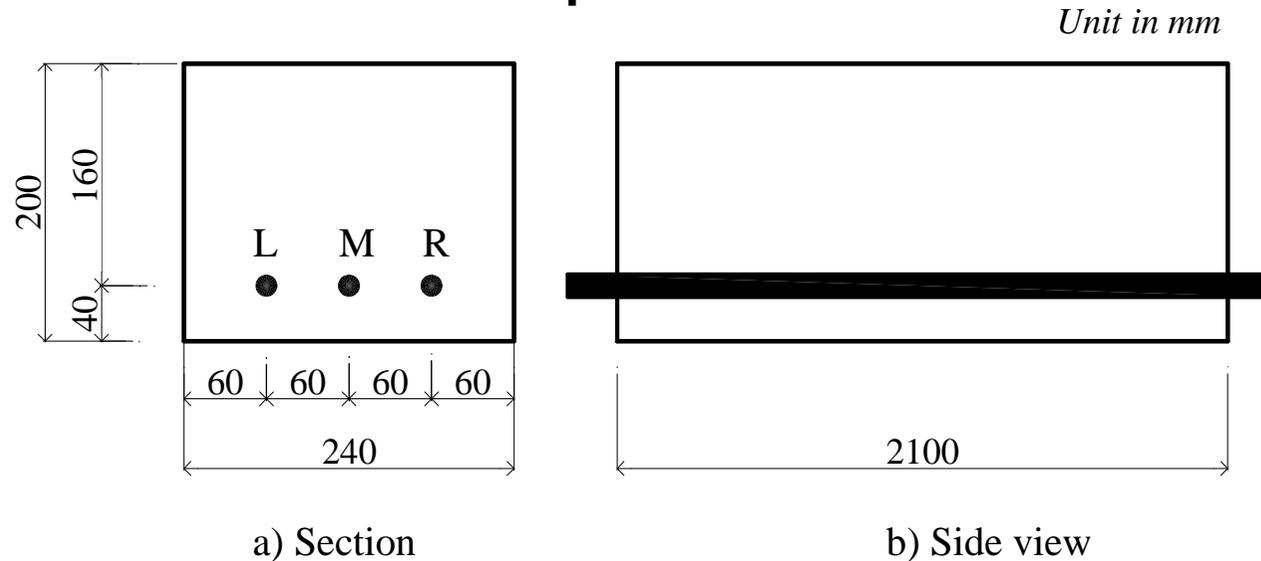
Simulated specimen tested by Oshita et al.

5mm mesh size

a) Specimen section

b) 3D Voronoi particles

Comparison of crack pattern and surface crack width

i)   Beam S0-10   ii)   Beam S0-20

a) Experimental

i) Corrosion ratio =10.2%   ii) Corrosion ratio =18.6%   iii) Corrosion ratio =26.4%

b) Analytical

○ Experiment
- - - - Analysis

External crack width (mm)

Average rebar corrosion ratio (%)
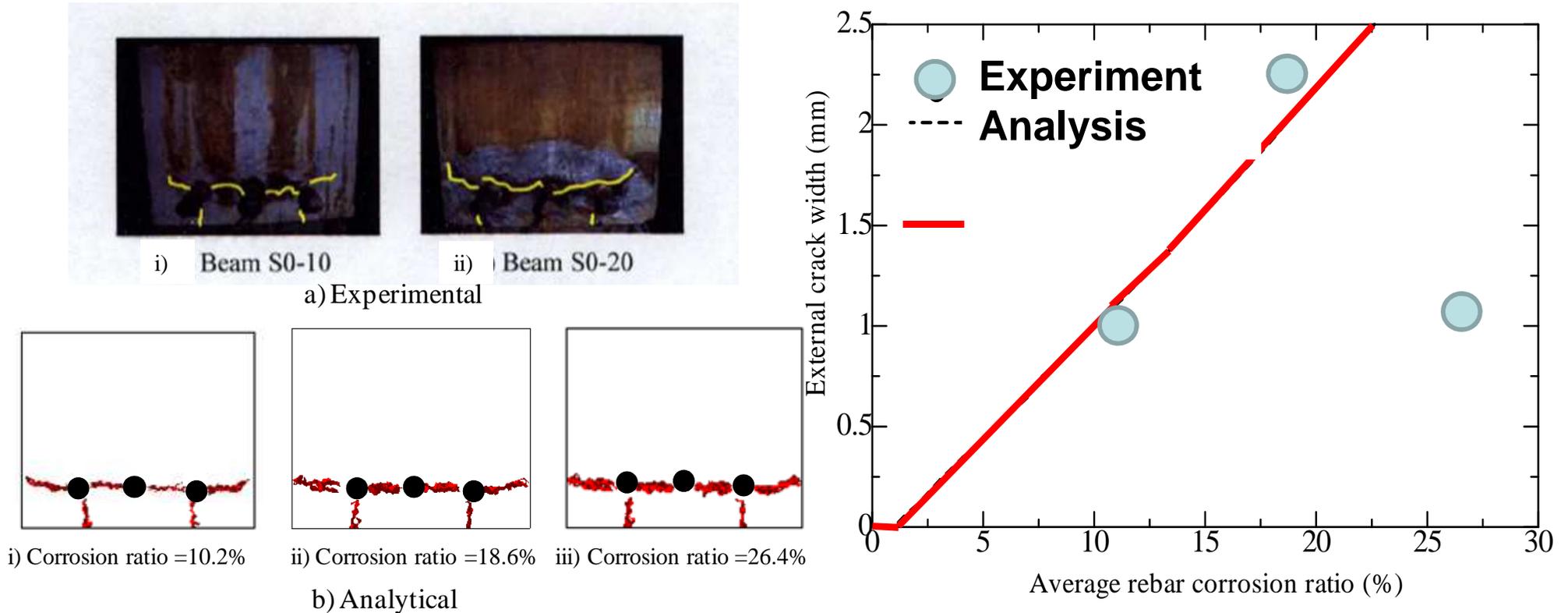
Cracks on beam end

Surface crack widths

The numerical method can simulate crack pattern and surface crack width

FOSS gauge

300
240
60

53 52 52 53
210

a) Section

Mihashi et al.

2500

b) Side view
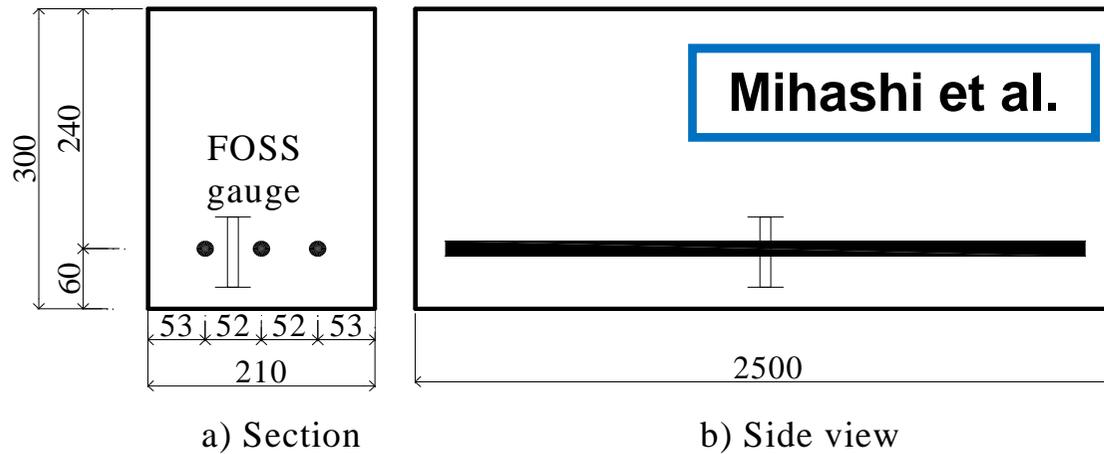
In the test, crack width between rebars was measured.

FOSS strain reading

RBSM analysis

Element strain (με)

Rebar corrosion ratio(%)
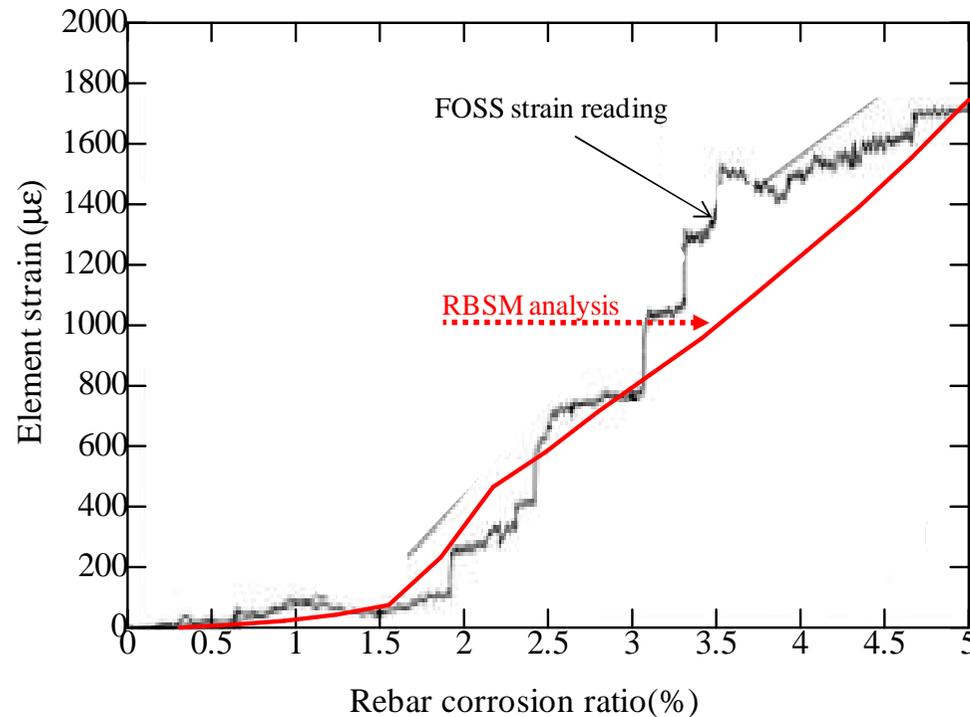
**The numerical method can simulate crack initiation and internal crack propagation**

CONTENTS

➤ **Fundamental view of corrosion crack propagation with single rebar specimen.**
**-Test results**
-Numerical results

➤ **Corrosion of multi rebars**
-Applicability of numerical method

➤ **Effect of rebar spacing**
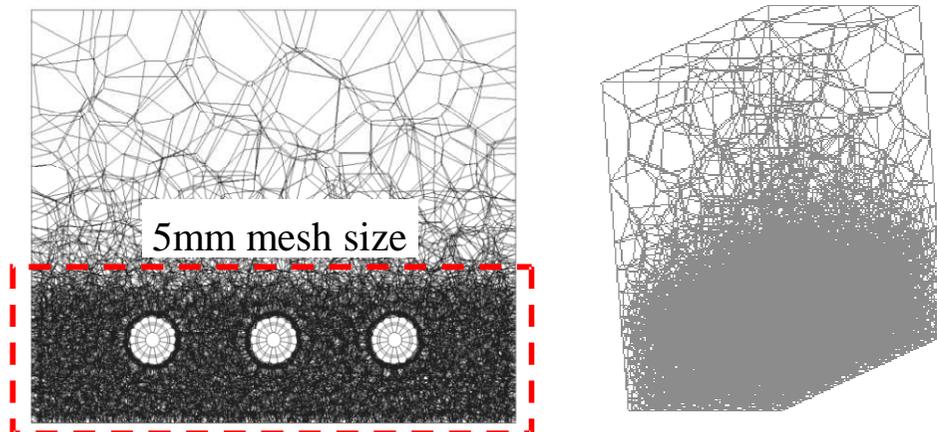**-Crack propagation behavior**

➤ **Conclusion**

3 D16

L   M   R

160

40

60 Sr Sr 60

W
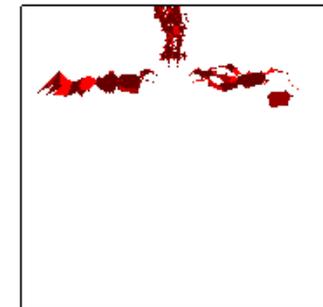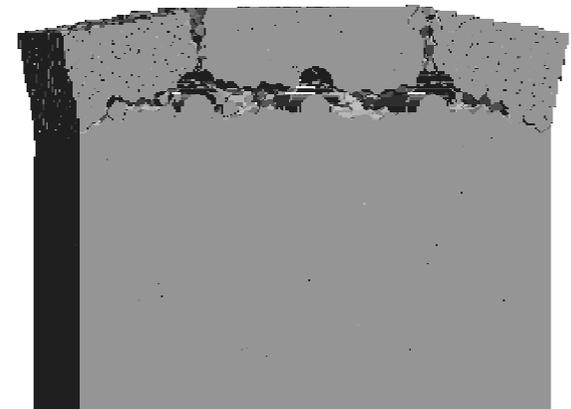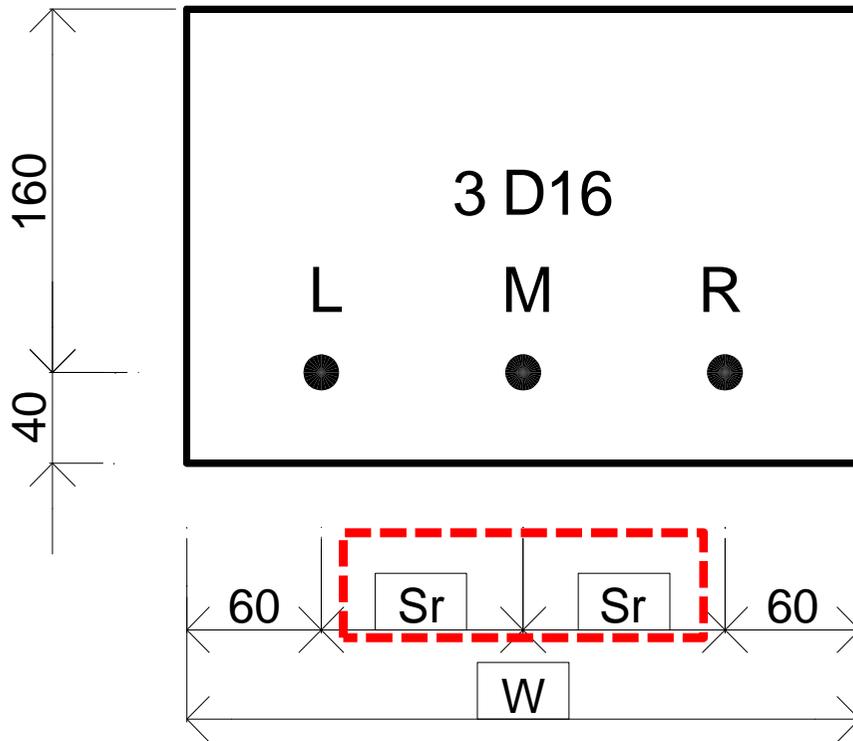
Specimen	Rebar spacing Sr (mm)	Specimen width W(mm)
Sr-40	40	200
Sr-60	60 test	240
Sr-200	200	520
Single	N/A	240

Only rebar spacing is varied from 40 to 200mm

40mm : minimum space which is usually decided by maximum aggregate size
200mm : often used for RC slab

CORROSION

Sr-40

Sr-60

Sr-200

0.5%   0.5%   0.5%

Sr-40   Sr-60   Sr-200

1.0%   1.0%   1.0%

Sr-40   Sr-60   Sr-200

1.9%   1.9%   1.9%

Sr-40   Sr-60   Sr-200

2.5%   2.5%   2.5%

σ

f_t

f_{tl}

w: crack width
$w = \varepsilon \cdot h$

$w_0 = 0.03$ $w_1 = 0.17$ w(mm)

For smaller spacing specimen, internal crack join at early stage. Both surface and internal crack develop.
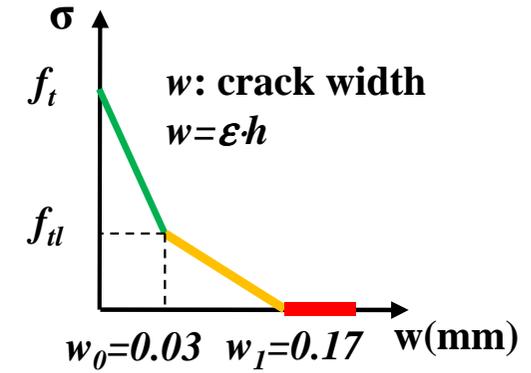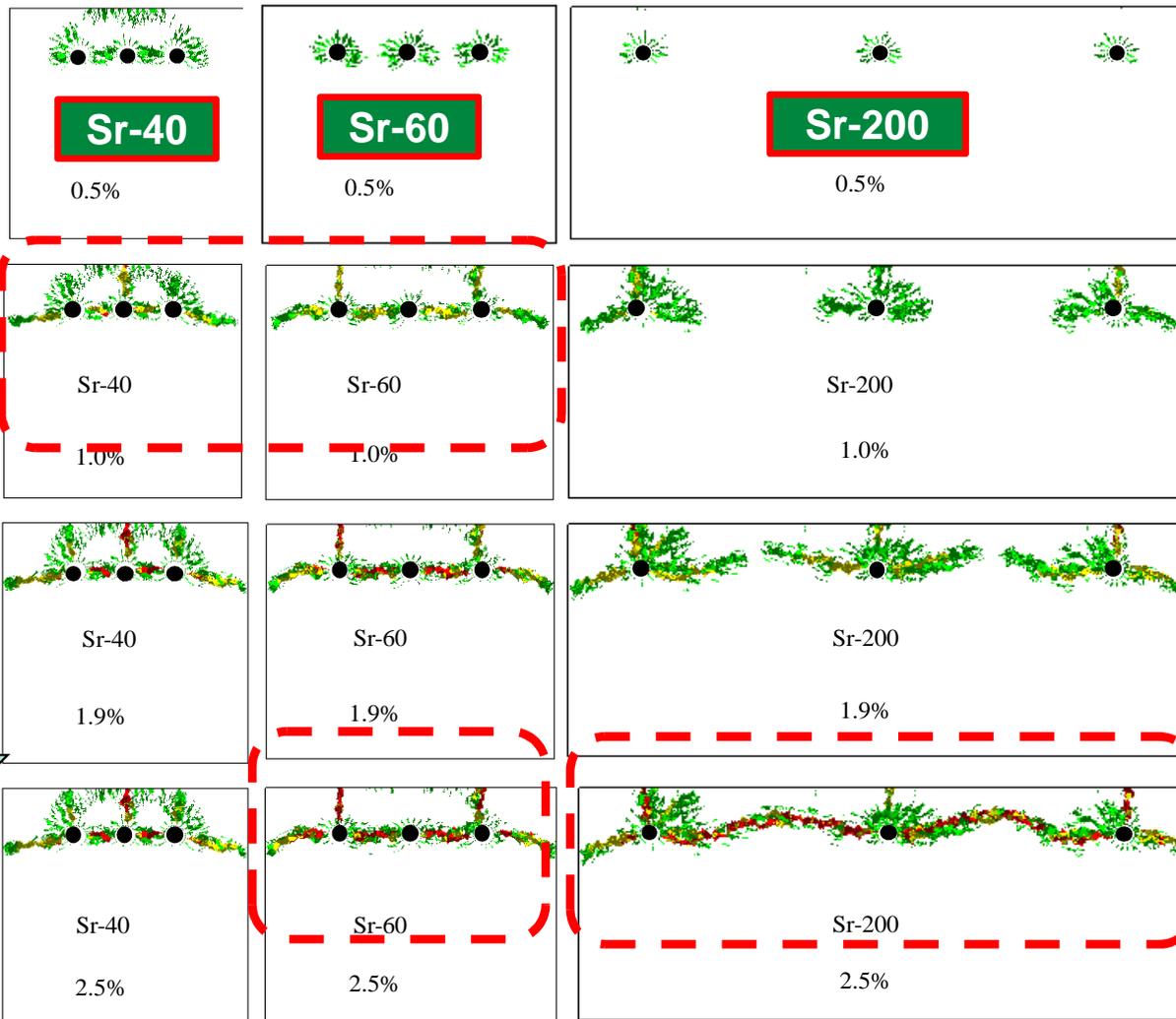For larger spacing specimen, crack develop from each rebar but each crack does not connect.

The crack pattern is affected by rebar spacing and observable surface crack pattern is different each case. In 40mm case, surface crack upon middle rebar is dominant and in 60 and 200mm cases surface crack at side rebar is dominant. Then, internal crack propagate in the specimen.

Conclusion

➢ The **applicability** of the analytical method was confirmed by the experimental results in terms of **crack patterns**, **surface crack width** and **internal crack width** propagation.

➢ In the case of multi rebar-corrosion, internal cracks joined together between rebars and developed to large cracks earlier than the ones in the single-rebar corrosion.

➢ The **dominance** and the **propagation** of **internal cracks** tend to cause de-lamination of the concrete cover.

➢ Due to **different boundary conditions such as width and rebar spacing**, internal damage situation may be different. So, the internal damage cannot adequately evaluate if the investigation is **only** based on the **surface condition** as being done in several current maintenance processes.
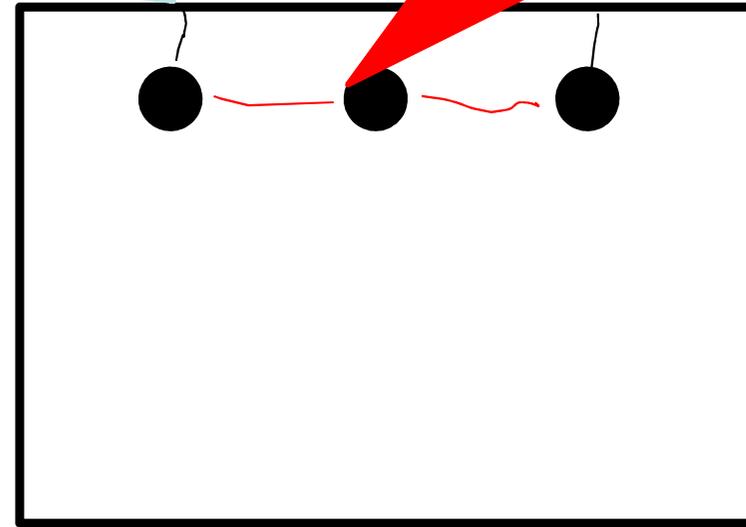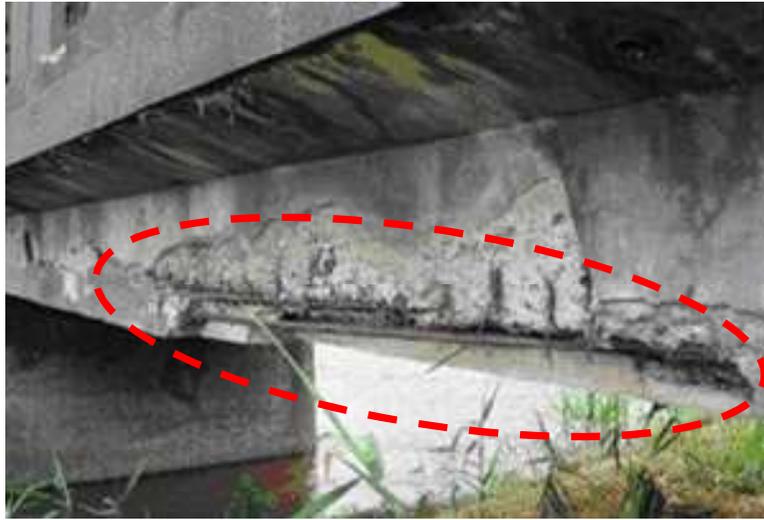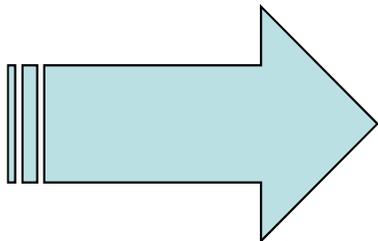
Thank you for your attention

Multi rebar specimen

Surface damage is visible
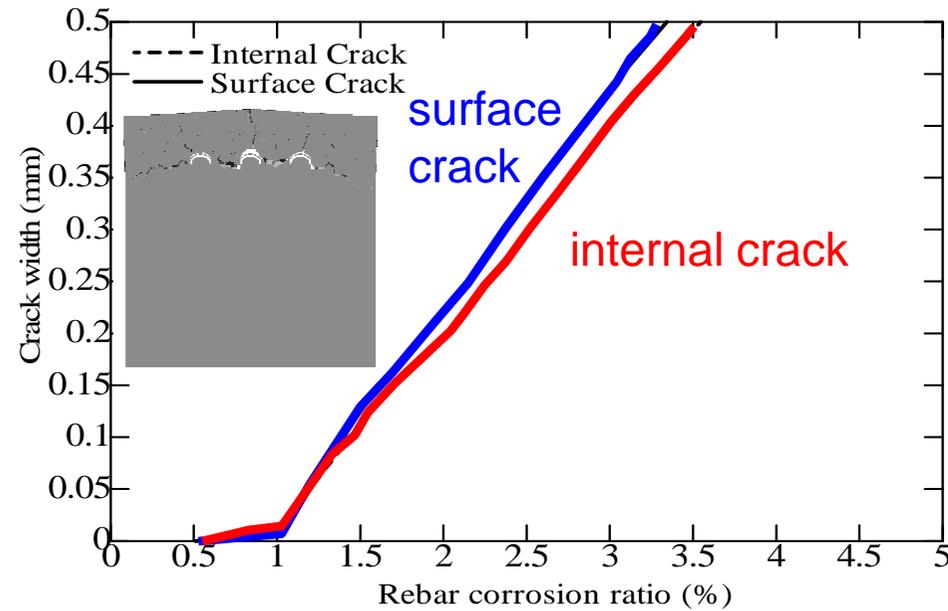
Inside damage is invisible

During the maintenance process, it is necessary to evaluate **inside damage** from **surface condition.**
The cracking propagation is influenced by boundary condition.
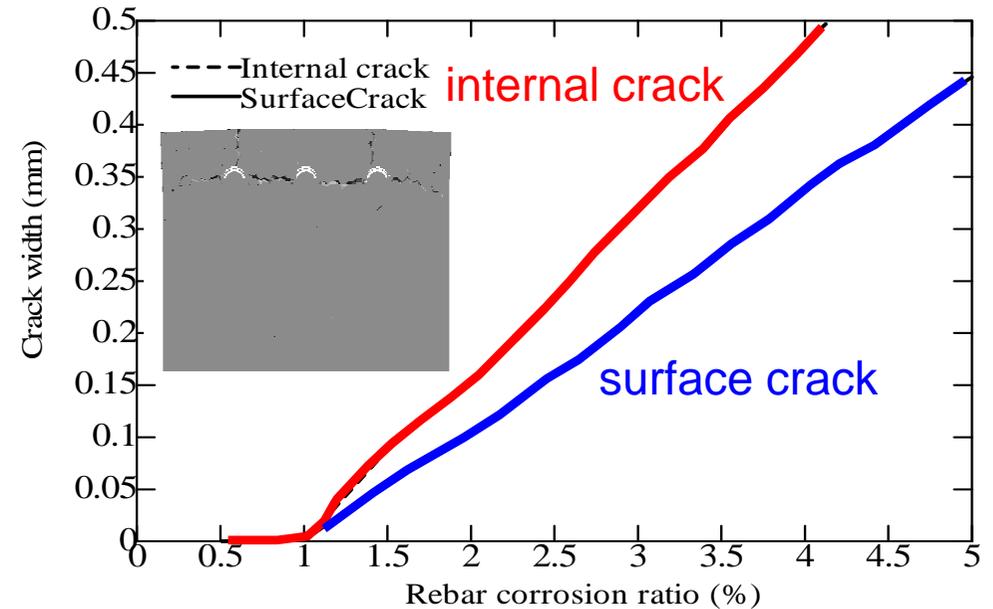The spacing is also boundary condition.

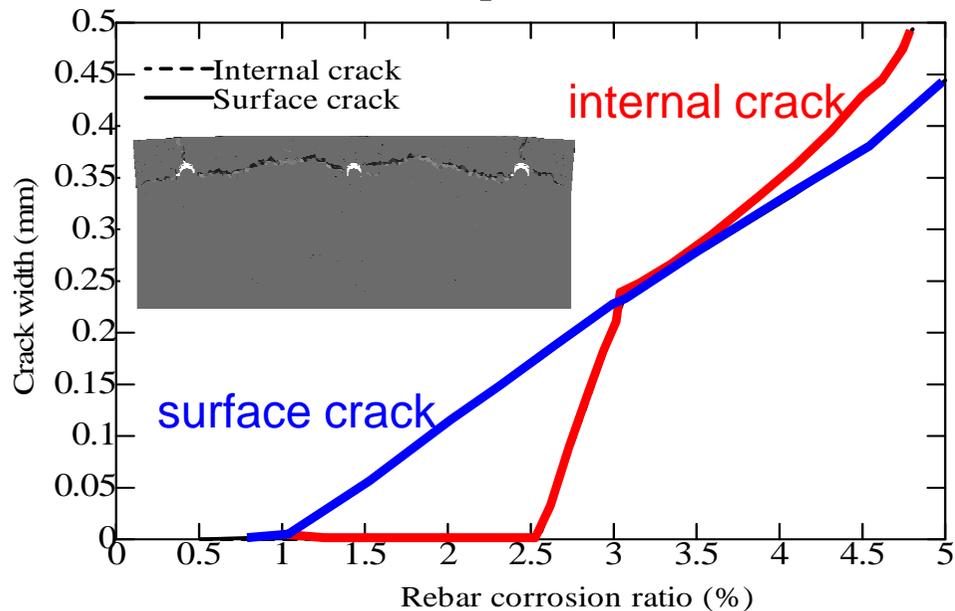**Make clear the effect of rebar spacing on surface and inside damage**

a) Specimen Sr-40

b) Specimen Sr-60

c) Specimen Sr-200

d) Single-rebar specimen

SCOPE OF THIS STUDY

New design

Existing structures

DAMAGE LEVEL

Many researches:

• **Corrosion initiation**
• **Effects of chloride and oxygen permeation**
• **Standards and regulations**

Example of damage of structure due to rebar corrosion

Surface crack

Rebar

Rebars

Internal cracks

Surface cracks

Build up volumetric expansion

H_2O, O_2, Cl^-

CONCRETE

Ironic current

$Fe^{2+}+2OH^-{\rightarrow}Fe(OH)_2$

OH^-

ANODE

RUST

Fe^{2+}

CATHODE

REBAR

Electron current

$Fe \rightarrow Fe^{2+}+2e^-$

$O^{2-}+H_2O + 4e^-{\rightarrow}4(OH)^-$

Crack patterns of a single -rebar specimen

Analytical 3D-deformation of a triple-rebar specimen

TIME

INITIATION   PROPAGATION   ACCELERATION   DETERIORATION

**LIFE-SPAN OF RC STRUCTURE IN CORROSIVE ENVIRONMENT**

For the maintenance of existing structures, evaluation of cracking behavior is important to achieve sustainable concrete structures and numerical method is required to predict the deterioration dependent on time.

RBSM (Rigid Body Spring Model)

RBSM is analytical model to simulate structural behavior by springs between Rigid Bodies.

Gravity point

Vertex
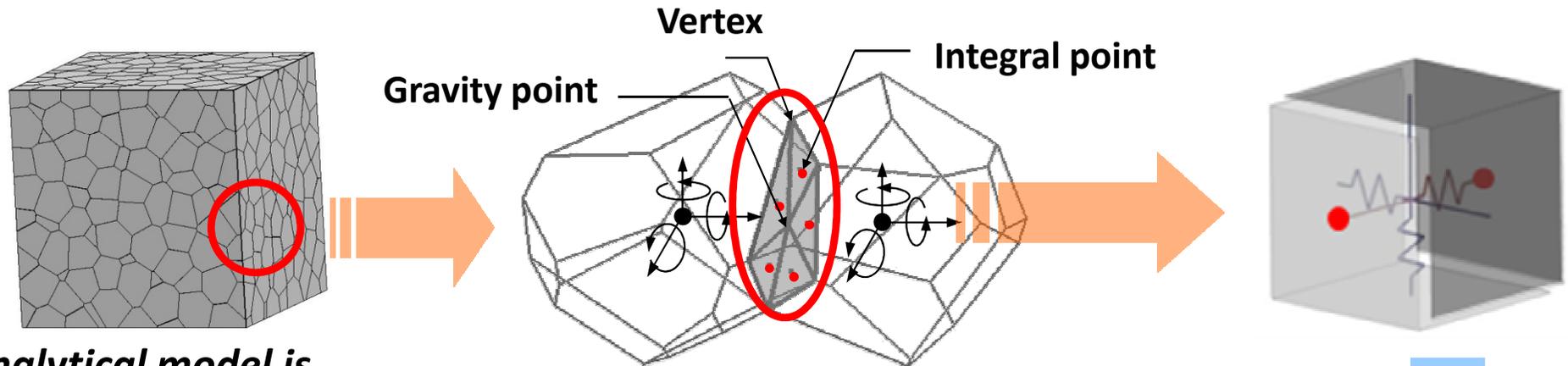
Integral point

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

A number of springs are set in boundary of each surface.

This model can evaluate the effect of bending and torsional moment automatically without rotational springs.

For reduction of elements dependency

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.
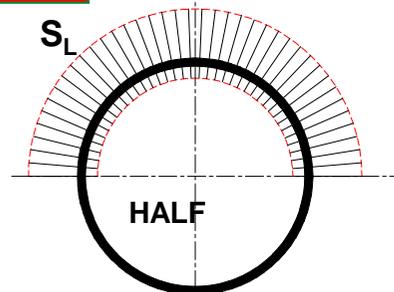
Experiment

Rebar corroded section

Local corrosion model
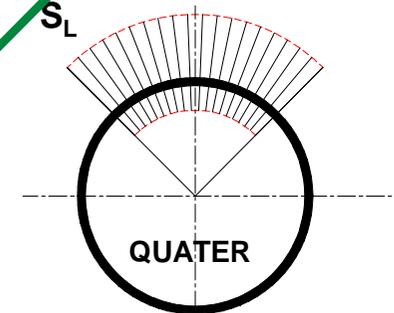
Expansion pressure distribution

S_u

UNIFORM

$S_u = S_L$

S_L

QUATER

S_L

HALF
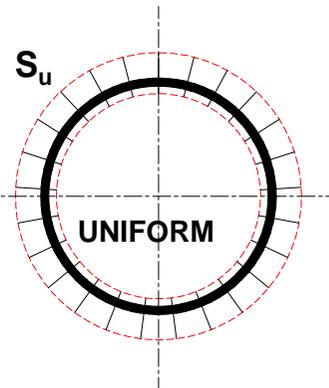
Penetration of corrosion products into cracks

Corrosion products

Top surface

Section through center of rebar

Experiment

Vertical crack

Initial rebar radius

Threshold value =0.1mm
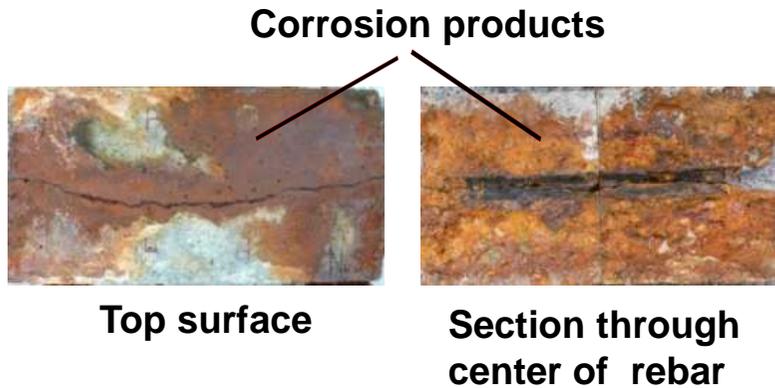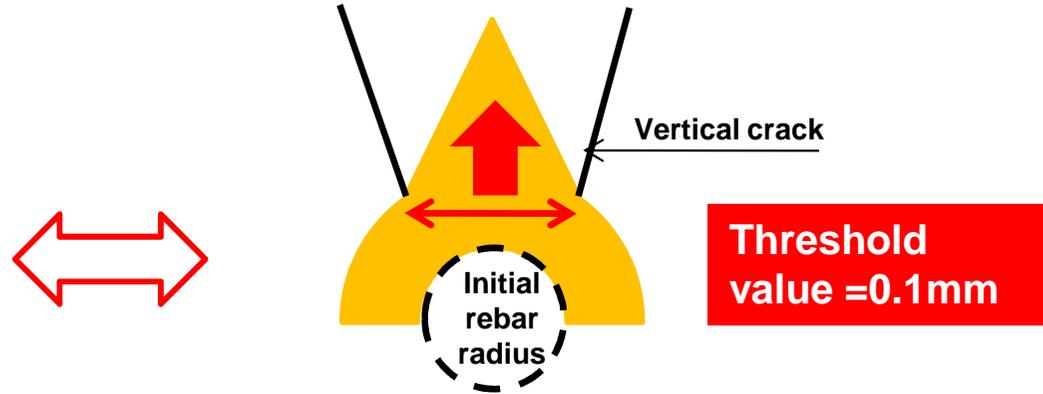
Schematic diagram

Normal spring i
$\varepsilon_{n,i}$: strain of normal spring i

Interface surface i
S_i is area of surface i

h_i

Only cracks in the hatched area are accounted

$V_{crk} = \sum_{1}^{NSPG} \varepsilon_{n,i} h_i S_i$

$V_i = \varepsilon_{n,i} h_i S_i$

V_i

V_{crk}

Initial rebar radius

U_{eff}

Initial rebar radius

U

$V_{cor}(U) = V_{cor,eff}(U_{eff}) + V_{crk}$

Reduction of free increase of corrosion

Computation volume of cracks in RBSM model

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Experimental results (cont'd)

Minor cracks

Visible cracks

No1

No2
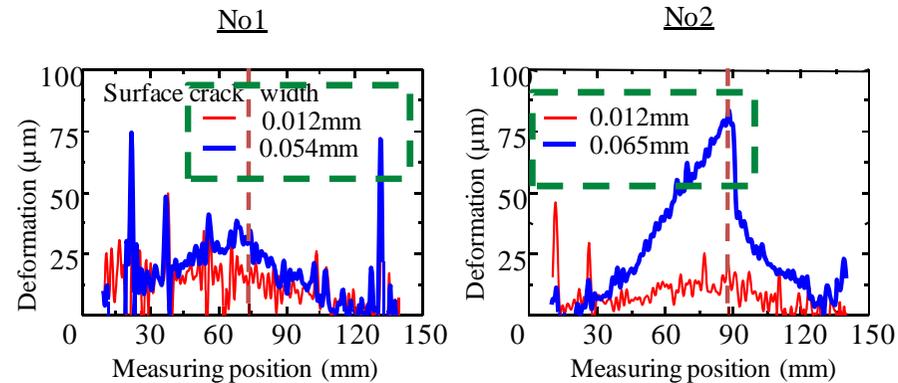
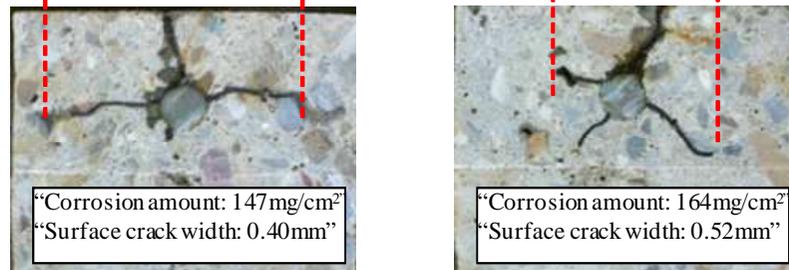(a) Surface deformation corresponding to minor surface crack width
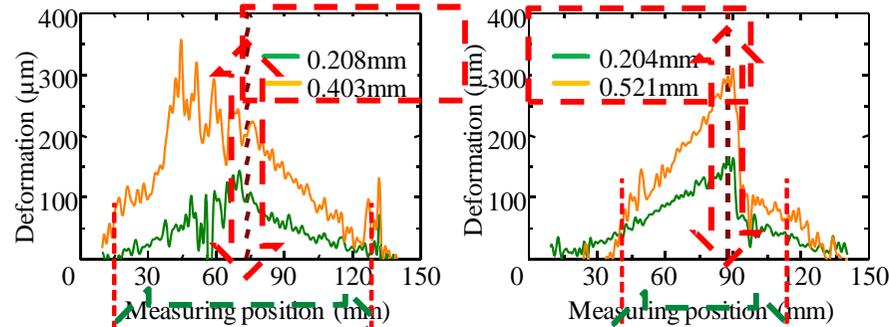
(b) Surface deformation corresponding to visible surface crack width

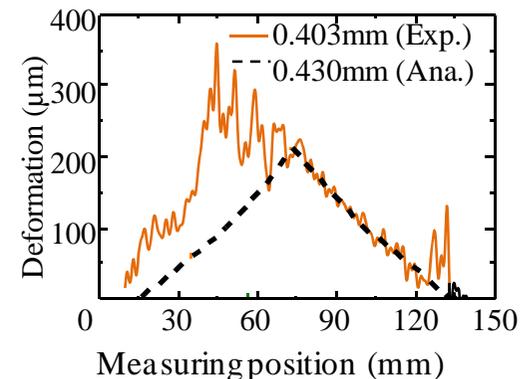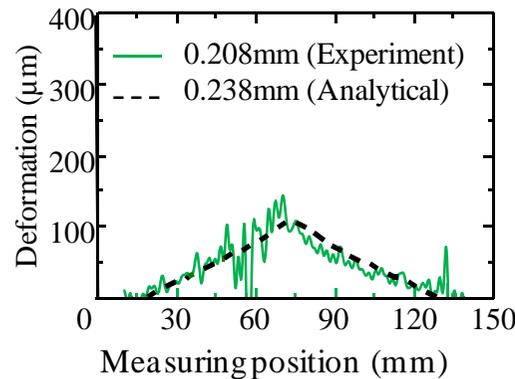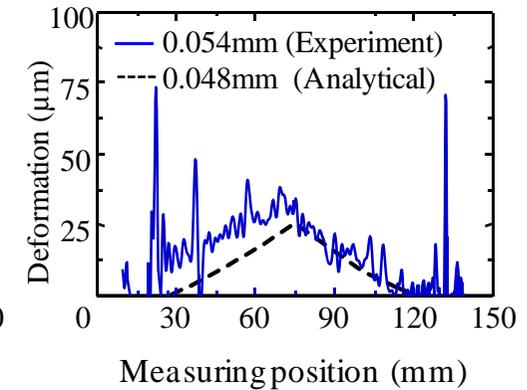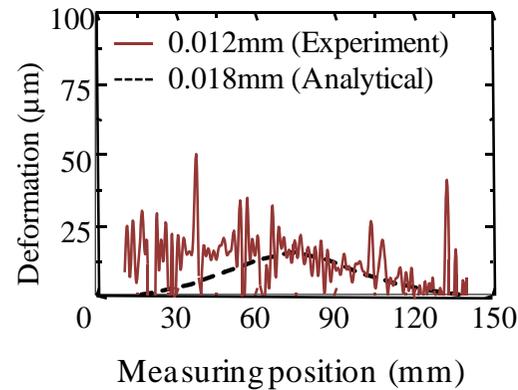"Corrosion amount: 147mg/cm²"
"Surface crack width: 0.40mm"

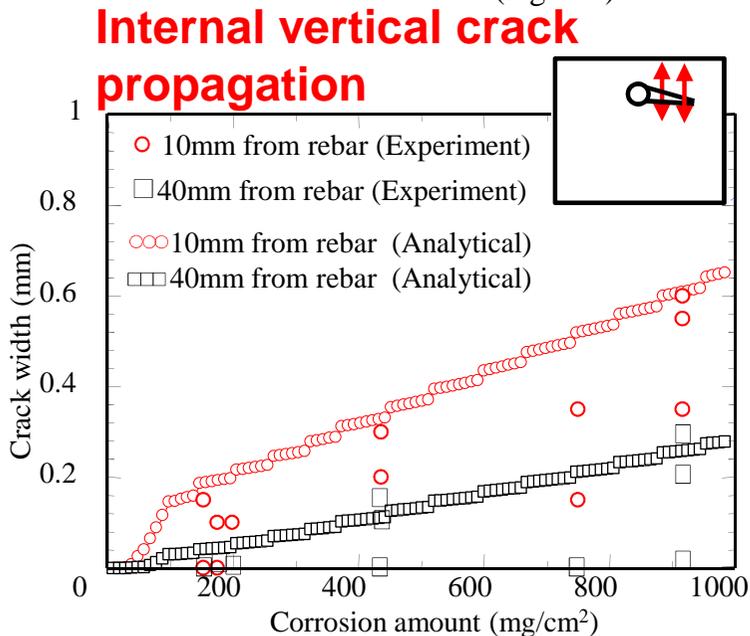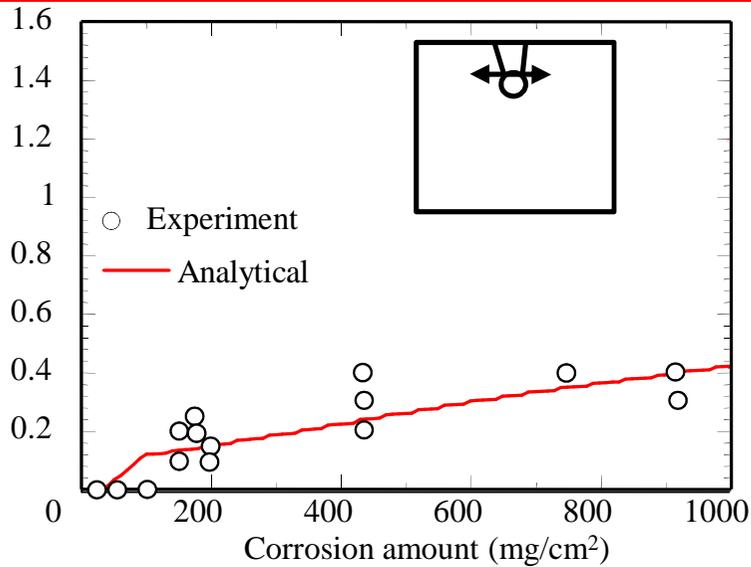"Corrosion amount: 164mg/cm²"
"Surface crack width: 0.52mm"

(c) Internal crack patterns

Surface vertical deformation

Applicability of analytical model

Analytical results (cont'd)

Internal vertical crack propagation
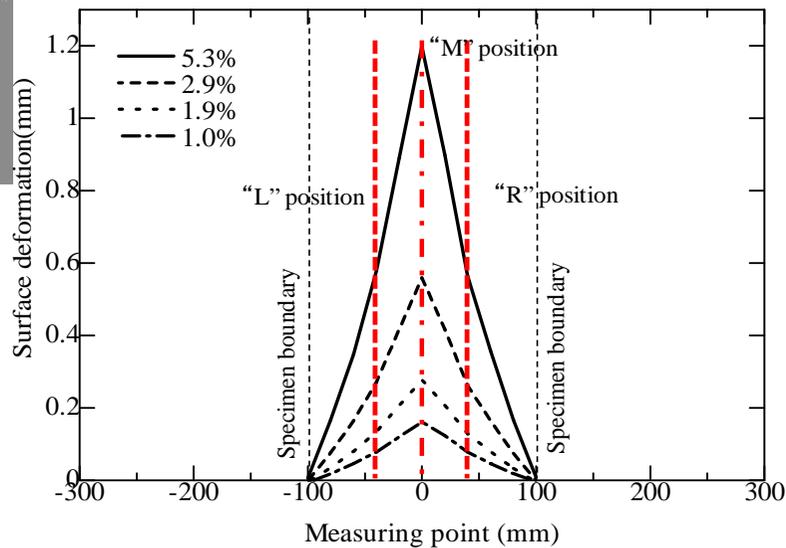
Internal crack width propagation

Surface vertical deformation

The good agreement with the test results shows applicability of the proposed analytical model
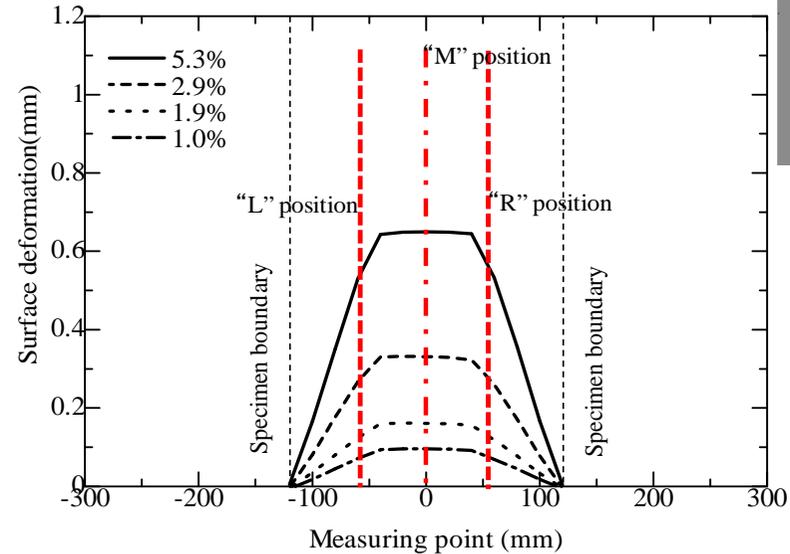
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Effect of rebar spacing

Surface deformation
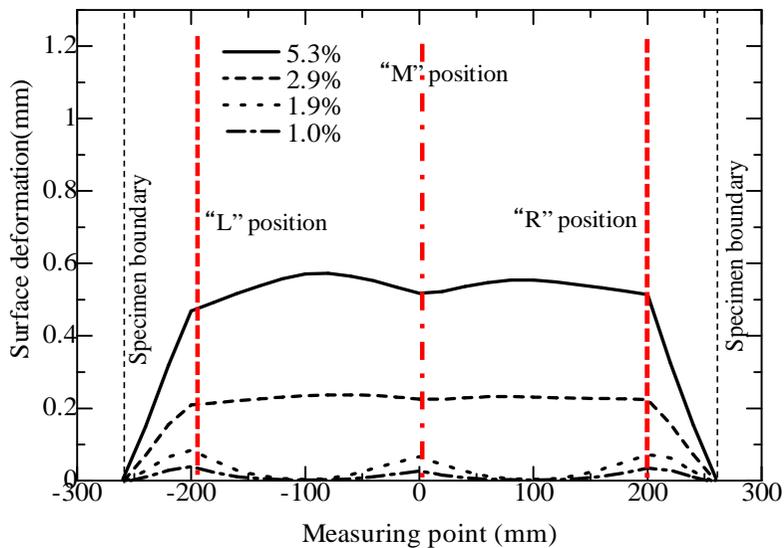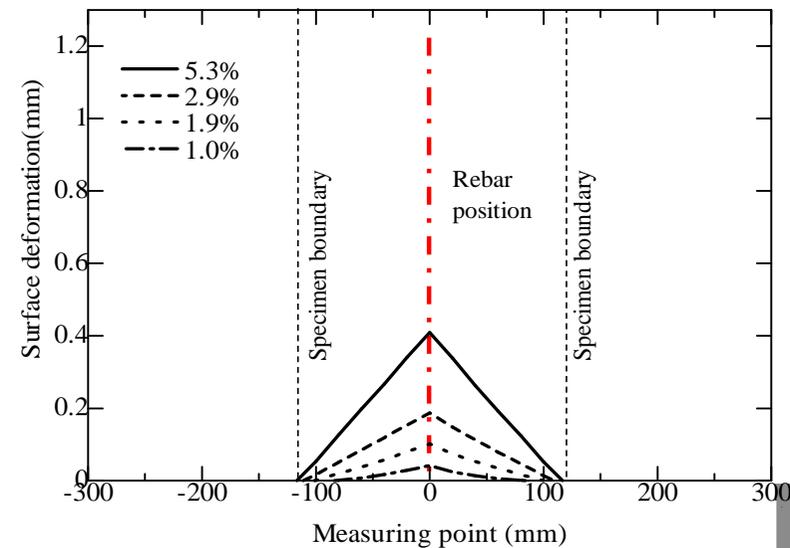

a) Specimen Sr-40

b) Specimen Sr-60

c) Specimen Sr-200

d) Single- rebar specimen

Different cracking behavior