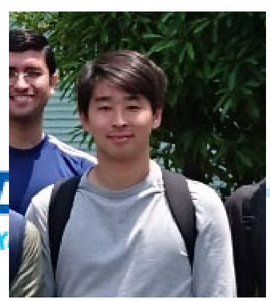
17th U.S.-Japan-New Zealand Workshop
on the Improvement of Structural Engineering and Resilience
Rydges Lakeland Resort, Queenstown, New Zealand
November 12-14, 2018

RESILIECY EVALUATOIN OF REINFORCED CONCRETE BUILDINGS

Sam Kono, Ryo Kuwabara, Fuhito Kitamura, Eko Yuniarsyia, Hidekazu Watanabe, Tomohisa Mukai, and David J. Mukai

Tokyo Institute of Technology, Yokohama, Japan
Building Research Institute, Tsukuba, Japan
University of Wyoming, Laramie, USA



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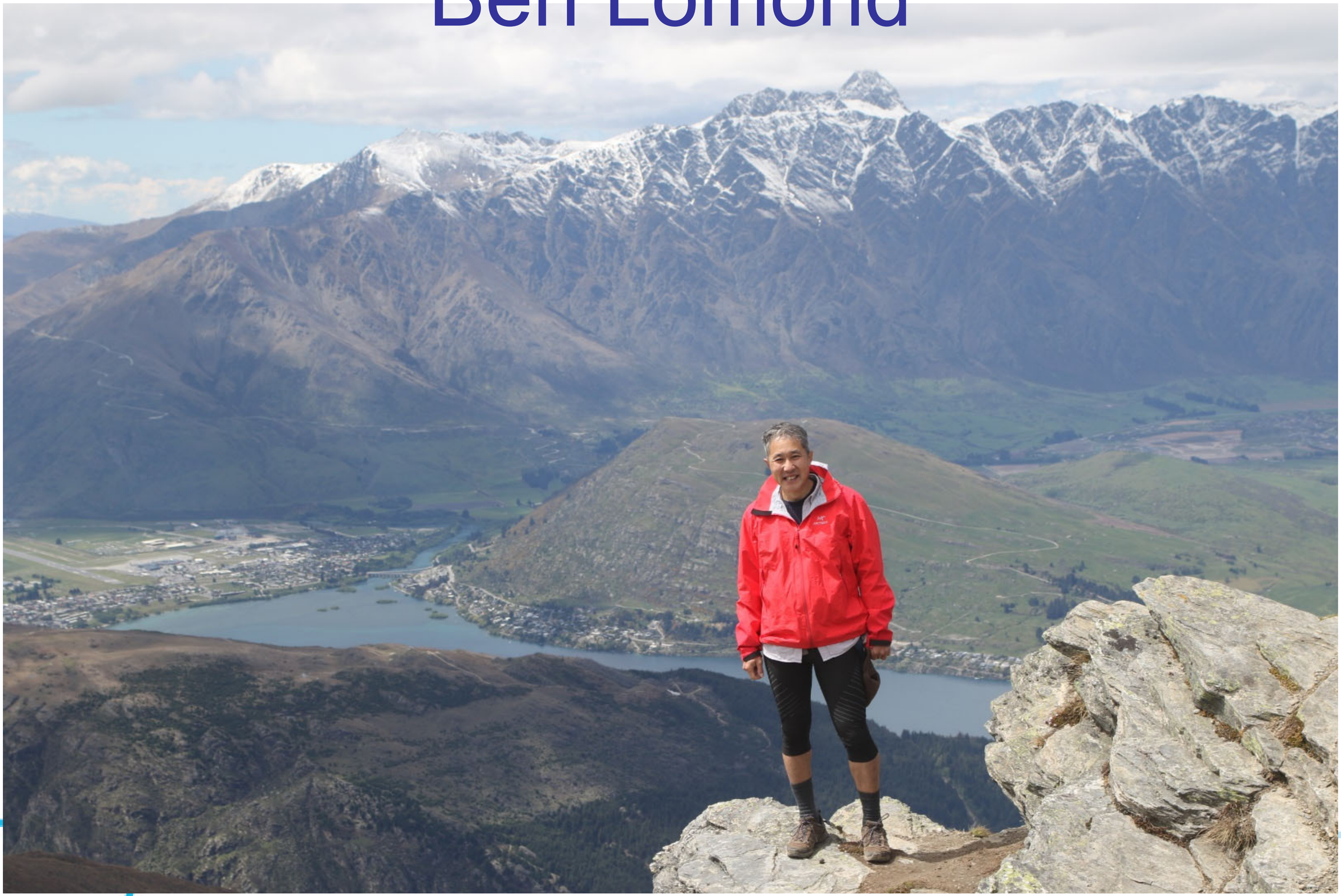


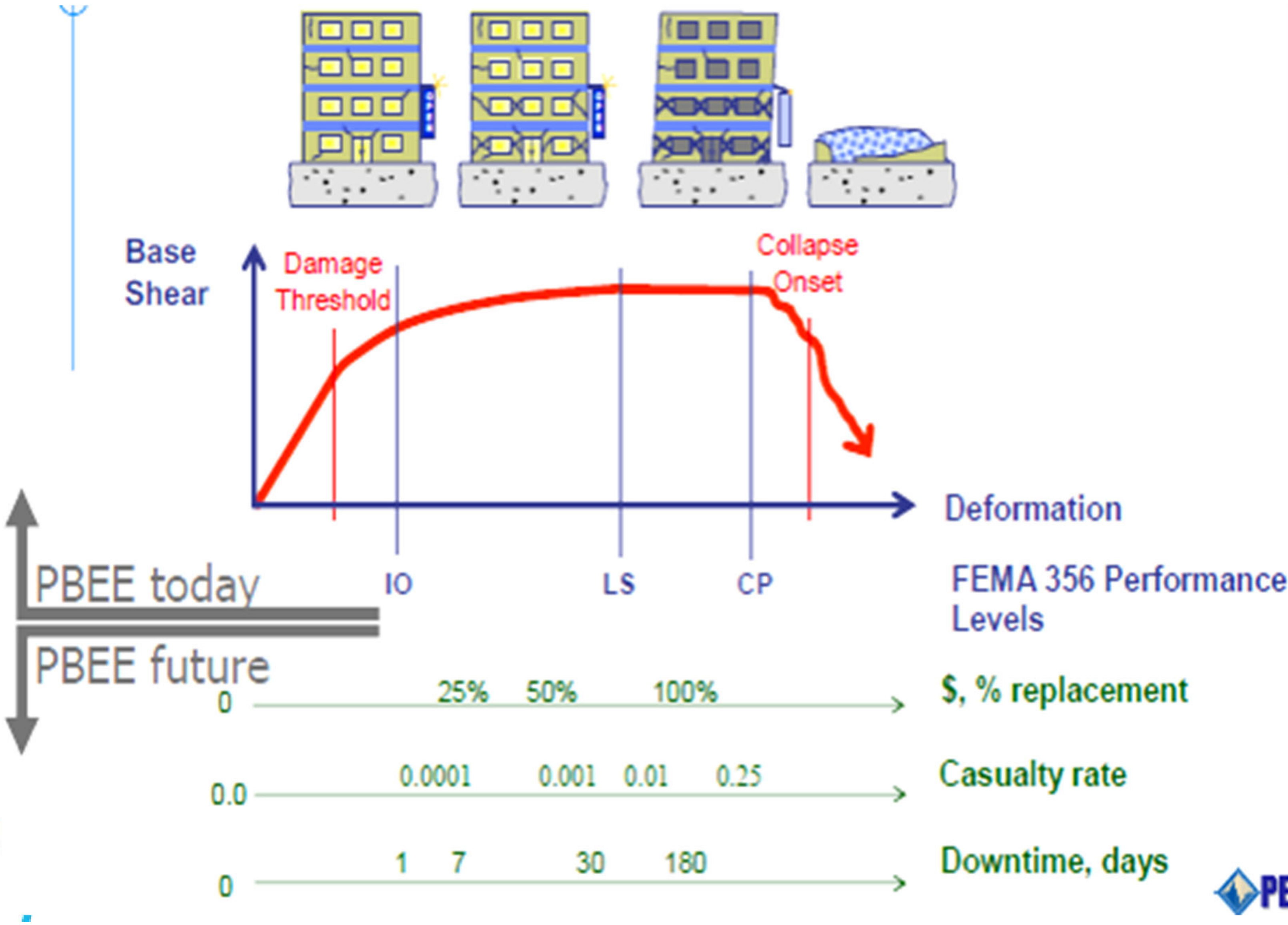
Lessons from 2016 Kumamoto EQ

- Safety is still the most critical issue.

- People want to use their buildings continuously after EQ's without losing any building functions.
  - Intermediate or severe damage to structural and non-structural elements cannot be accepted anymore.

Current design issues

(Evolution of PBEE methodology)



Evaluation of minor/intermediate damages of RC buildings

Continual functionality

using real scale five-story RC buildings

The experiment was conducted by NILIM and BRI.
Tokyo Tech was one of three universities who collaborated with them.

From Tokyo tech
Mr. Eko Yuniarsyah
Mr. F. Kitamura
Prof. H. Watanabe
Prof. S. Kono

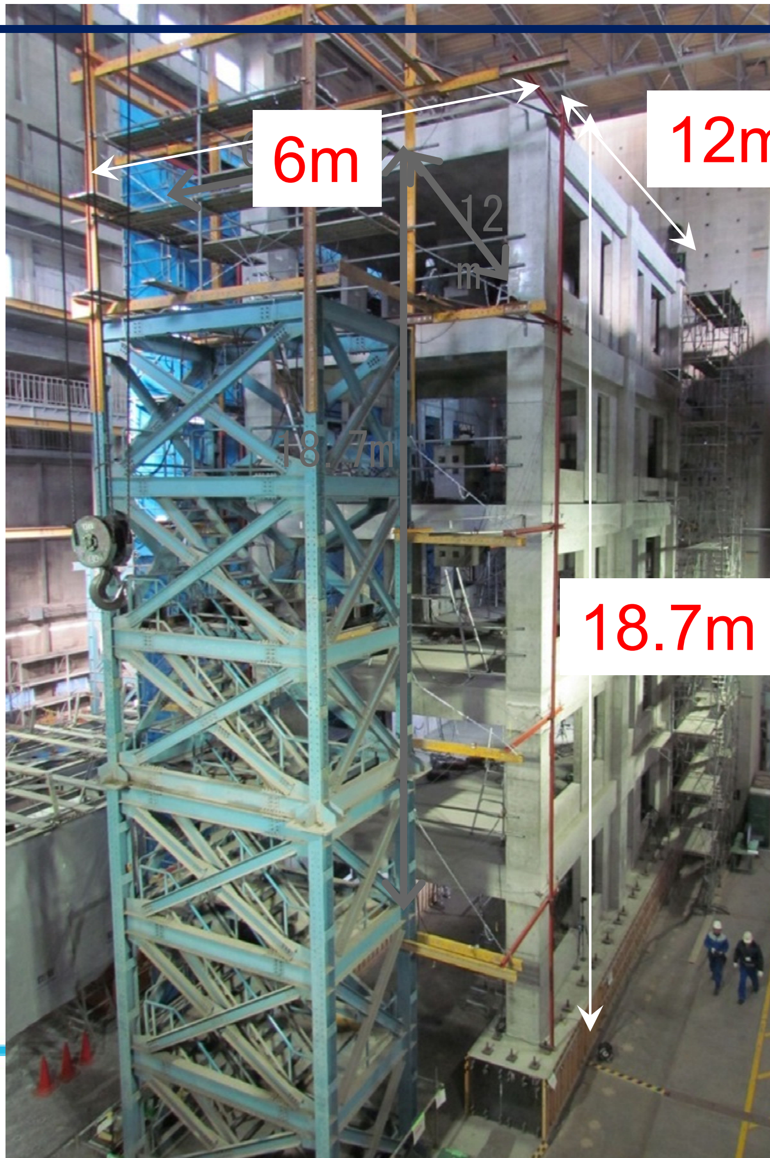
Objectives

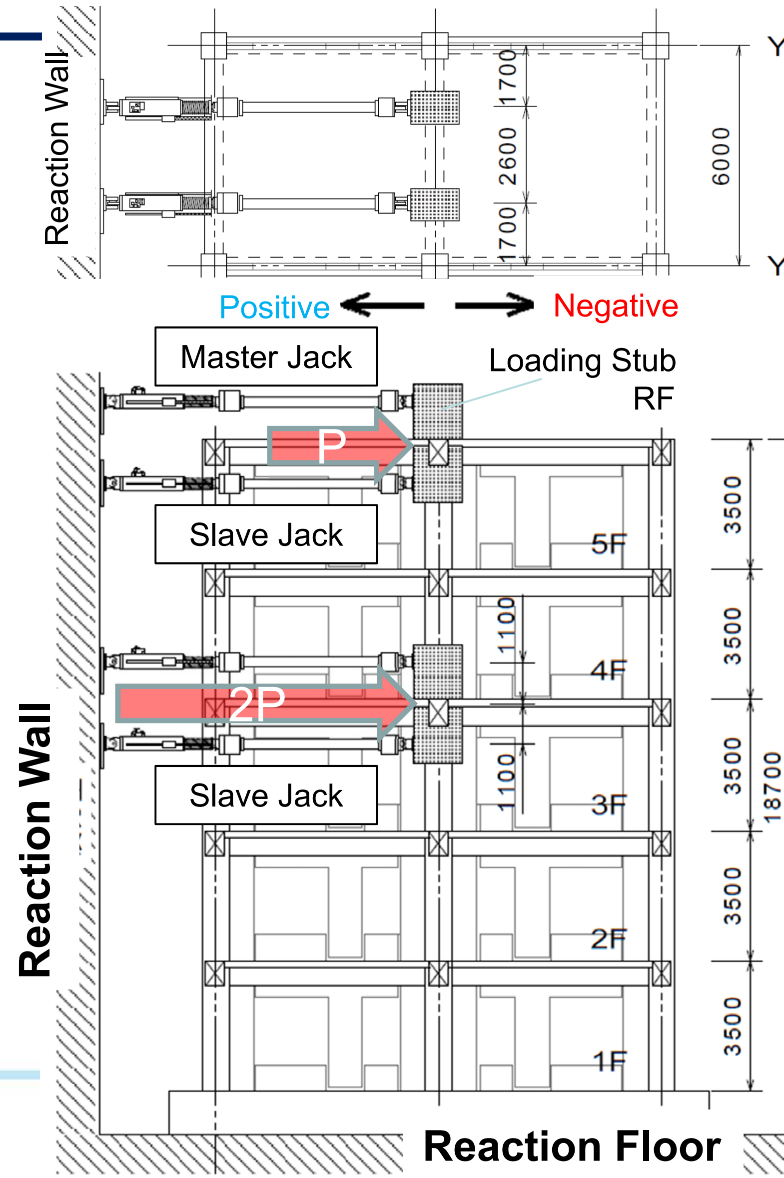
set up by Tokyo Tech

- Simulate the behavior of a 5-story building specimen with FE analysis.
- Simulate damages
  - numbers/width/length of cracks
  - area of cover spalling
  - extent of concrete crushing
  - extent of rebar yielding/bucking/fracturing

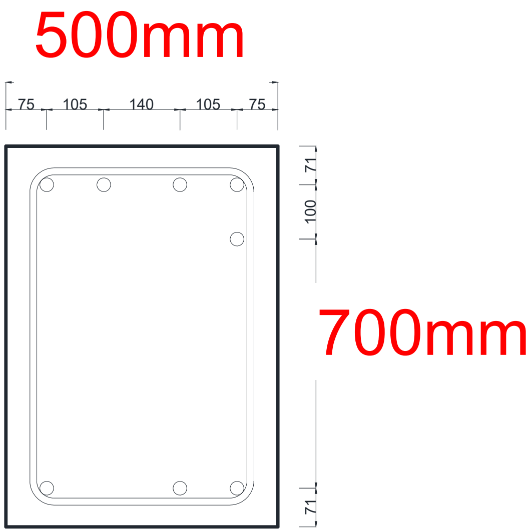
Specimen

The experiment was conducted by NILIM and BRI. Tokyo Tech was one of three universities who collaborated with them. (Papers in WCEE 2017)

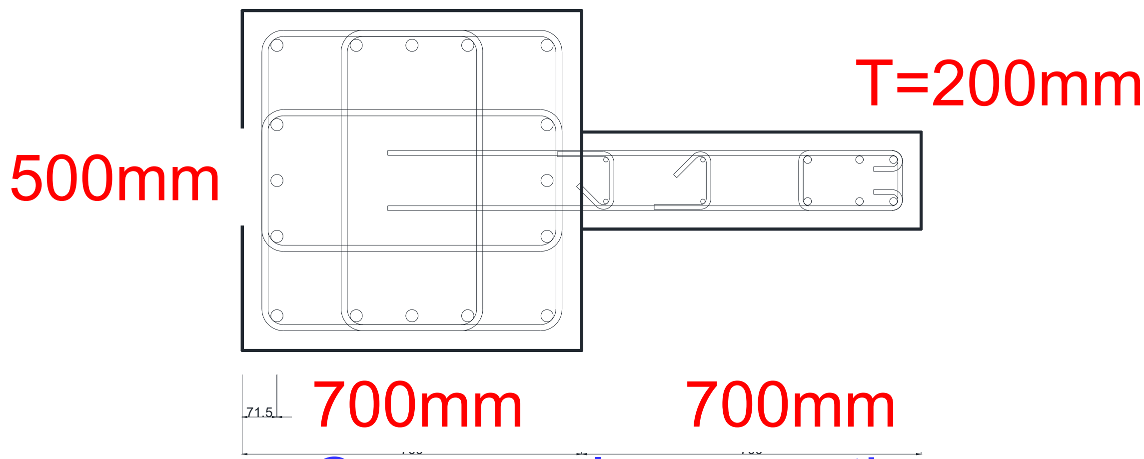




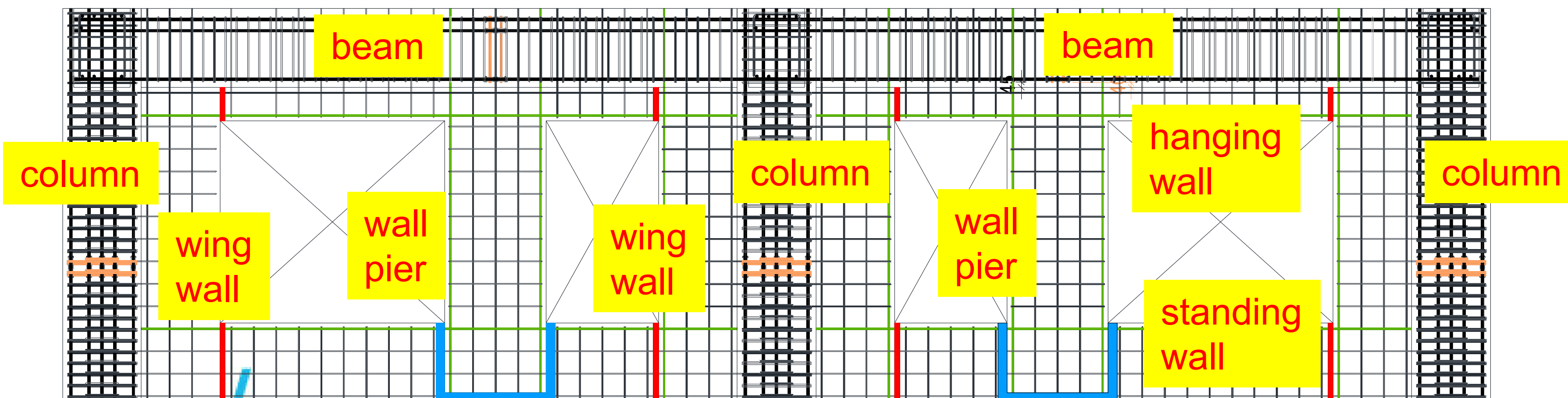
Specimen



Beam section

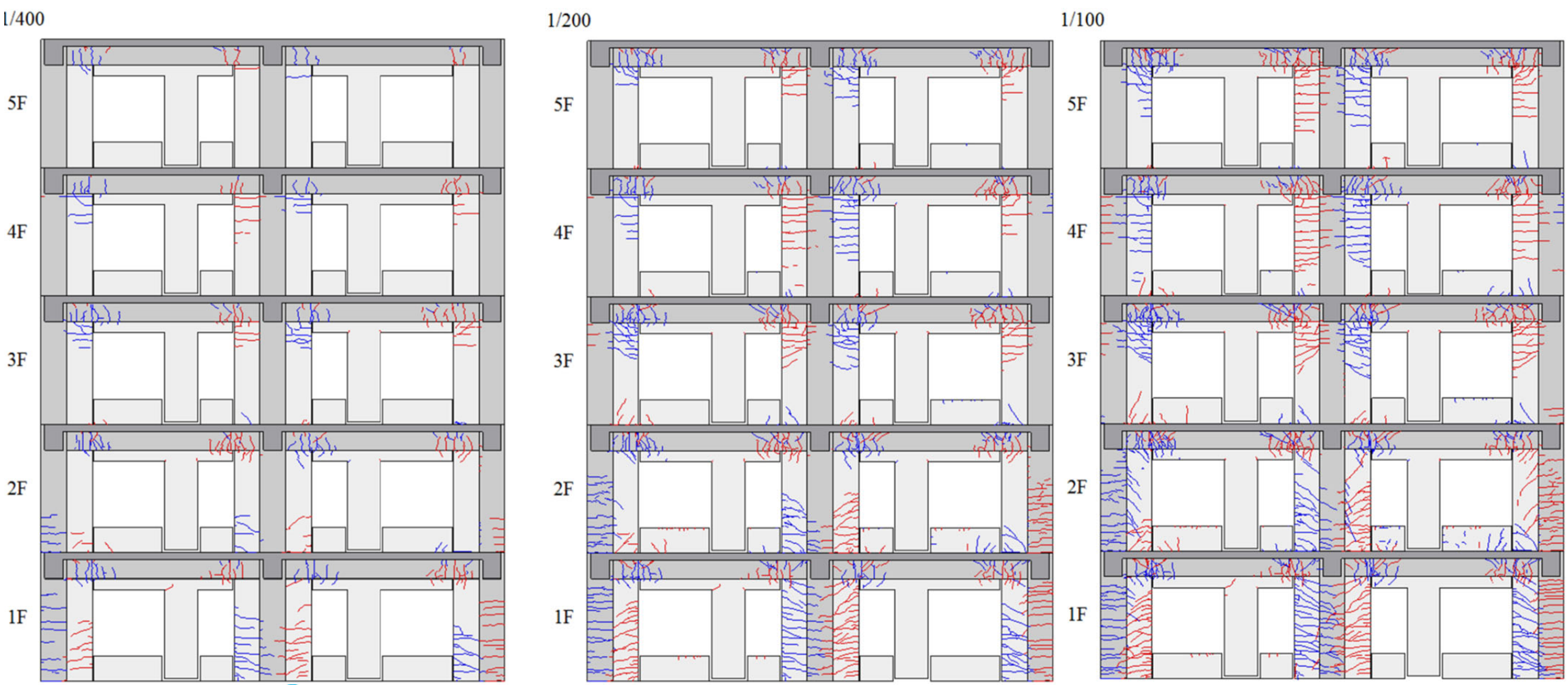


Corner column section



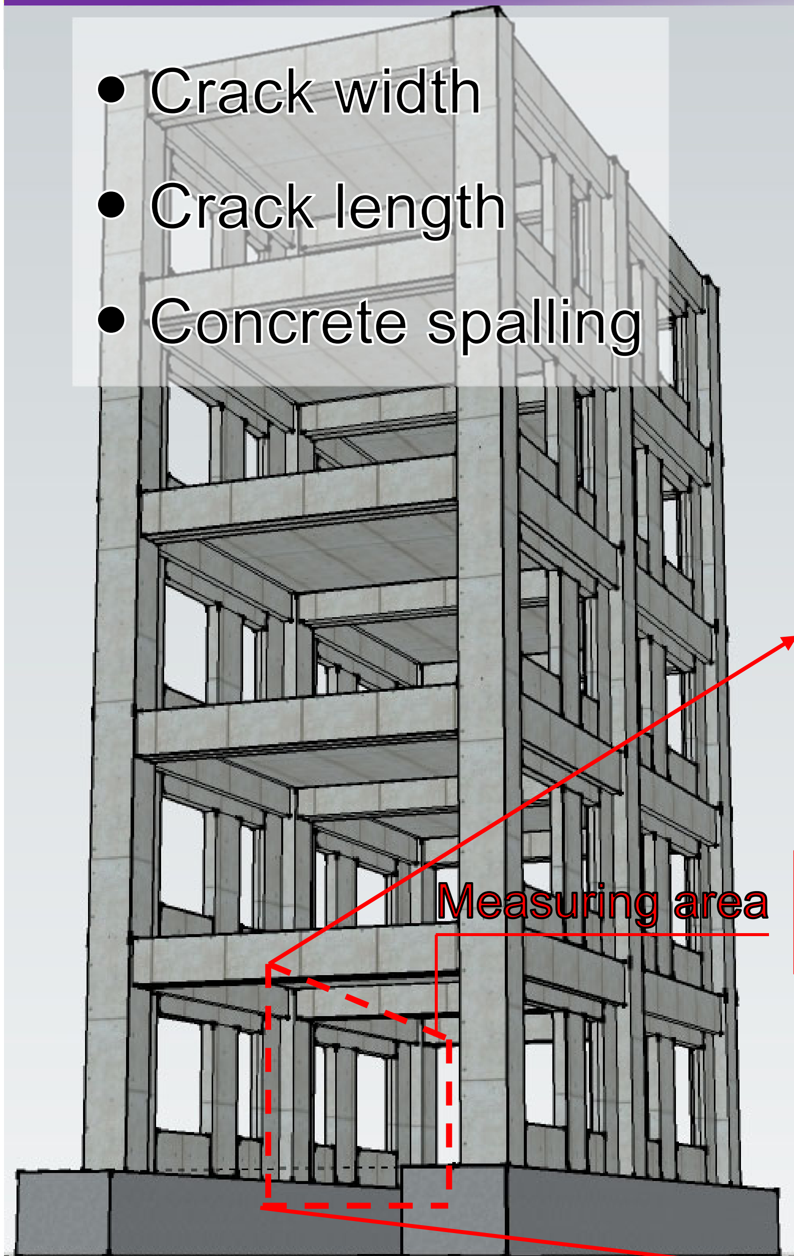
Typical story elevation in the longitudinal direction

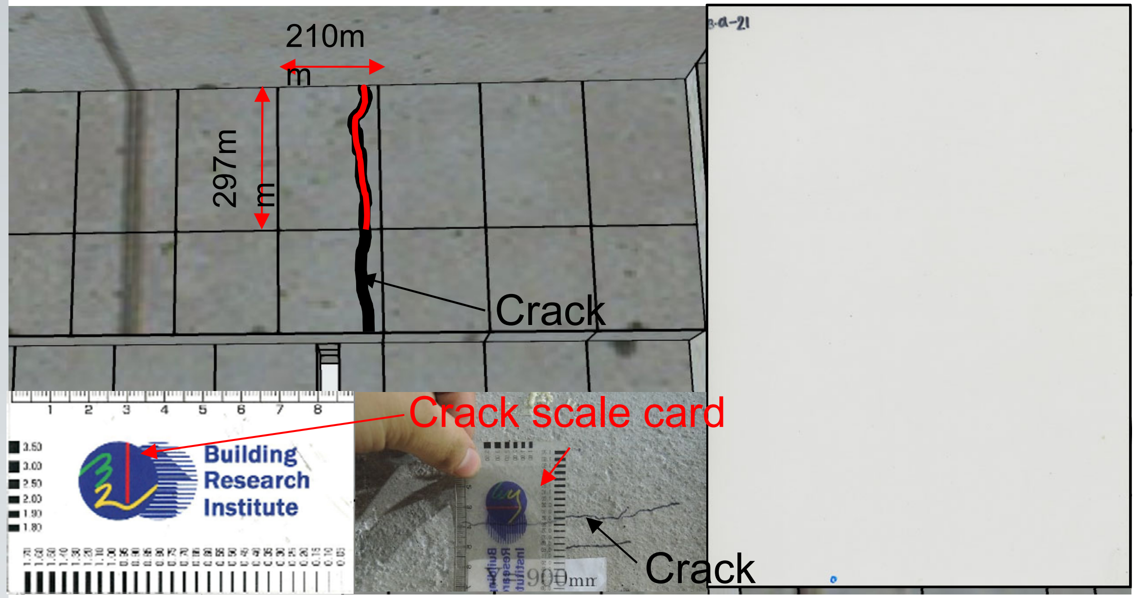
Crack distributions

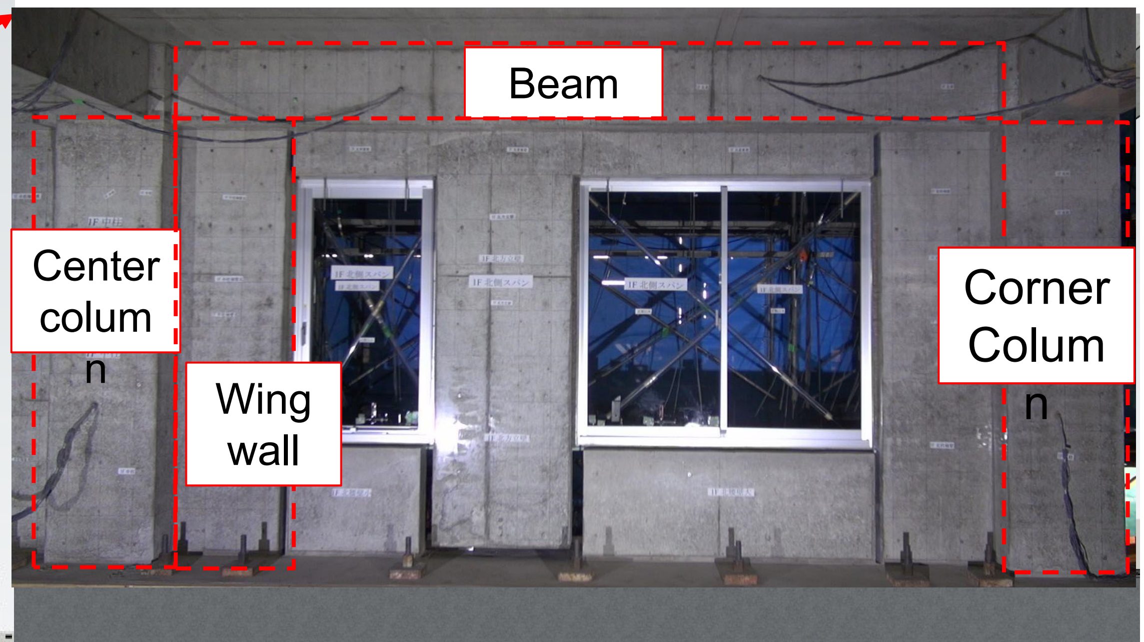


R=0.25% R=0.5% R=1%

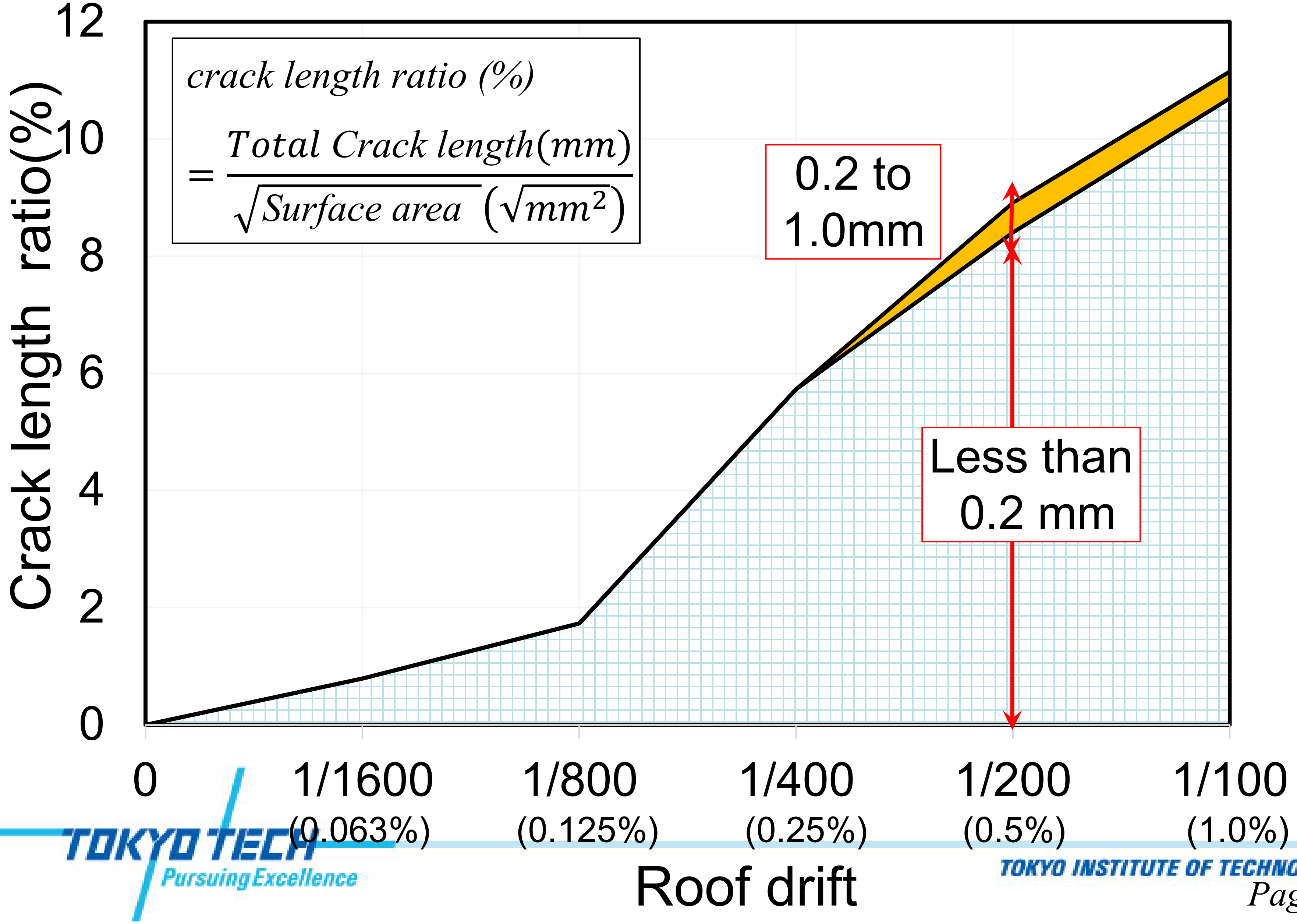
■Crack measurement



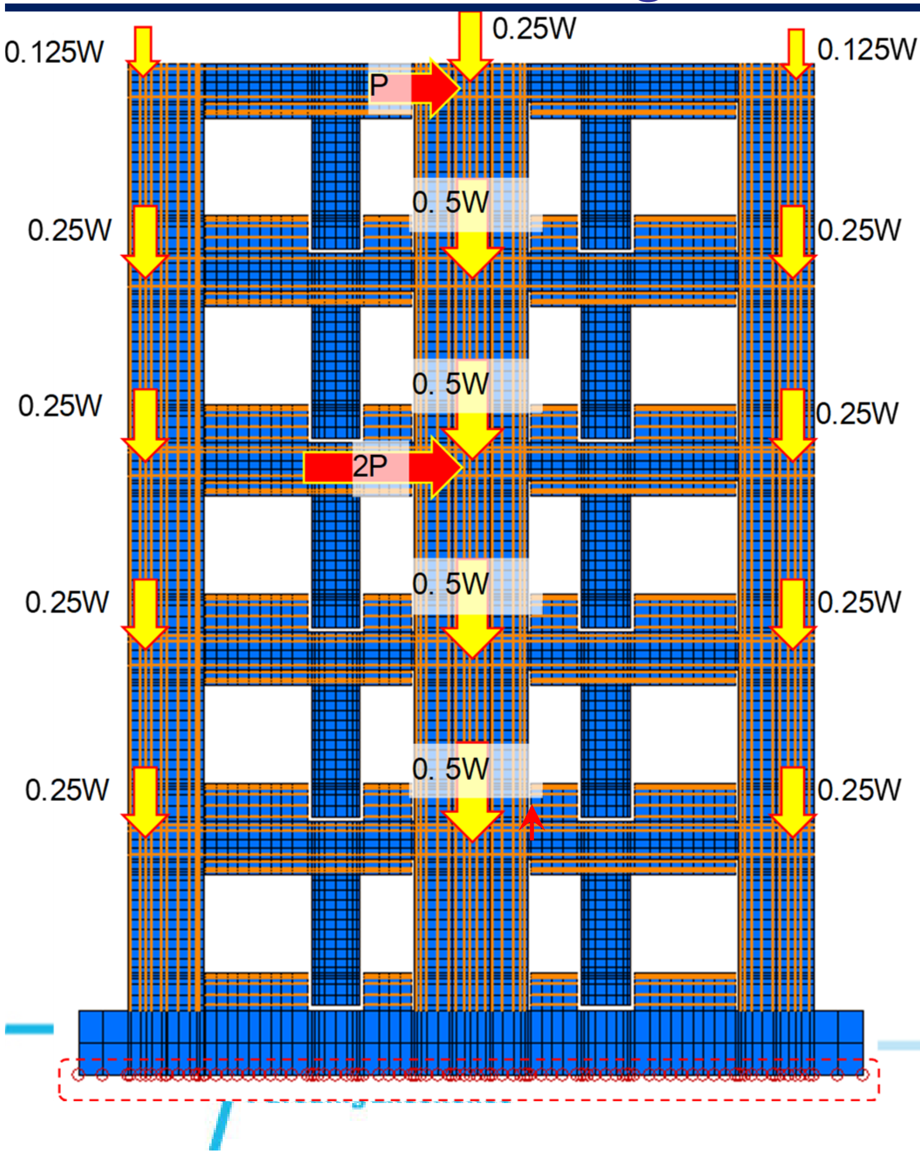


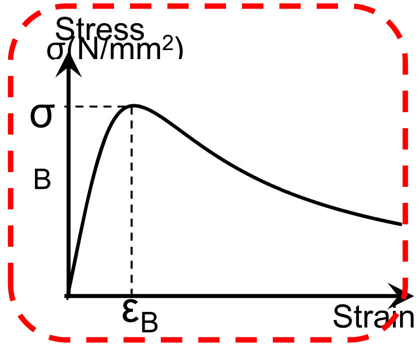


Summary of recorded cracks

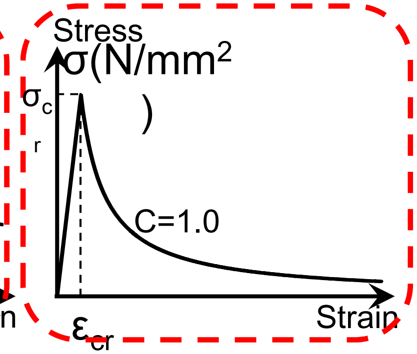


Numerical model
using FEM Program “FINAL”



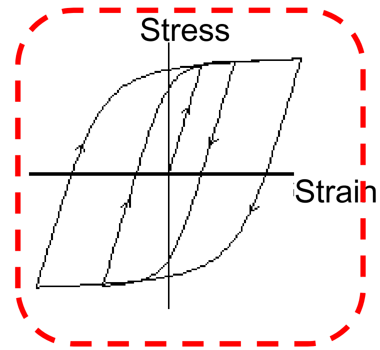


Concrete(Comp.)
Modified Ahmad Model)



Concrete (Tens.)
(Izumo Model)

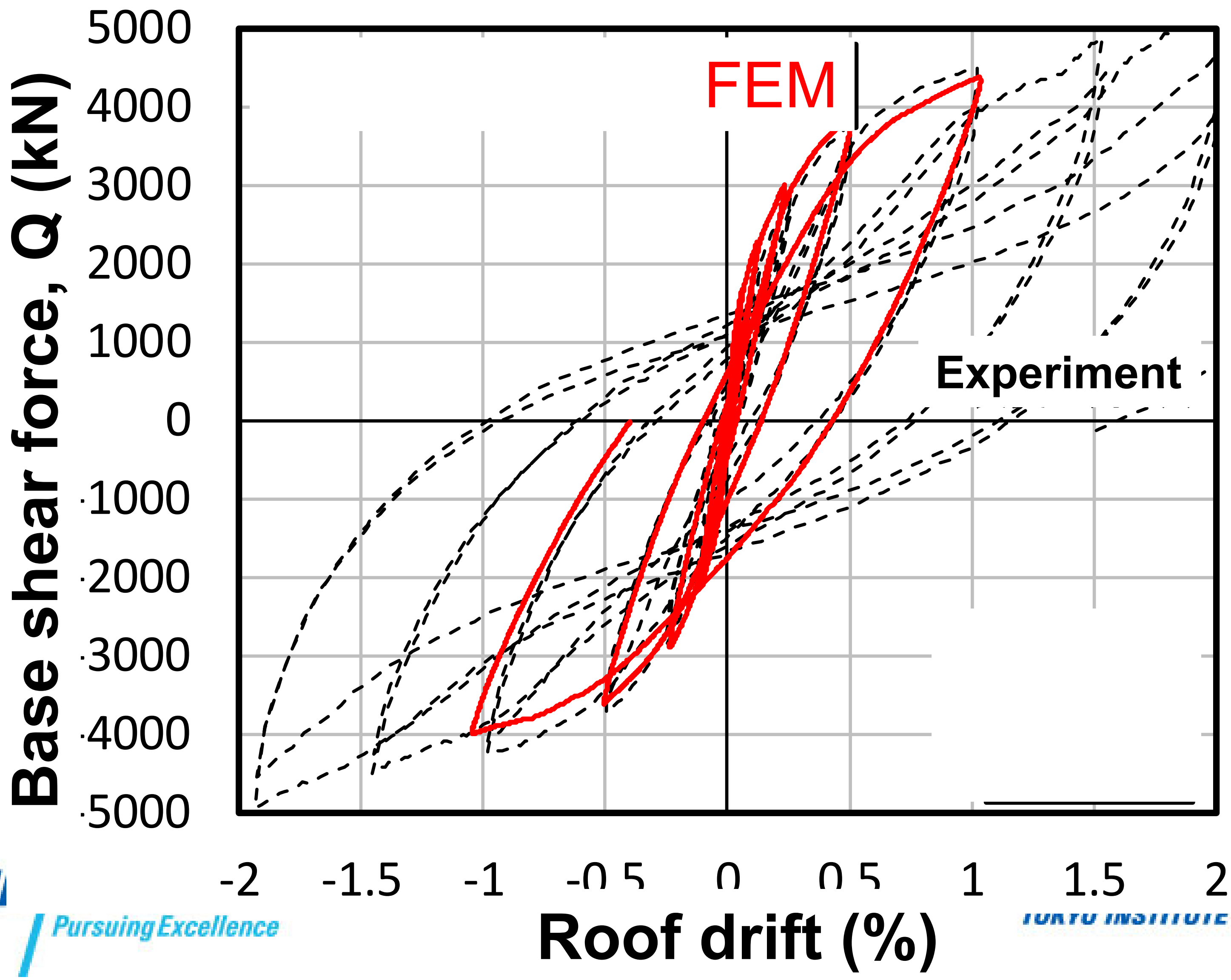
Stress-Strain relations



Reinforcement
(Modified Menegotto–Pinto model)

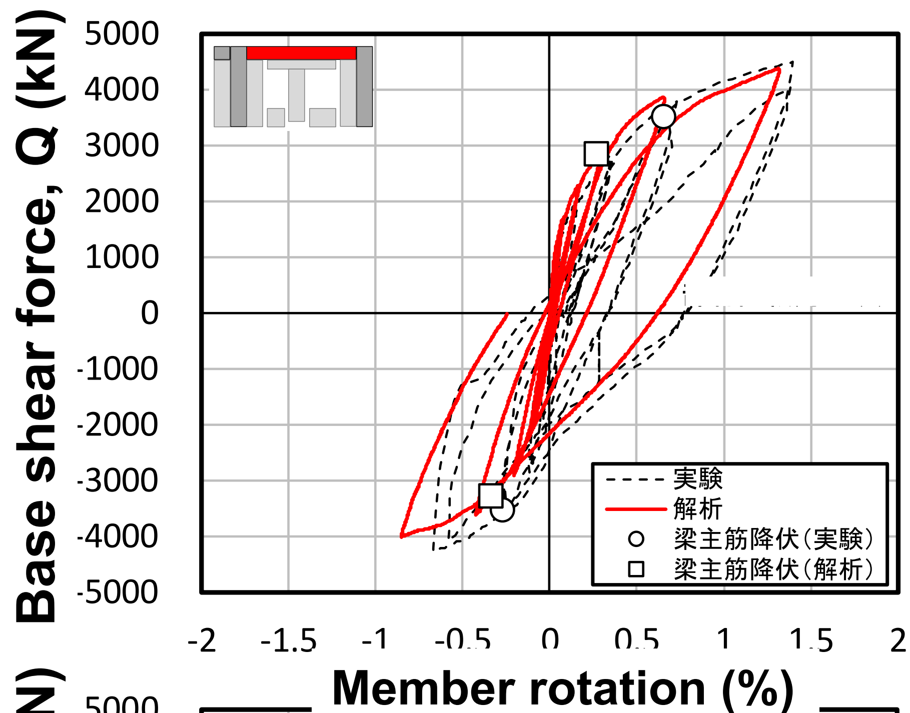
FEM Results

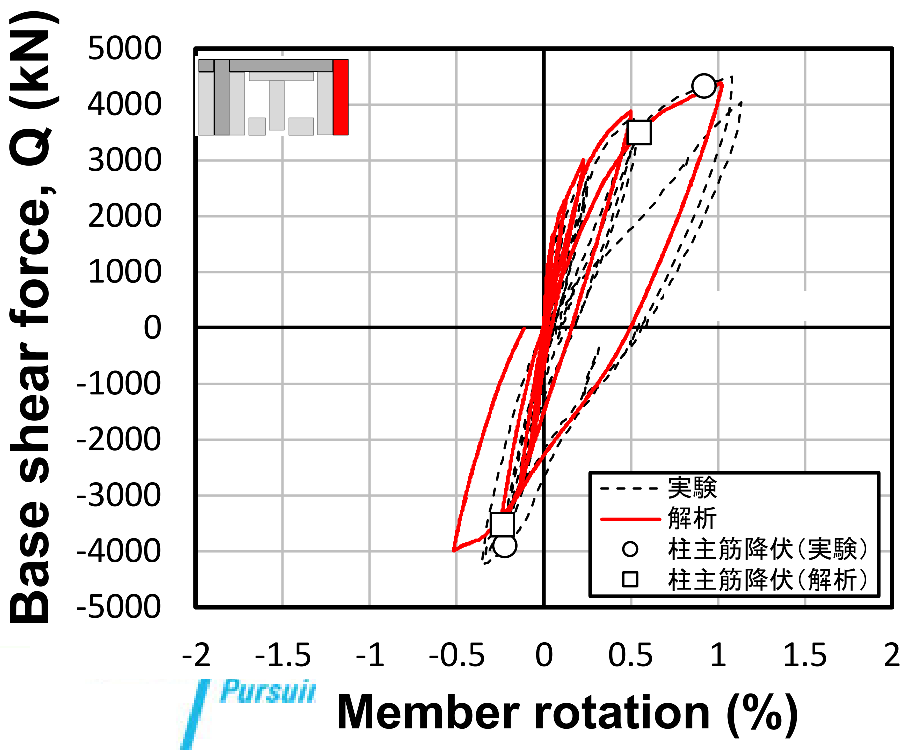
Base shear force – Roof drift relation

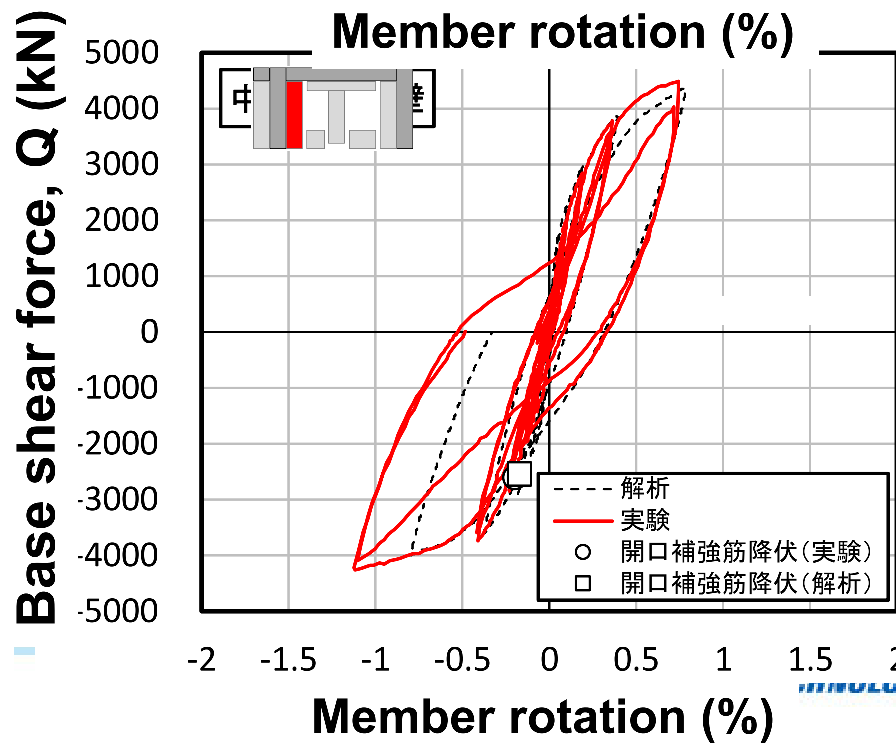


FEM Results

Member level







Flexural crack simulation

1. Spacing (Number of cracks)
   - CEB-FIP Model Code

2. Width
   - Use axial strain of FEM

3. Length
   - Flexural analysis based on FEM

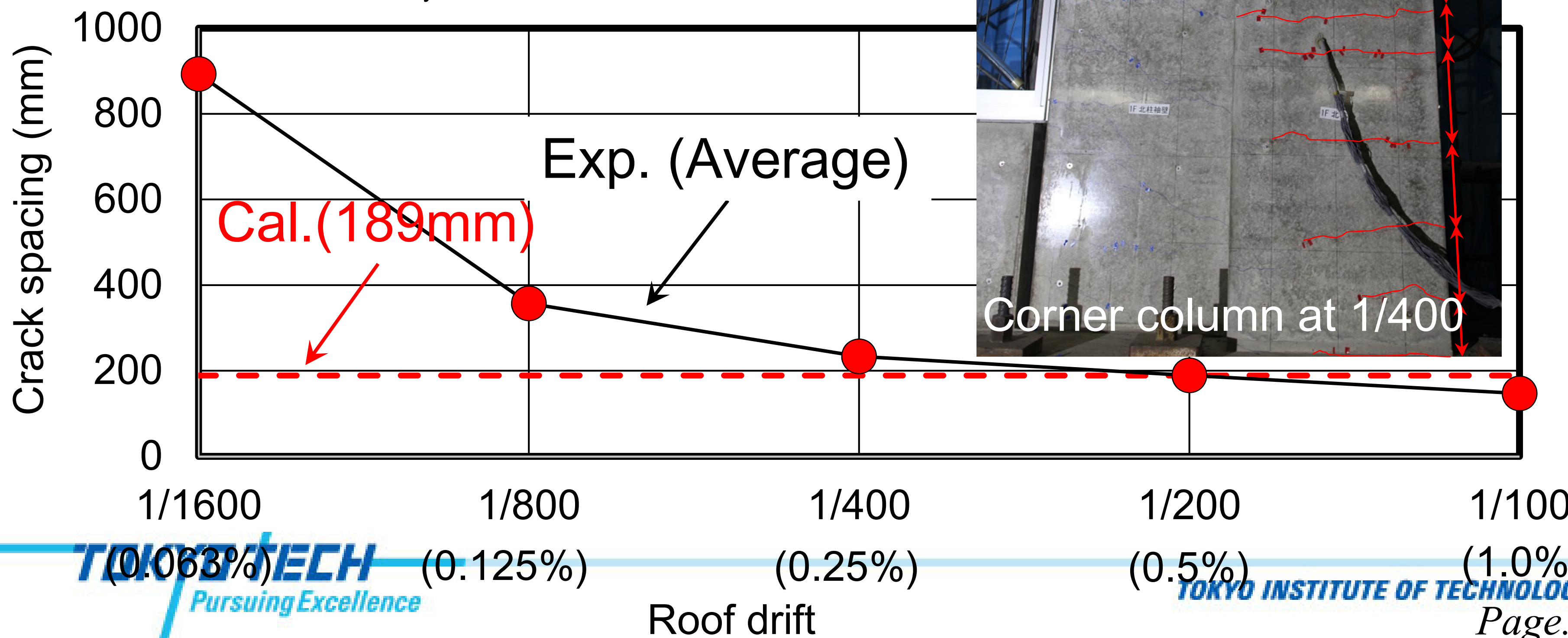
Flexural crack simulation

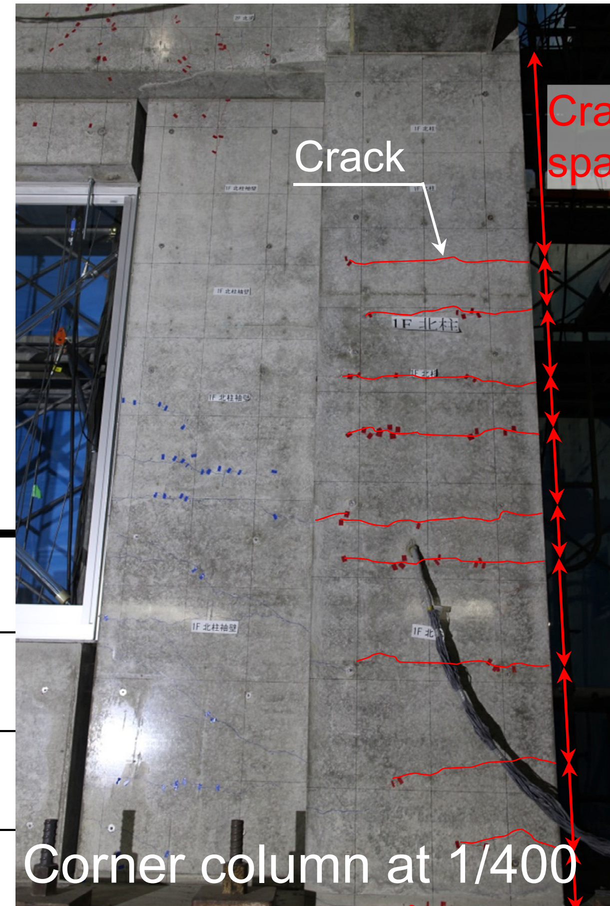
1. Spacing

Crack spacing formula (CEB-FIP 1978)

$$s_{rm} = 2\left(c_s + \frac{s_y}{10}\right) + k_1 k_2 \frac{d_{by}}{p_y}$$

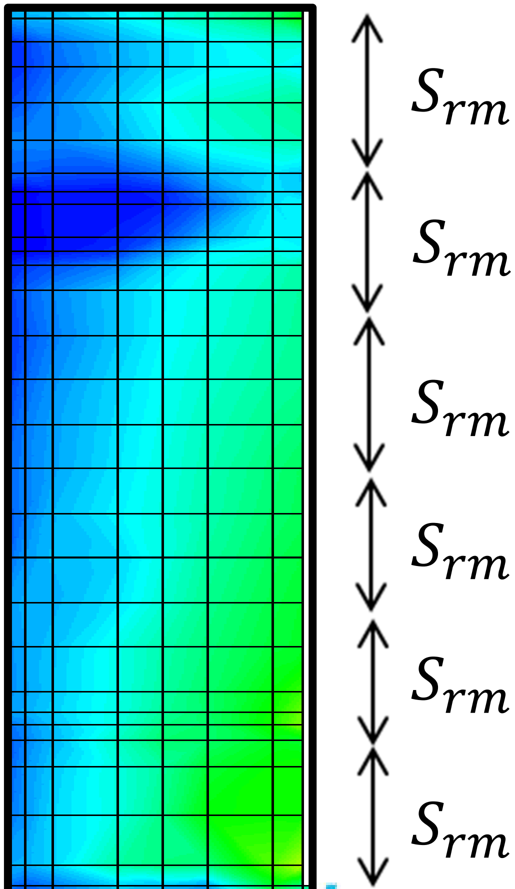
s_{rm}=mean crack spacing, c_s=clear concrete cover, S_y=maximum spacing between longitudinal bars, k_1=factor that takes into account bond properties of reinforcing bar=0.4 for deformed bars, k_2=factor that takes into account strain gradient, k_2=0.25(ε_1+ε_2)/ε_1, ε_1 and ε_2 correspond to the largest and smallest concrete tensile strain, d_{by}=longitudinal bar diameter, p_y=ratio of the area of reinforcement effectively bonded to the concrete to the cross-sectional





Flexural crack simulation

2. Width



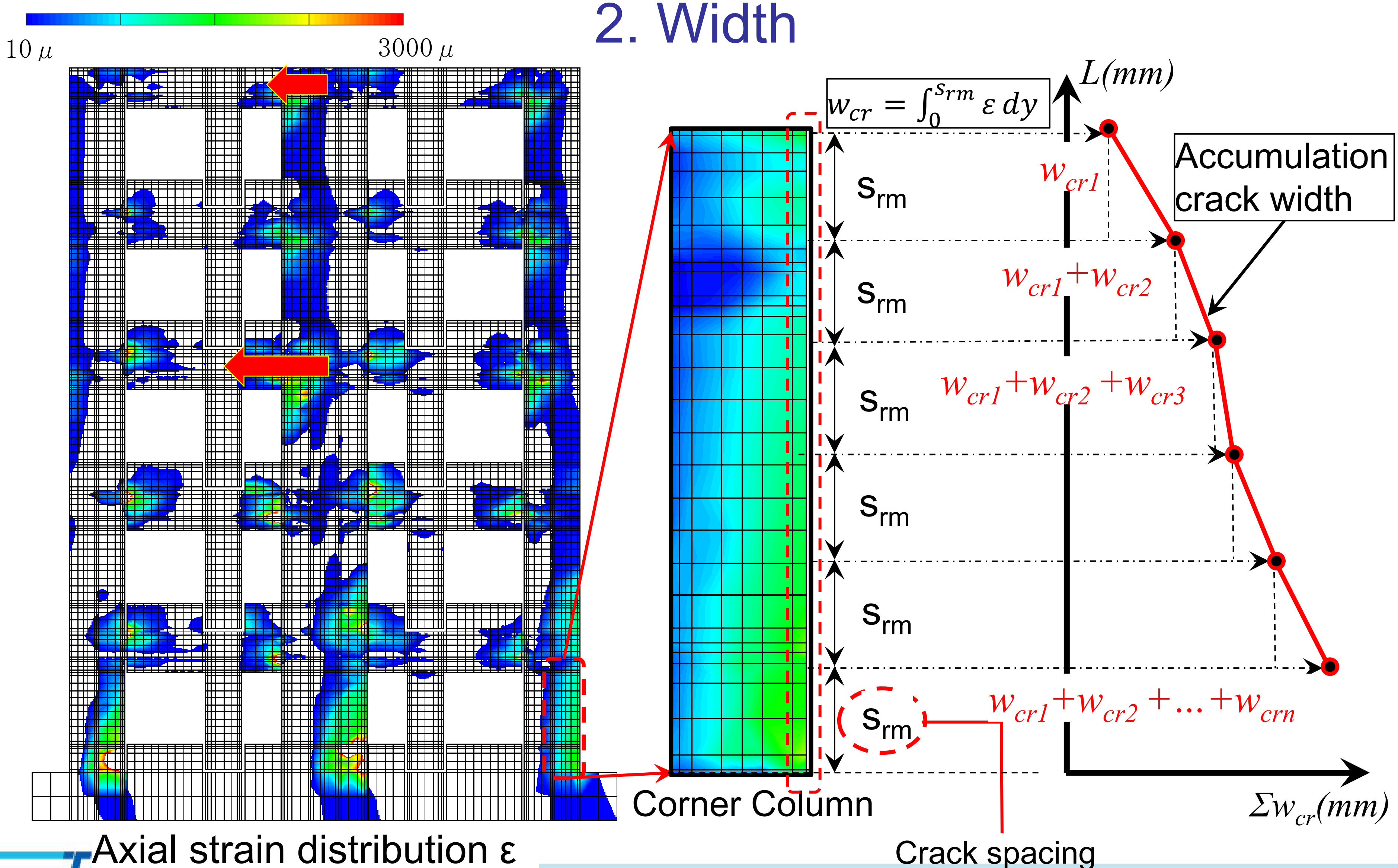
The crack width of the *i*-the crack, w_i, in a region (from h_i to S_{rm}+h_i) is expressed as:

$$\boxed{w_i = \int_{h_i}^{S_{rm}+h_i} \varepsilon_{zz}\, dz}$$

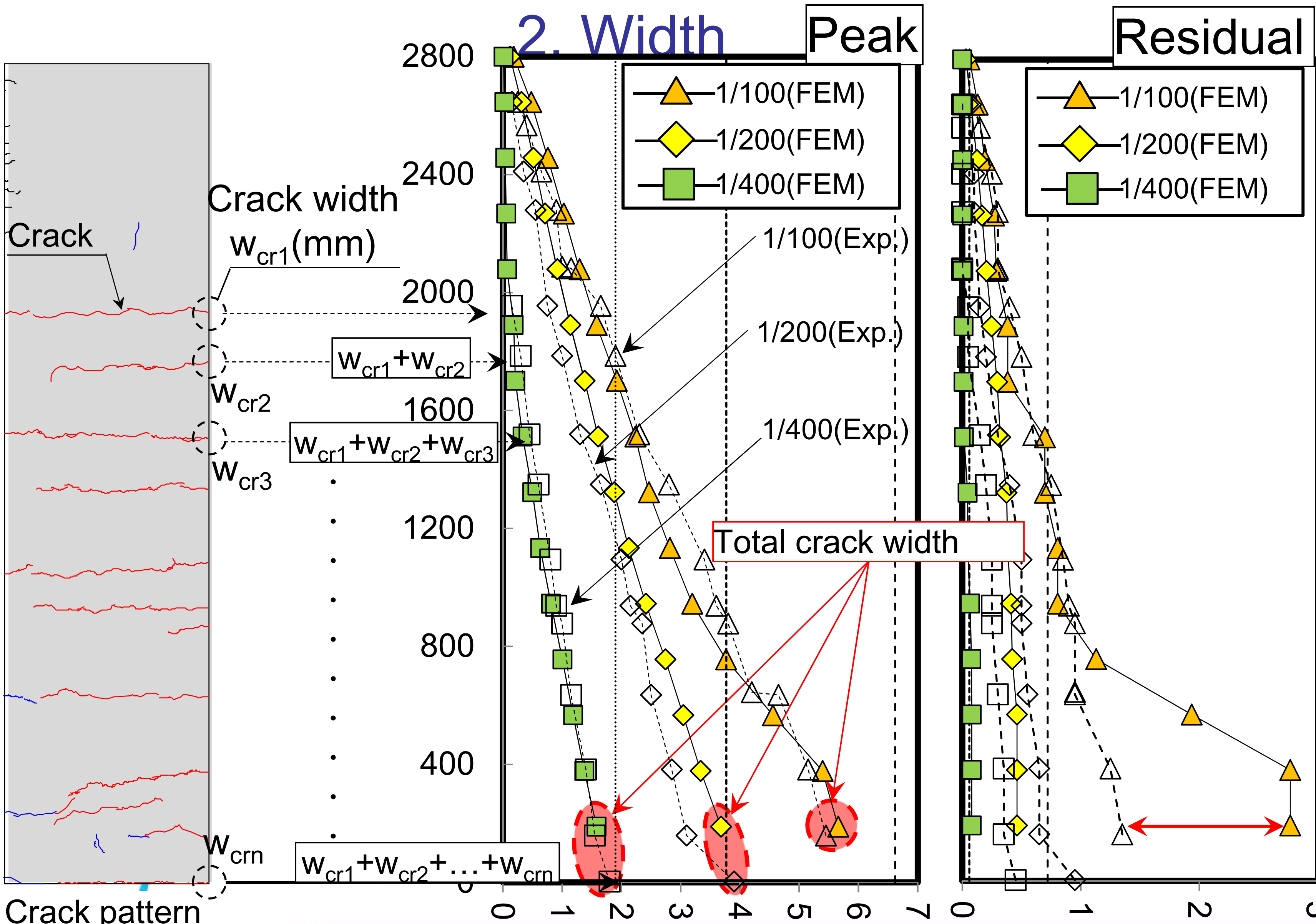
Assumption: axial strain is caused by cracks but not concrete (concrete does not deform).

Flexural crack simulation

2. Width



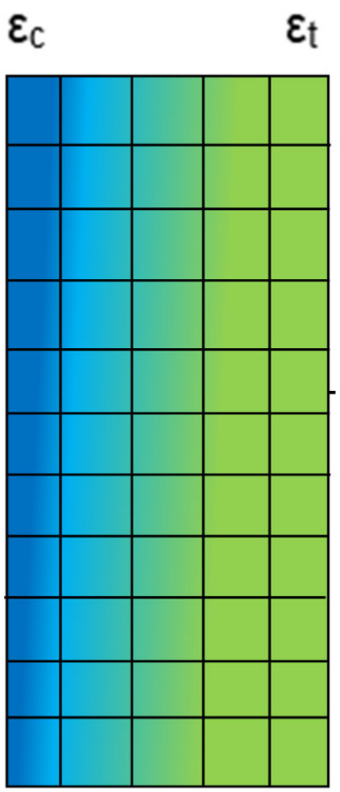
Flexural crack simulation

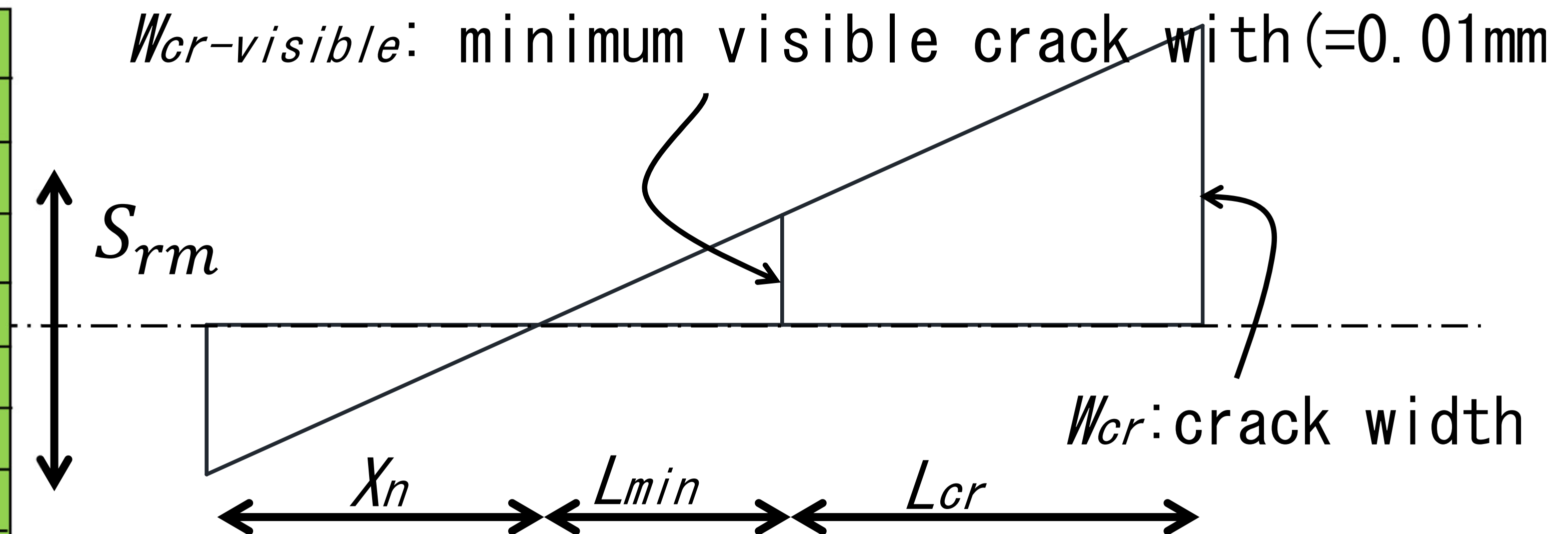


Crack pattern
at 1/400(0.25%)
Corner column (Exp.)

Flexural crack simulation

3. Length

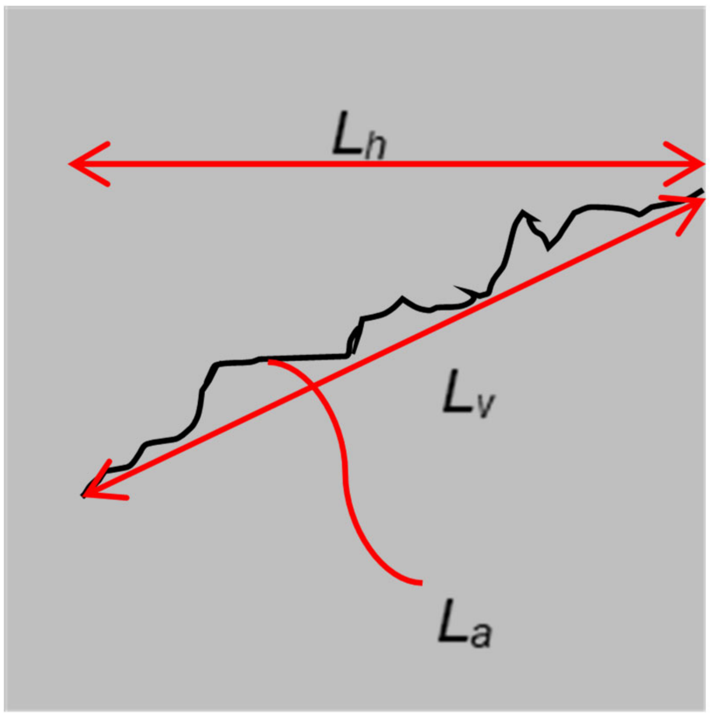




Xn: neutral axis depth(mm)
Lmin: invisible crack length(mm)
Lcr: Visible crack length(mm)

Flexural crack simulation

3. Length



$$\alpha_1 = \frac{L_v}{L_a} \quad \text{(detouring\&meandering)}$$

$$\alpha_2 = \frac{L_v}{L_h} \quad \text{(horizontal to diagonal)}$$

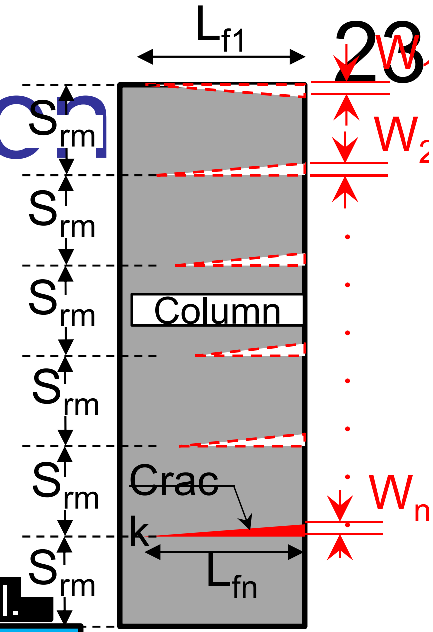
L_h: Horizontal projection

L_a: Real crack length

L_v: Distance between two points

Flexural crack simulation

Procedure flow



Nonlinear Finite Element Analysis

Axial strain distribution

CEB-FIP 1978

1. Crack spacing S_{rm}

Izumo et al.

Visible crack width $W_{cr\text{-}visible}$

2. Crack width(Peak)

3. Horizontal crack length

Exp.

Conversion factor α(exp.)

Correction factor α1, α2(exp.)

Exp.

2. Crack width(Residual)

3. Curved&meandering crack length $L_1 \sim L_n$

Residual Crack Summary

ΣL_{fi} for 0mm < W < 0.2mm
ΣL_{fi} for 0.2mm < W < 1mm
ΣL_{fi} for 1mm < W < 2mm

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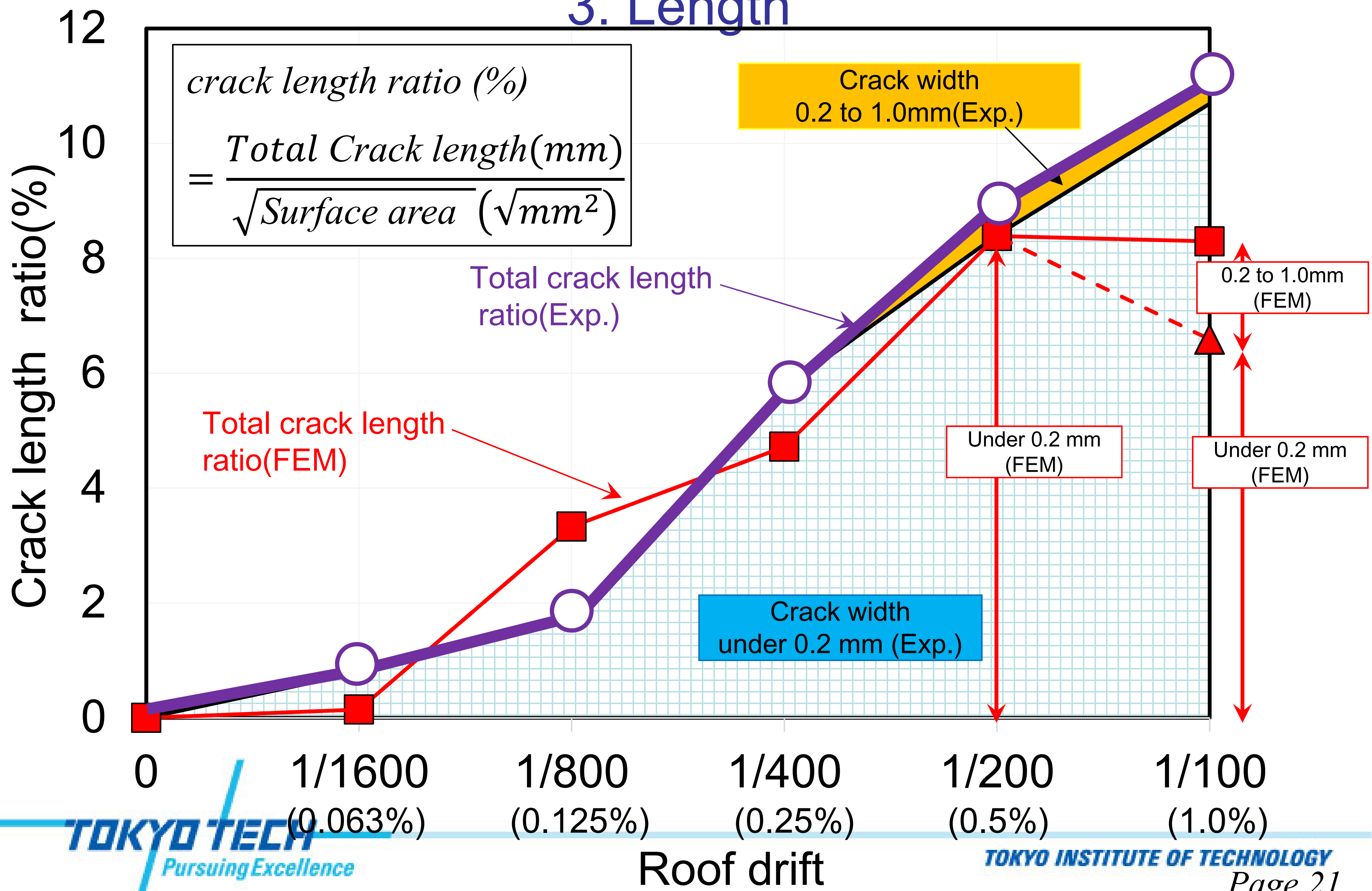
Flexural crack simulation

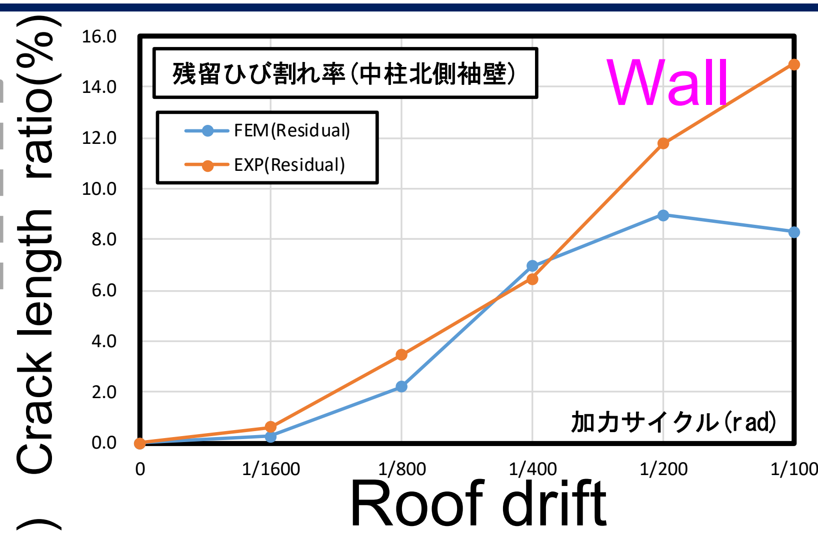
3. Length

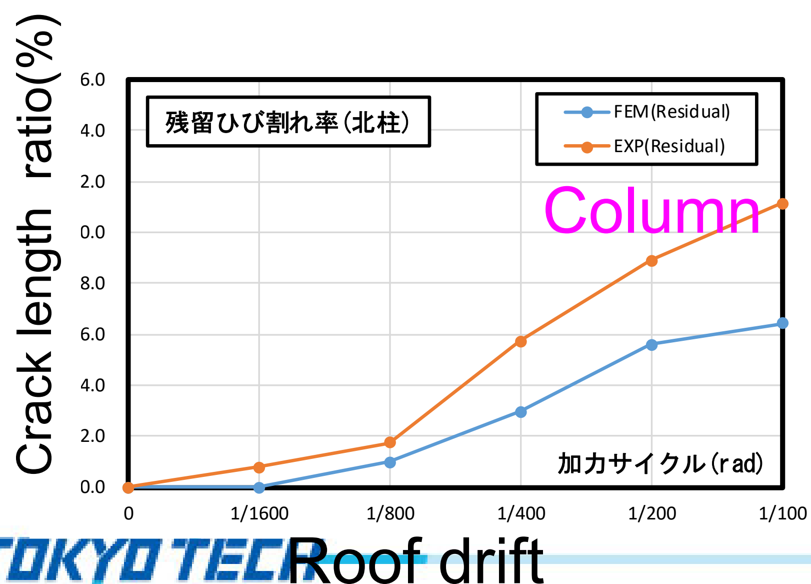


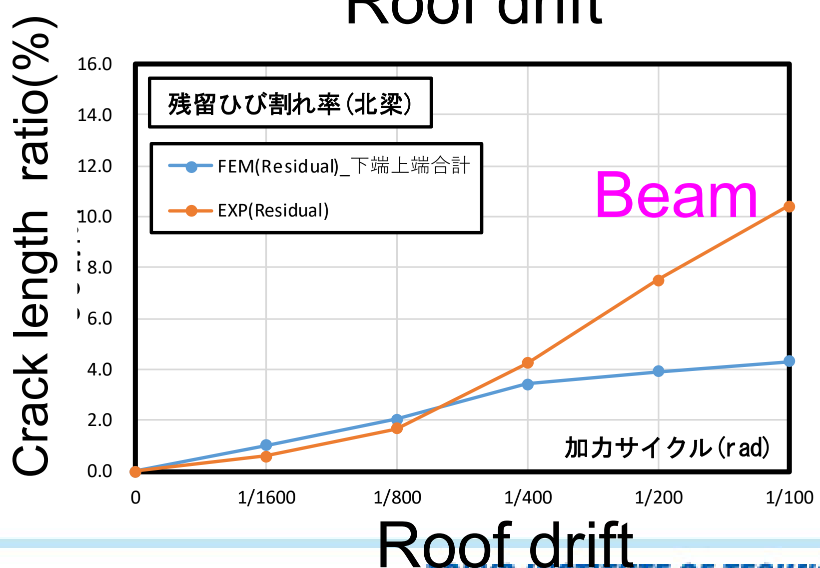
Flexural crack simulation

Final results

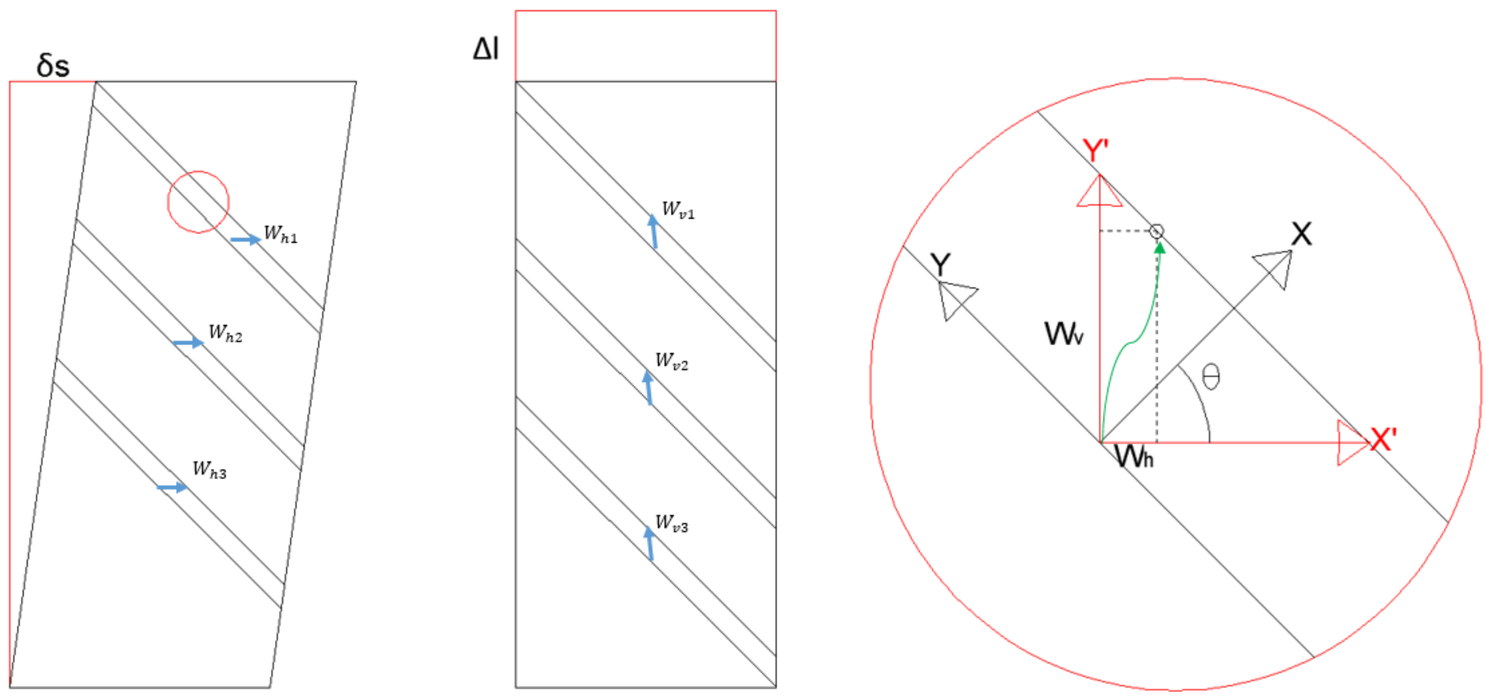
$$\text{Residual crack length ratio} = \frac{\Sigma(\text{Residual crack length})}{\sqrt{\text{Surface area}}} \times 100$$



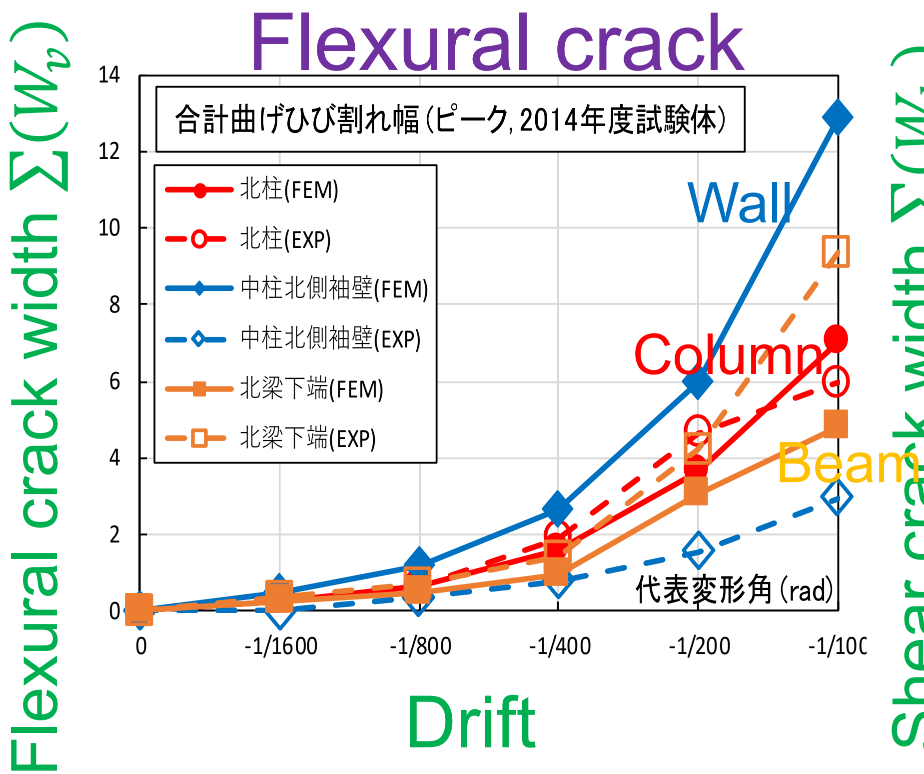


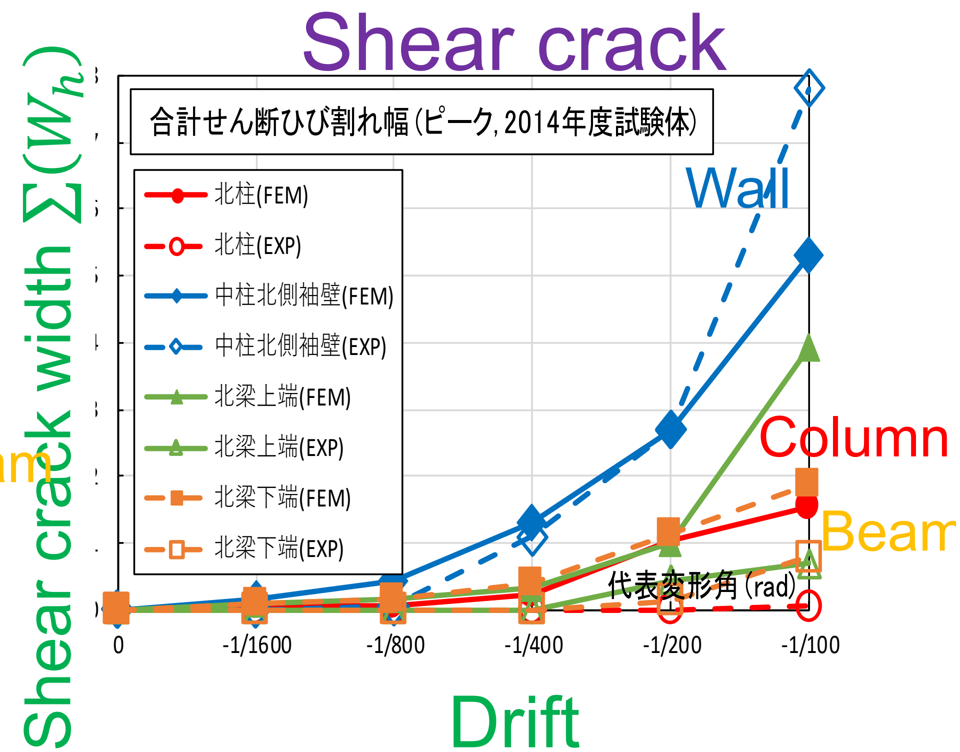


Coordinate conversion



Summary of Experiment and Simulation

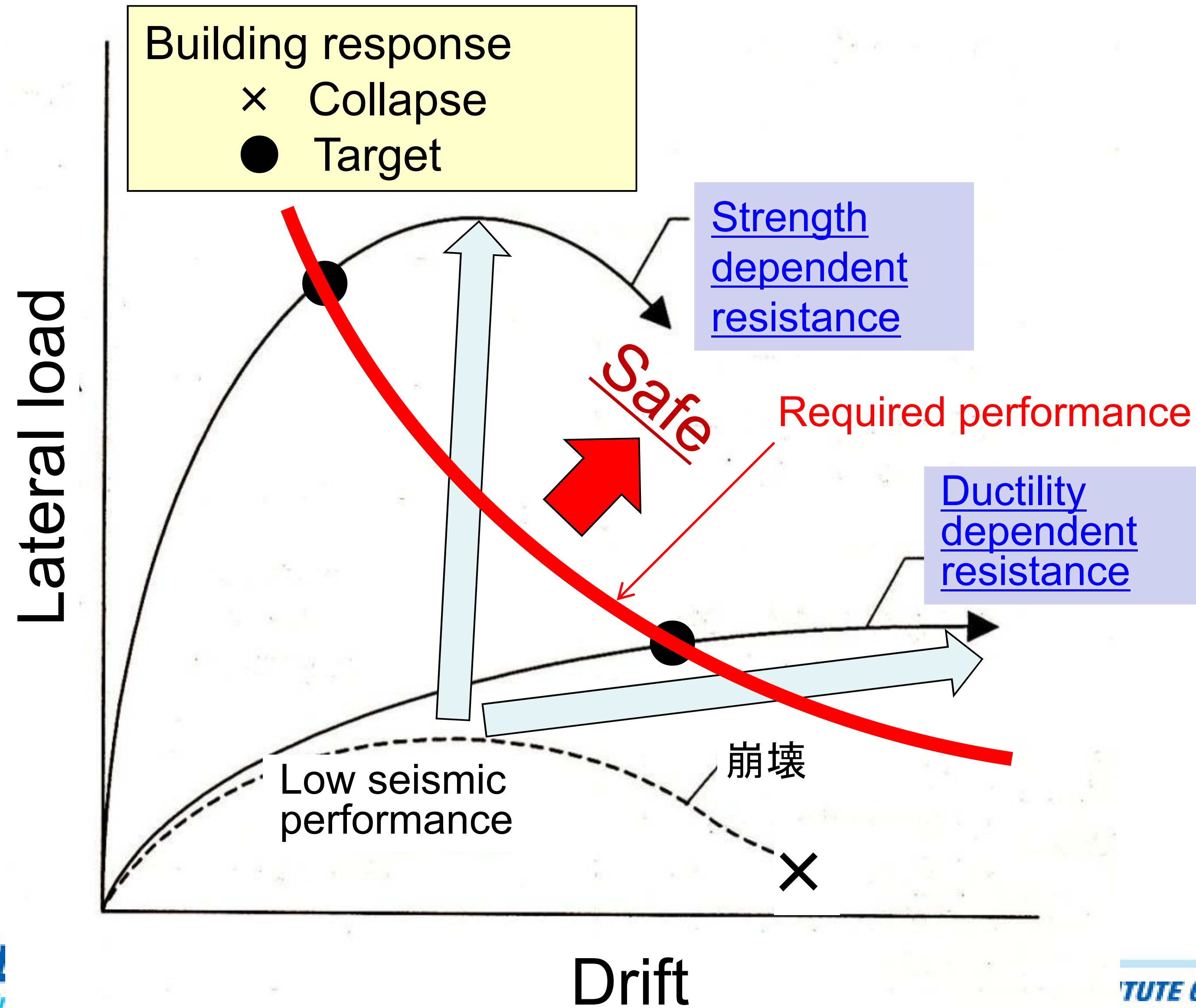




Summary of crack evaluation

- In order to assess damage states of reparability limit state, cracks were numerically simulated and compared to the test results for the five story RC building.
  - Crack width and spacing were well simulated for peak points but not so for unloaded points.
  - Crack length was simulated from FEM results by considering limit visible width.
  - Finally, *computed crack length ratio* agreed with experimental results.

Design concept for safety limit state
(1981 Design Standard)

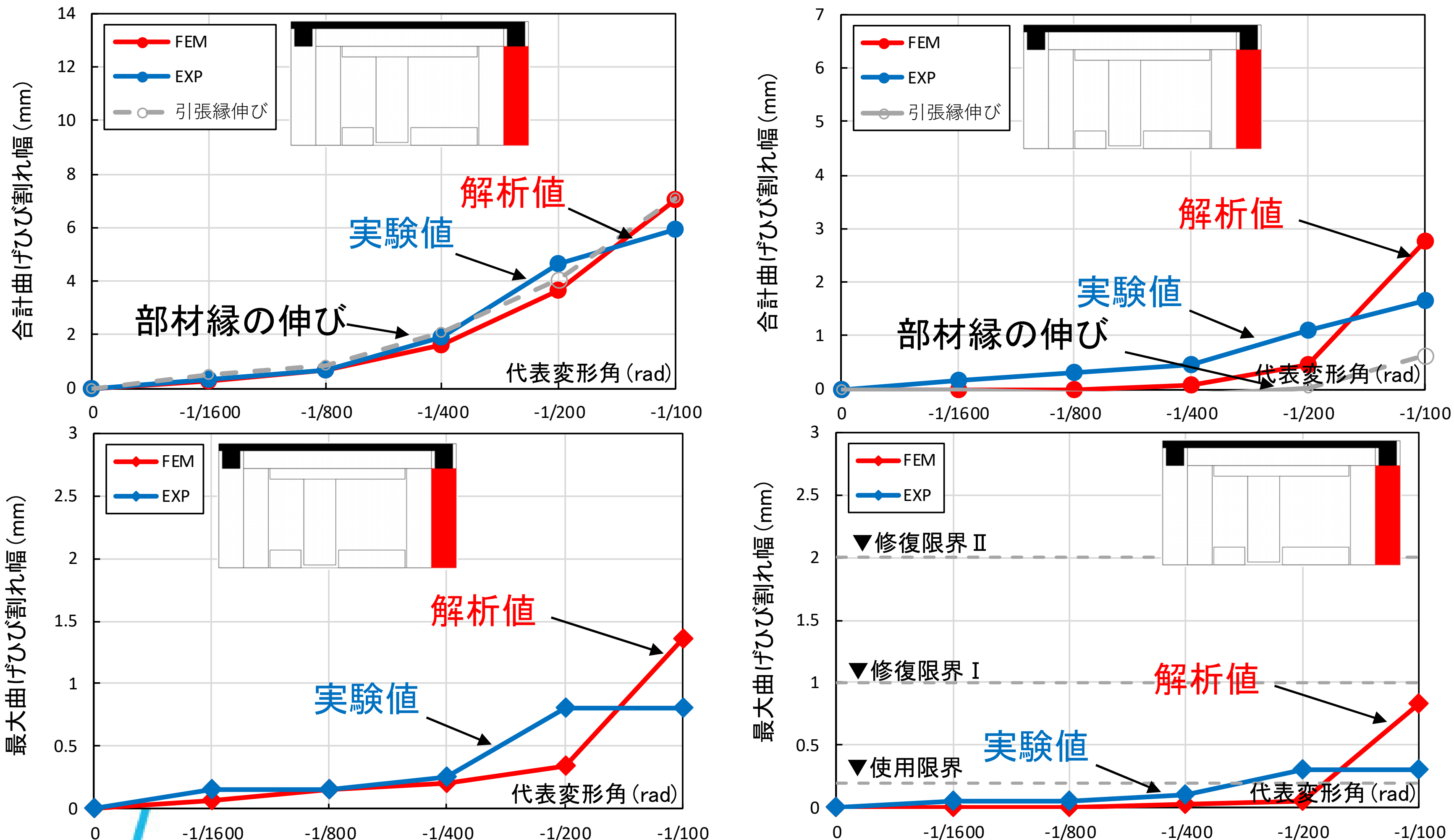


ひび割れ幅の比較

ピーク時曲げひび割れ幅　｜　残留曲げひび割れ幅

合計曲げひび割れ幅

最大曲げひび割れ幅



合計ひび割れ幅および最大ひび割れ幅の実験値と解析値の比較
（2014年度試験体北柱）

Shear Crack Width and Shear Drift Component in RC Beams with High Strength Transverse Rebars

Ricky Rinaldi, Advisor: Prof. Susumu Kono, Tokyo Institute of Technology

Introduction

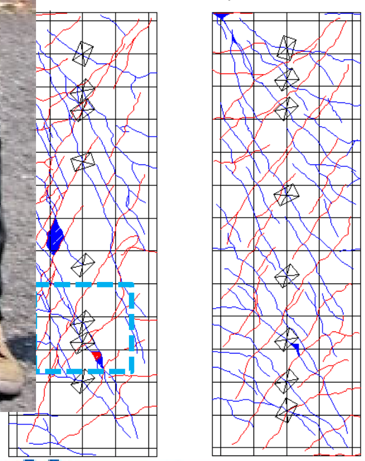
Cra r in
eva on
rei ures.
A s AIJ
Gu rack
wid hear
def ates
the eam
spe

Kumamoto Earthquake (BRI, 2016)

Cra were measured using crack
gau ere attached perpendicular to
the as shown on Fig. 2. Shear
cor measured using diagonal
dis wing equations were used to
cor mponent (W_{hi}) with shear drift
cor

$$\delta_s = \sum_{i=1}^{n} W_{hi}$$

Figure 1 Crack Gauges



(a) Specimen #1 (b) Specimen #2

Figure 2 Crack Pattern

Experimental Result

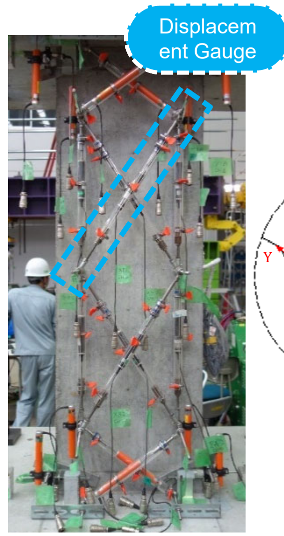


Figure 3 Displacement Gauges

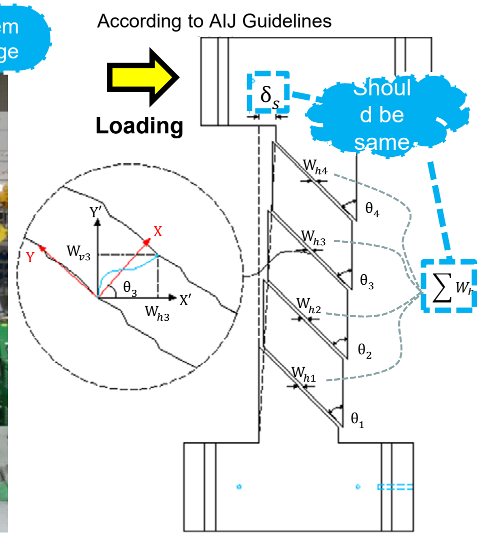


Figure 4 Relation between Crack Width and Shear Deformation

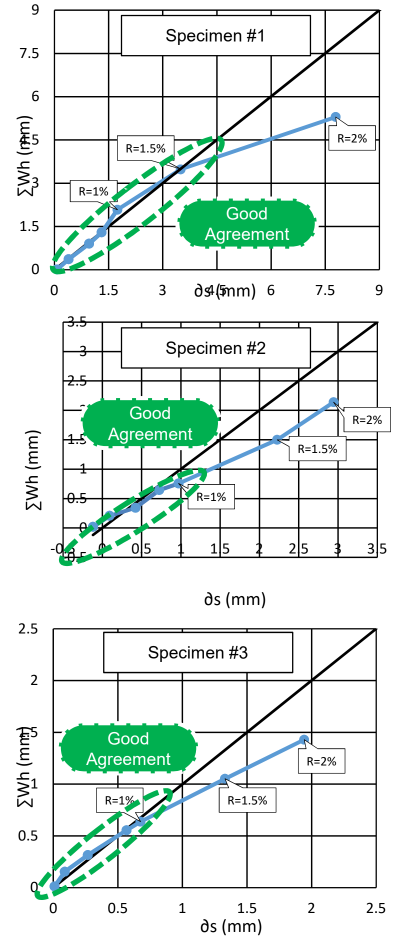


Figure 5 Horizontal Crack Comp. ($\sum W$ - Residual Shear Drift (δ_s)

Conclusion

The summation of horizontal component of cracks has good agreement with shear drift component. Compared to higher residual drift, the crack gauges picked up shear drift component better at lower residual drifts.

Contribution to Society

This study provides a better understanding of earthquake damage on RC structures, and contributes to the development of low damage structural system and resilient structures.

Pursuing Excellence

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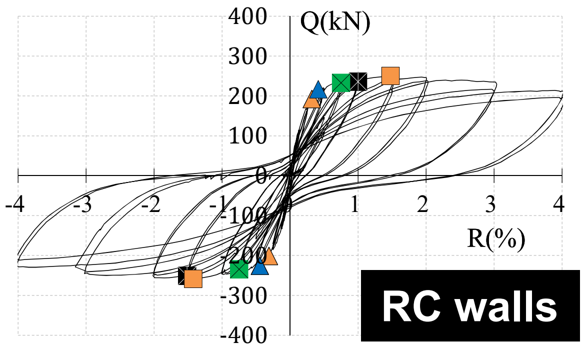
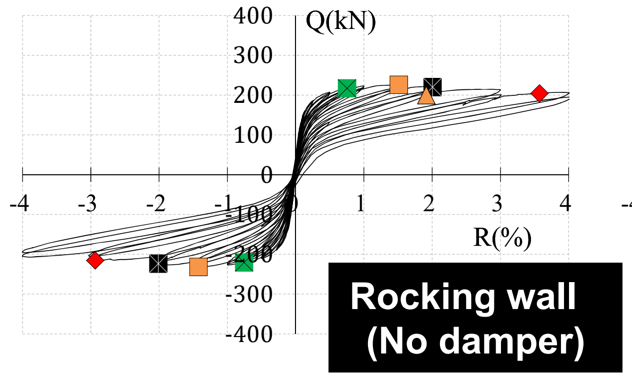
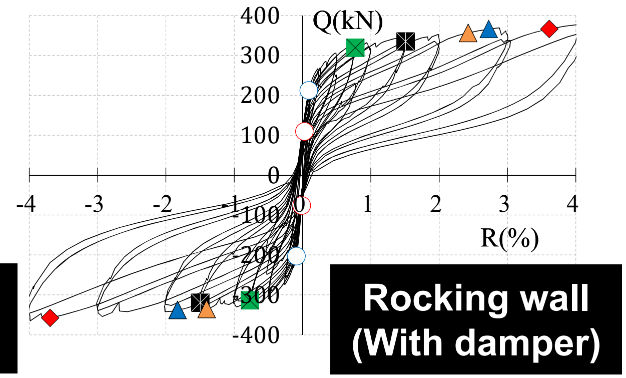
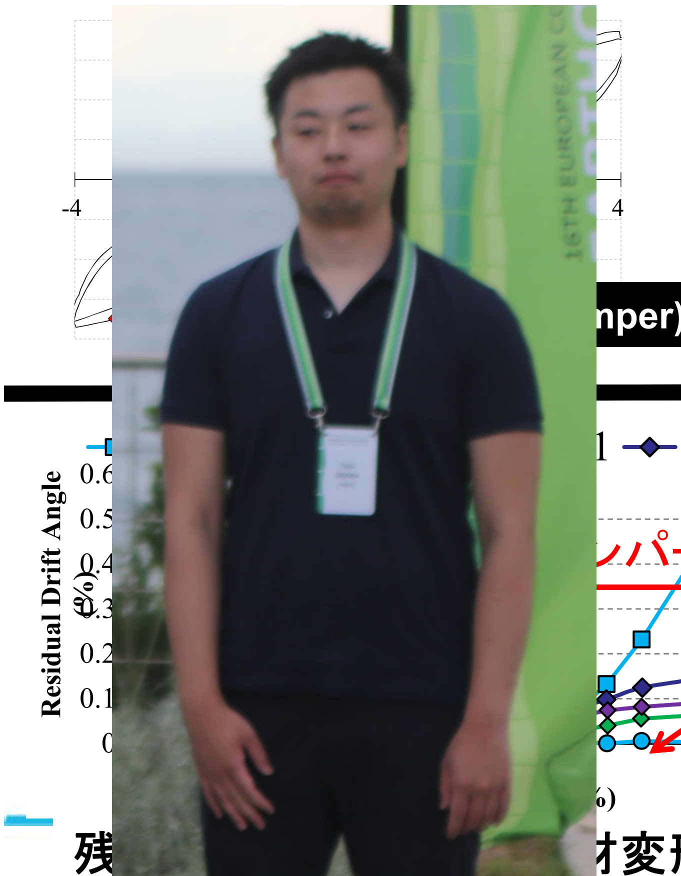
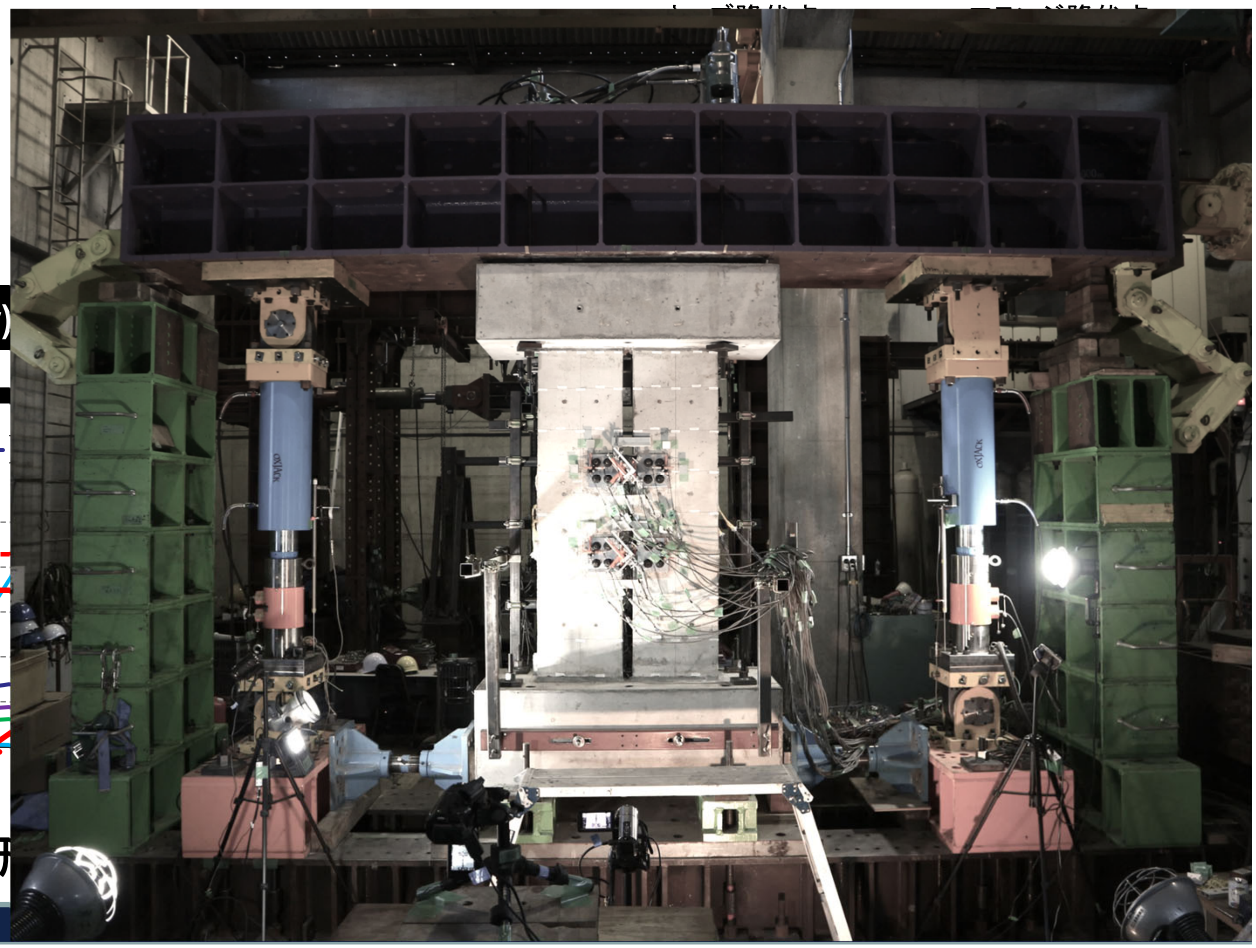
■Rocking system (Ductility with resiliency)











Kamo River, Kyoto

Damage to RC Structures at Kumamoto Earthquake, 2015

Kumamoto

Uto municipal office

Kumamoto

Kumamoto

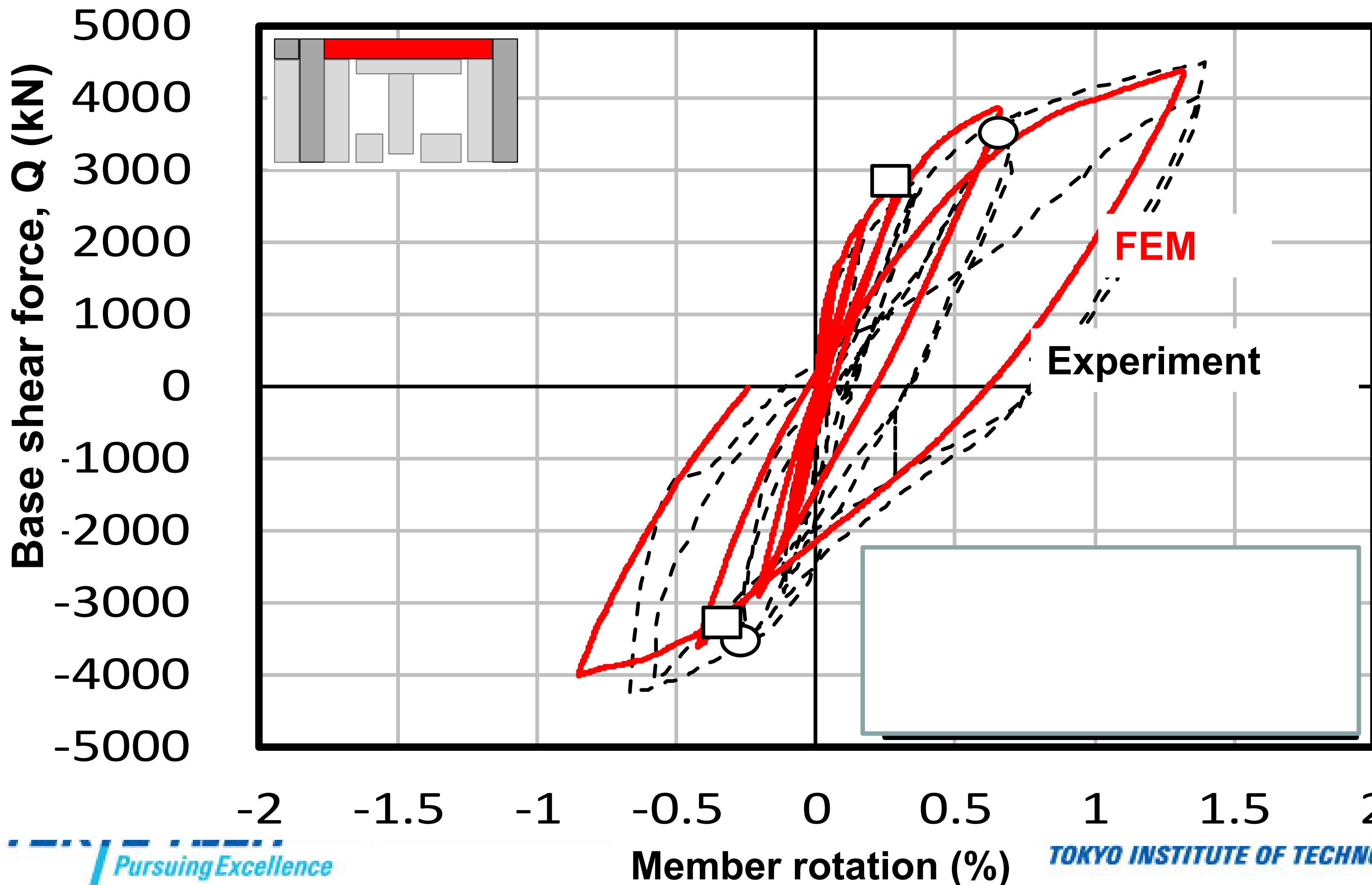
Kumamoto

New call from the society

- How to make a quick recovery after EQ’s with losing no/minor loss of building functions.

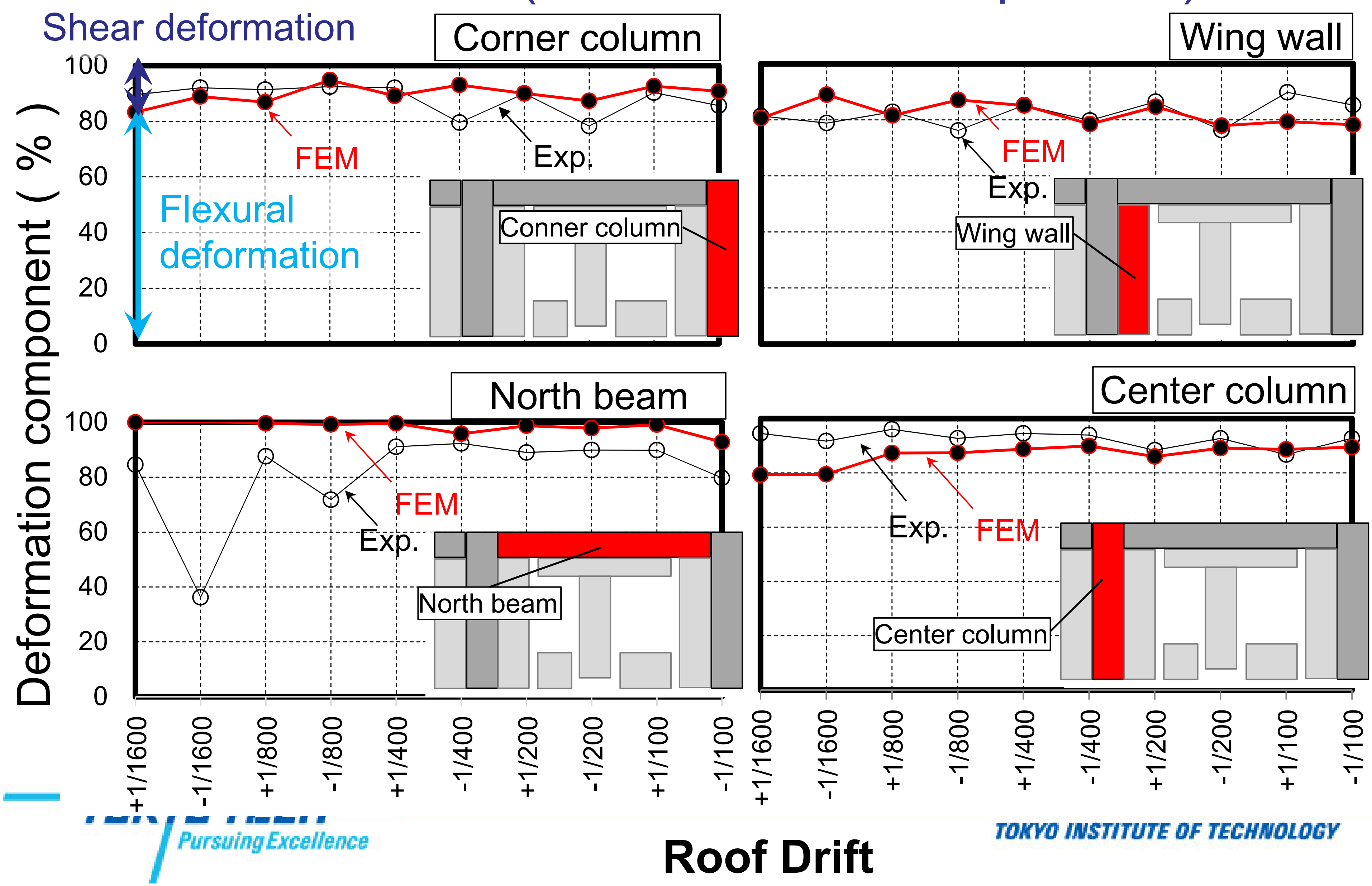
FEM Results

Member level (Q-θ relation)



FEM Results

Member level (deformation decomposition)



Flexural crack simulation

2. Width

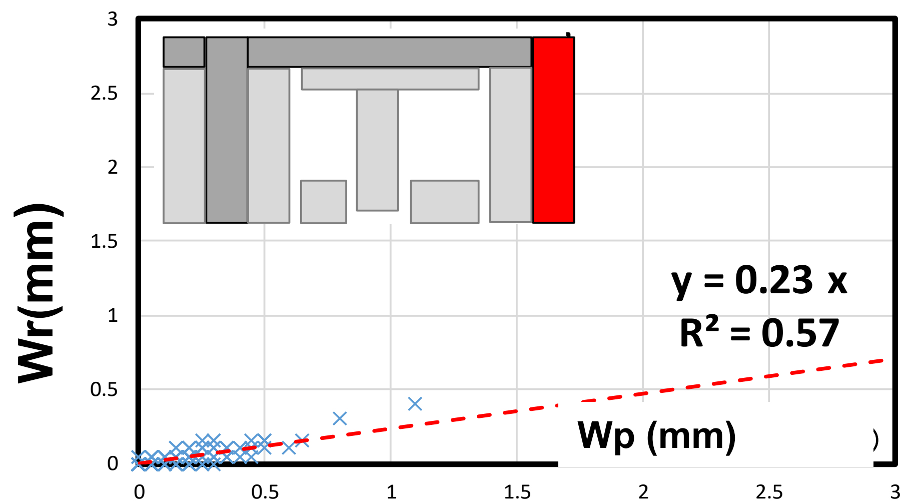
Relation between residual crack width (Wr) and peak crack width (Wp)

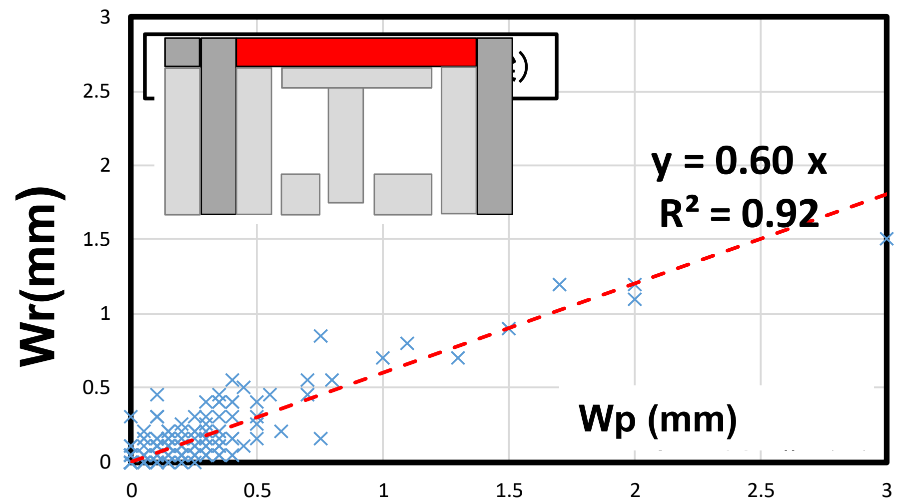
$$Wr=\alpha Wp$$

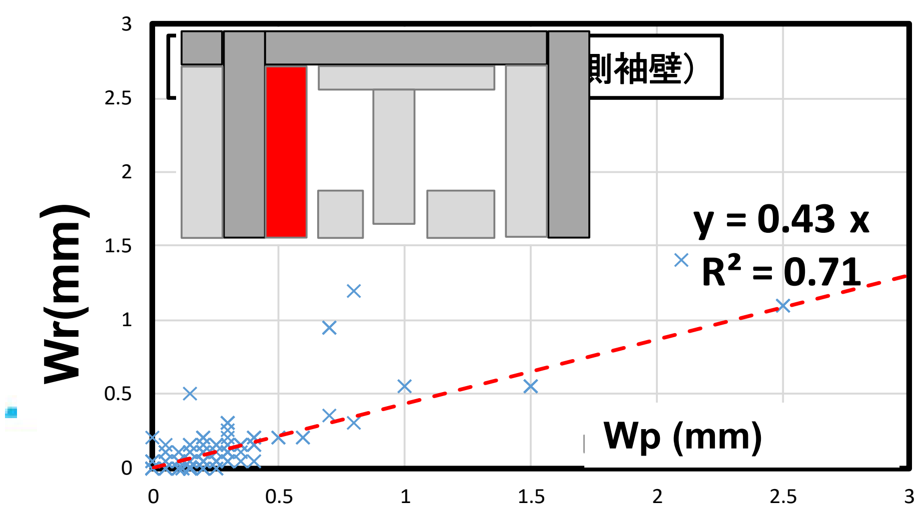
α=0.23(Column), 0.43(Wall,), 0.60(Beam)

Flexural crack simulation

2. Width

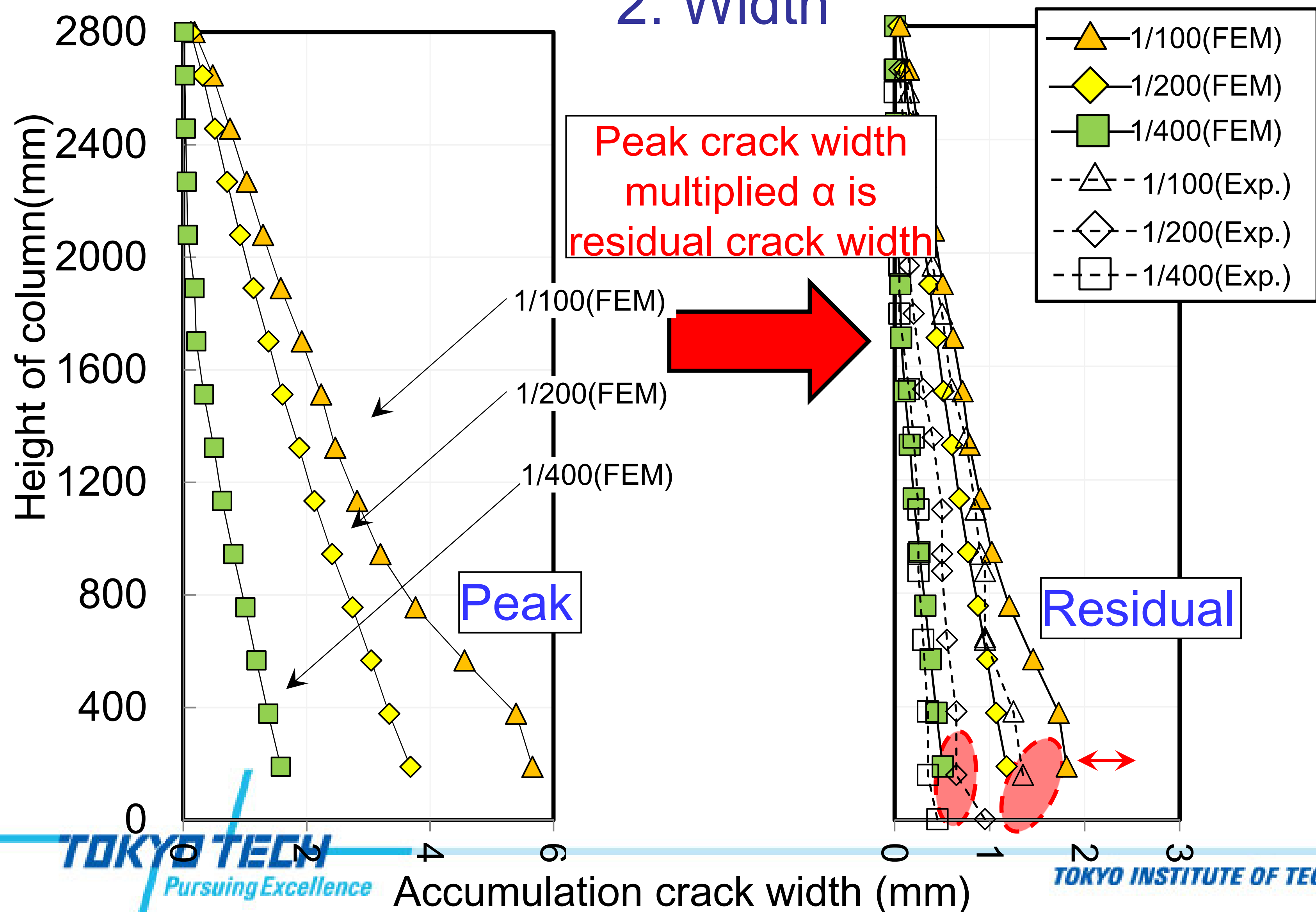






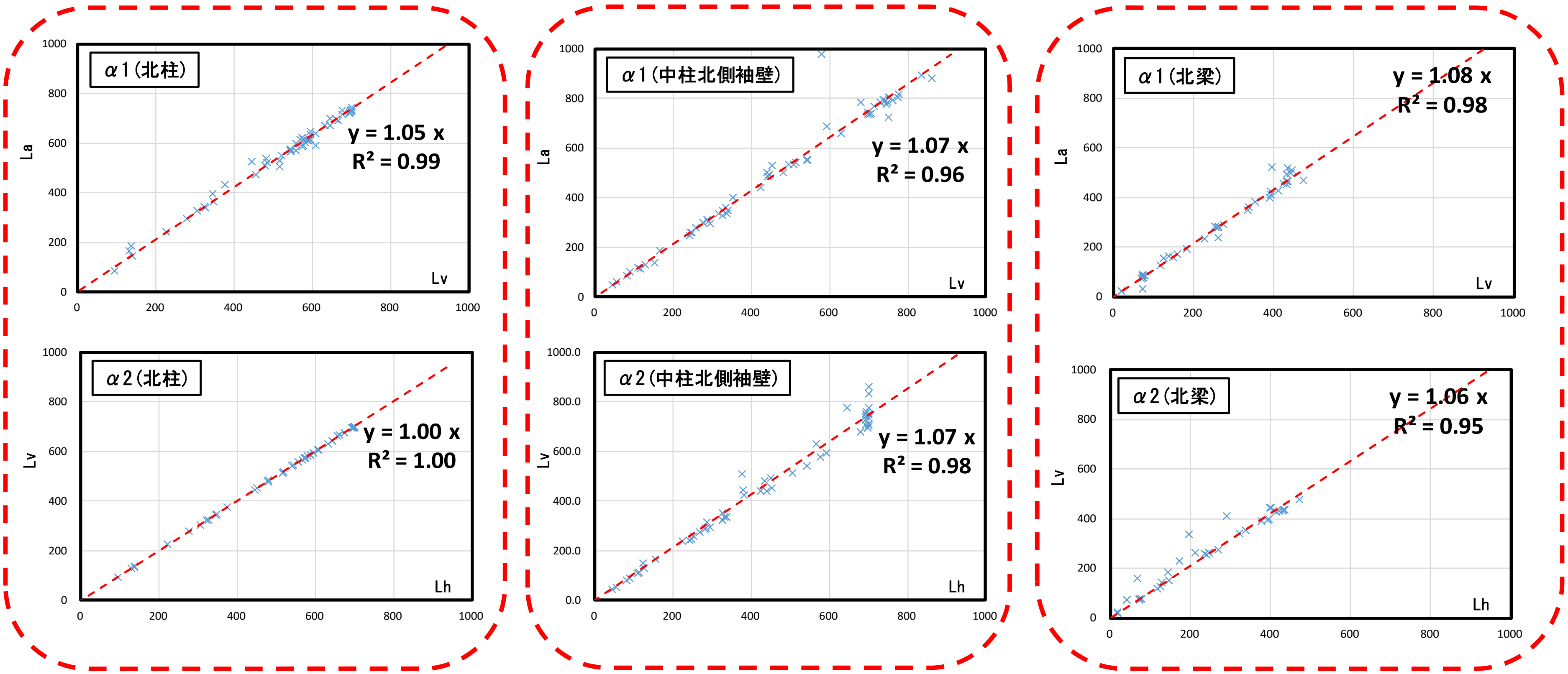
Flexural crack simulation

2. Width



Flexural crack simulation

3. Length



$$\boxed{Crack\ length = \ L_h \times \alpha_1 \times \alpha_2}$$