

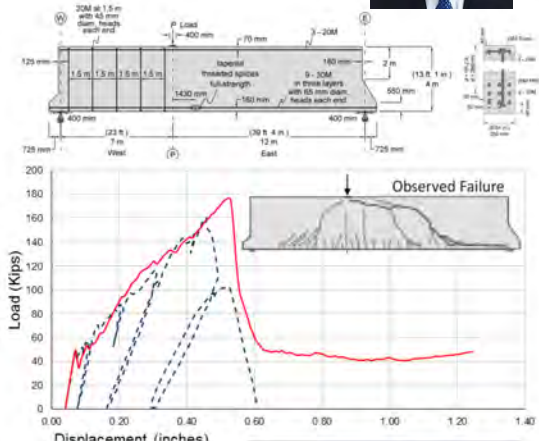
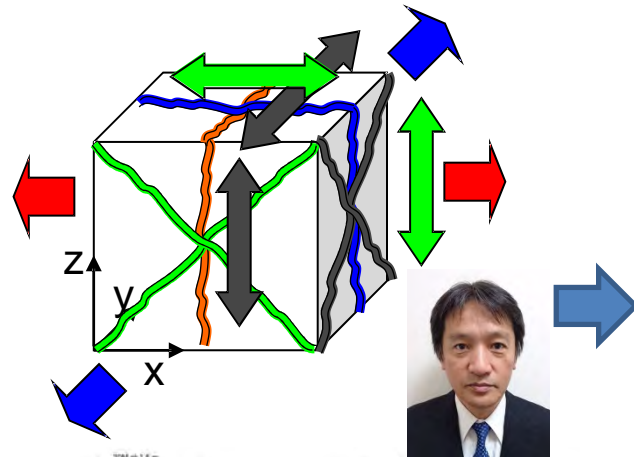
# 新設構造物の性能照査と既設構造物の 点検データ同化

新設構造の終局限界照査から、**中長期の使用限界照査や評価(環境/荷重)へ、適用範囲が拡大**

既設構造の点検データと非線形解析を混成→**利点と弱点を相互補完して維持管理へ貢献**

高次非線形解析の**今後**: 新設・既設を問わず

# ひび割れ(crack)=RC構造非線形性の主因



	Compression	Tension	Shear transfer
Core Constitutive Laws	<p>Stress - Strain</p> $\sigma = E_0 K_C \varepsilon_e$ $\varepsilon = \varepsilon_e + \varepsilon_p$ <p>Maekawa et al. 2003<sup>6</sup></p>	<p>Stress - Strain</p> $\sigma = E_0 K_T \varepsilon_e$ $\varepsilon = \varepsilon_e + \varepsilon_p$ <p>Maekawa et al. 2003<sup>6</sup></p>	<p>Shear stress - Slip or Strain</p> $\tau = \int_{-\pi/2}^{\pi/2} R'_i(\alpha, \delta, \theta) \sin \alpha d\theta$ <p>Maekawa et al. 2003<sup>6</sup></p>
Enhanced model for High cycle Fatigue	<p>Fracture parameter <math>K_C</math> considers time dependent plasticity &amp; fracturing and cyclic fatigue damage</p> $dK_C = \left( \frac{\partial K_C}{\partial t} \right) dt + \left( \frac{\partial K_C}{\partial \varepsilon_p} \right) d\varepsilon_p$ <p>Time dependency    Cyclic fatigue</p> $\left( \frac{\partial K_C}{\partial \varepsilon_p} \right) = \lambda - \text{when } F_x = 0$ $\left( \frac{\partial K_C}{\partial \varepsilon_p} \right) = - \left( \frac{\partial F_x}{\partial \varepsilon_p} \right) \left( \frac{\partial F_x}{\partial K} \right) + \lambda - \text{when } F_x = 0$ $\lambda = K^{-1} \cdot (1 - K^4) \cdot g \cdot R$ <p>El-Kashif and Maekawa 2004<sup>10</sup></p>	<p>Fracture parameter <math>K_T</math> considers time dependent fracturing and cyclic fatigue damage</p> $dK_T = F dt + G d\varepsilon_e + H d\varepsilon_c$ <p>Time dependent fracturing    Cyclic fatigue damage</p> <p>Maekawa et al. 2003<sup>6</sup>, Hisasue 2005<sup>14</sup></p>	<p>Accumulated path function <math>X</math> reduce shear associated with cyclic fatigue damage</p> $\tau = X \cdot \tau_0(\delta, \omega)$ <p>function    original model</p> $X = 1 - \frac{1}{10} \log_{10} \left\{ 1 + \int  d(\delta/\omega)  \right\} \geq 0.1$ <p>Contact density model by Li &amp; Maekawa 1989<sup>15</sup>, Modification of accumulated path function by Gebreyouhannes 2006<sup>16</sup></p>
Physical meaning	Decrease of stiffness and plasticity accumulation by continuous fracturing concrete	Decrease of tension stiffness by bond fatigue	Decrease of shear transfer normal to crack by continuous deterioration of rough crack surface

Maekawa, K. and **Fukuura, N.** (2014): Nonlinear Modeling of 3D Structural Reinforced Concrete and Seismic Performance (Chapter 11), Infrastructure Systems for Nuclear Energy, John Wiley & Sons

Univ. of Toronto (2015 Collins): size-effect of shear mode failure

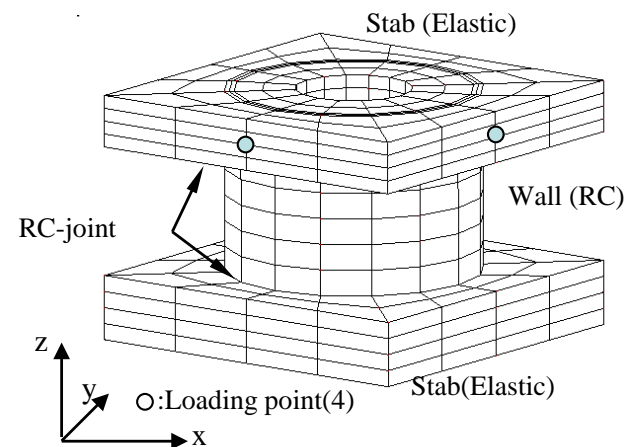
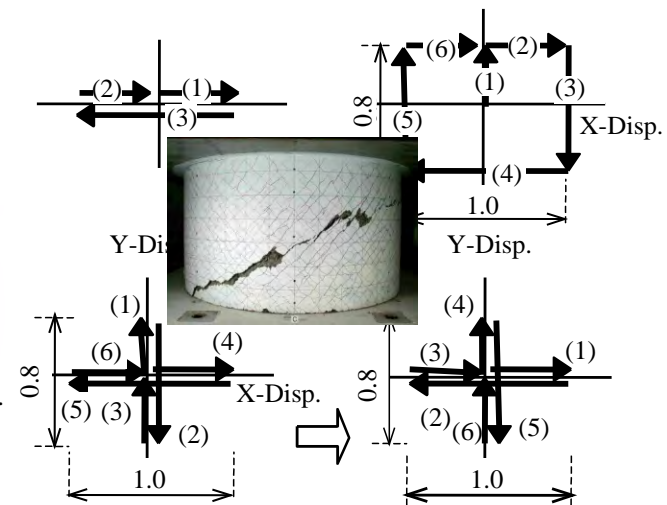
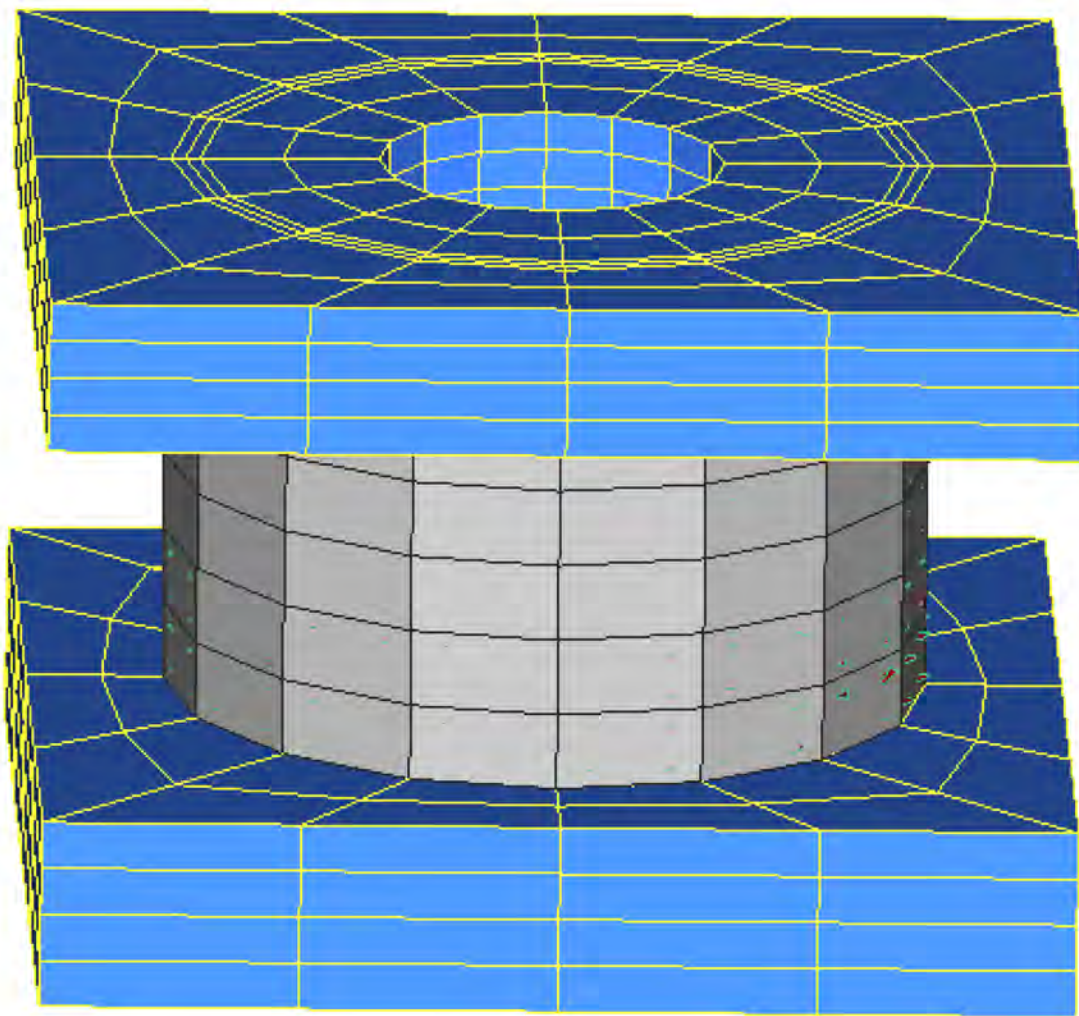
地盤内を走る断層もRCせん断ひび割れも、同種の現象



# 荷重作用の多様性に対応：非直交多方向ひび割れ

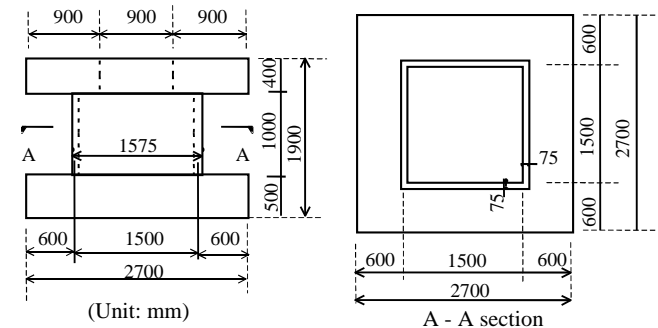
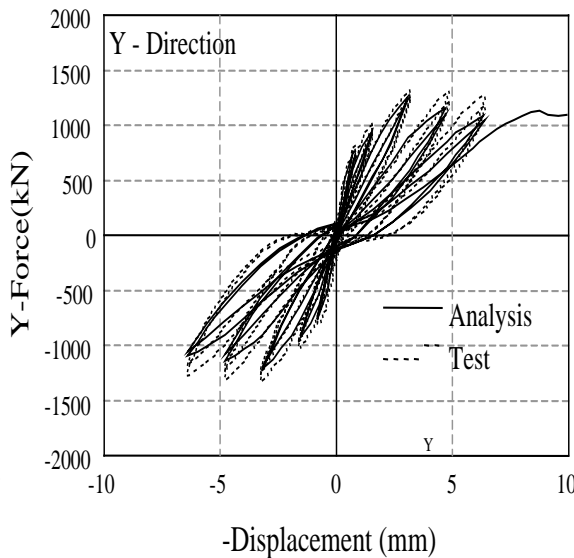
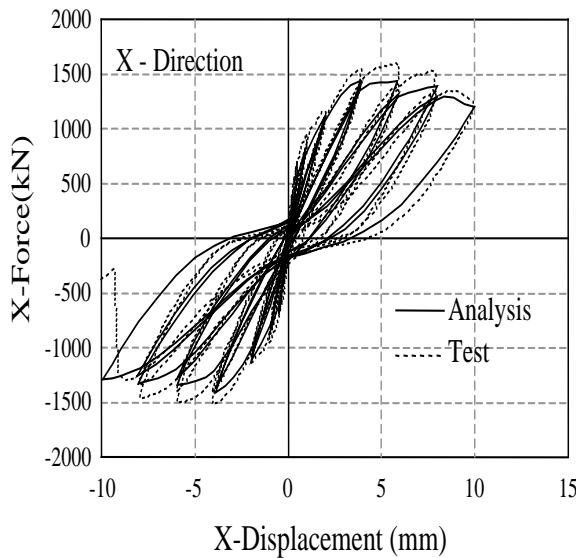
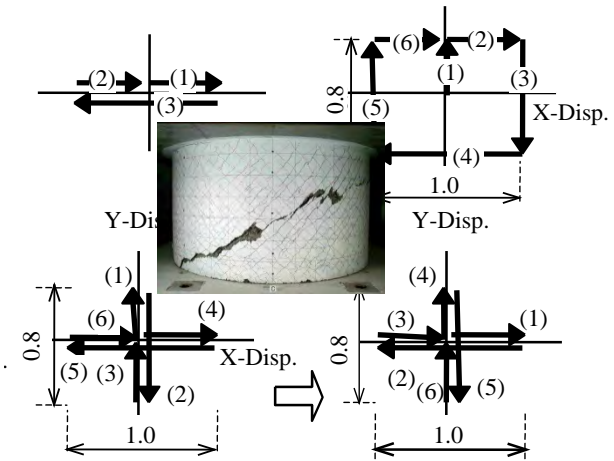
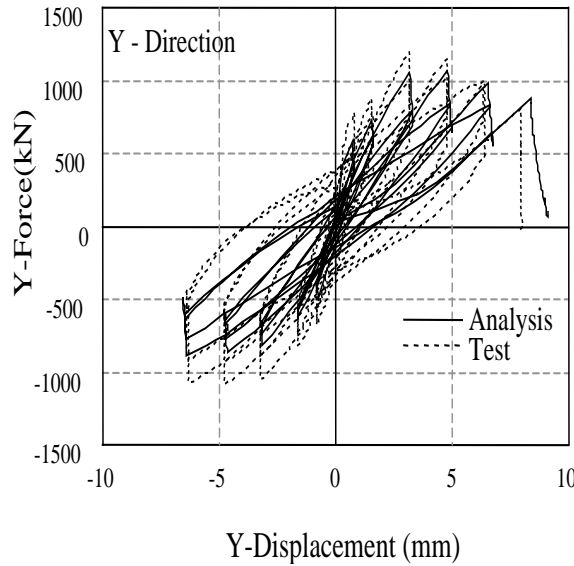
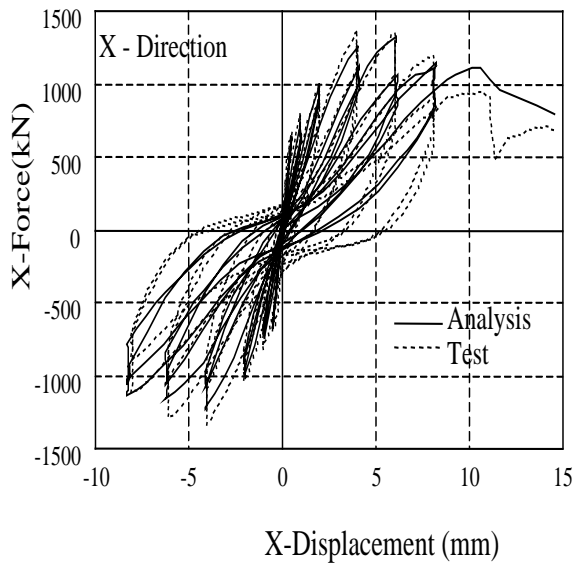
ひび割れを含む有限体積の平均応力ひずみ関係が出发点  
 多くのモデル→淘汰→次世代の要求に会うもの(あるがままに)

by Dr. Fukuura,  
 COMSE Eng.



NUPEC, Kajima, Taisei

有限体積内で、ひび割れは多方向に交差

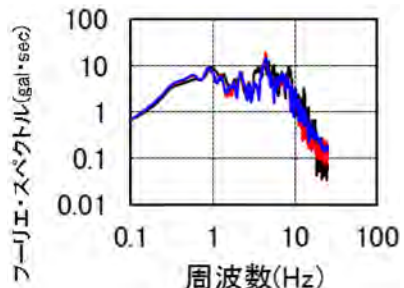
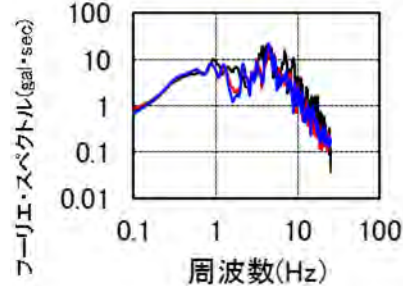
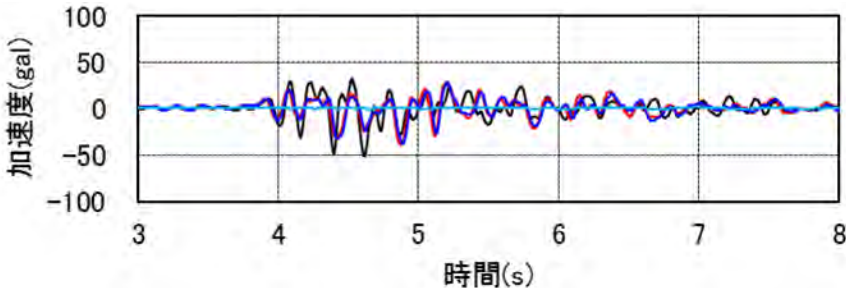
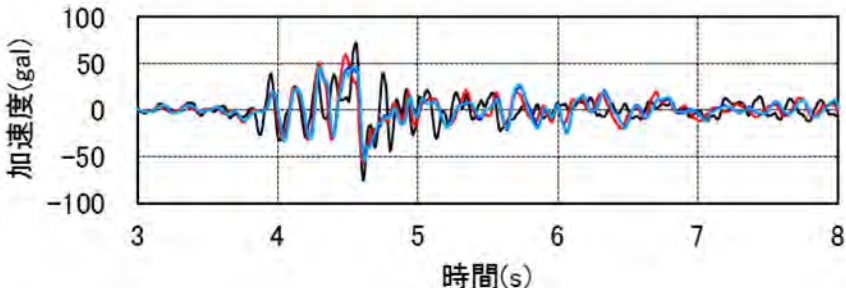
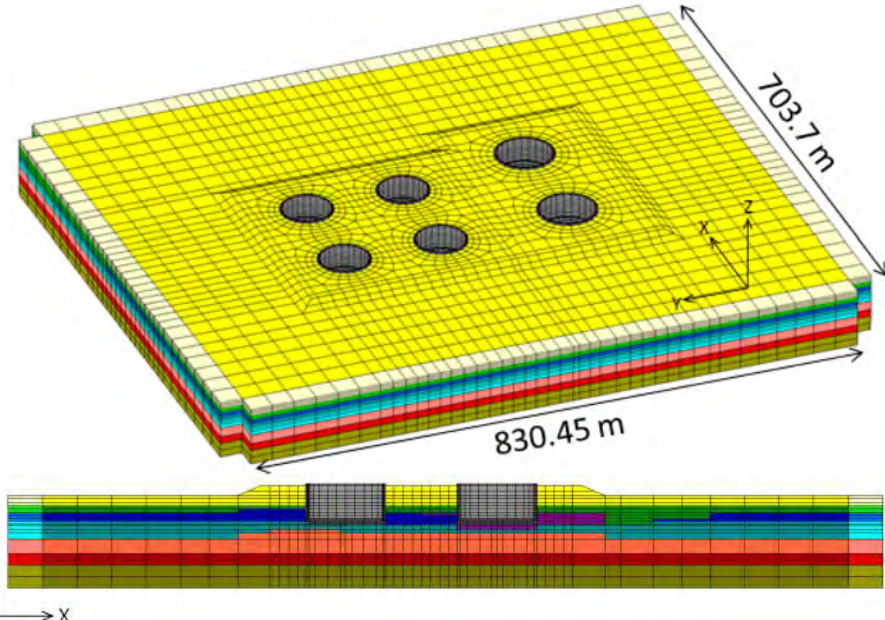
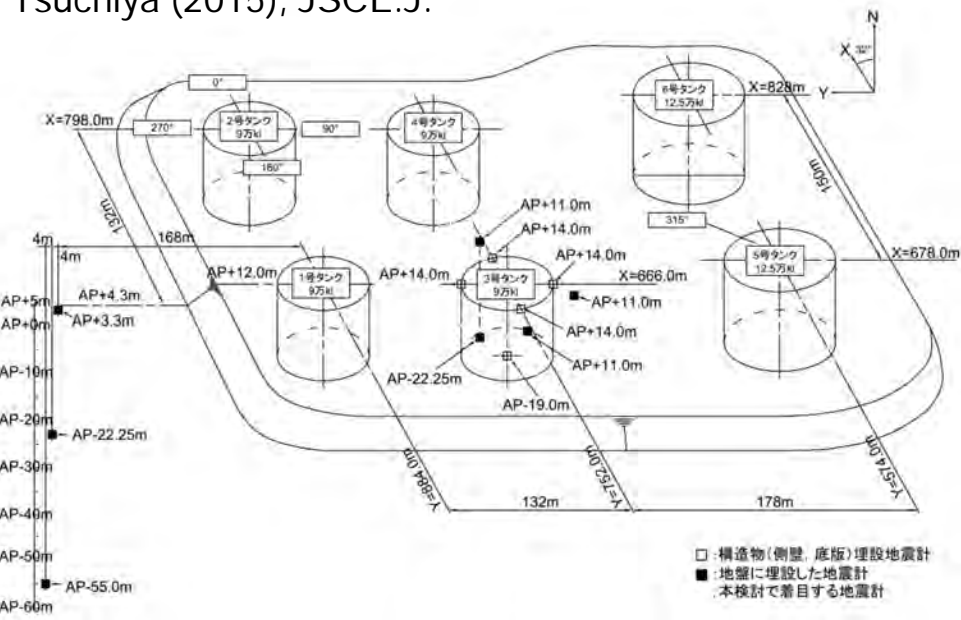


Chijiwa, Harada, Maekawa, Tsuchiya (2015), JSCE.J.

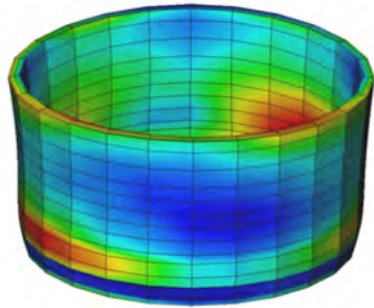
**RC構造と地盤から構成されるプラントが、構造設計の対象に**



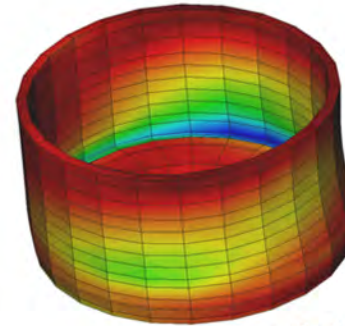
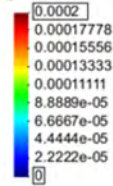
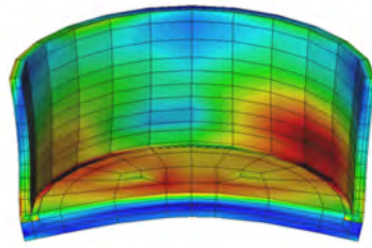
Chijiwa, Harada, Maekawa,  
Tsuchiya (2015), JSCE.J.



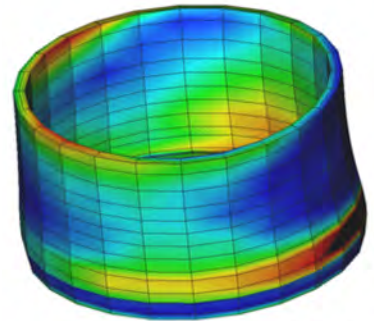
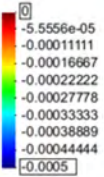
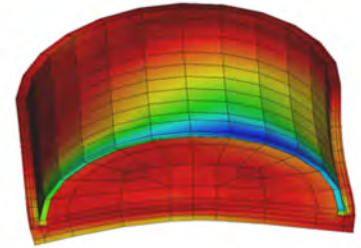
# 単一構造と無限地盤で設計：照査では一体として



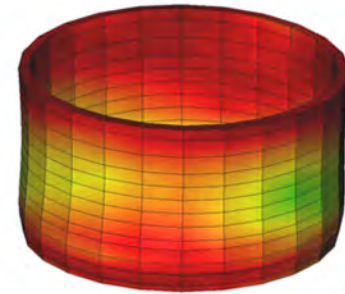
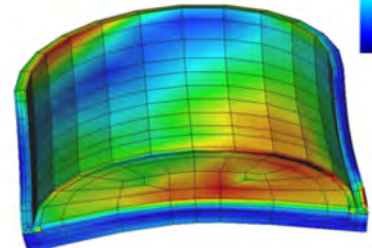
-Y方向から見た描画



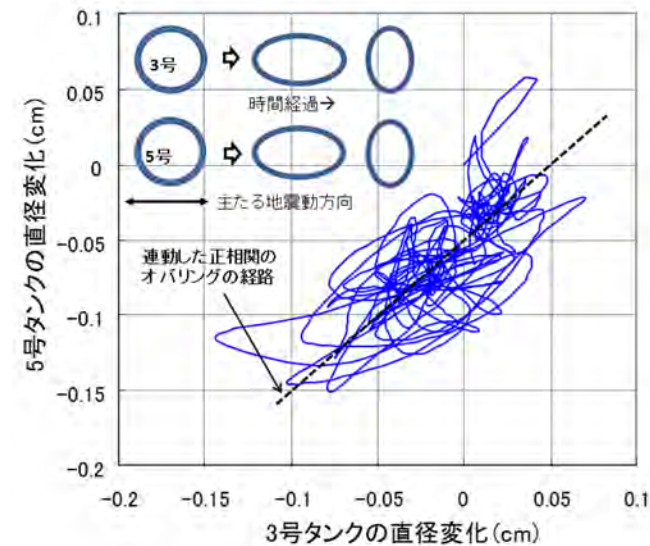
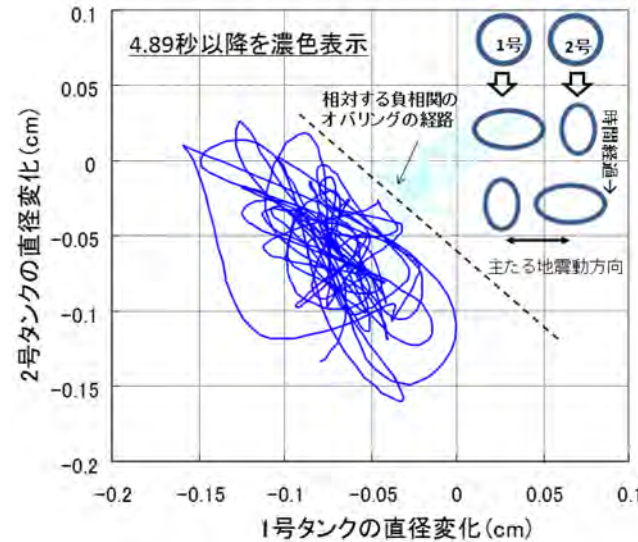
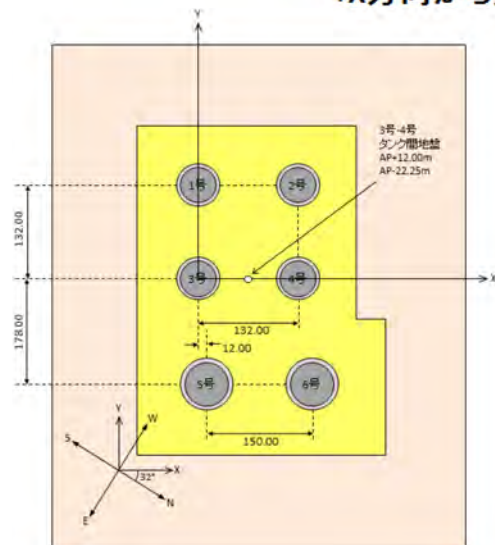
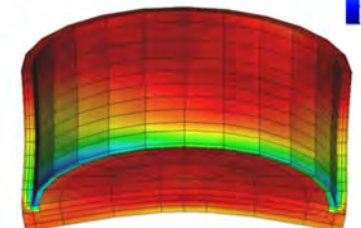
-Y方向から見た描画

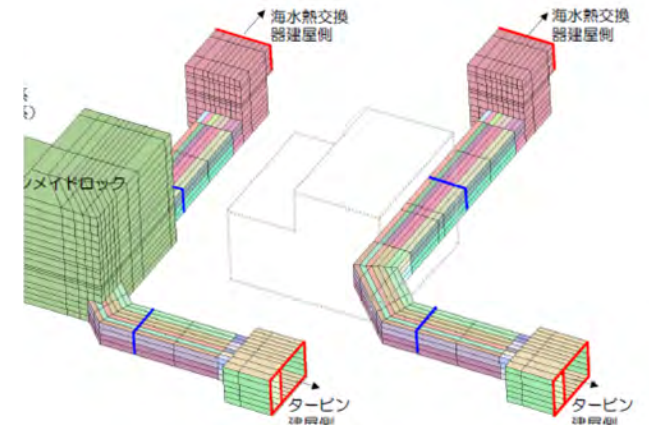
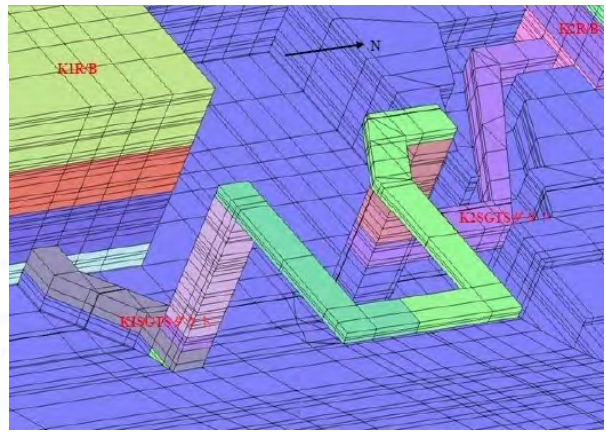
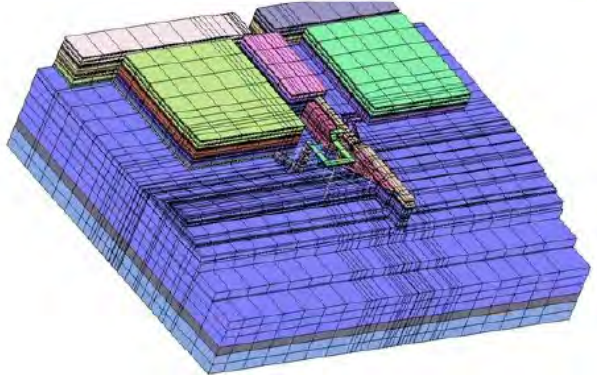
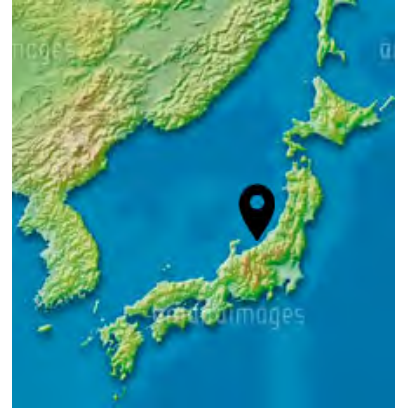
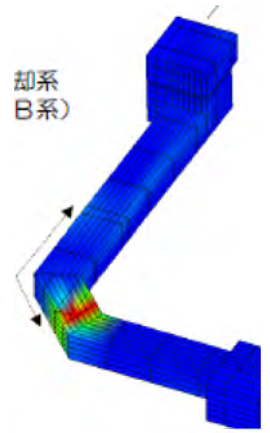
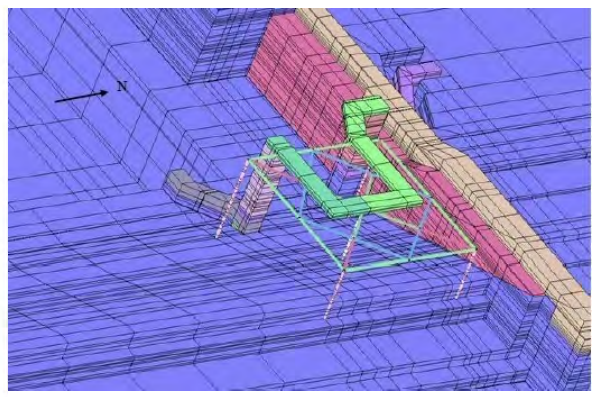
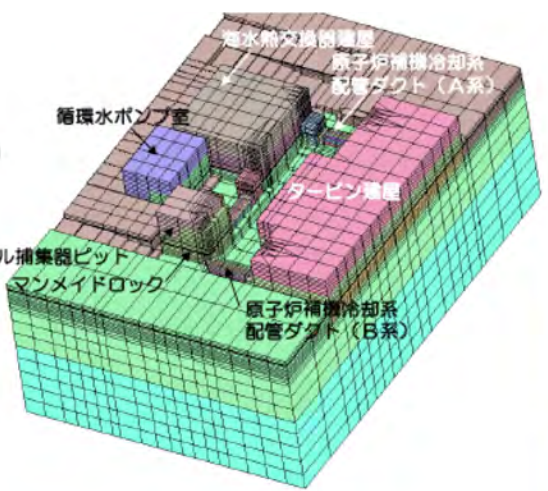


+X方向から見た描画



+X方向から見た描画



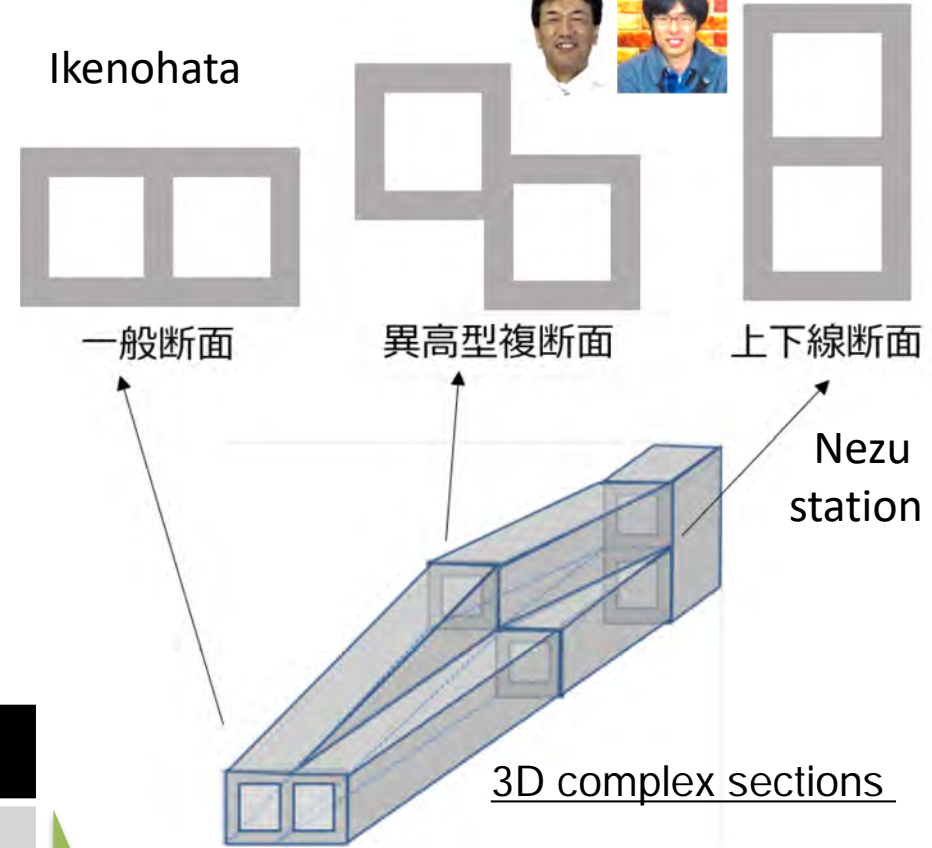




Nishigaki, Konishi, Tsuchiya, Maekawa  
2016, JSCE



Subway tunnels of Tokyo Metro: safe or not?  
👉 How to examine the performance?



methods	Assessment
Displacement Response method by code	To be Strengthened for wider ranges ⇒ huge money!
2D FEM	To be strengthened but ⇒ Zones of strengthening are shortened!
3D FEM	



3D full dynamic analysis and design makes benefits.

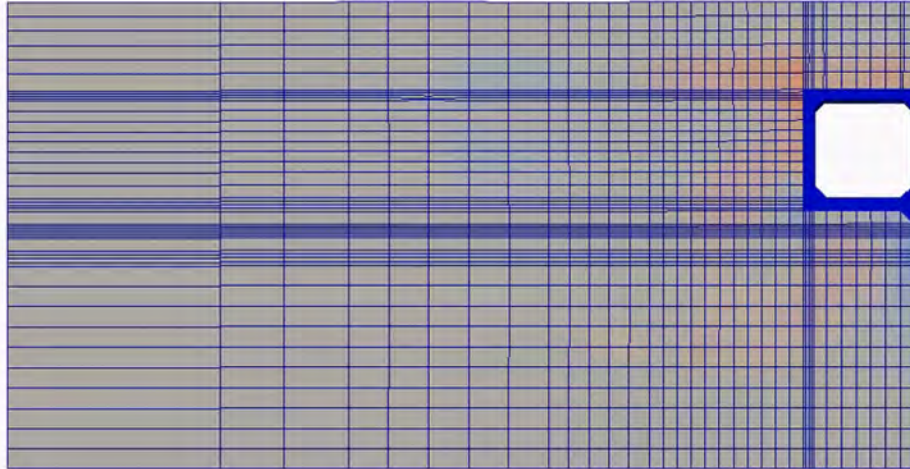
👉 verification by mock-up experiments

Magnified disp.:10 times

Shear strain

principal strain

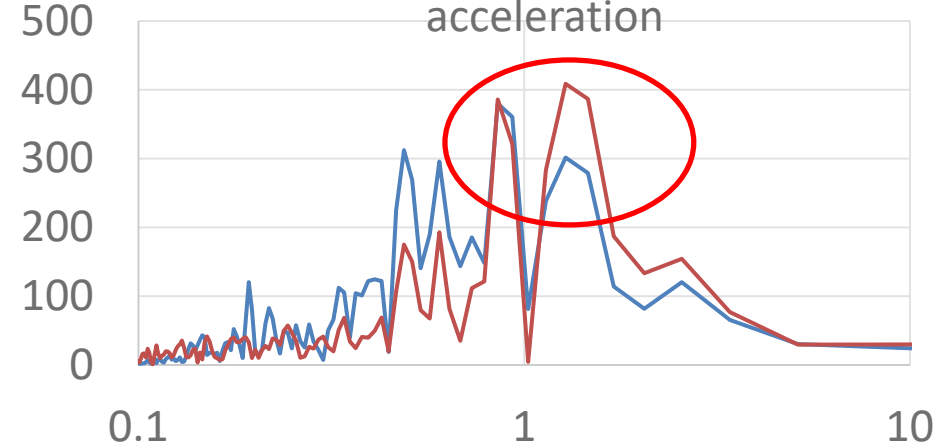
N=37



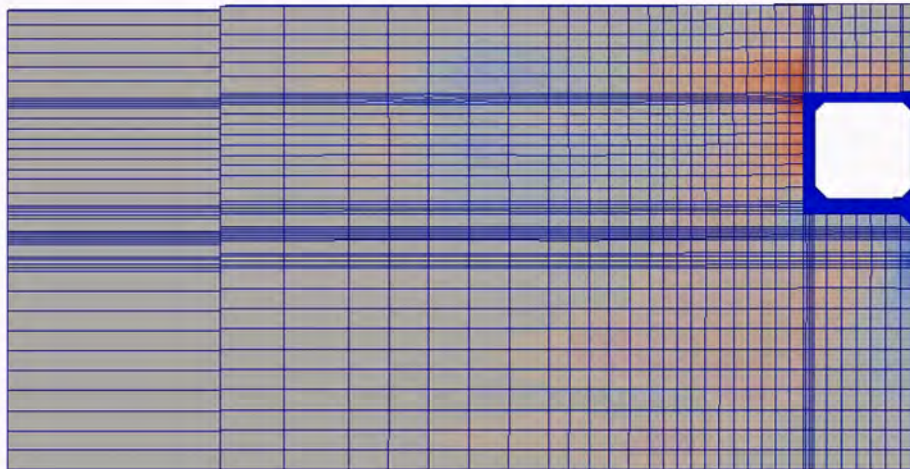
-3.000e

N=37

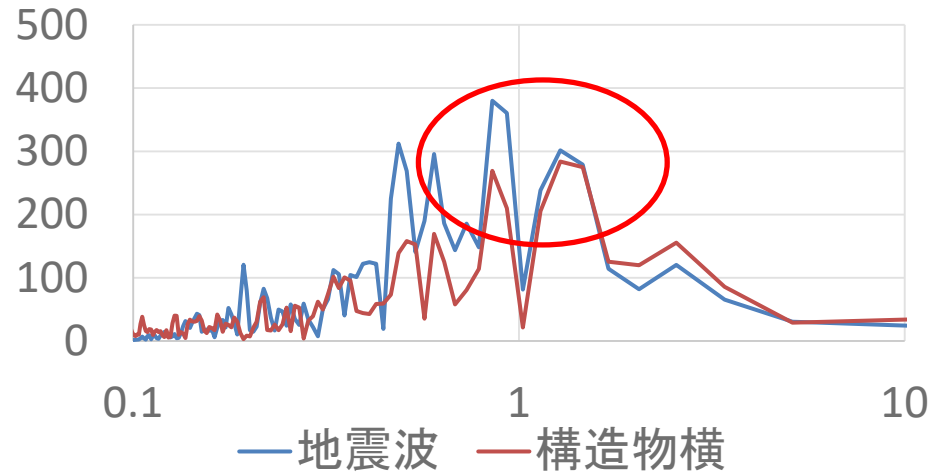
Fourier Spectrum of response acceleration



N=10



N=10

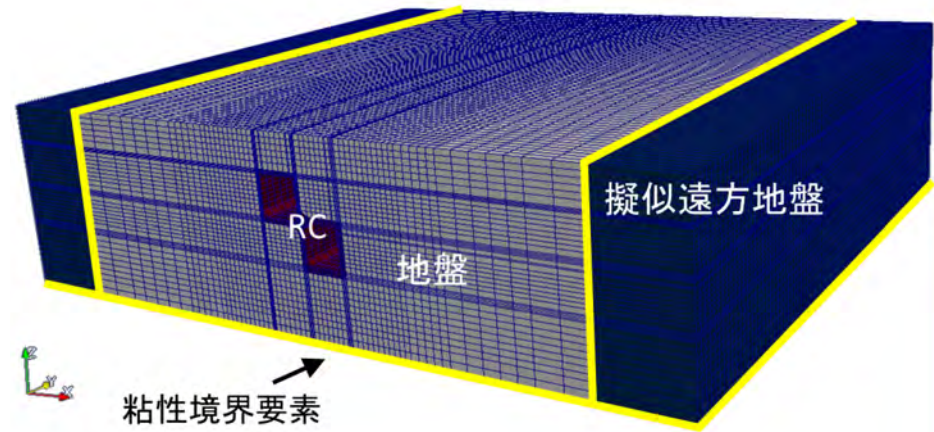
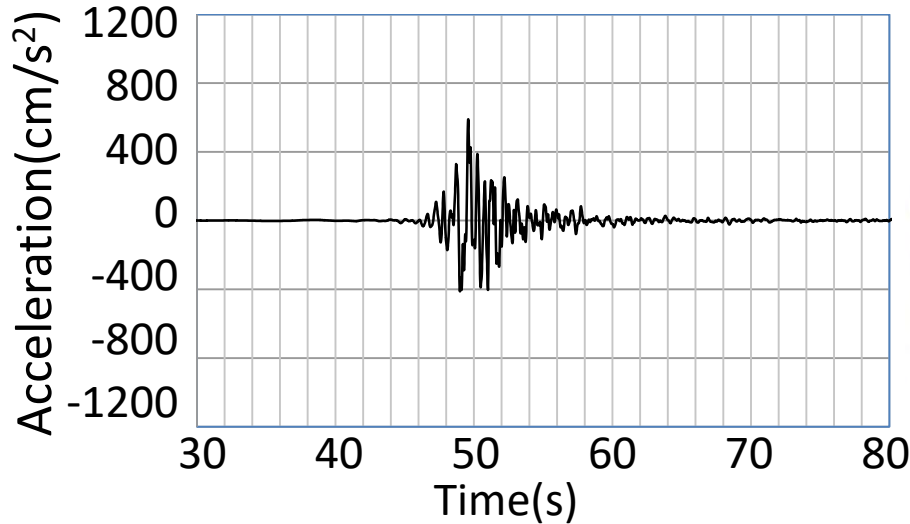


Large N-value → large soil deformation induced → much damaged RC duct

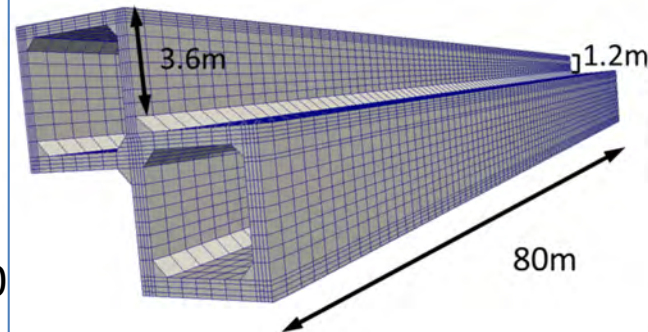
Quasi-viscos far-field boundary  
 Soil characteristics: site inspection  
 Tokyo Metro: Near-field earthquake  
 estimated around Tokyo



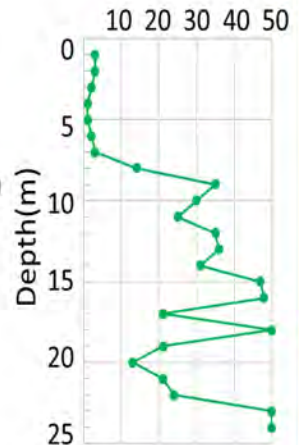
▪ input acceleration at the base-rock



▪ FE mesh of tunnels

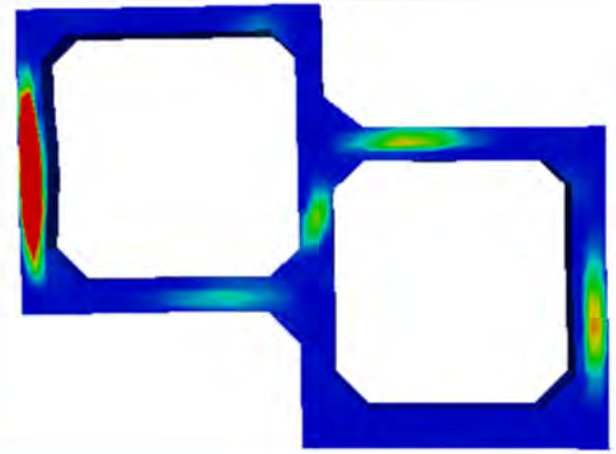
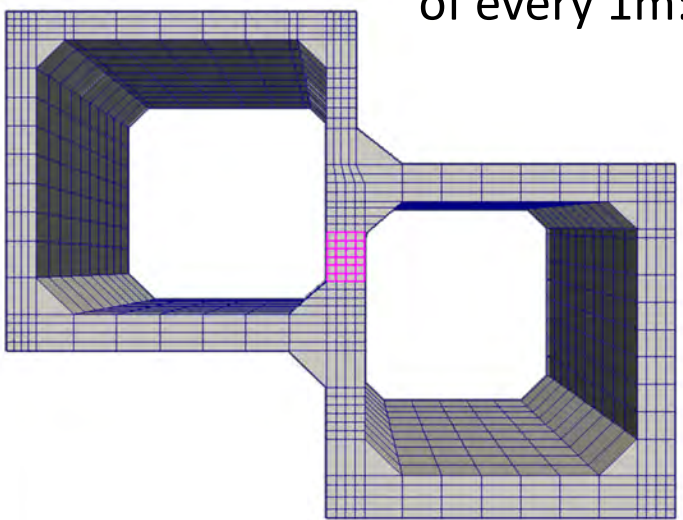


▪ N-value

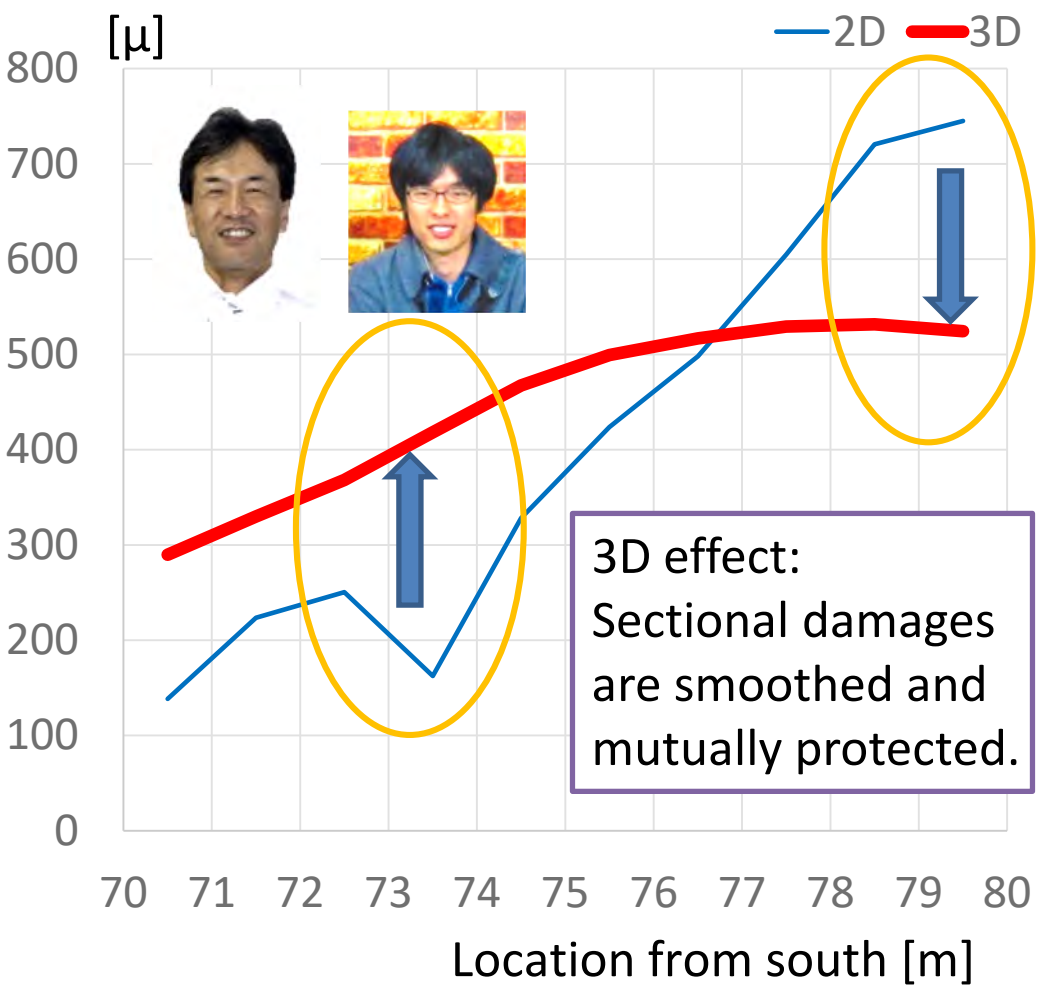


## comparison

2D section  
of every 1m:



## Volume averaged principal strain



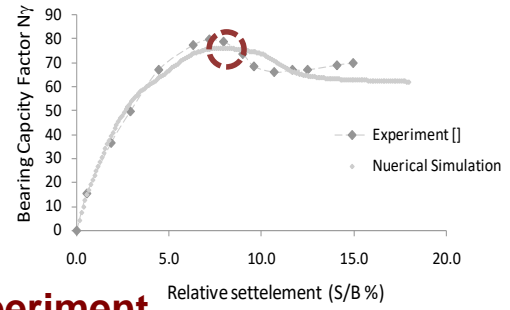
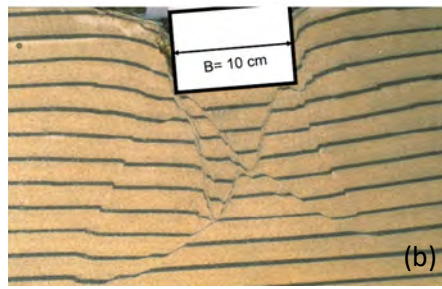
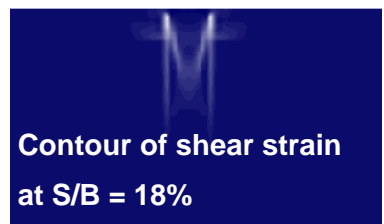
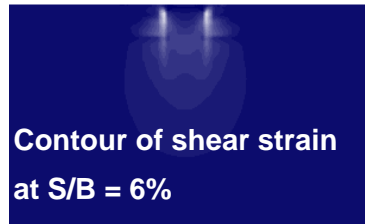
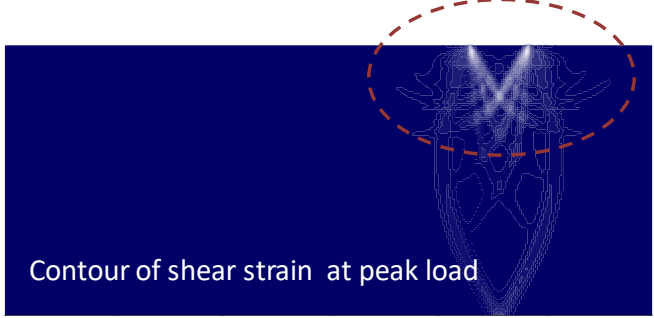
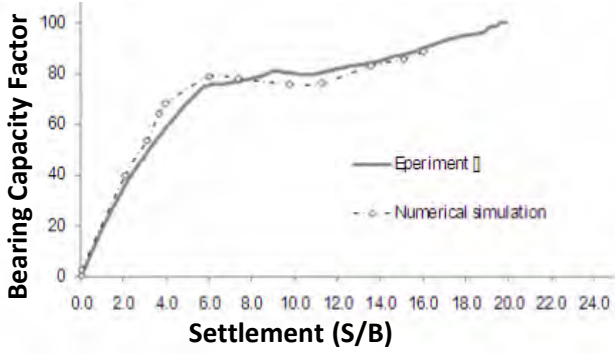
Sectional Damages are moderated due to interaction of adjacent sections.  
It means that the local strengthening may reach the wider ranges.

**地盤特性と構造諸元の3次元構造から、損傷が相互に抑えられる**

地盤内を走る断層は、せん断変形の局所化として計算される

Soltani, Maekawa 2014

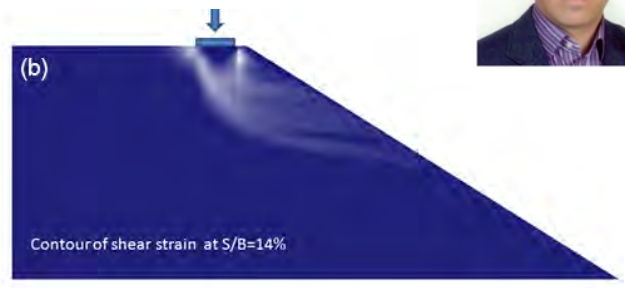
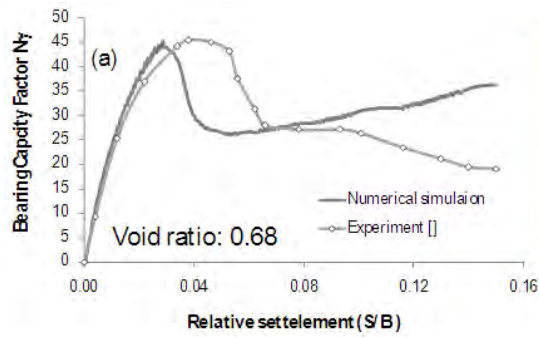
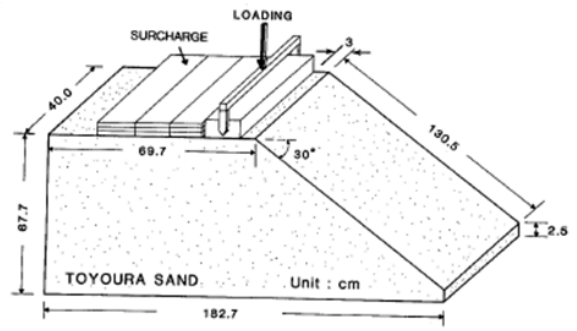
➤ Bearing capacity of a Rigid Footing (Tatsuoka *et al.* 1988)



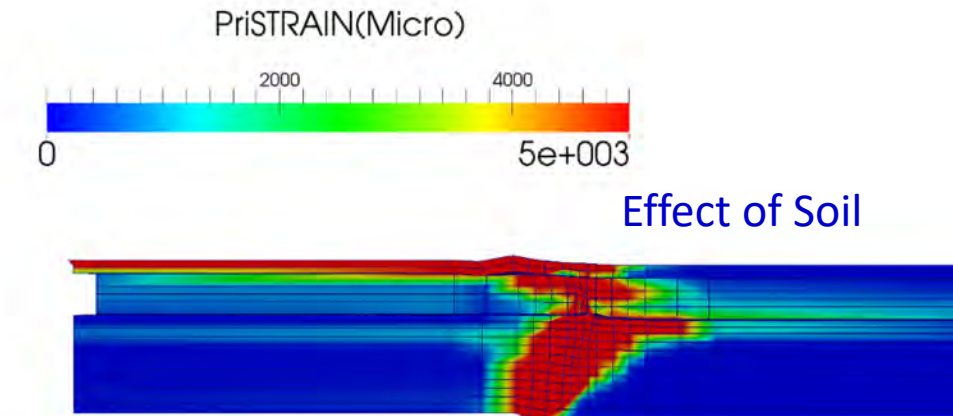
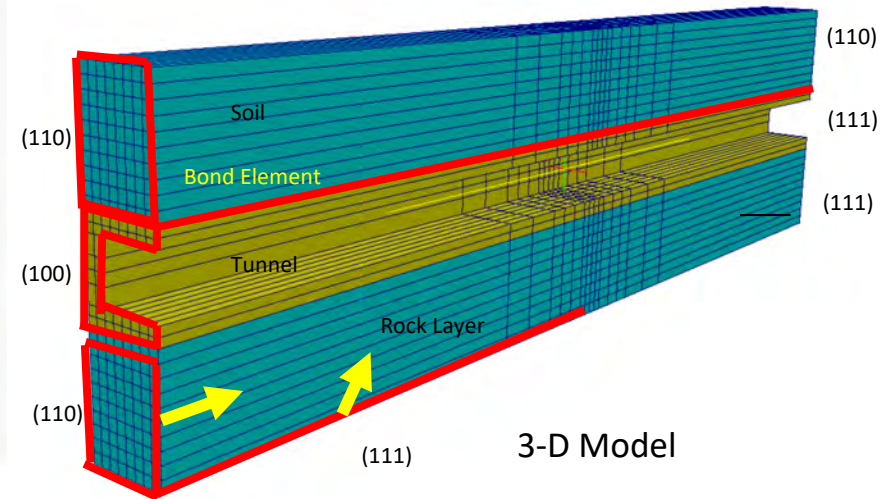
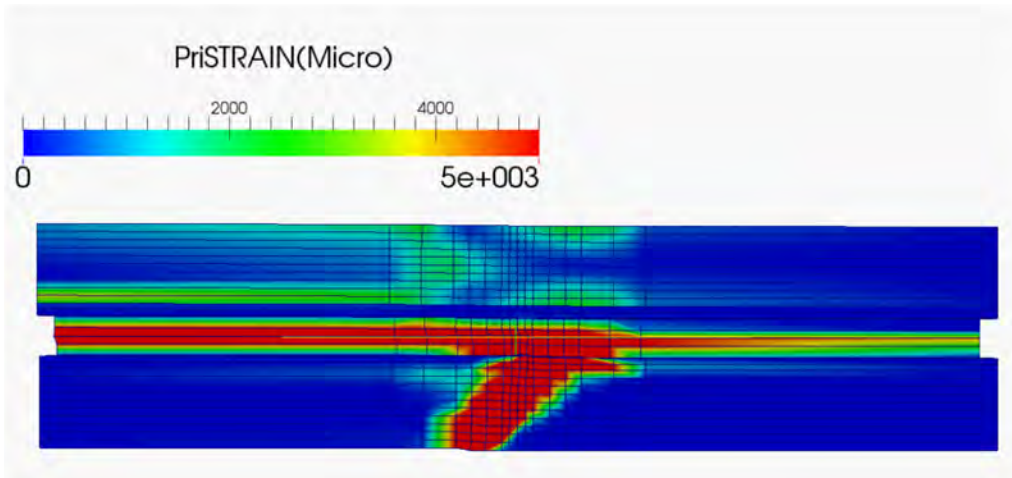
Large Scale Experiment

Small Scale Experiment

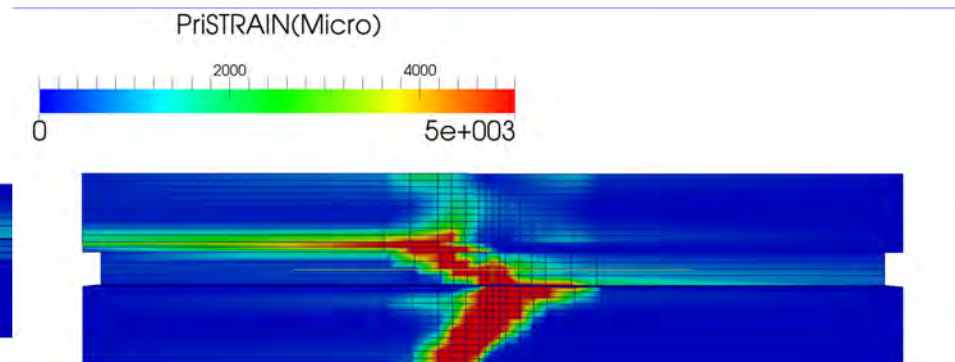
➤ Bearing capacity of a Sandy Slope (Huang *et al.* 1994)



## 異なる材料を貫通するせん断の帯の相互作用



Web Reinforcement 0.1%,  
Without Soil (>41 cm)

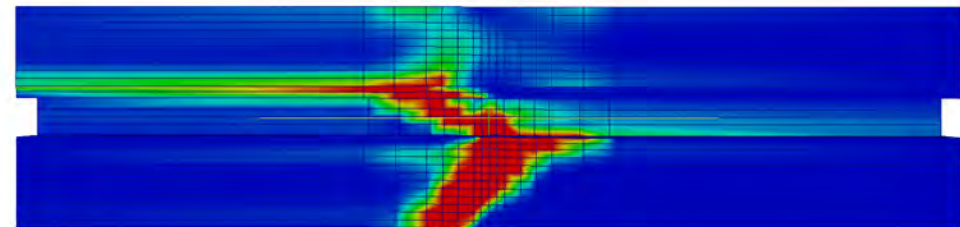
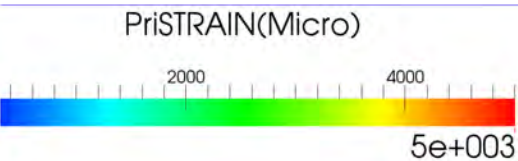
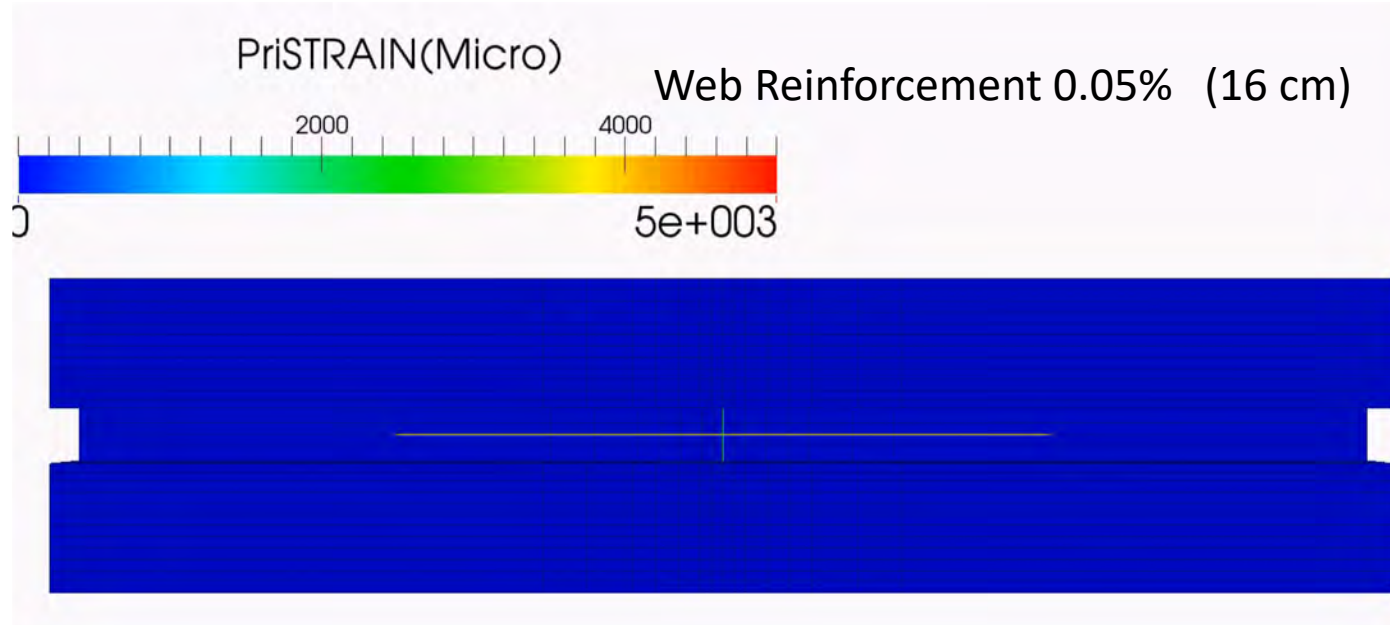


Web Reinforcement 0.1%(8.5 cm)

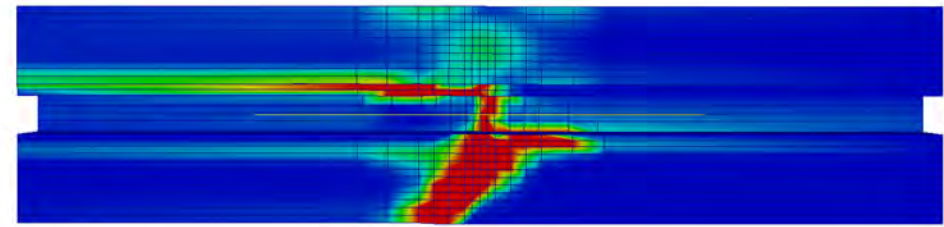
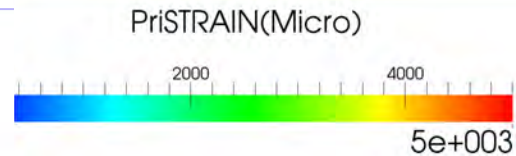
## 異なる材料を貫通するせん断の帯と相互作用

### ❖ Variation of Stiffness

- ❖ The side wall of the Tunnel was given a web reinforcement of 0.05% to make the tunnel more stiff
- ❖ The change in failure pattern can be clearly seen
- ❖ The system fails approximately 16 cm slip along the fault line
- ❖ Higher Stiffness of the Tunnel leads to a lesser stable system



Web Reinforcement 0.1% (8.5 cm)



Web Reinforcement 0.2% (7.6 cm)

# 新設構造物と既設構造物解析 終局限界と使用限界状態の照査

両者にまたがる材料特性

乾燥収縮（自己乾燥）とクリープ  
気象条件（特に降雨）

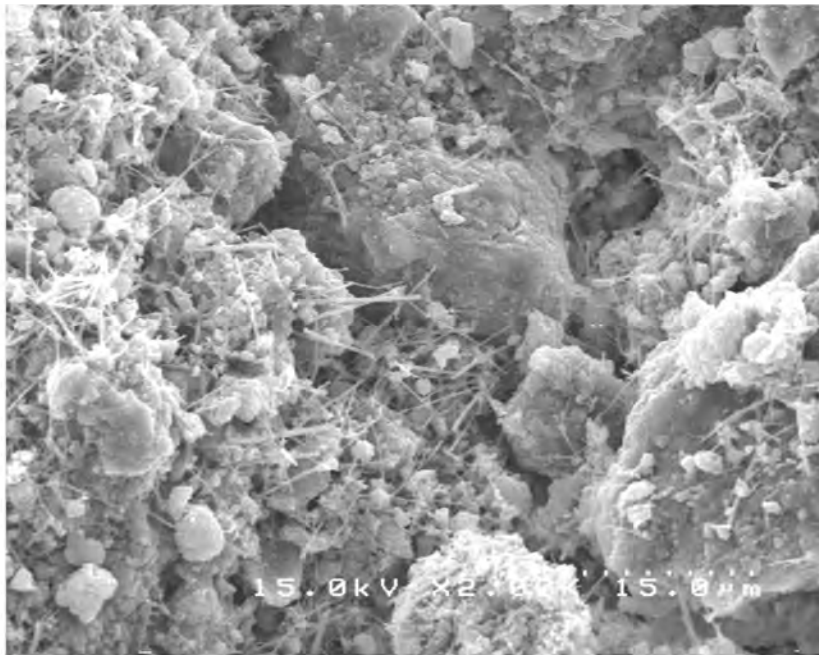
これまで簡易な方法を設計に  
しかし、そろそろ限界か？！



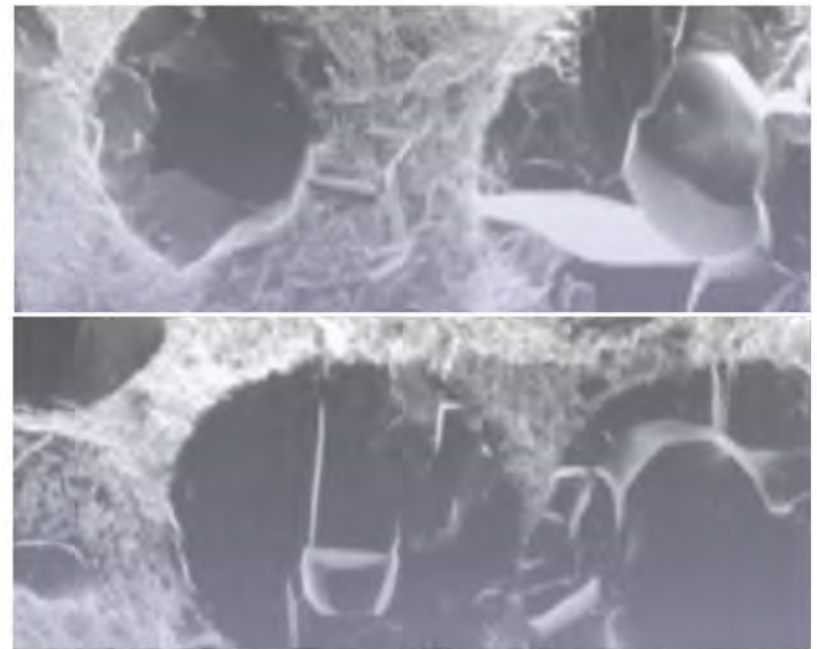
石田先生  
DuCOM チームリーダー



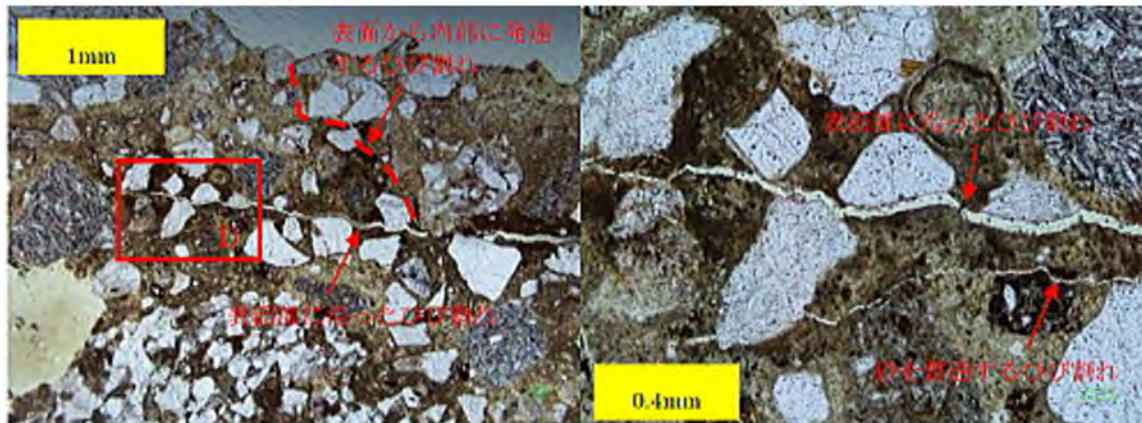
# ！！水！！:マルチスケール材料一構造システム



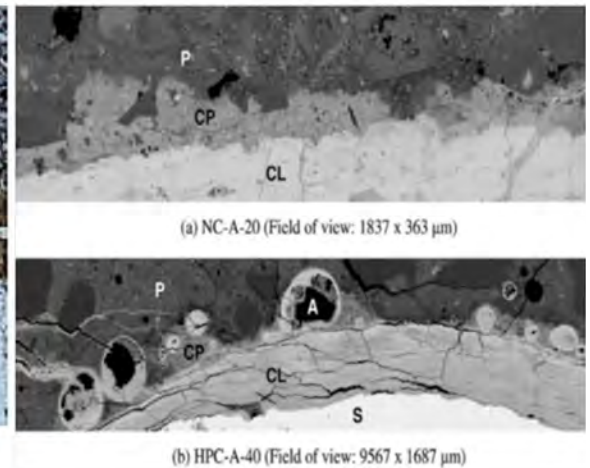
ナノスケール, CSH and Etringite

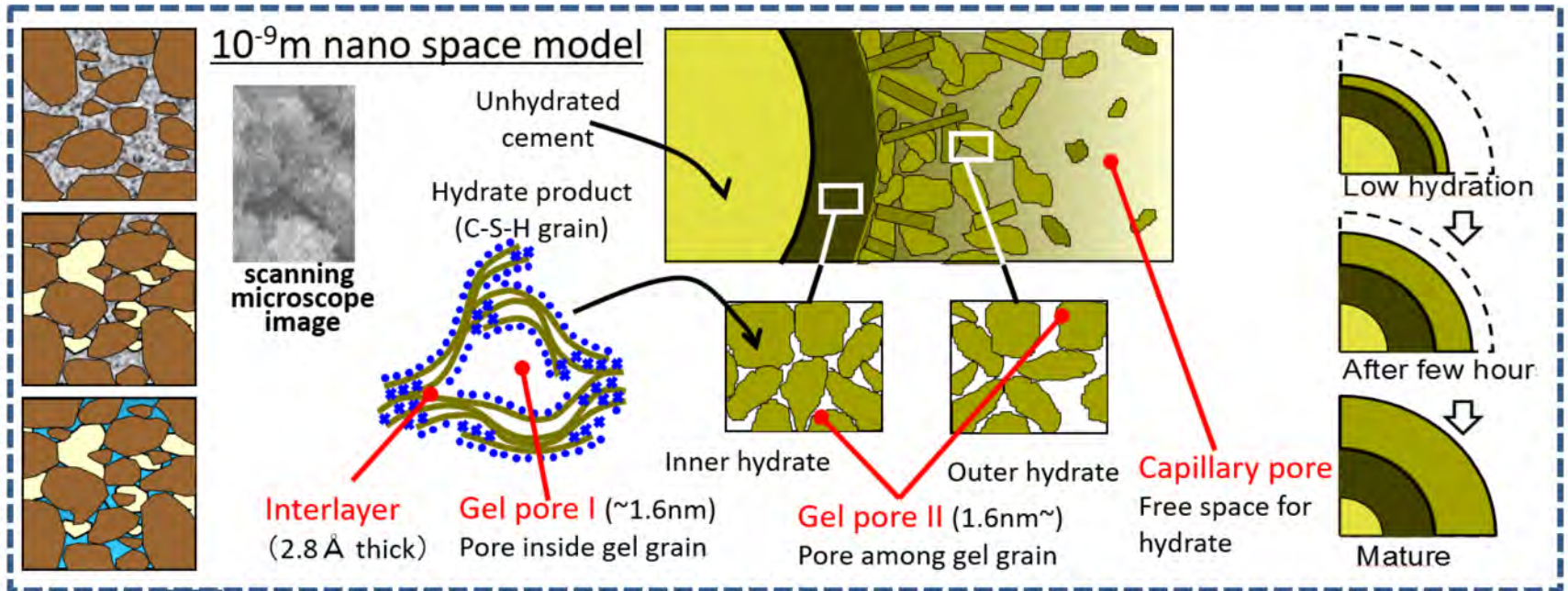


マイクロスケール, 微細気泡と氷の結晶  
Cover-sheet; Journal of Advanced Concrete Tech.



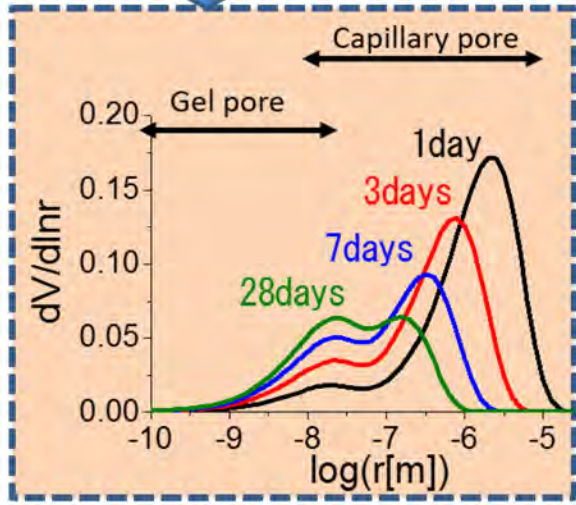
ミリメートルスケール, ASR-corrosion-gels



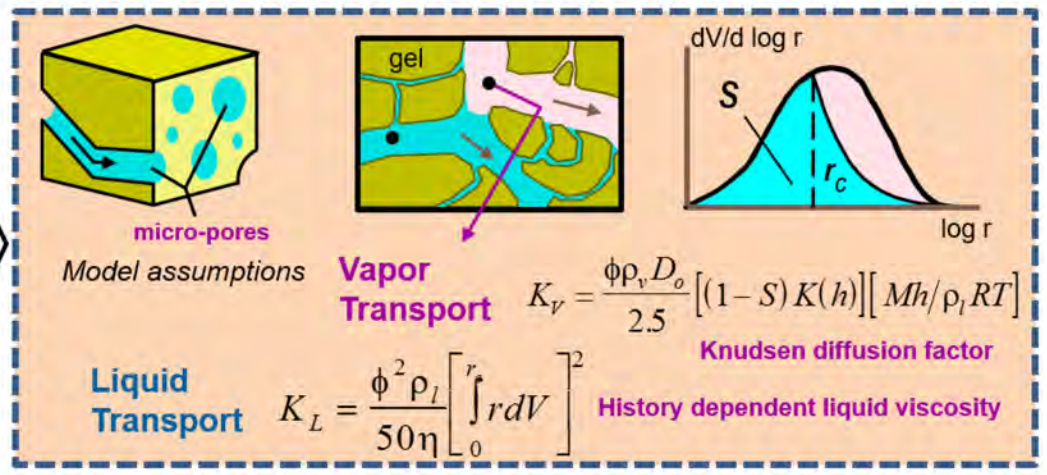


Integration

Maekawa, Ishida, Kishi (2008) Multi-scale Modeling of Structural Concrete



**10<sup>-9</sup>m → 10<sup>-6</sup>m** space structures

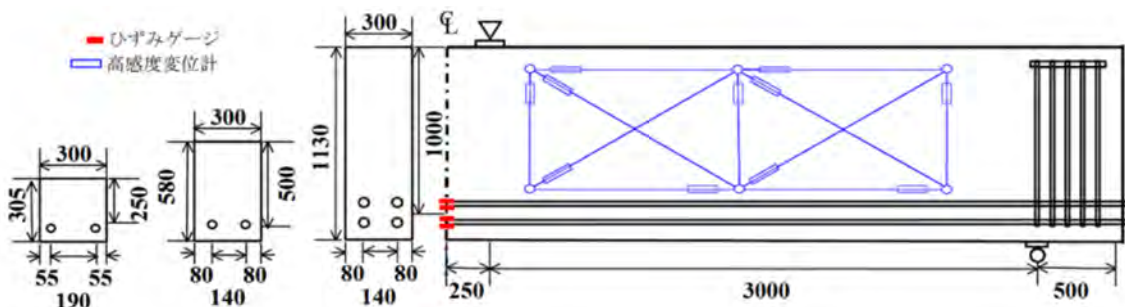


**10<sup>-9</sup>m → 10<sup>-6</sup>m** pore moisture state and motion

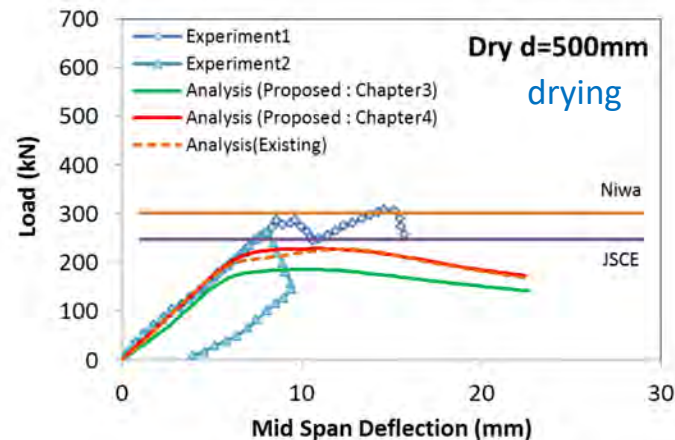
# 乾燥・自己収縮とせん断耐力

exp by Mitani, Sato, Journal of ACT 2011

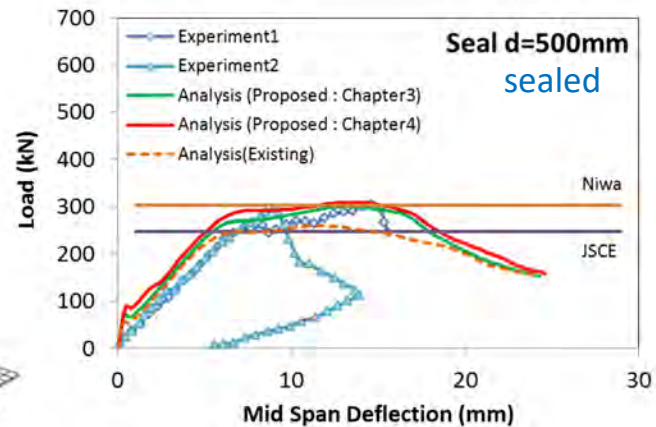
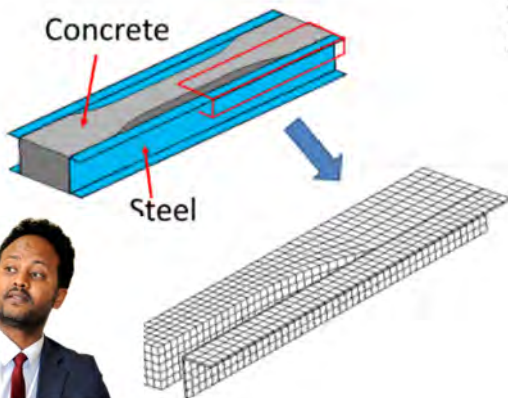
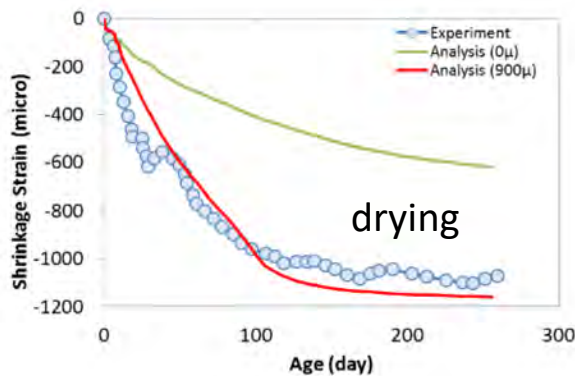
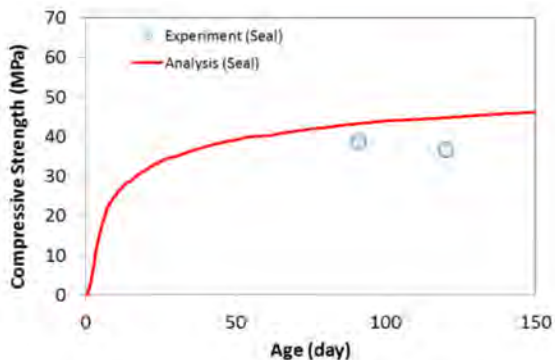
## 自己・自然乾燥の影響をせん断強度の評価に取り込める



Shear Loading of RC by drying and Sealed Curing



### Compressive strength development

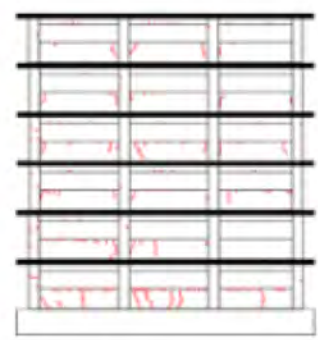


Drying shrinkage of specimen with aggregate shrinkage (900μ)

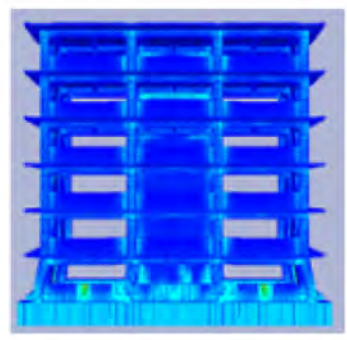
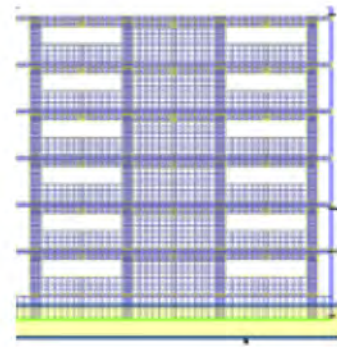


Chijiwa, Maekawa (2016), J. ACT

薄肉部材で構成される構造では、乾燥収縮の影響あり

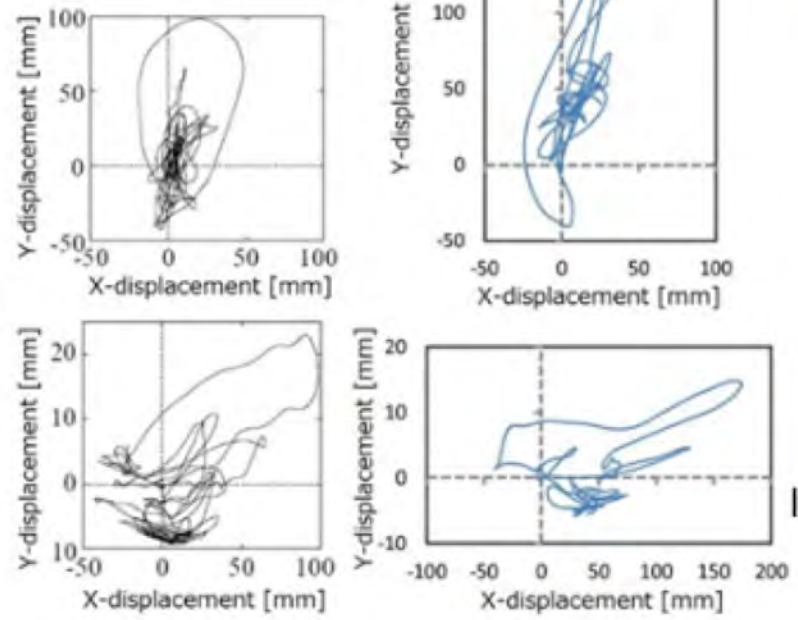


Hygro-analysis just before shaking

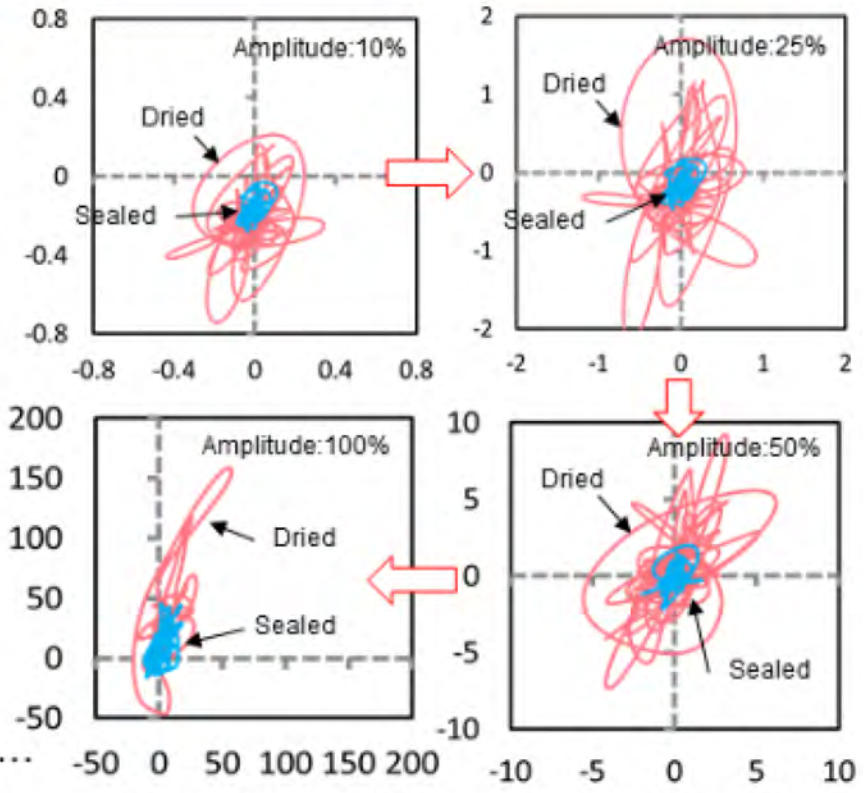


(a) Observed shrinkage cracks in the experiment

Chijiwa et al. 2015



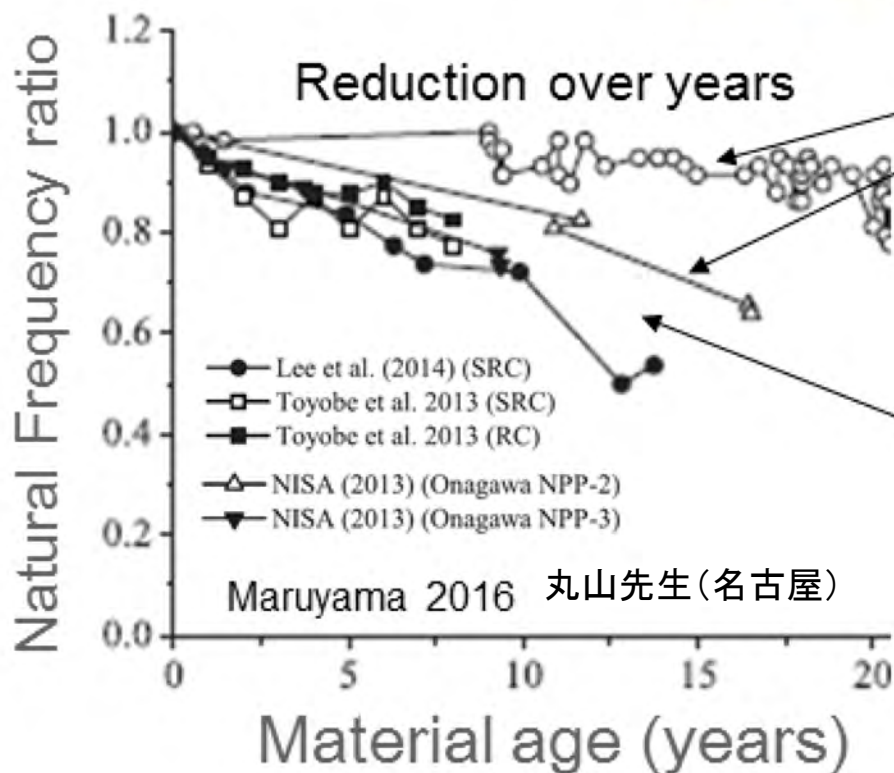
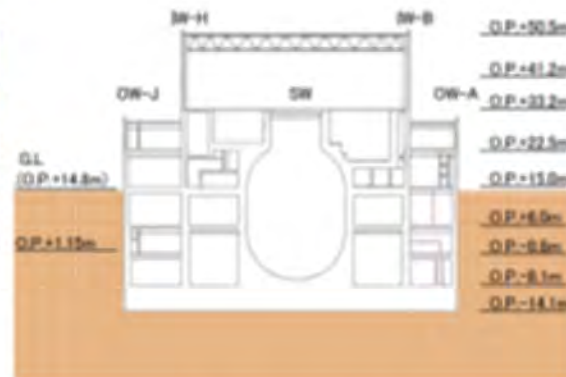
If no drying...



(b) Displacement of 2<sup>nd</sup> floor in horizontal direction(X-Y) (Lateral axis : X, Vertical axis : Y, Unit: mm)

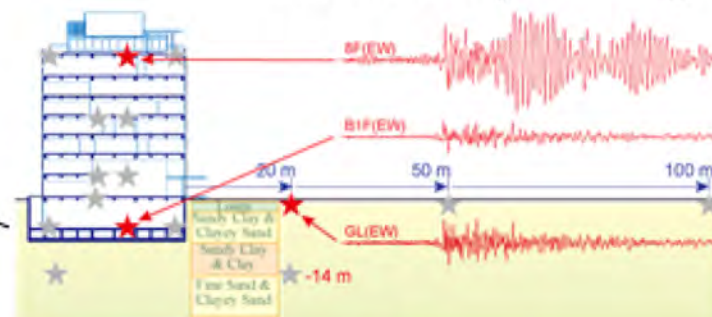
Kurihara, Chijiwa, Maekawa  
(2017) J. Advanced Conc. Tech.

乾燥が動的特性に及ぼす効果には、寸法効果がある



Large scale power plant

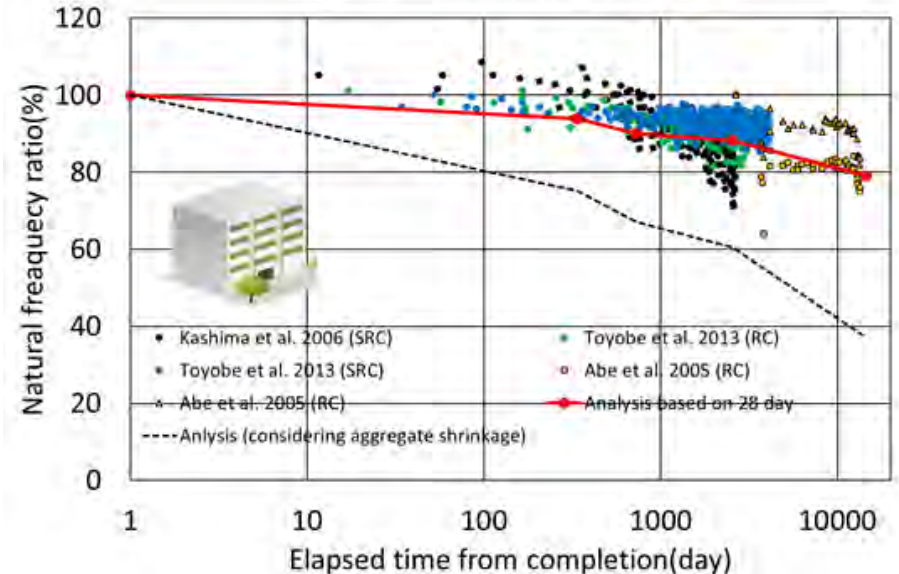
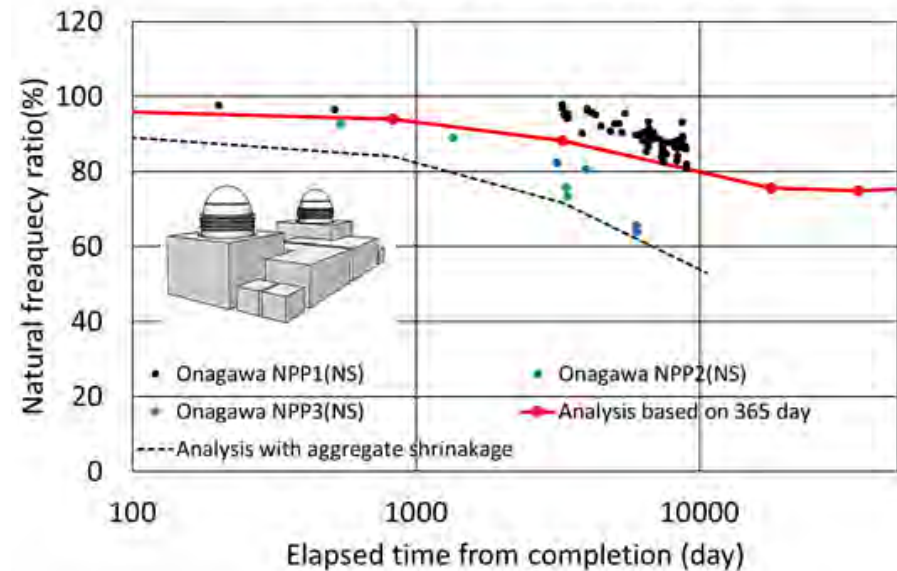
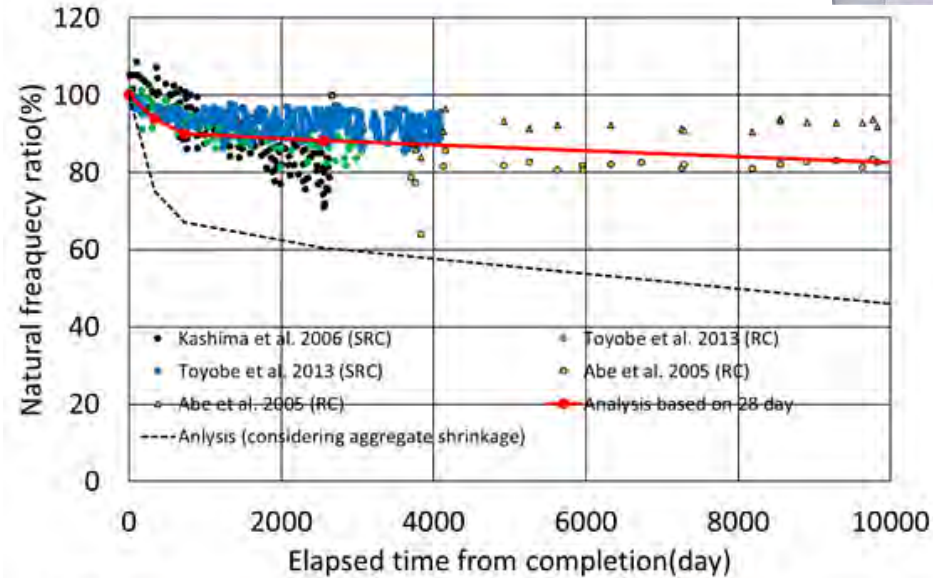
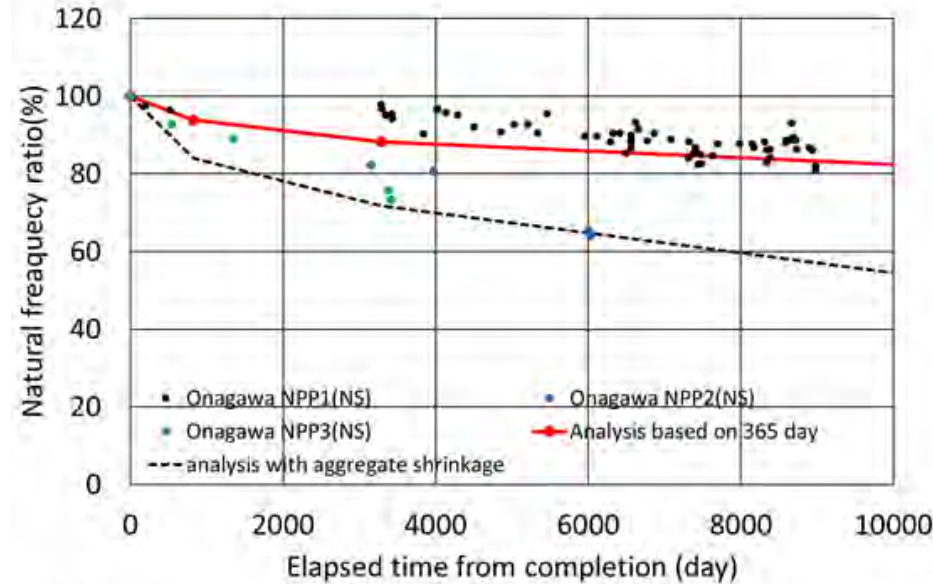
Middle story building



## 骨材収縮は厚肉部材に対して相対的に大きい影響を与える

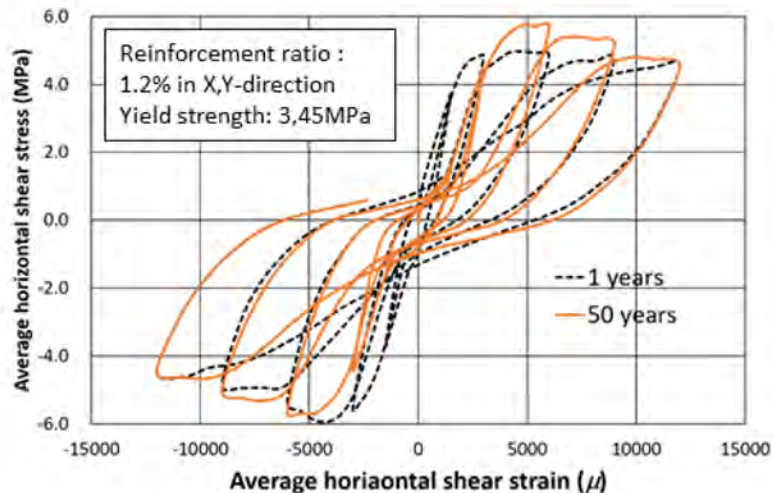
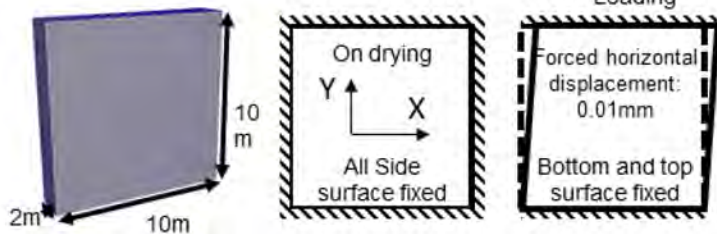
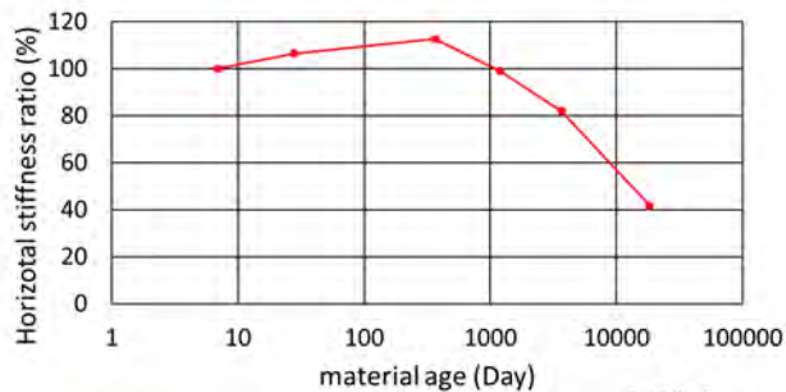


Kurihara, Chijiwa, Maekawa  
(2017) J. Advanced Conc. Tech.

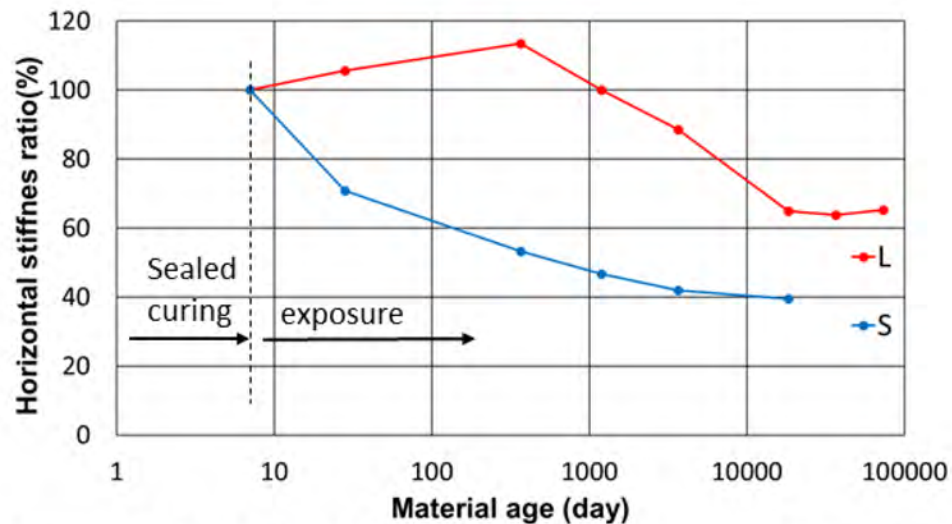


# 乾燥収縮とひび割れ: 影響有り だが、怖くはない

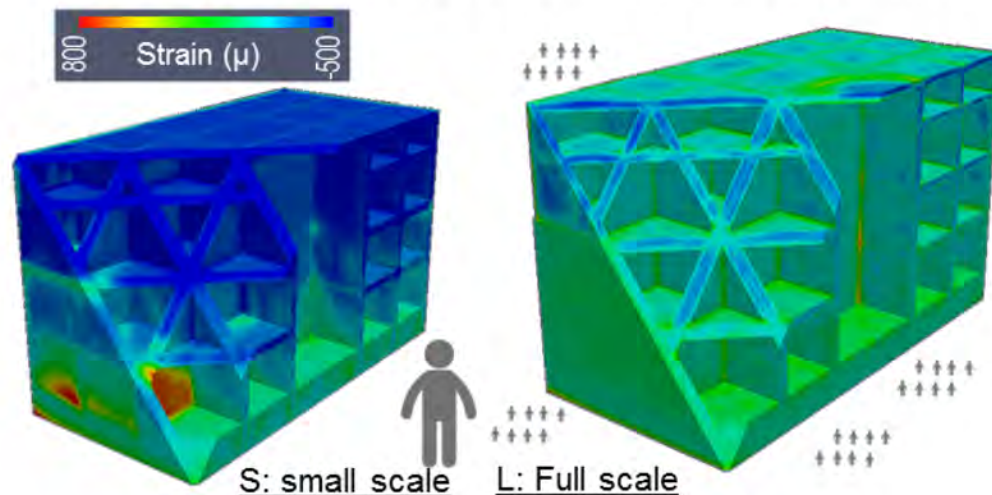
Kiruhara, Chijiwa, Maekawa (2017), J. Advanced Conc.Tech.



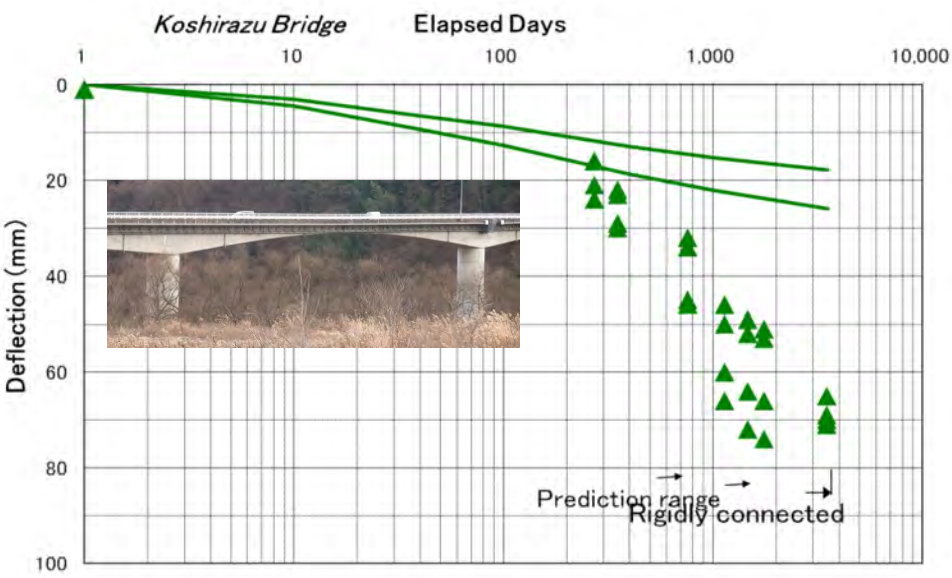
乾燥が復元力特性に与える影響は小さい



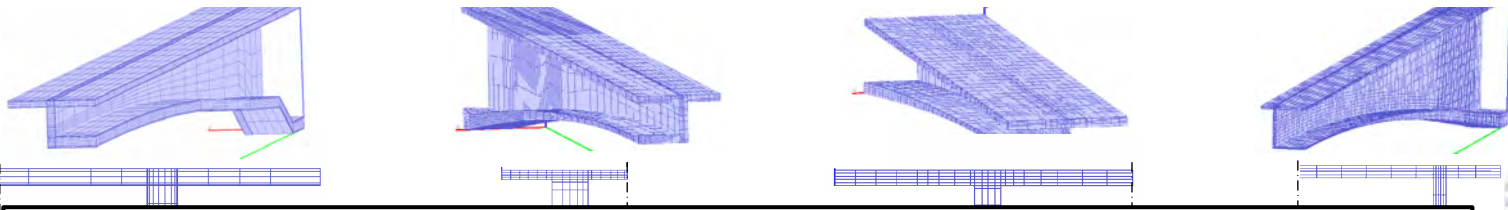
Exposed to 60%RH for 50 years: 250 times deformed



JSCE Design Code (2012) **乾燥が長期の曲率変化をもたらす。平均ひずみの変化は小さい**







**乾燥が長期の曲率変化を与え、数十年にわたり継続**



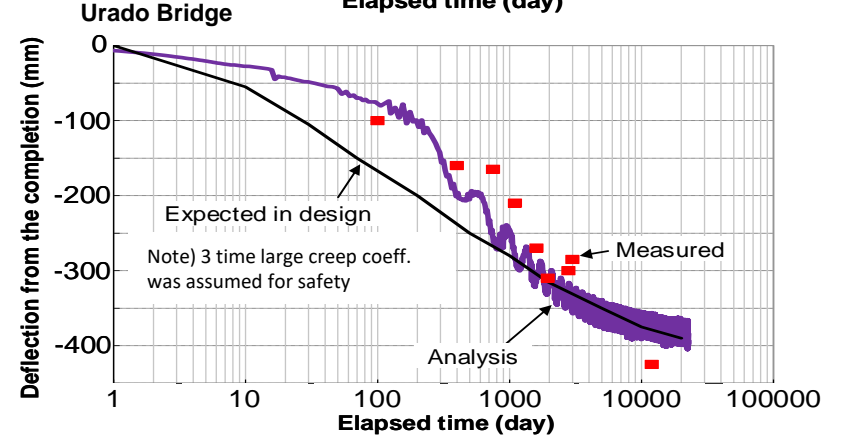
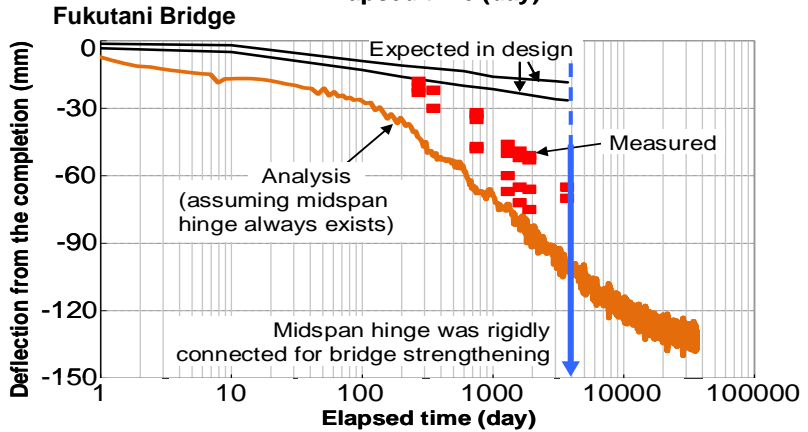
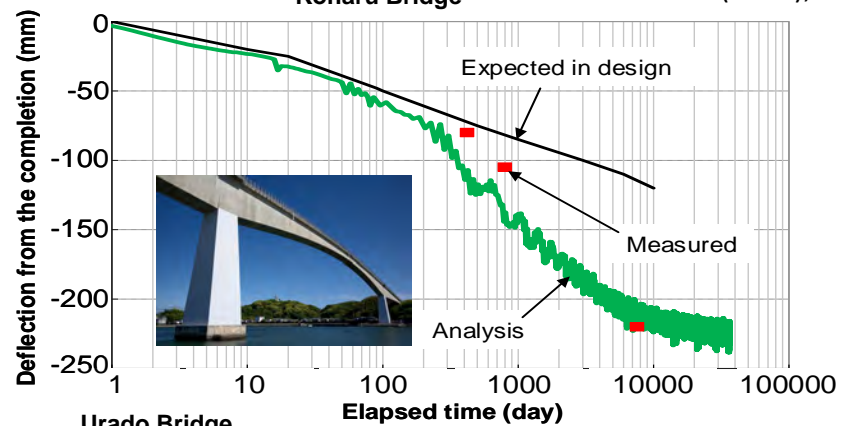
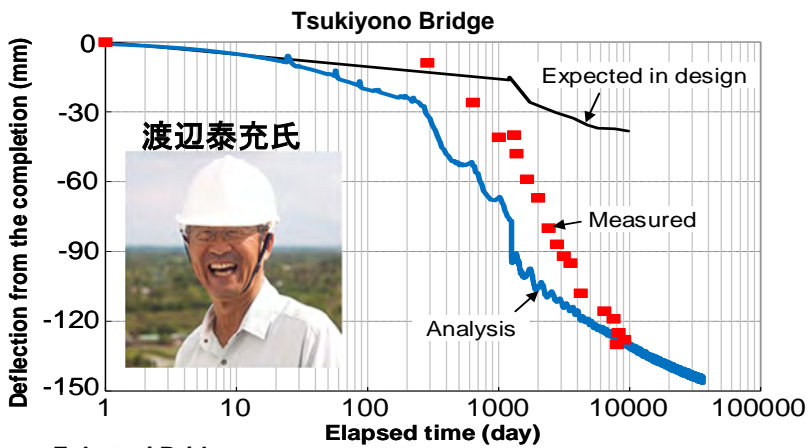
Tsukiyono Bridge

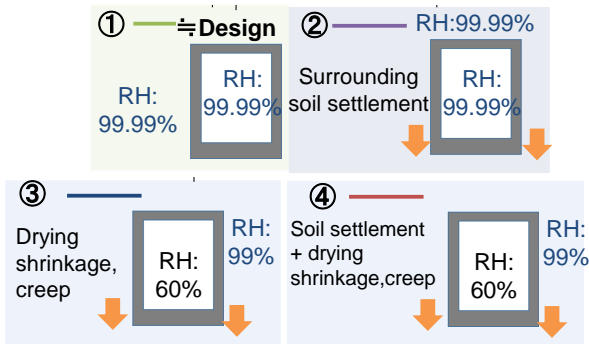
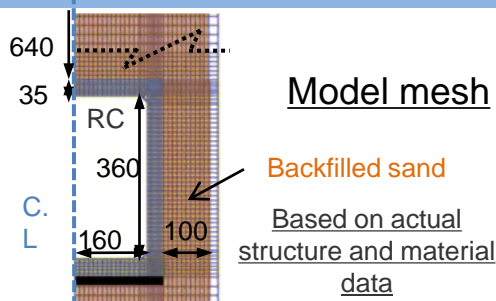
Konaru Bridge

Fukutani Bridge

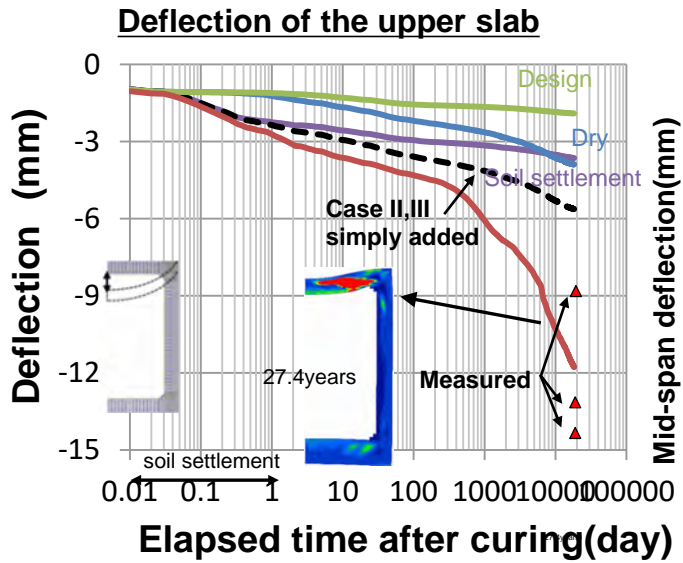
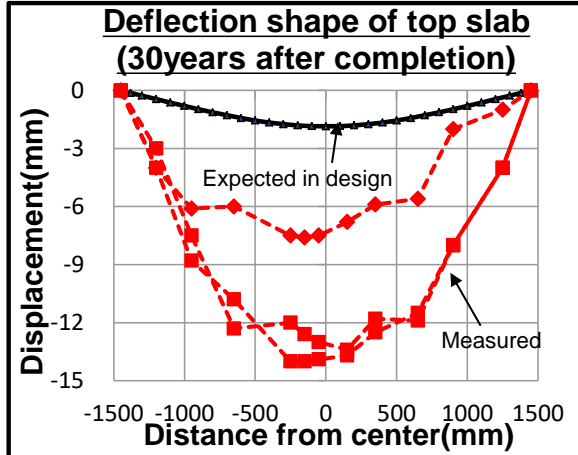
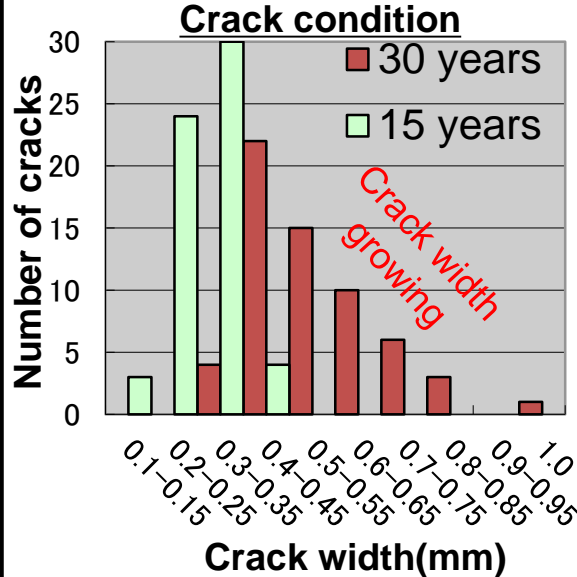
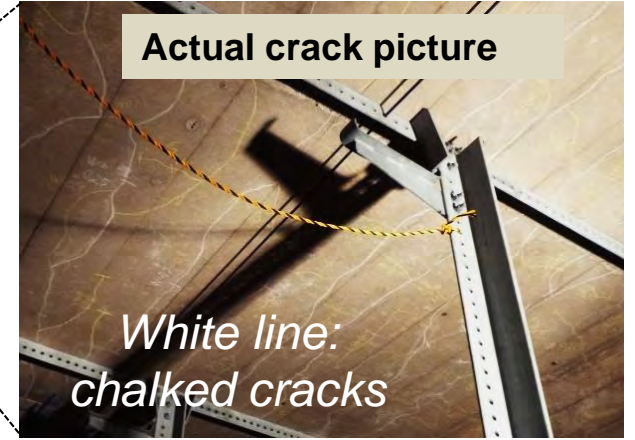
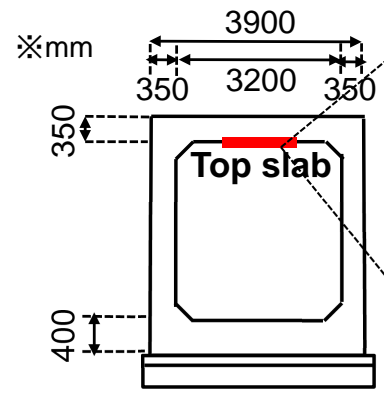
Urado Bridge

Ohno, Chijiwa, Suryanto, Maekawa (2012), J.of ACT



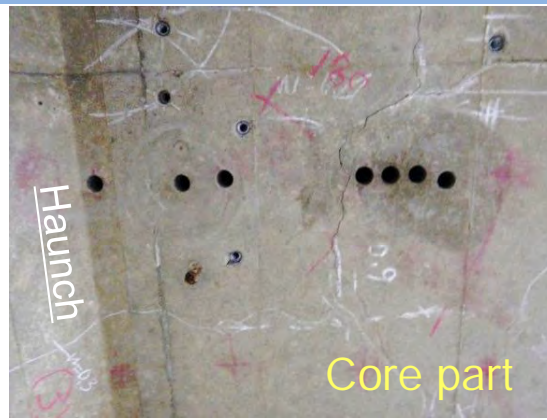


**Excessive deflection for about 20 years after construction and cracking but no yielding of steel**

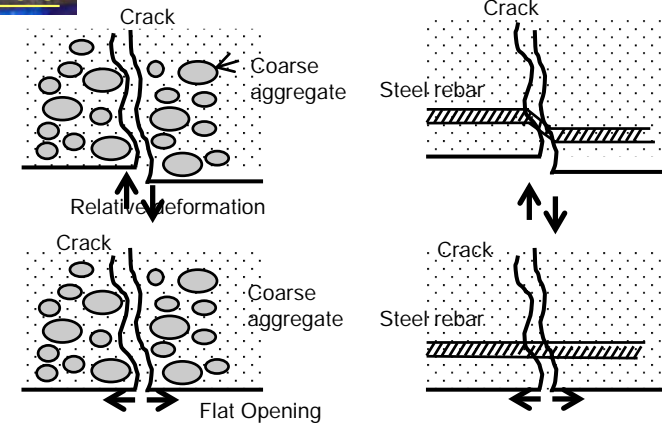
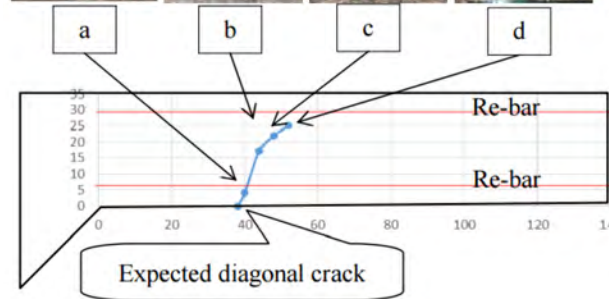
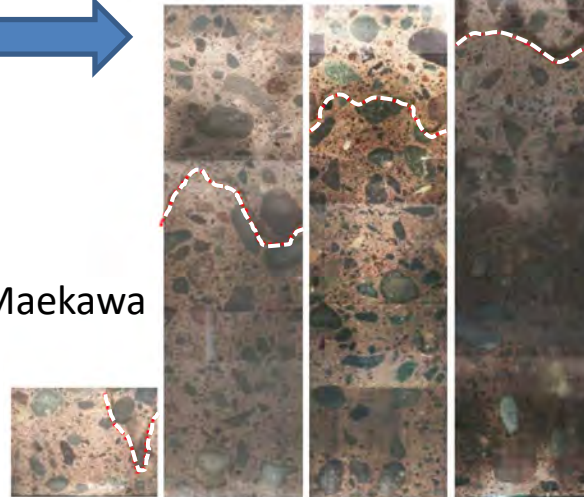


**Deflection excess 3~4times of prediction**

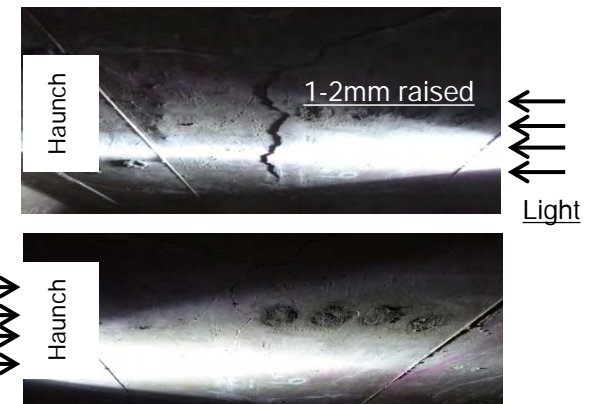
**Mechanism? ⇒ means of repair and strengthening**



Zhu, Kunieda, Maekawa  
*J. of ACT, 2016*



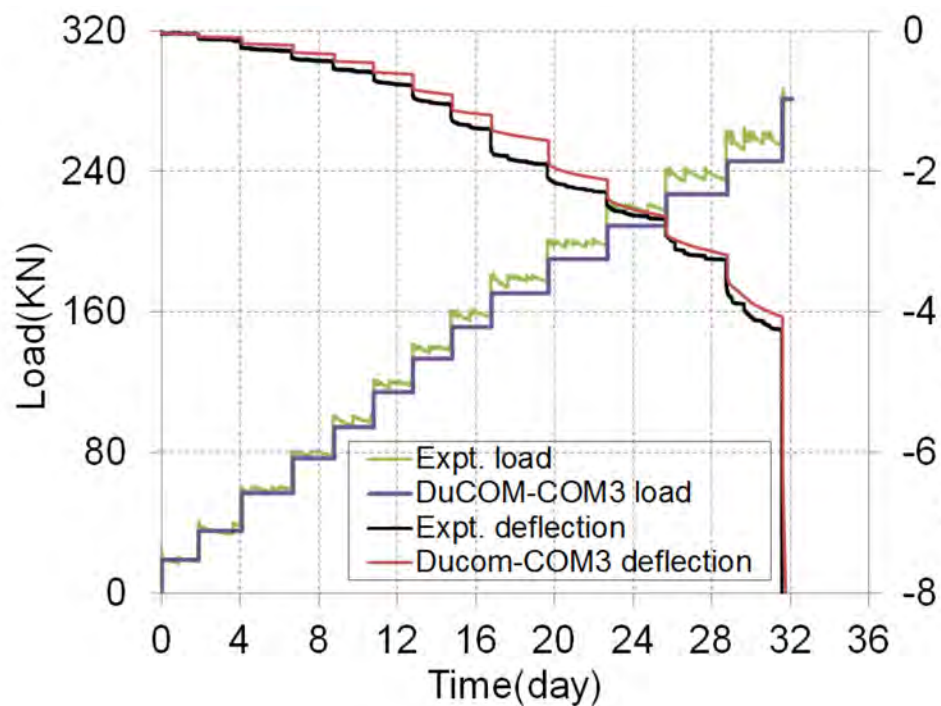
(2) Use light to check the shadow



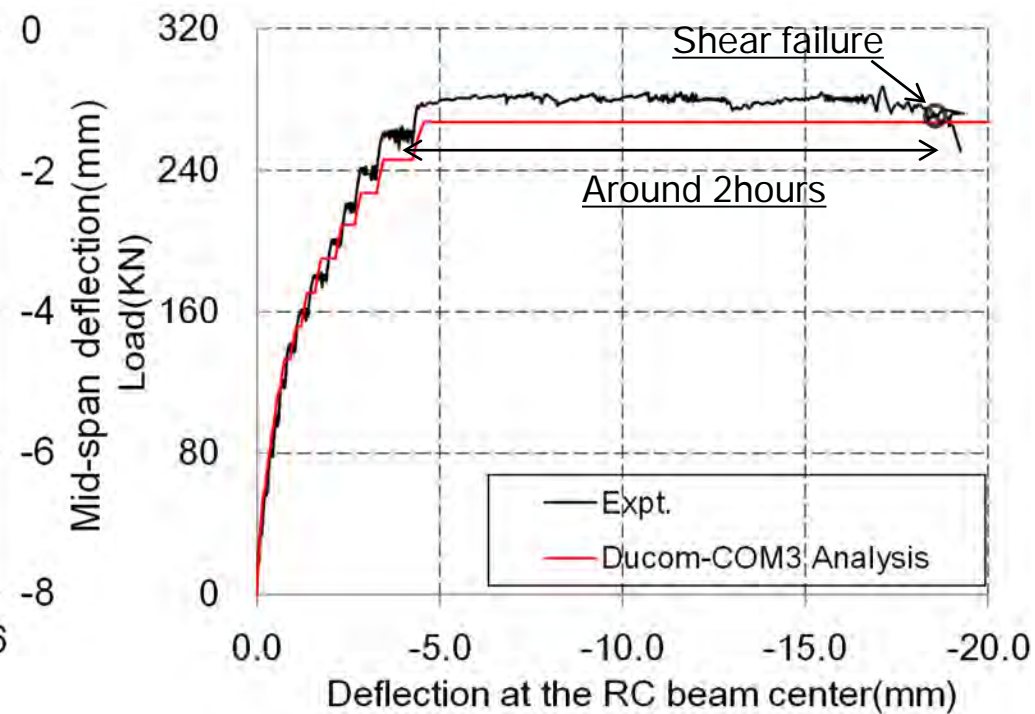
# 持続荷重によるせん断耐力の低下は、やはり起こる！

Zhu, Nakarai, Maekawa 2016 J.ACT

Time-dependent deflection



Relationship between Load and deflection



Experiment

Analysis

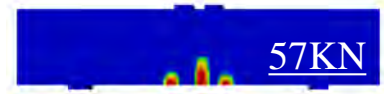
Concrete strength(35.8<sup>th</sup> day)

57.3MPa

56.5MPa

First flexure crack

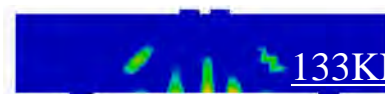
60KN



57KN

First diagonal crack

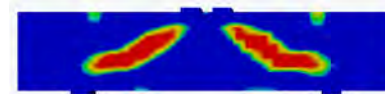
119-140KN



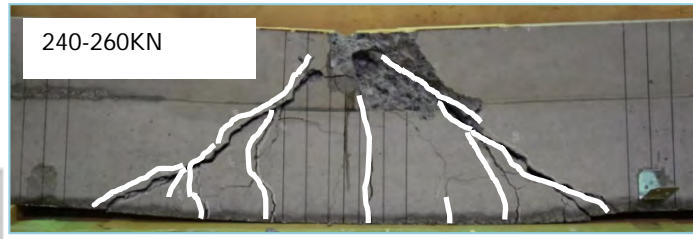
133KN

Final shear failure force

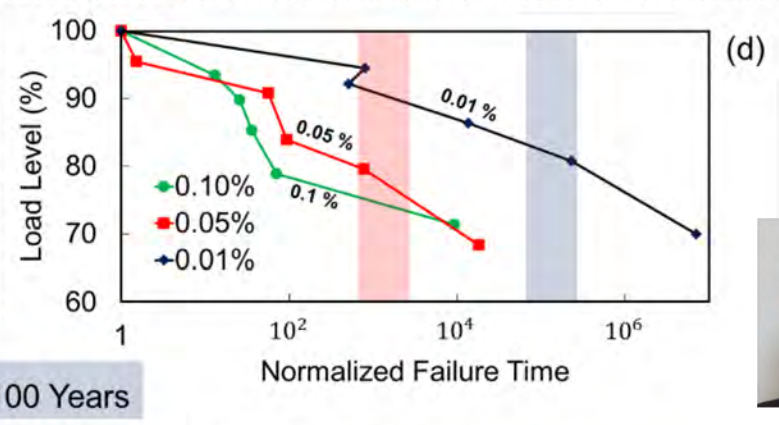
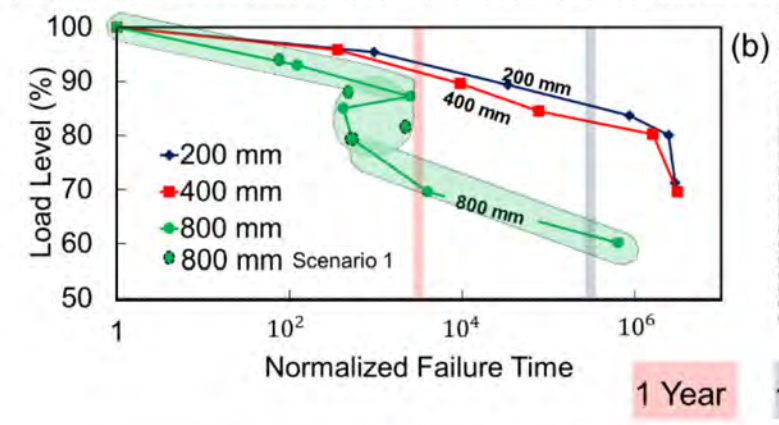
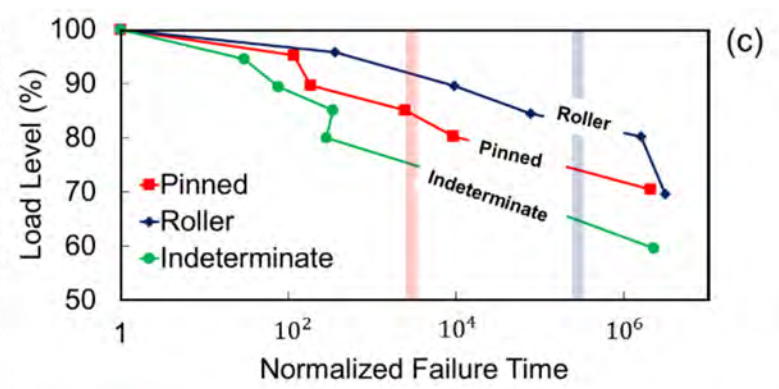
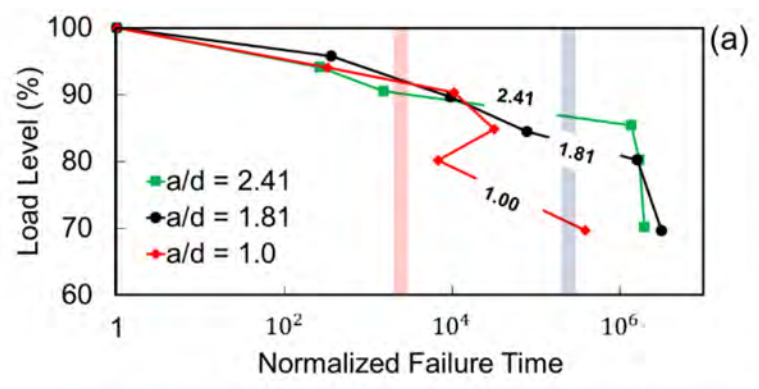
280KN



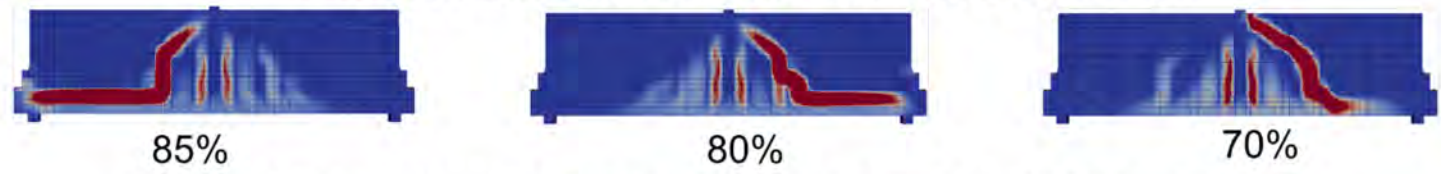
267KN (95%)



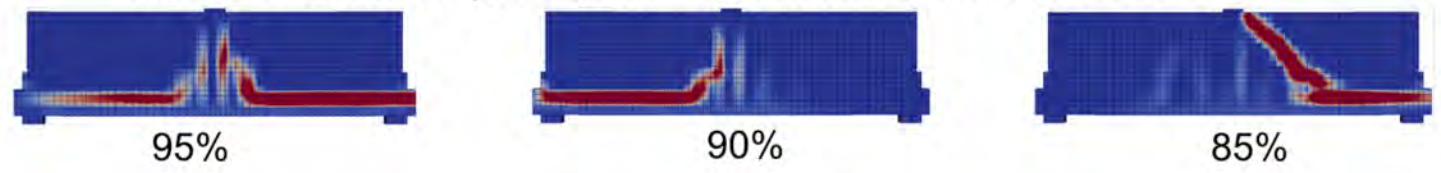
# 予測:遅れせん断破壊に至る複数のルートがある



Failure Patterns for  $a/d = 1.81$  at various load levels



Failure Patterns for plate width = 800 mm at various load levels



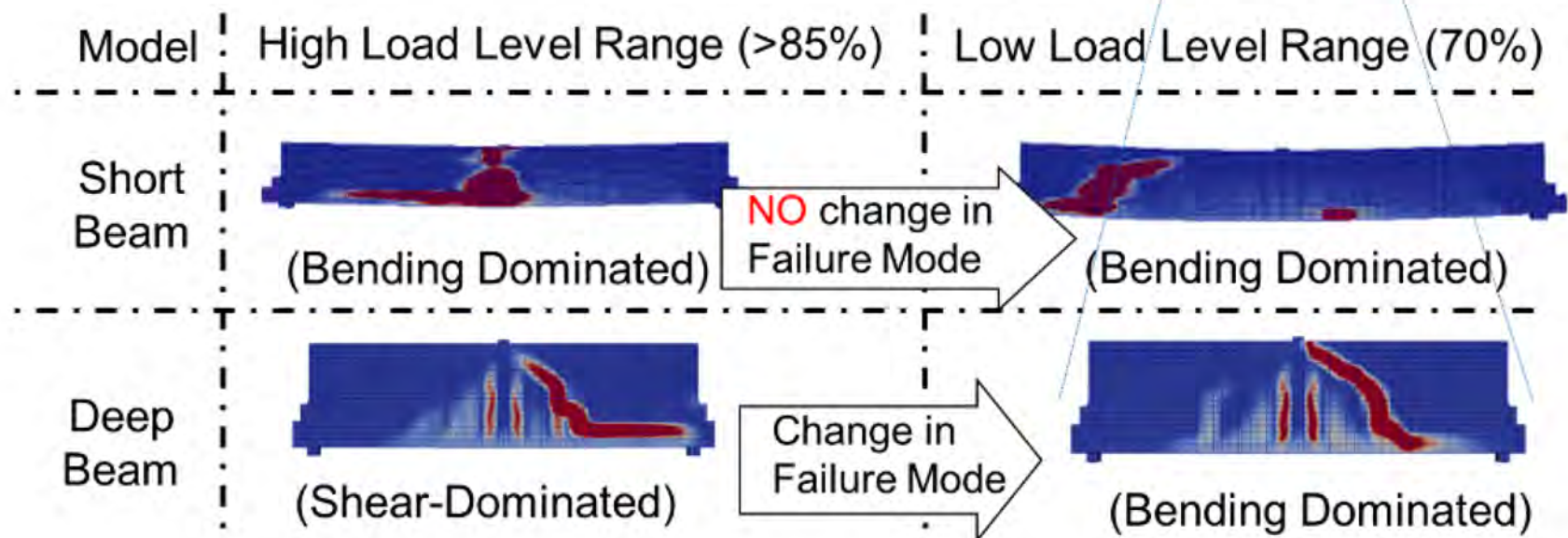
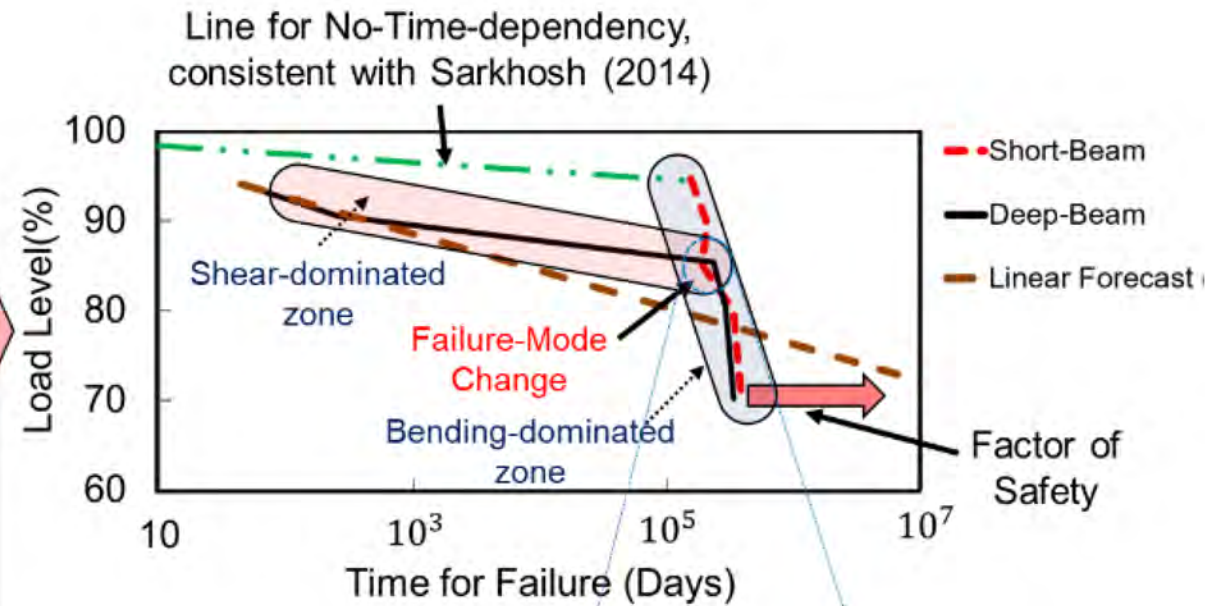
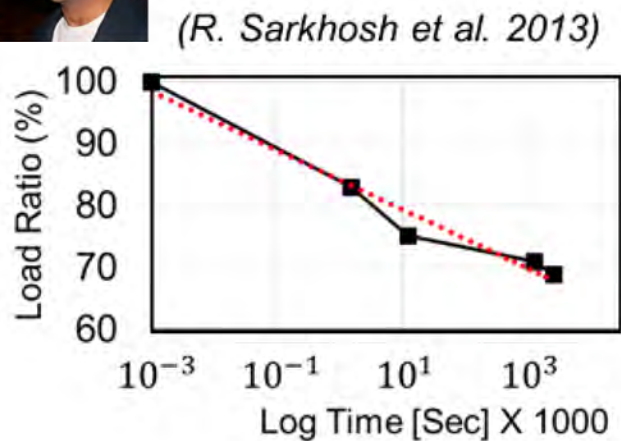
Nikhil and Maekawa  
2017 J.ACT

# 予測:遅れせん断破壊に至る複数のルートがある

Nikhil and Maekawa 2017  
J.ACT



遅れせん断破壊には複数のモードがあり、S-T曲線は一見、複雑

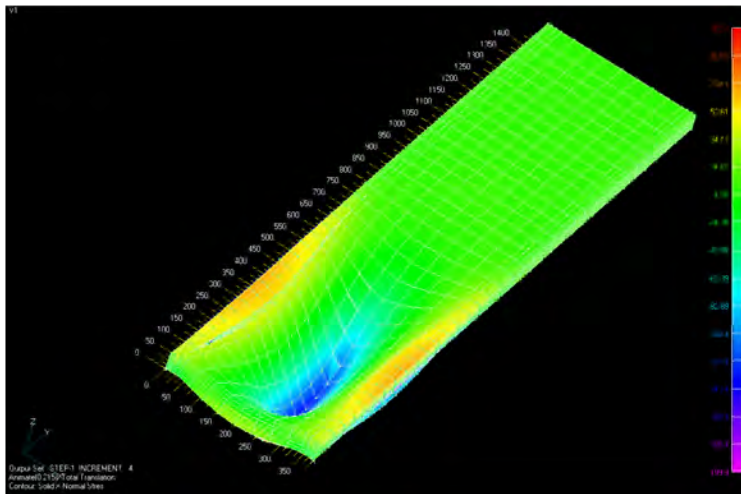


並列計算環境必須: J. ACT Mishima, An, Tsuchiya, Maekawa

### FATIGUE



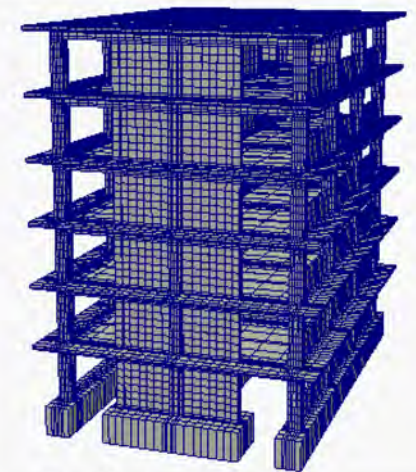
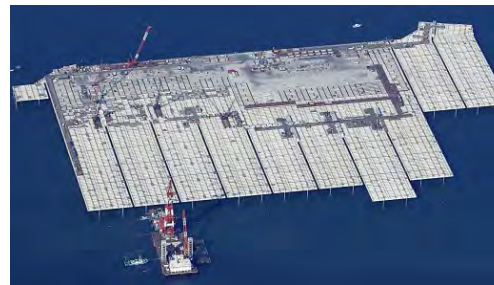
10<sup>6</sup>-10<sup>7</sup> cycles, lower stress level  
single sided, 10-50 years



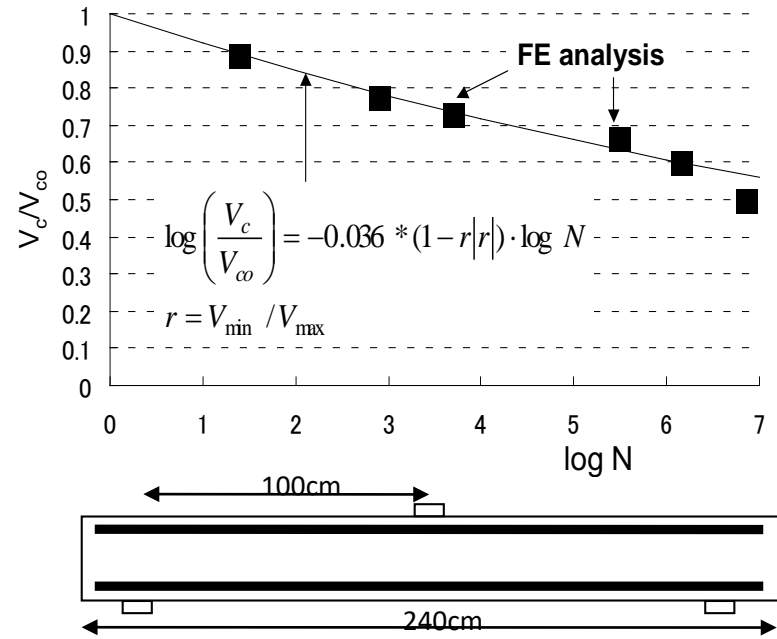
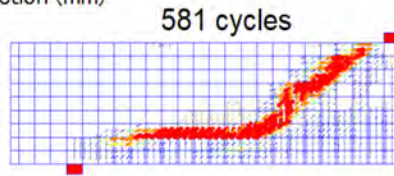
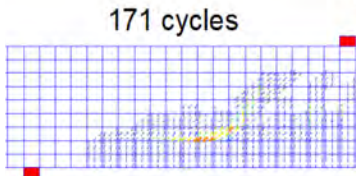
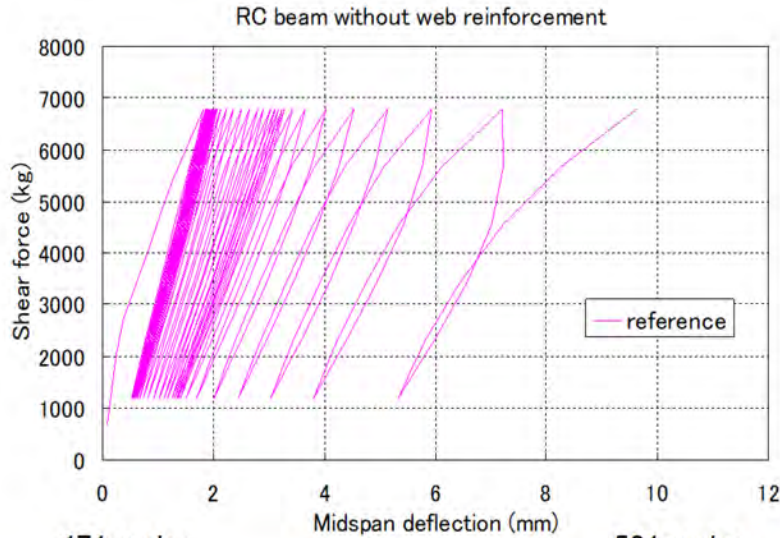
### EARTHQUAKE



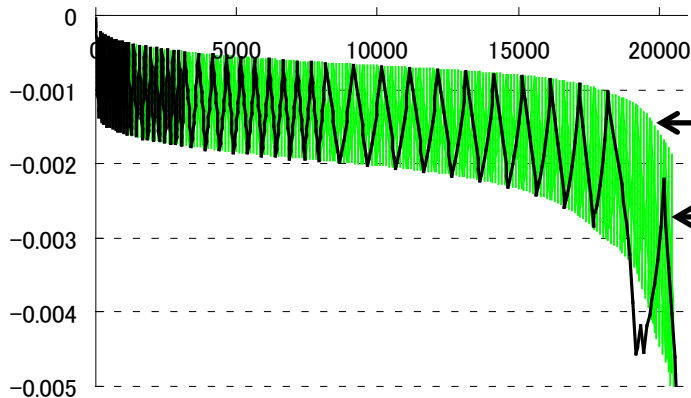
10-20 cycles, much high strain level (e-defense)  
reversed cyclic, 10-60 sec



Maekawa et al. 2006,  
Chijiwa et al. 2015  
Journal of Advanced Concrete Tech.



normal RC beams without any web reinforcement



**疲労解析に計算の高速化が不可欠**

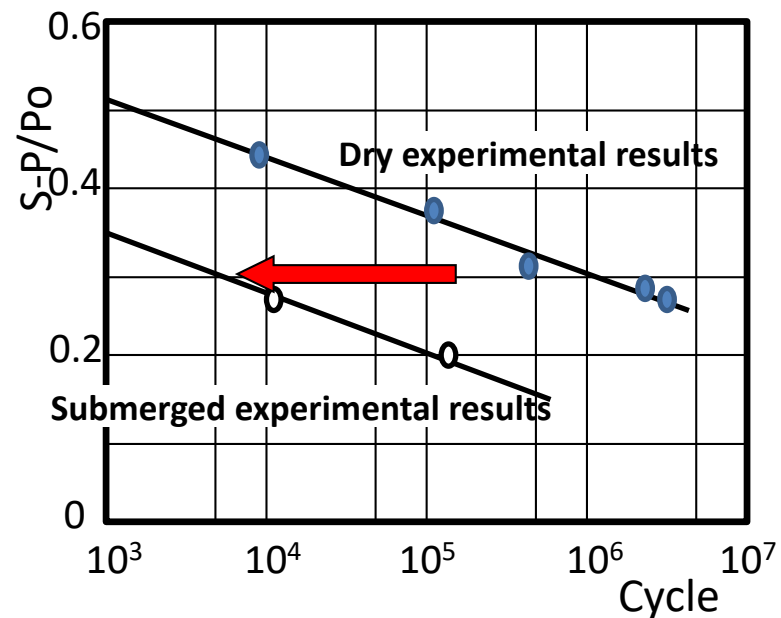
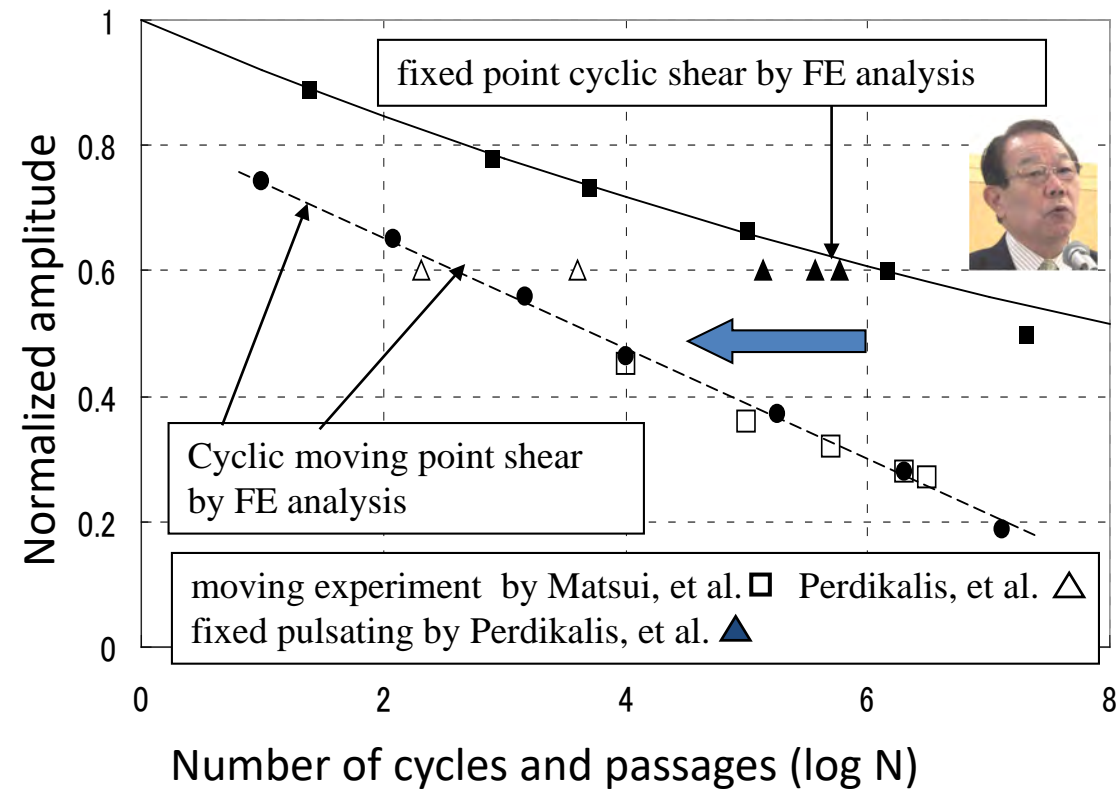
time integration :  $\Delta t$

logarithmic time integration :  $t \Delta(\log t)$

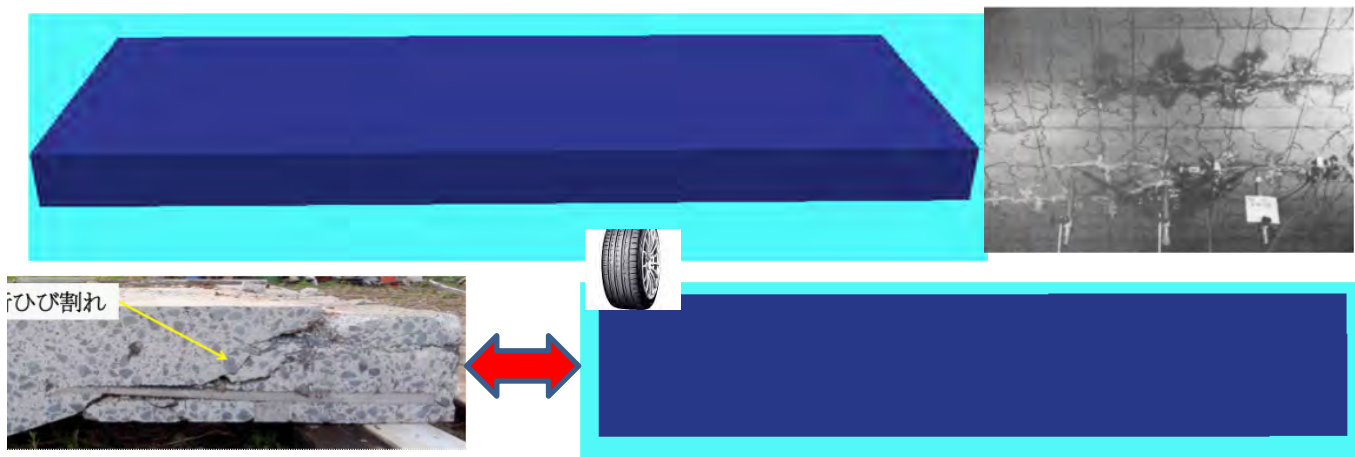
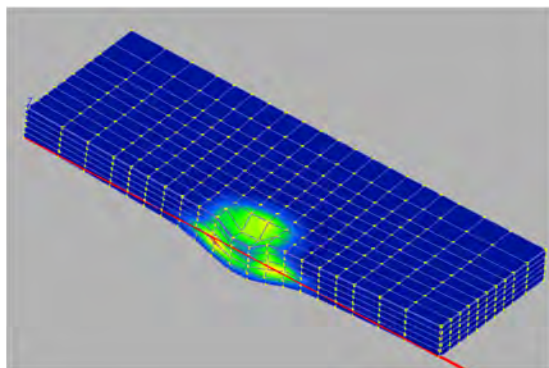
evolution term:  $dK = Fdt + Gd\varepsilon \rightarrow Ftd(\log t) + Gd\varepsilon$







**防水は大切で効果抜群  
ただし、防水の寿命は??**



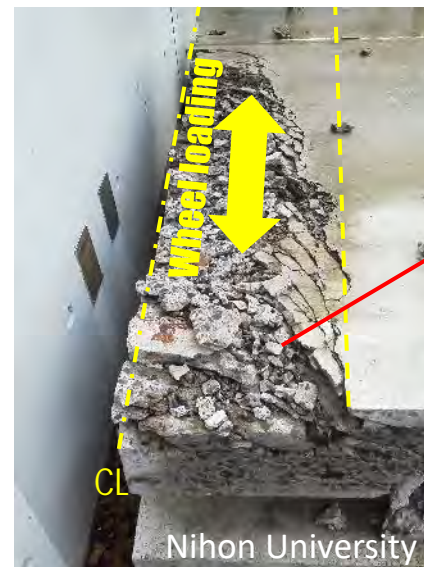
### Aggregation on Highway bridge deck



### Wheel loading test of RC slab specimen



### VTR (Inspection)



Aggregation lead the failure of specimen



### Sawn specimen after loading test

# The affinity: Porous material (skeleton) with water

Soil



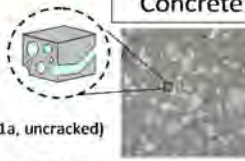
## Soil skeleton

Volume:  $(1-n)V$   
 Density:  $\rho_s$   
 Displacement:  $u_i$   
 Pore water  
 Volume:  $nV$   
 Density:  $\rho_f$   
 Displacement:  $u_i + w_i/n$

Biot's theorem:  $\sigma_{ij} = \sigma_{ij}^* + \delta_{ij} p$

## Saturated concrete

$\rho = (1-n)\rho_s + n\rho_f$   
 concrete skeleton pore water



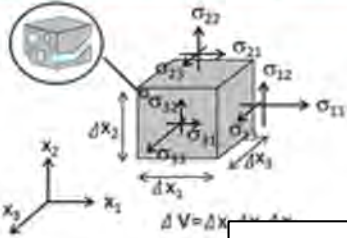
Concrete

## Total stress:

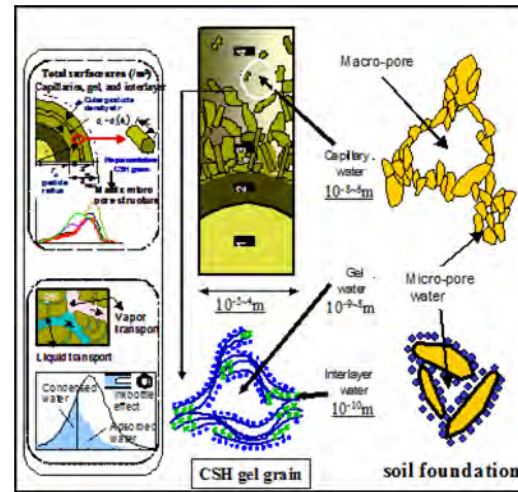
$\sigma_{ij} = \sigma_{ij}^* + \delta_{ij} p$  .....(1a, uncracked)

$\sigma_{ij} = \sigma_{ij}^* + \delta_{ij} \cdot l_i \cdot p$  ....(1b, cracked)

## Dynamic equilibrium equations for a saturated skeleton

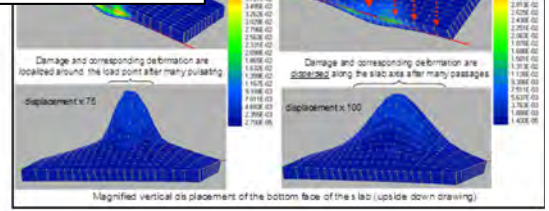
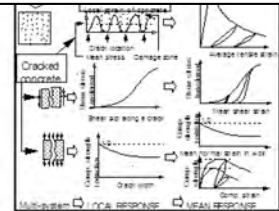
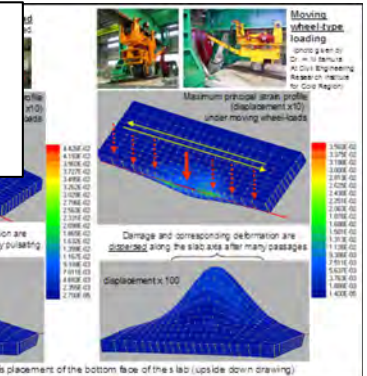


- a) normal to plane  $x_2-x_3$  —  $\sigma_{11,1}$
- b) normal to plane  $x_3-x_1$  —  $\sigma_{12,2}$
- c) normal to plane  $x_1-x_2$  —  $\sigma_{13,3}$
- d) gravity force —  $\rho g_1$
- e) mass of skeleton —  $(1-n)\rho_s$
- f) acceleration of skeleton —  $u_{i,tt}$
- g) mass of water —  $n\rho_f$
- h) acceleration of water —  $(u_i + w_i/n)_{,tt}$

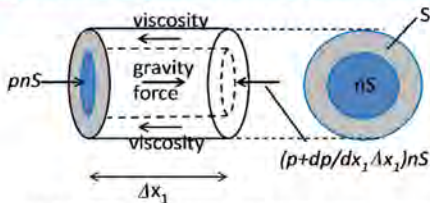


- (1) Equilibrium in direction  $x_1$   
 $\sigma_{11,1} + \sigma_{12,2} + \sigma_{13,3} + \rho g_1 = \rho(u_{1,tt} + w_{1,tt}/n)$
- (2) Generalization for each coordinate axis  
 $\sigma_{ij,j} + \rho g_i = \rho(u_{i,tt} + w_{i,tt}/n)$

**地盤の有効応力解析と支配方程式は同じ  
 物理現象の違いを構成則で代表**



## Dynamic equilibrium equations for fluid materials in the skeleton



- a) porous area —  $S$
- b) normal to plane  $x_2-x_3$  —  $\rho_f \Delta x_1 n S$
- c) gravity force —  $\rho_f g_1 \Delta x_1 n S$
- d) permeability —  $K_1$

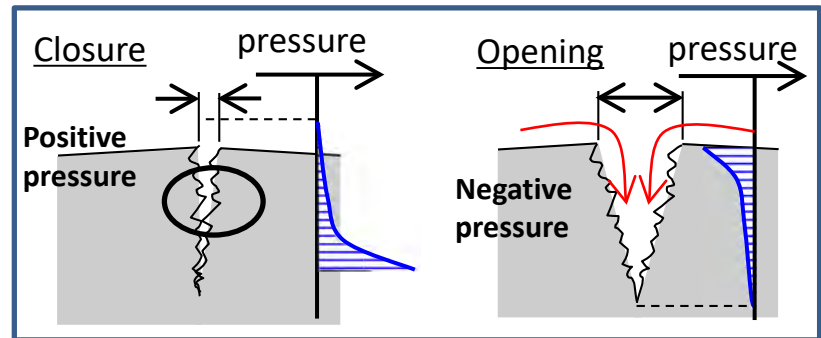
- (1) Viscosity — resistant force exerted by contact with skeleton  
 From simple assumption; without any acceleration (static movement)  
 $\kappa p_{,1} = w_{1,t}$   
 $\rho_f \Delta x_1 n S = 1/\kappa w_{1,t} \Delta x_1 n S$

- (2) Dynamic equilibrium

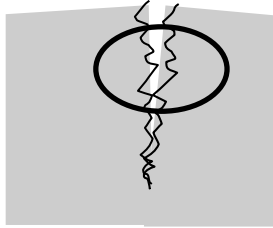
$\rho_f \Delta x_1 n S + \rho_f g_1 = 1/\kappa w_{1,t} + \rho_f (u_{1,tt} + w_{1,tt}/n)$   
 pressure gravity viscosity mass x acceleration=force

$u_i = u_i + \frac{w_i}{n} \quad \leftarrow (n)$

$\rho_i = \rho_f (u_{i,tt} - g_i) + \rho_f \dot{w}_{i,tt} / n + \frac{1}{K_1} \dot{w}_{i,t} \quad \leftarrow (o)$



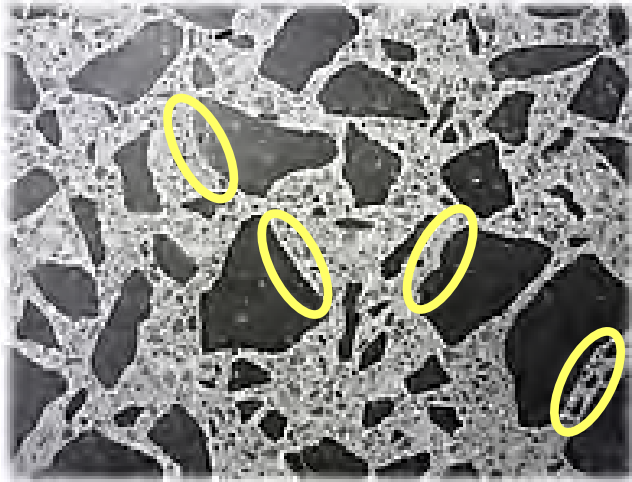
Maekawa et al (2015) J. of Material in Civil Eng., ASCE



Pore pressure inside closing cracks



Transferred to capillary pores large pores located around interfaces of aggregates and cement paste



Cement paste bonding is deteriorated.  
Cyclic pressure made by crack-closure



*"cannot see the forest for the trees"*  
(focus on the details, and miss the main point: idiom)

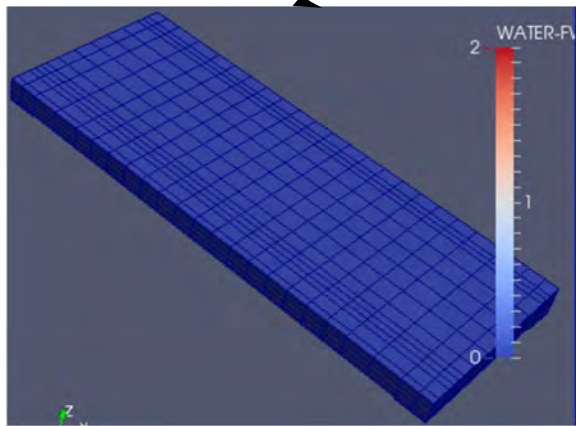
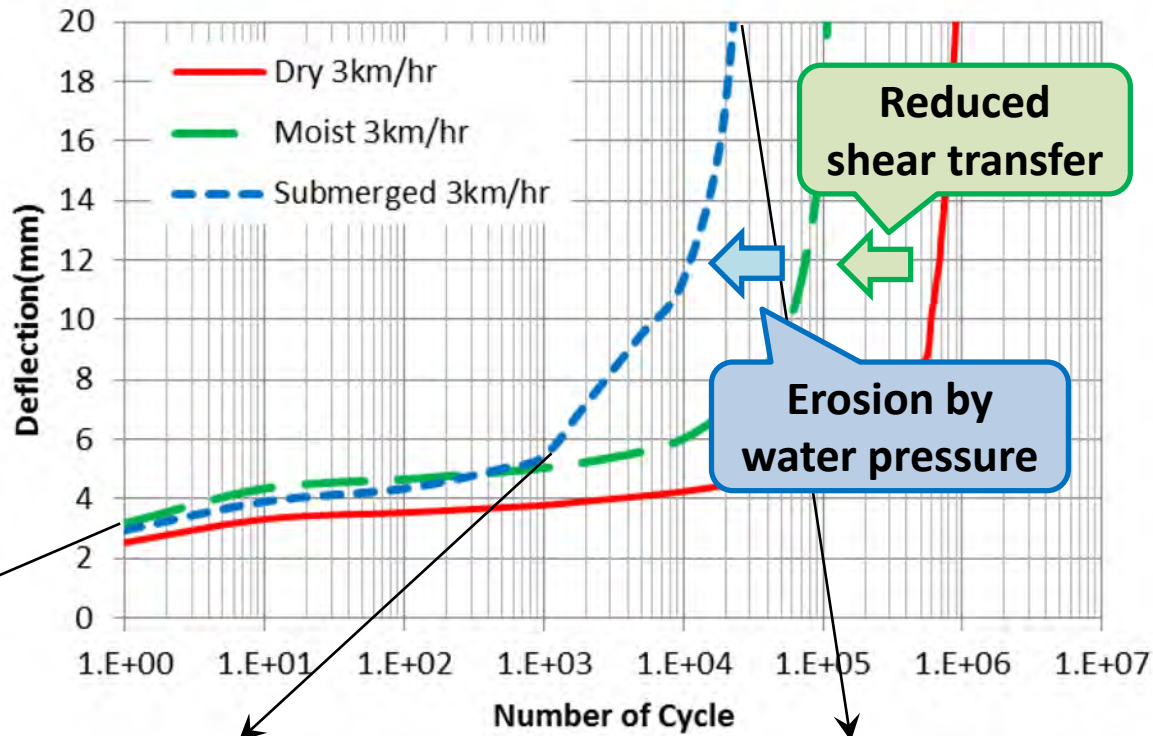


*"Engineers shall see both the forest and the trees"*

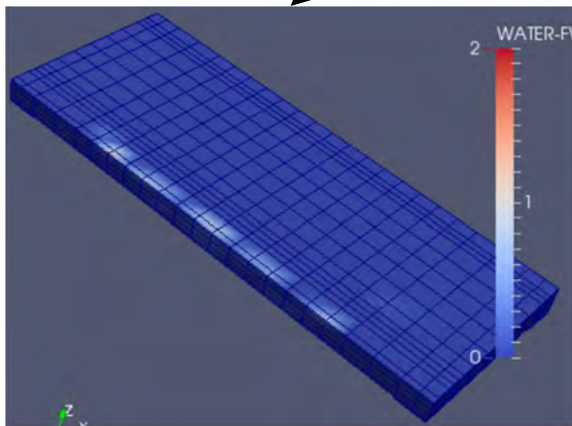
部材が厚く、疲労で壊れない床版も、帯水が継続すると壊れ得る！

Dry air	High cycle loads
Wet condition	Fracture energy, strength, shear transfer
Stagnant water (condensed)	Furthermore, Erosion, disintegration

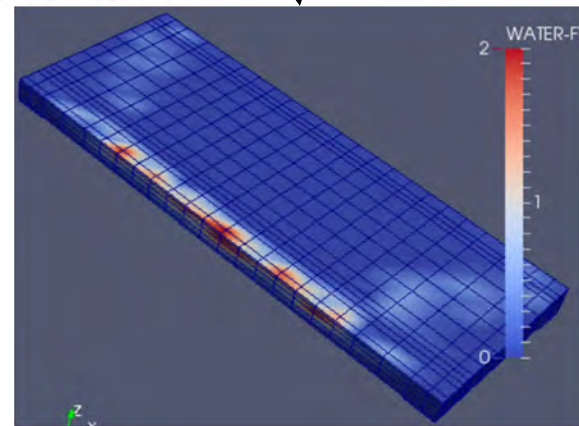
Load level = illegal level



走行N=1回



走行N=1,000回



走行N=30,000回

# 非線形数値解析で扱えない構造工学上の問題

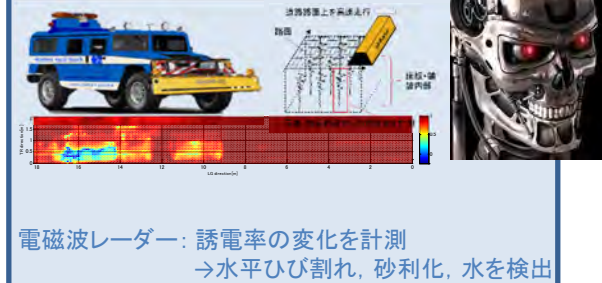
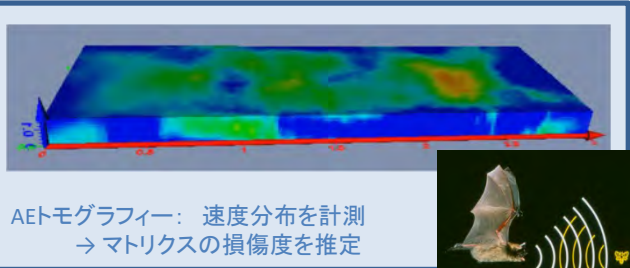
- (1) 施工不良： 現実に多くの構造物の劣化の主因
- (2) 本当の荷重、環境条件(ex過去の過積載) 疲労の主因
- (3) 本当の境界条件： 本当に滑り、回転する？
- (4) 設計ミス、設計図面との違い： どうにもこうにも？

しかし、上記の事項は現時点での構造の検査情報に潜んでいる！  
検査情報は上記の結果を多かれ少なかれ反映している。

検査情報と数値解析を一体同化:Data Assimilation  
現状を推定し、さらに将来予測→マネジメントに繋がる

**ITIL** Laboratory on Innovative Techniques for Infrastructures (ITIL)  
インフラ先端技術共同研究拠点

**東京大学**  
THE UNIVERSITY OF TOKYO



**目視調査** **損傷入力**

目視評価: 貫通ひび割れ, 浮き, 剥落

**微小強制振動法: 共振周波数を計測**  
→ マトリクスの平均的な損傷度を推定

開発中



開発済

開発中

開発済

**損傷情報に変換**  
ひび割れ、マトリクスの損傷、水

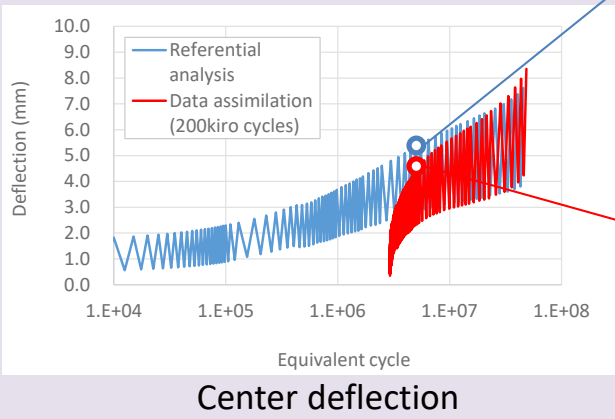
**ドローン: ひび割れ位置・方向**  
+ 浮き・さび汁

開発済

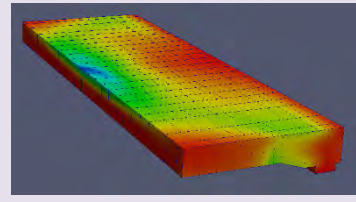
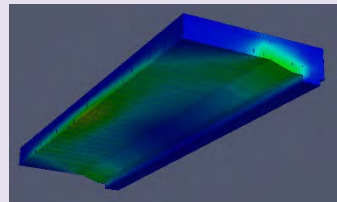
**内部損傷状態を補完推定**

## マルチスケール統合解析によるデータ同化

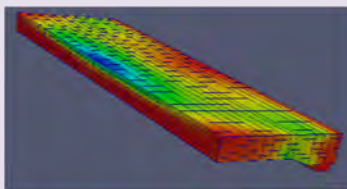
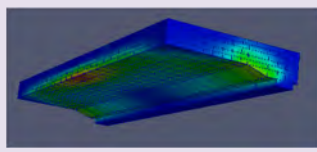
### 床版試験体の輪荷重疲労解析



通常の解析



データ同化解析



ほぼ同じ状態

どこから始めても余寿命が予測可能に

データ同化

既設床版



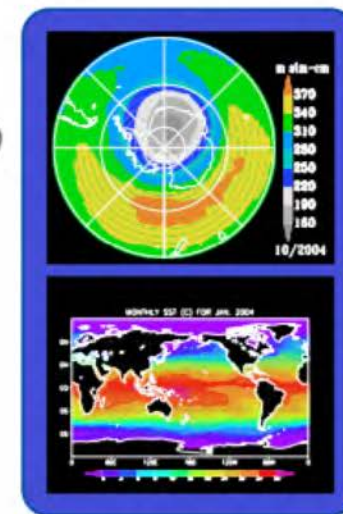
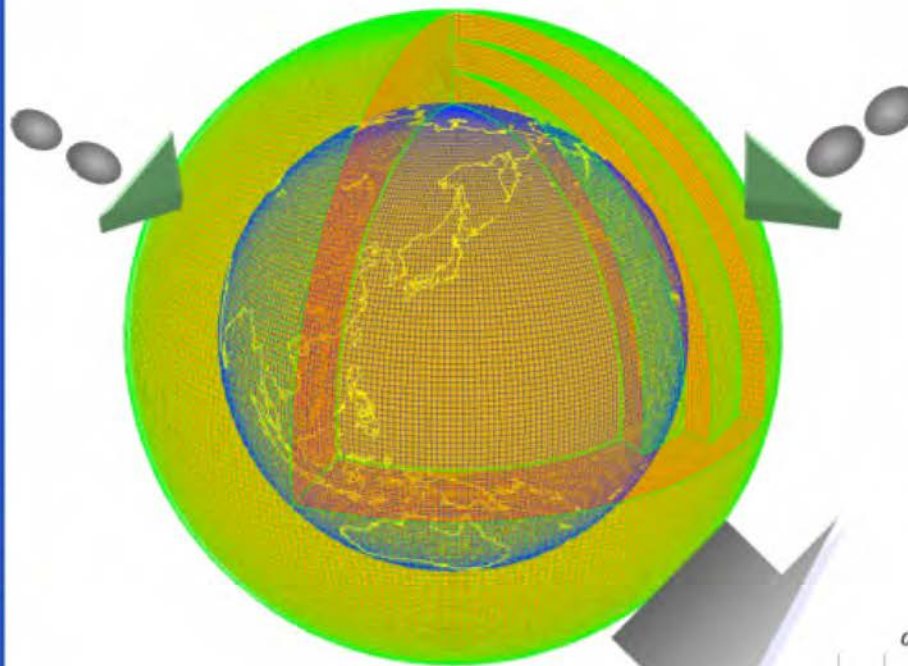
固定及び移動式モニタリング・センシング = 橋梁の点検・モニターと同じ



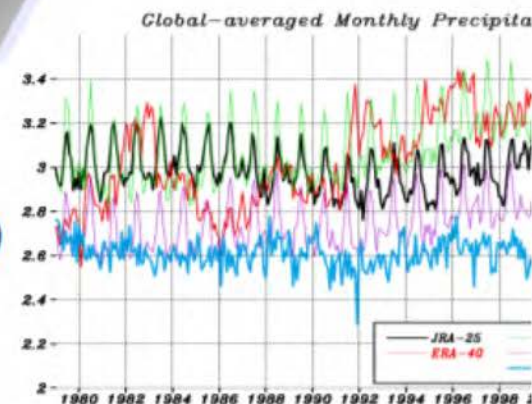
# 観測点間の科学的内挿→未来予測

背景：高度情報技術と大気海洋モデルの進歩：

過去100年の経験の延長線上に未来は見えない！地球温暖化

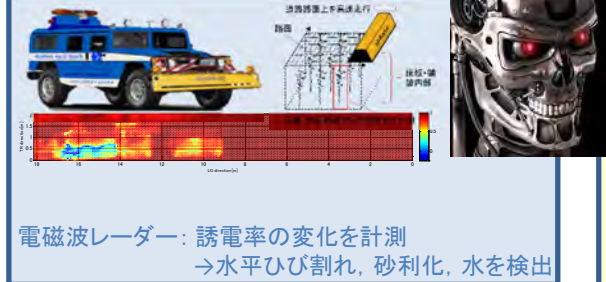
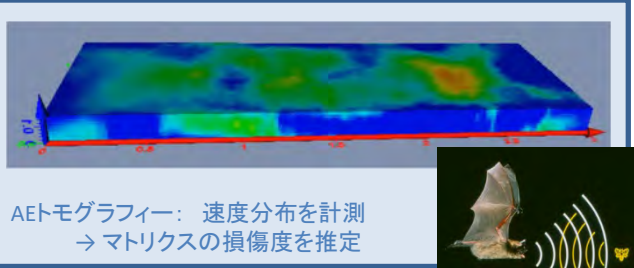


数値モデル  
(物理法則の離散近似)



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**微小強制振動法**：共振周波数を計測  
→マトリクスの平均的な損傷度を推定

開発中



開発済

開発中

開発済

**損傷情報に変換**  
ひび割れ、マトリクスの損傷、水

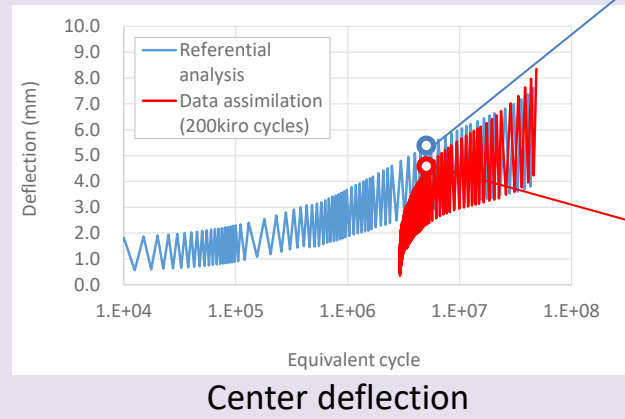
**内部損傷状態を補完推定**

**ドローン**：ひび割れ位置・方向 + 浮き・さび汁

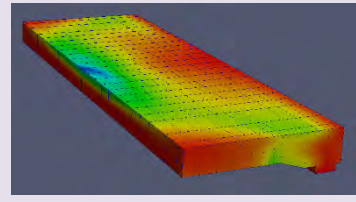
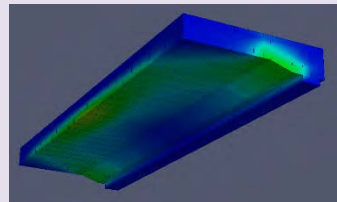
開発済

## マルチスケール統合解析によるデータ同化

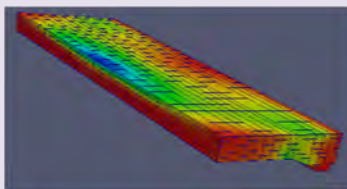
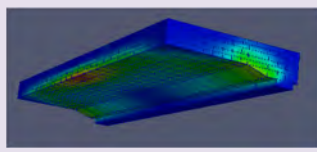
### 床版試験体の輪荷重疲労解析



通常の解析



データ同化解析



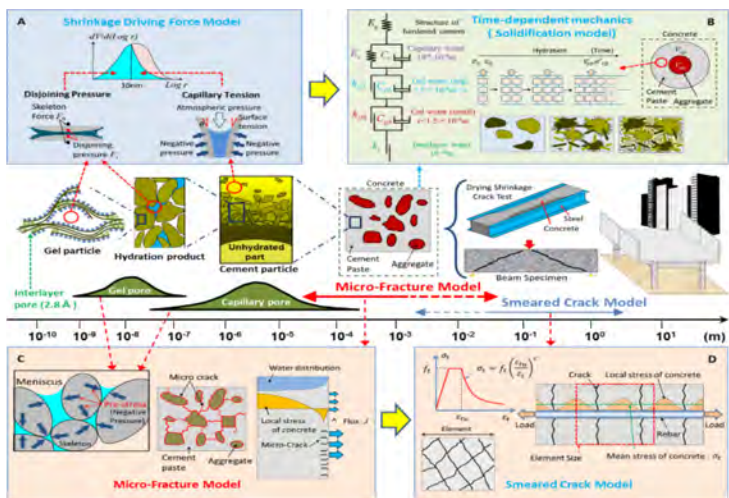
ほぼ同じ状態

どこから始めても余寿命が予測可能に

データ同化

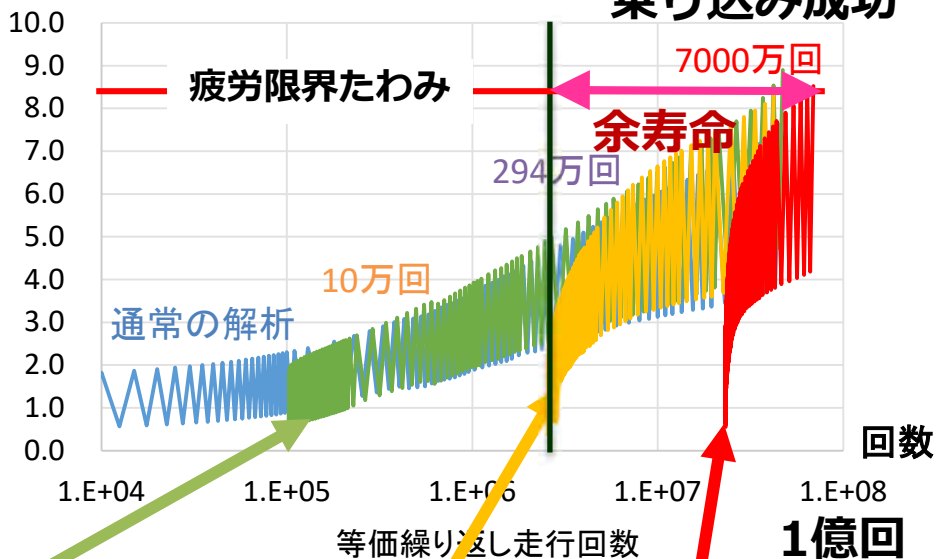
既設床版

# データ同化:RC床版の余寿命予測システム

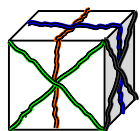


## RC床版の疲労たわみ予測 データ同化による乗り込み成功

たわみ (劣化の指標) (m)

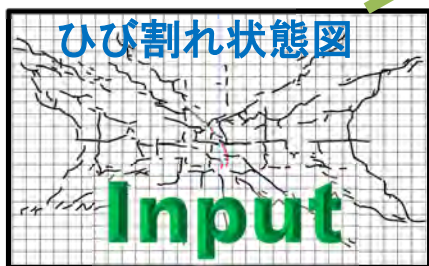


6方向ひび割れモデルで構造内部のひび割れを推定  
Predictor-corrector法

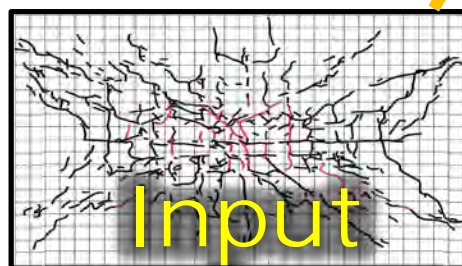


RC床版裏面のひび割れ図 (実測) を初期値としてMS解析に

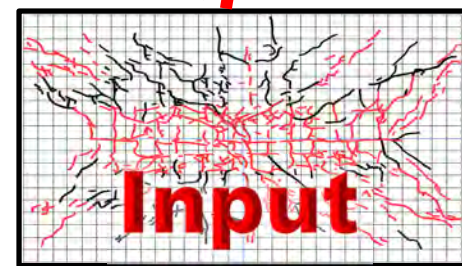
载荷回数



10万回



294万回



2306万回

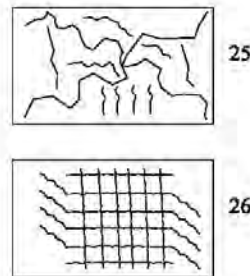
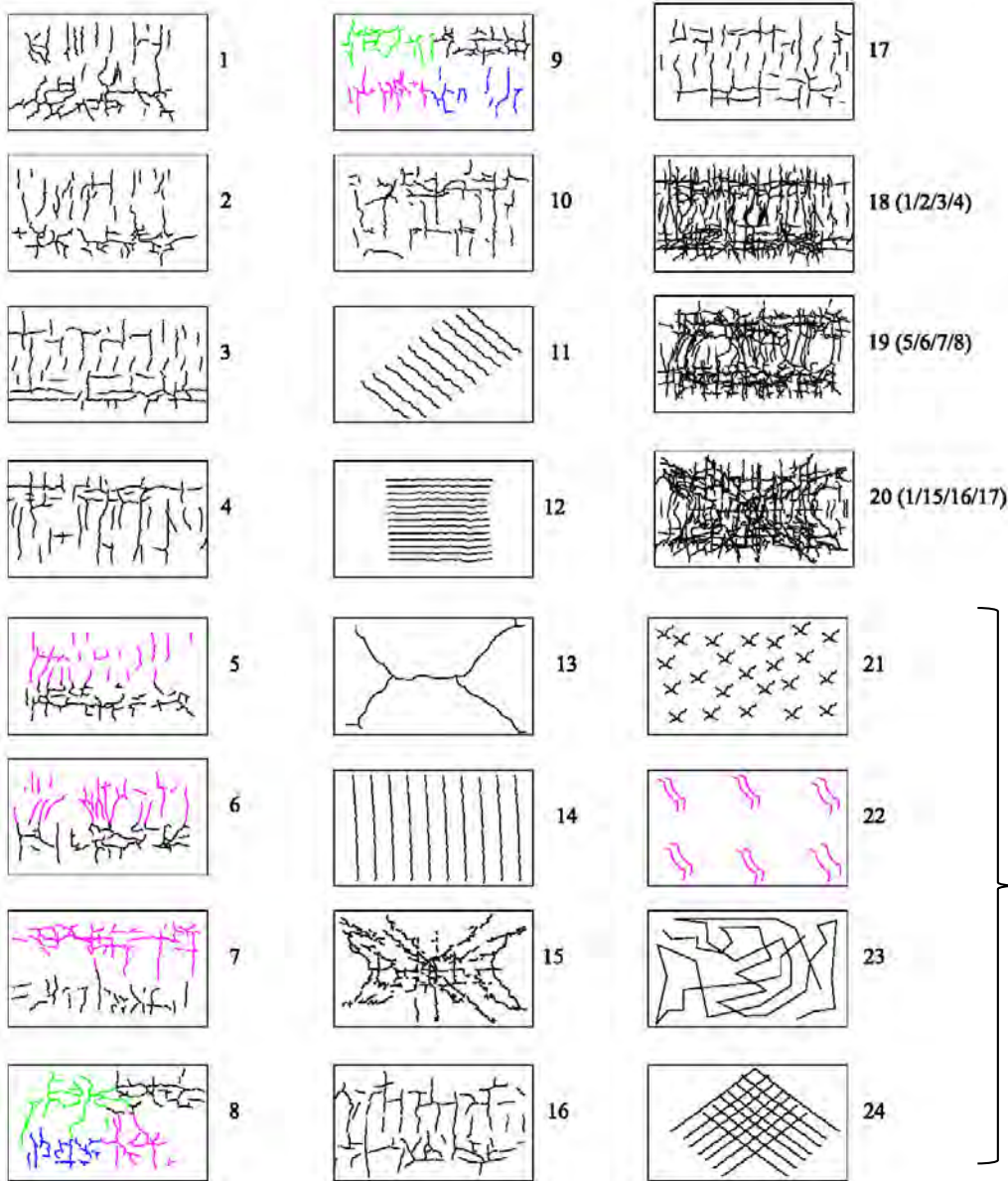
裏面のひび割れ状況から, RC床版の内部損傷と余寿命を predictor-corrector法で推定

# 床版余寿命評価に関わるひび割れパターン

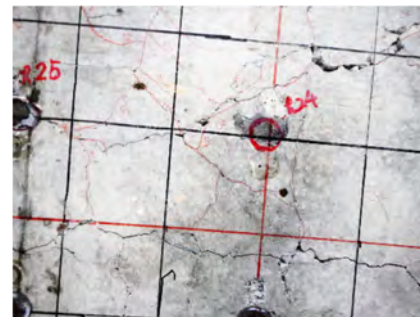
## 実橋梁の点検で得られた割れ図(1000近い)

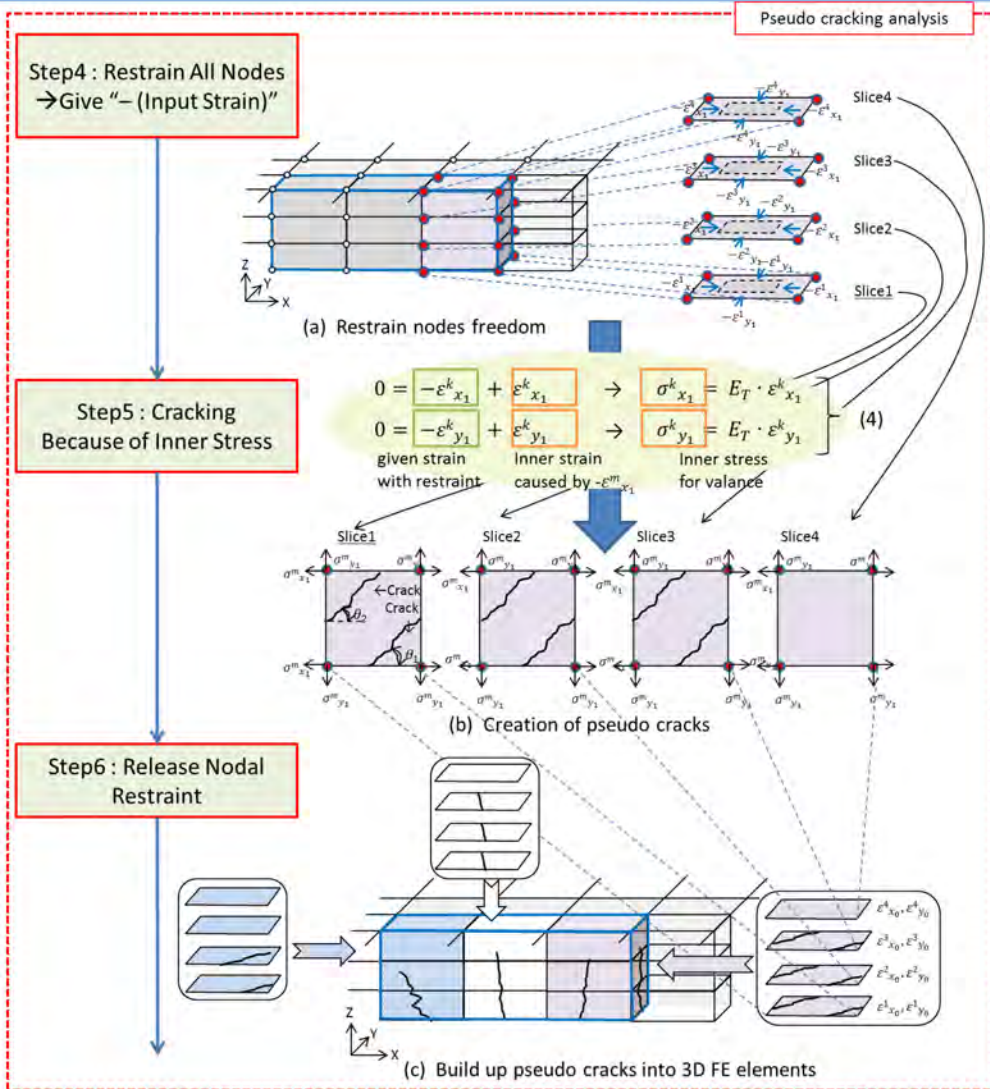
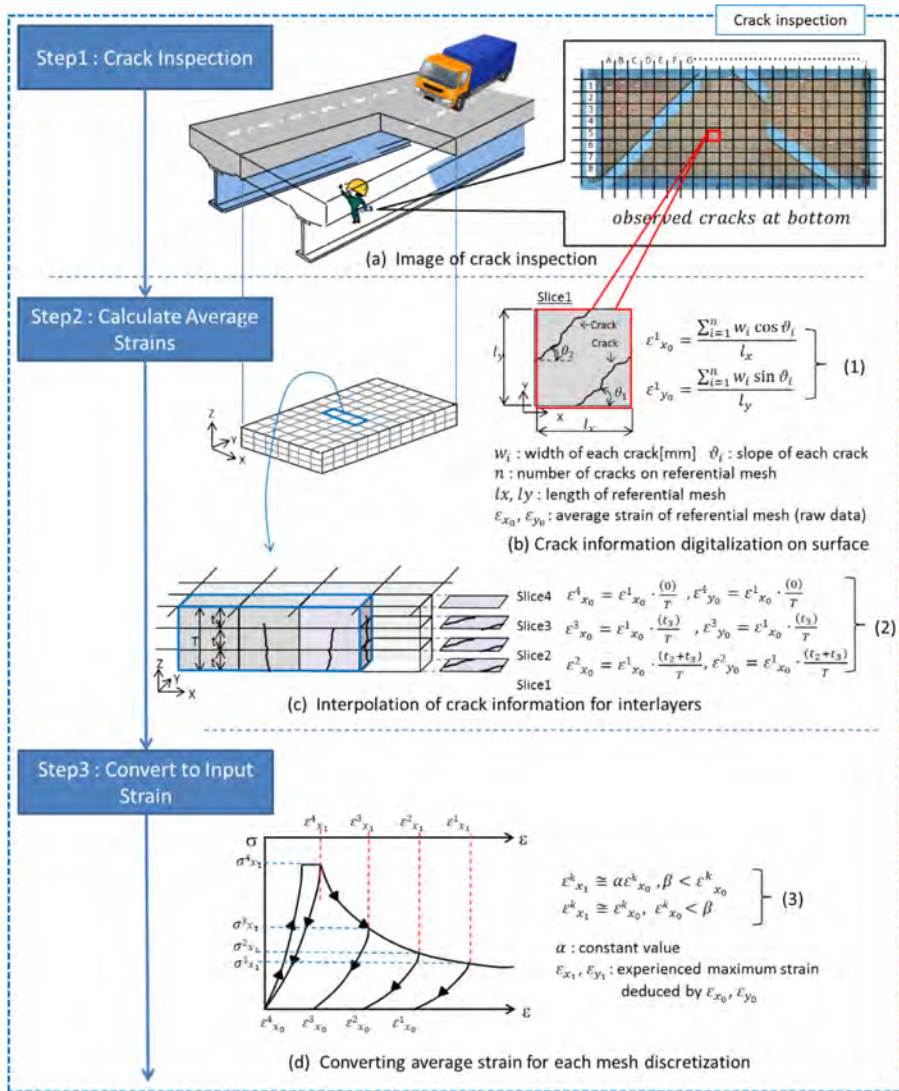
## 試行的に作成したひび割れ図

高速道路の床版ひび割れ図(例)



## 余寿命のランキングと 余寿命の期待値は？





Fujiyama et al. (2011). Pseudo-cracking data assimilation, J. Advanced Concrete Technology

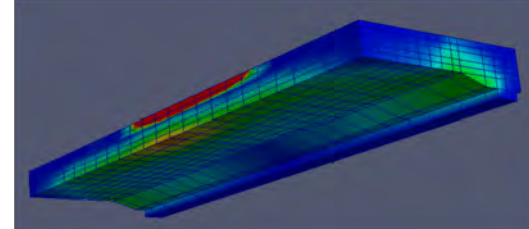
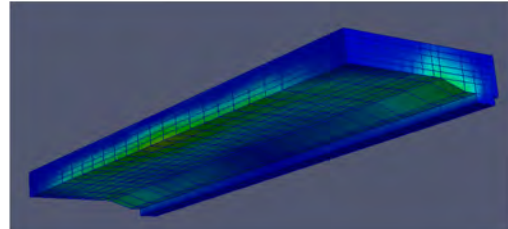
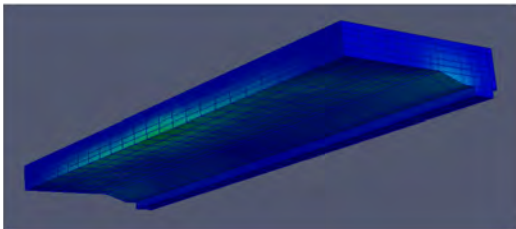


① 2.94 million cycle

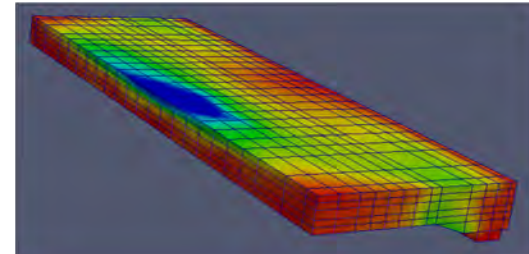
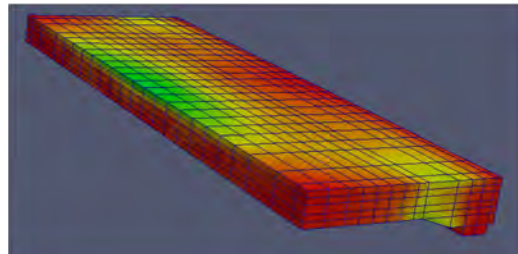
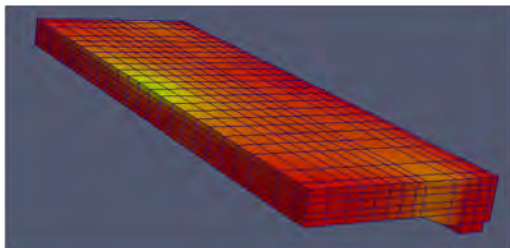
② 3.37 million cycle

③ 5.42 million cycle

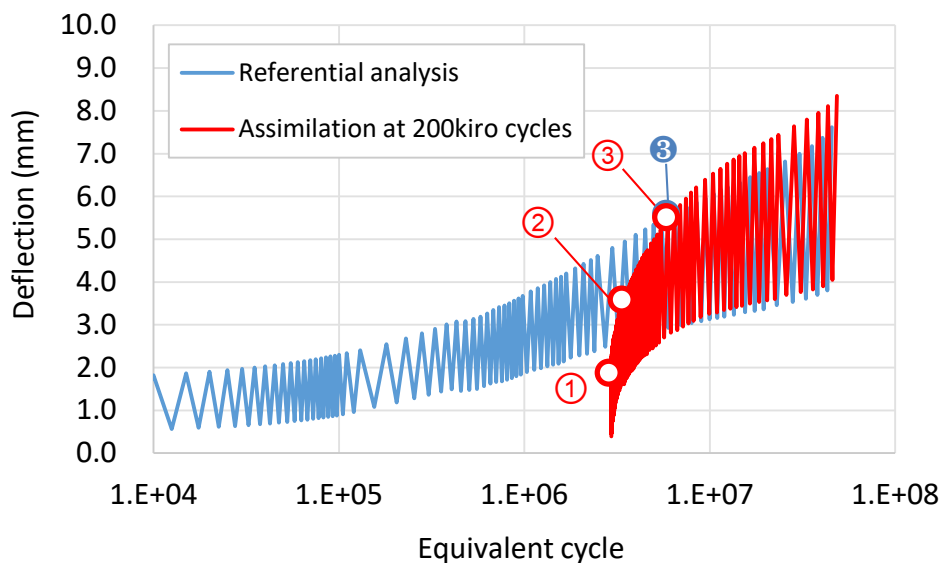
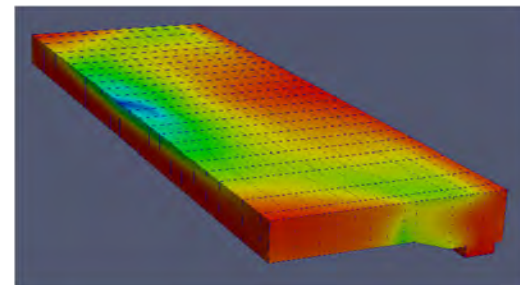
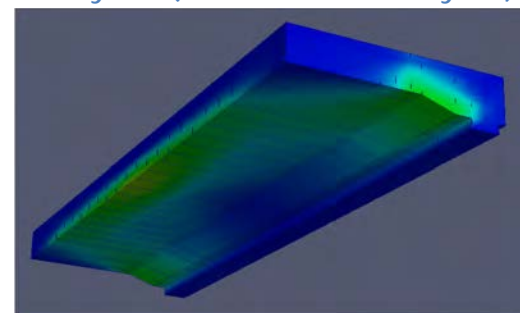
(a) Lower face



(b) Upper face



③ 5.42million cycle (Referential analysis)



(c) Center deflection

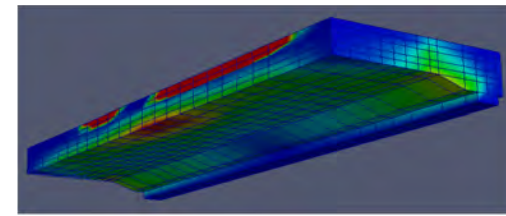
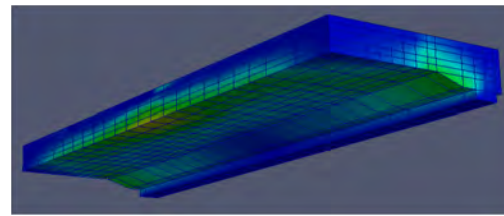
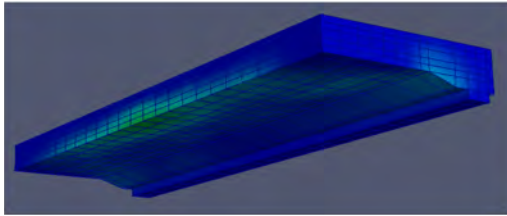


① 23.06 million cycle

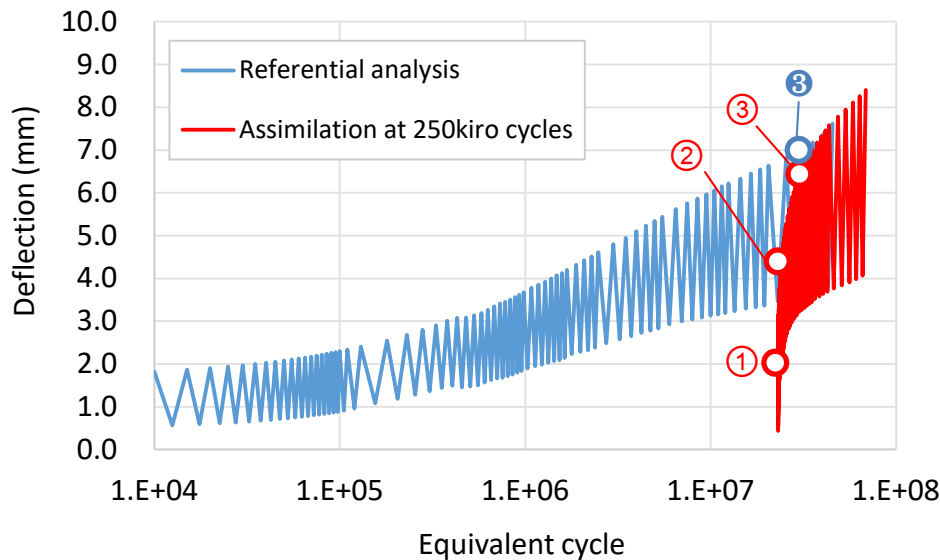
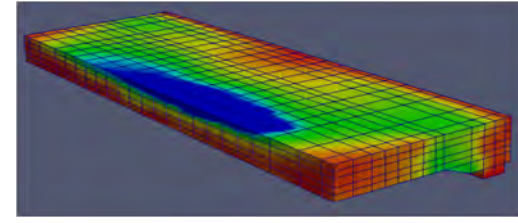
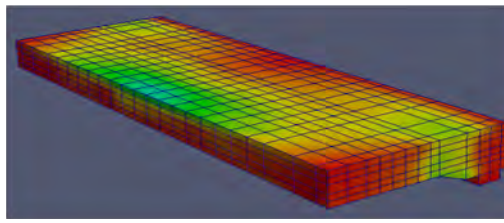
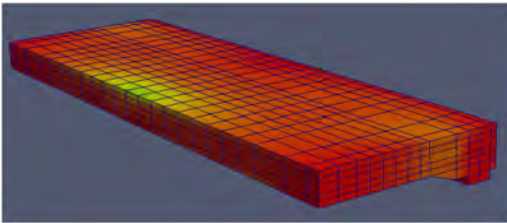
② 24.04 million cycle

③ 31.54 million cycle

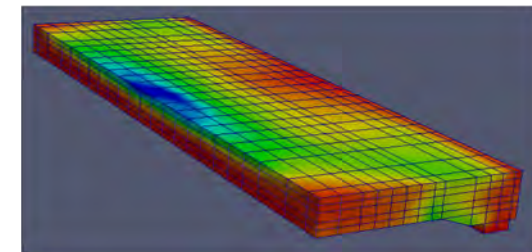
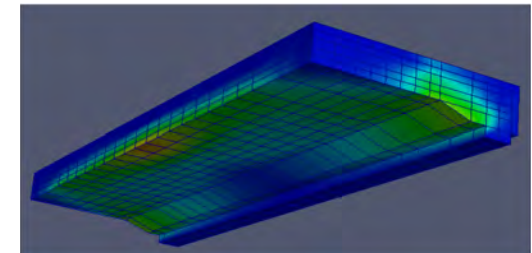
(a) Lower face



(b) Upper face



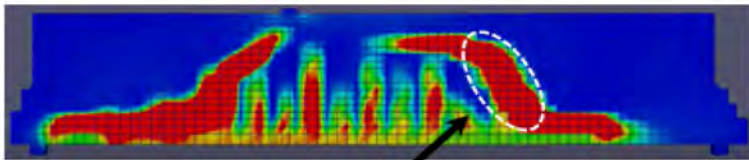
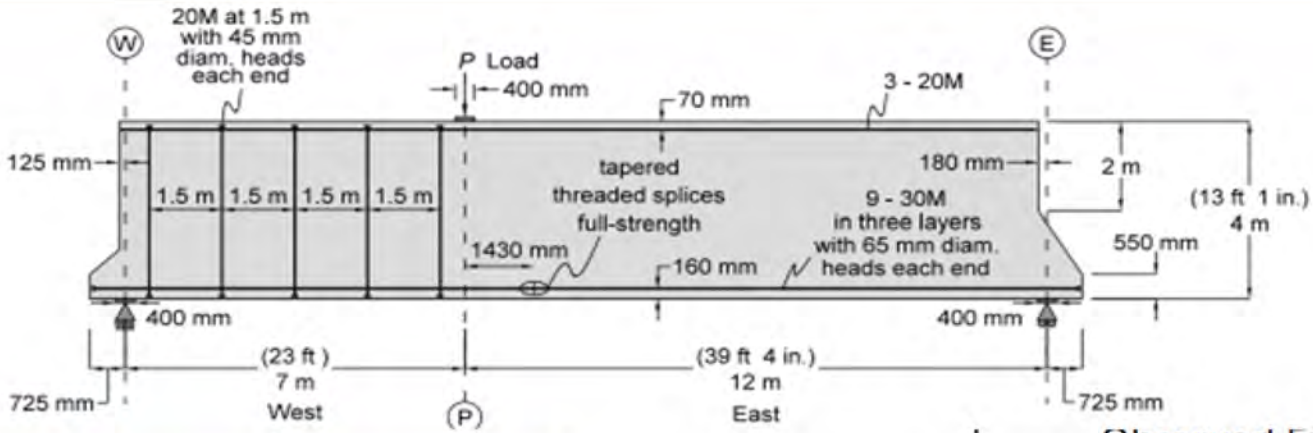
③ 31.5million cycle (Referential analysis)



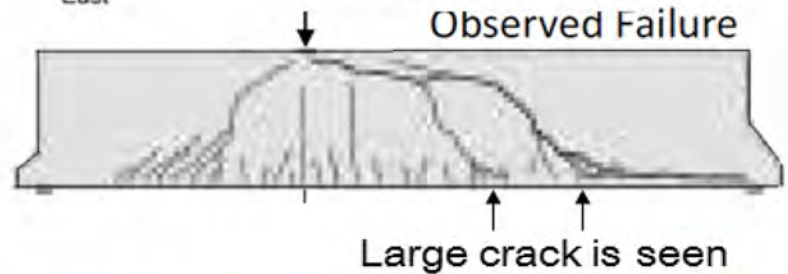
(c) Center deflection



# 目視情報から面外せん断の位置推定の過程例

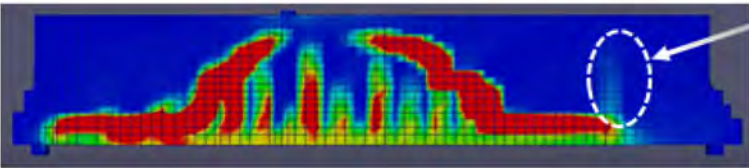


After **predictor-corrector cycles**, the crack direction is modified as the most probable internal cracks.



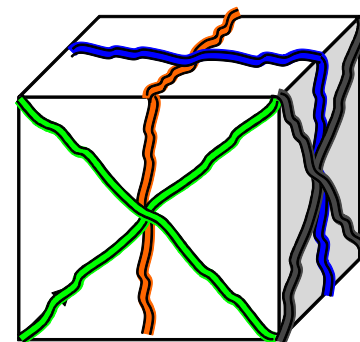
Surface crack is fixed as inspection does.

If crack is assumed far from the reality, this gets mechanically inactive.

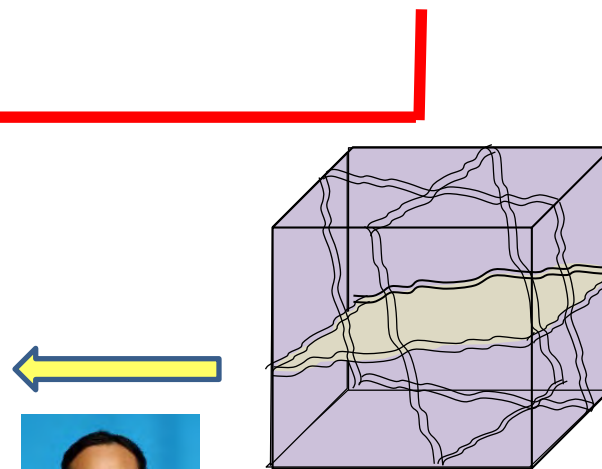
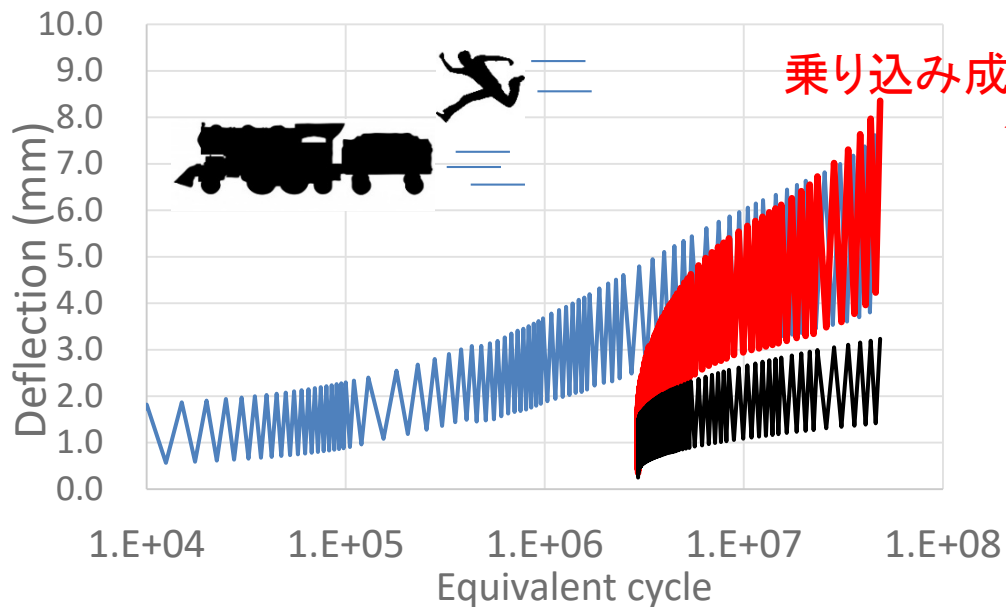




データ同化に必要な数理モデルには合理性、妥当性が必須



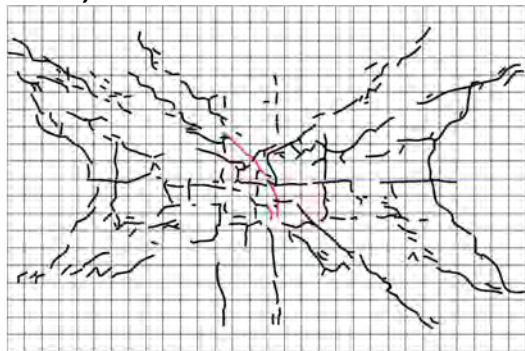
独立6方向の非直交ひびわれ  
or 3方向ひび割れ投影モデル



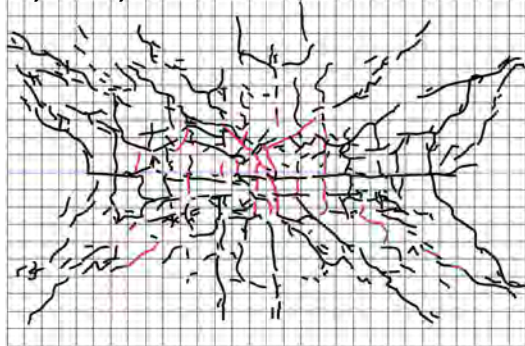
独立3方向のみの  
非直交ひびわれ



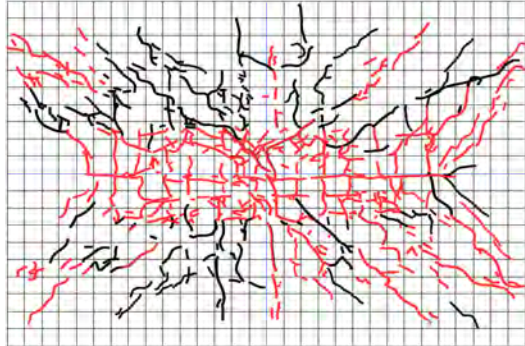
100,000回



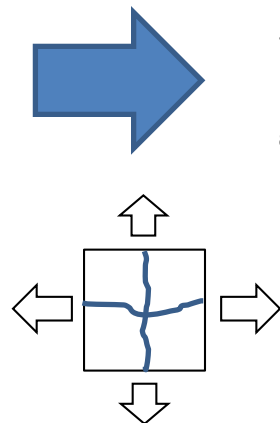
2,000,000回



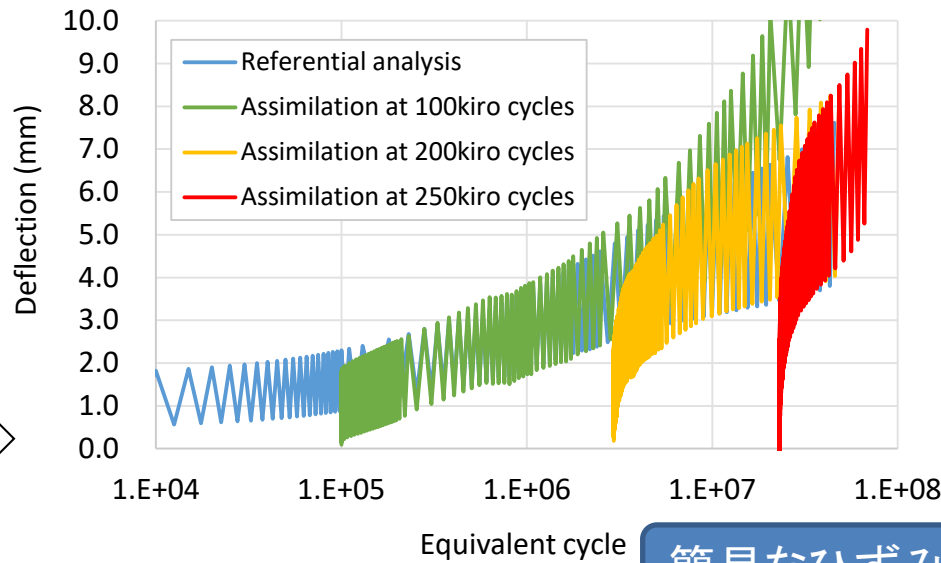
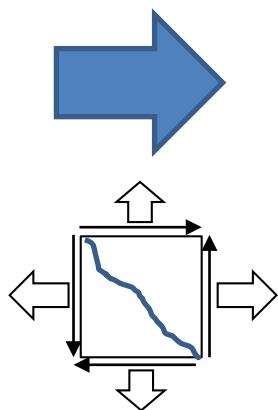
25,000,000回



X,Y 引張  
ひずみのみ

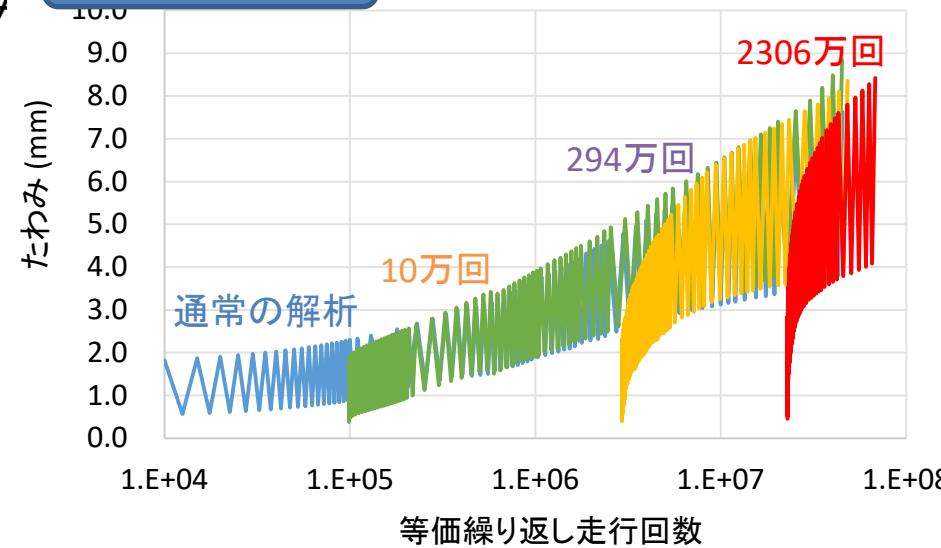


せん断ひずみ  
(ひび割れの  
方向)も考慮



簡易なひずみ

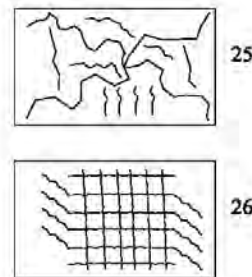
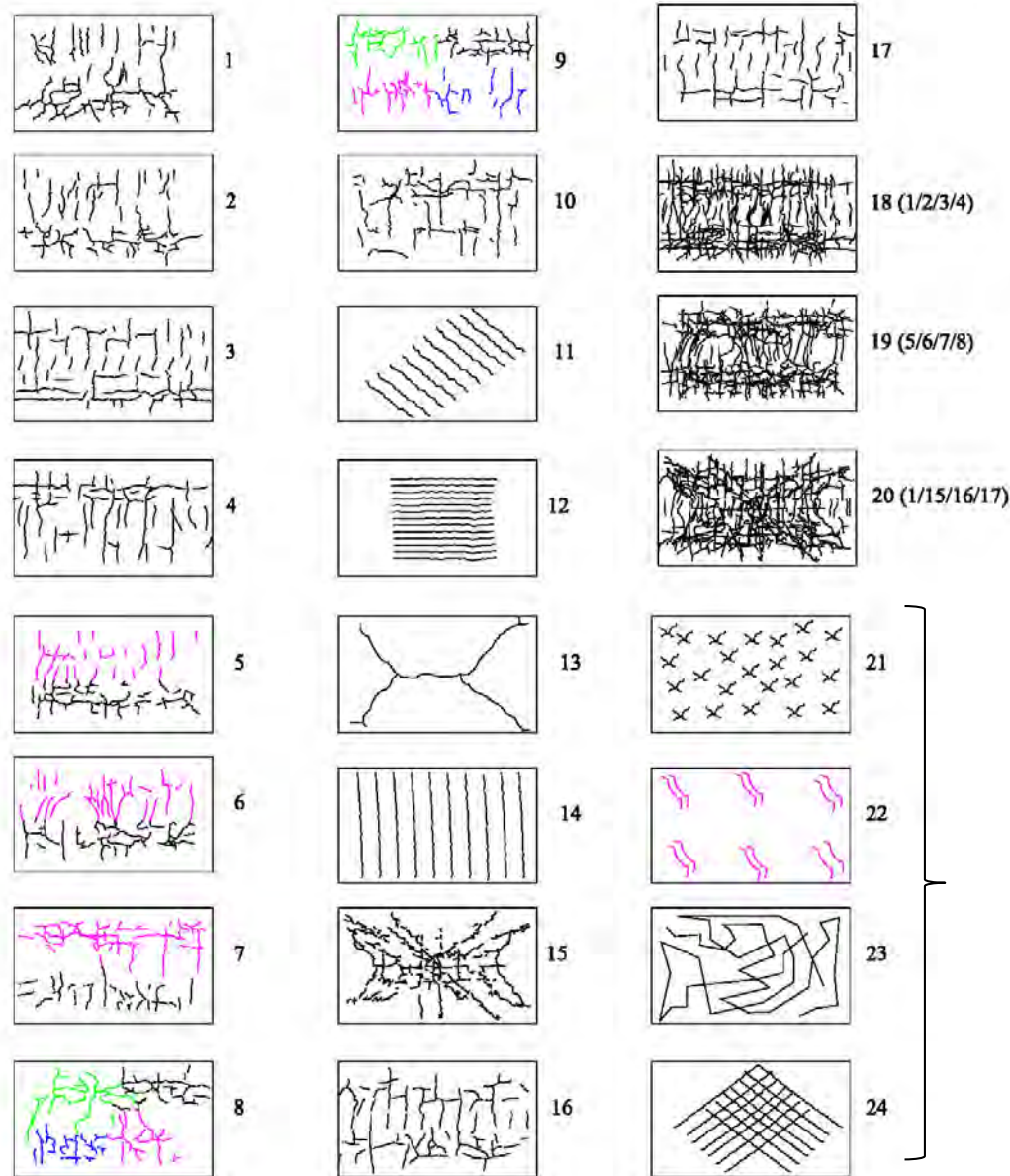
厳密なひずみ



等価繰り返し走行回数

# 床版余寿命評価のAI活用

## 試行的に作成したひび割れ図



人工的に作った  
パターンも教師  
データに

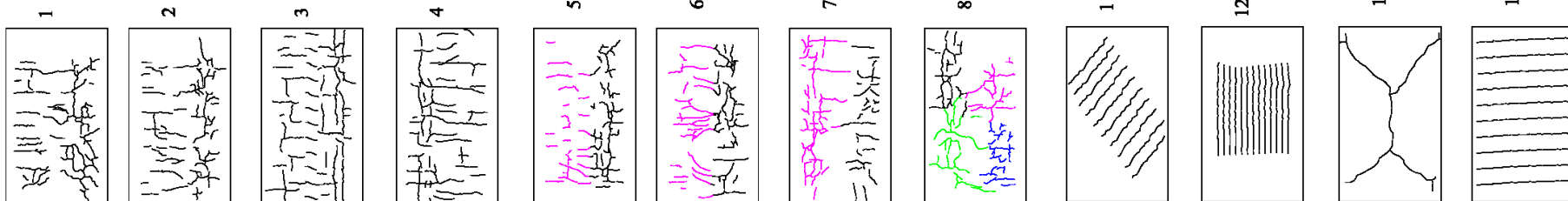
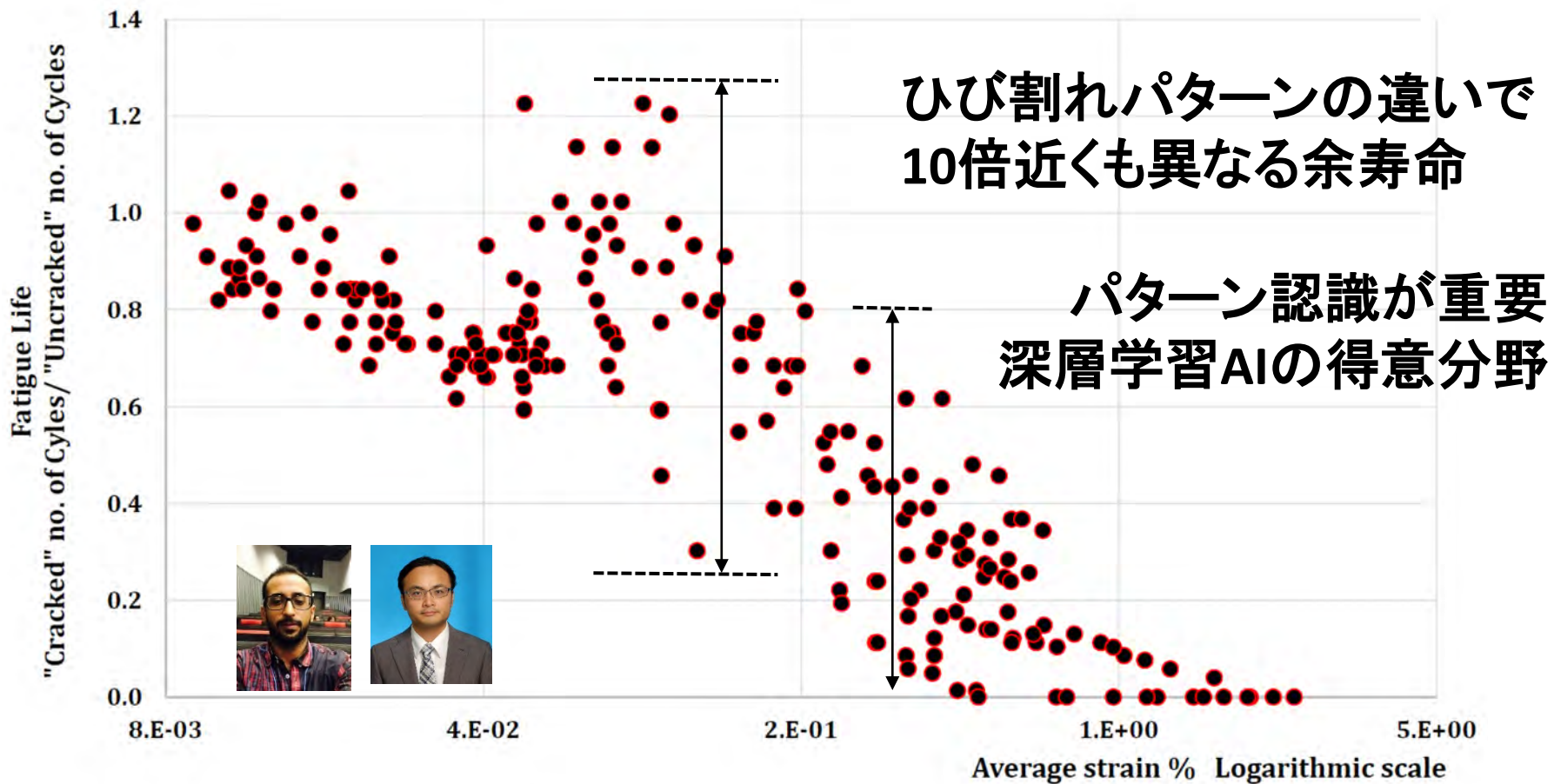


様々なひび割れ状況における床版の余寿命を、データ同化で計算



AI学習により、データ同化の結果を総合化し、現場では計算無しで即時の余寿命診断

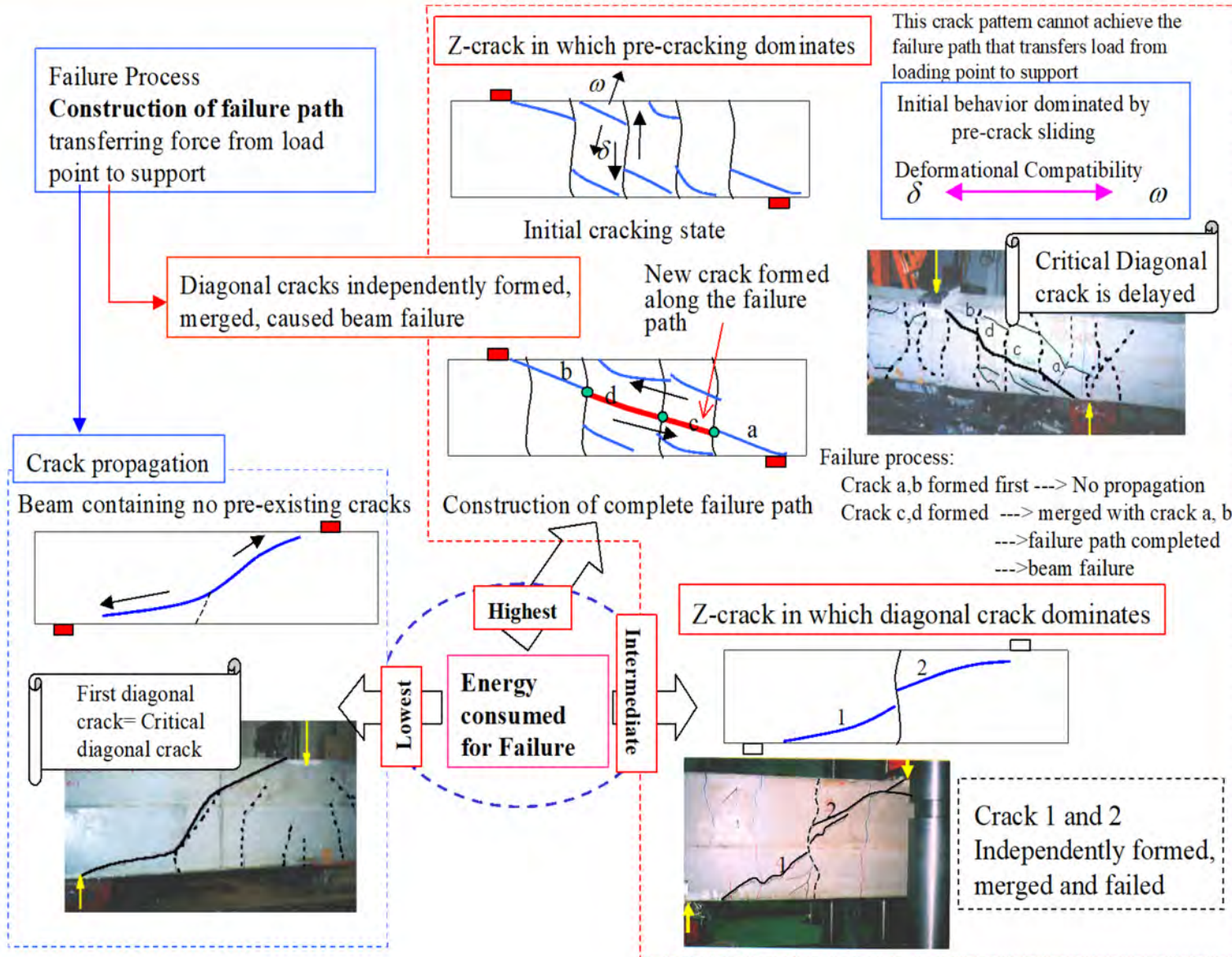
高速道路の床版ひび割れ図(例)



# 非直交ひび割れ群の相互作用



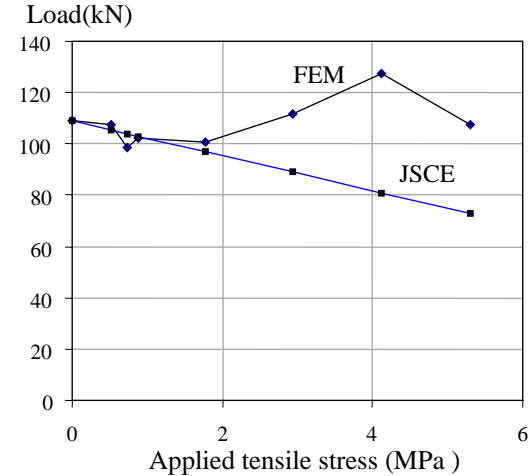
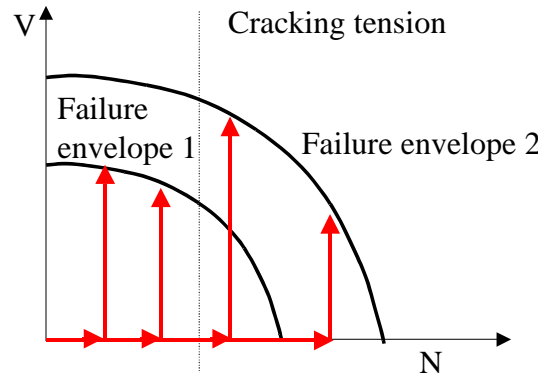
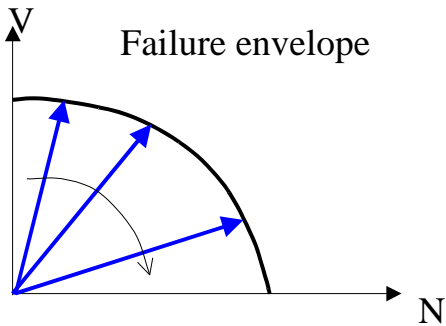
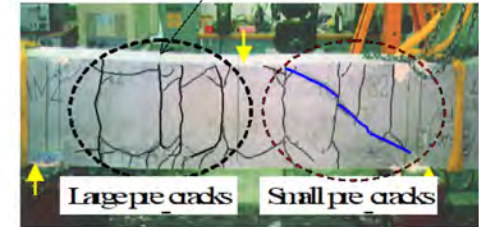
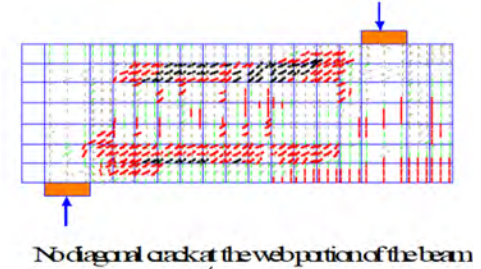
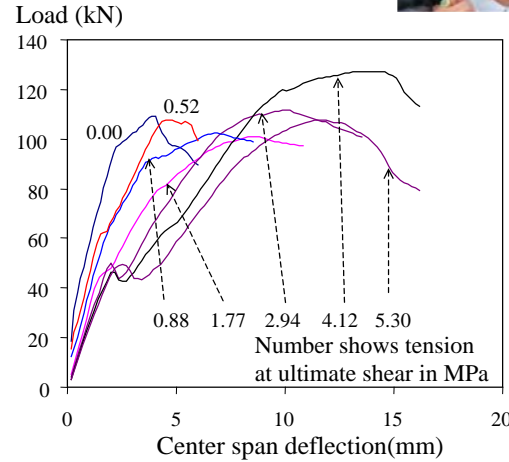
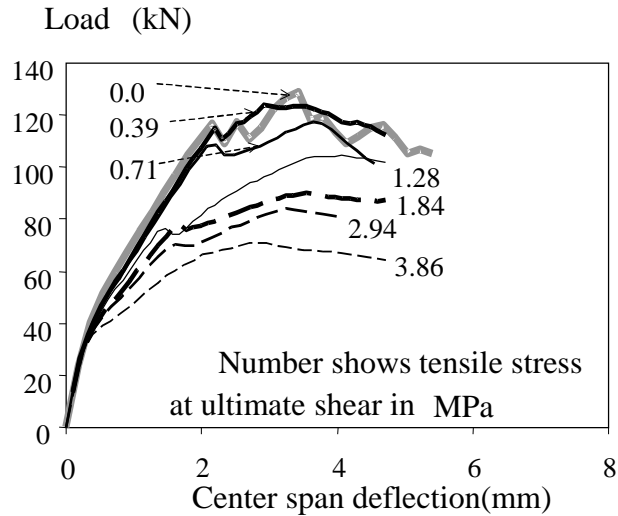
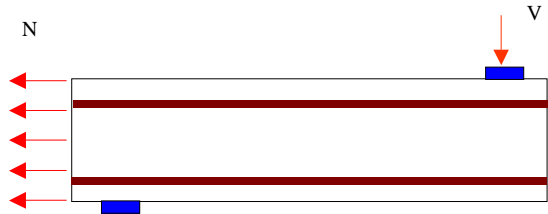
Prof. A. Pimanmas



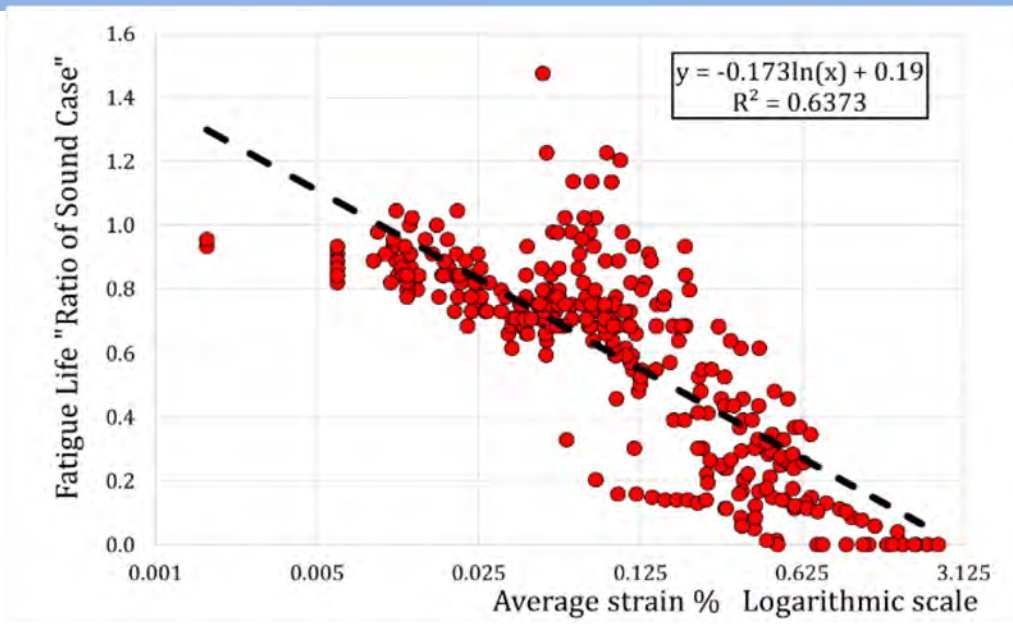
非直交ひび割れ群は、相互のひび割れ進展に相互に影響を及ぼす。

# ひび割れパターンは損傷履歴の足跡

Prof. A. Pimanmas



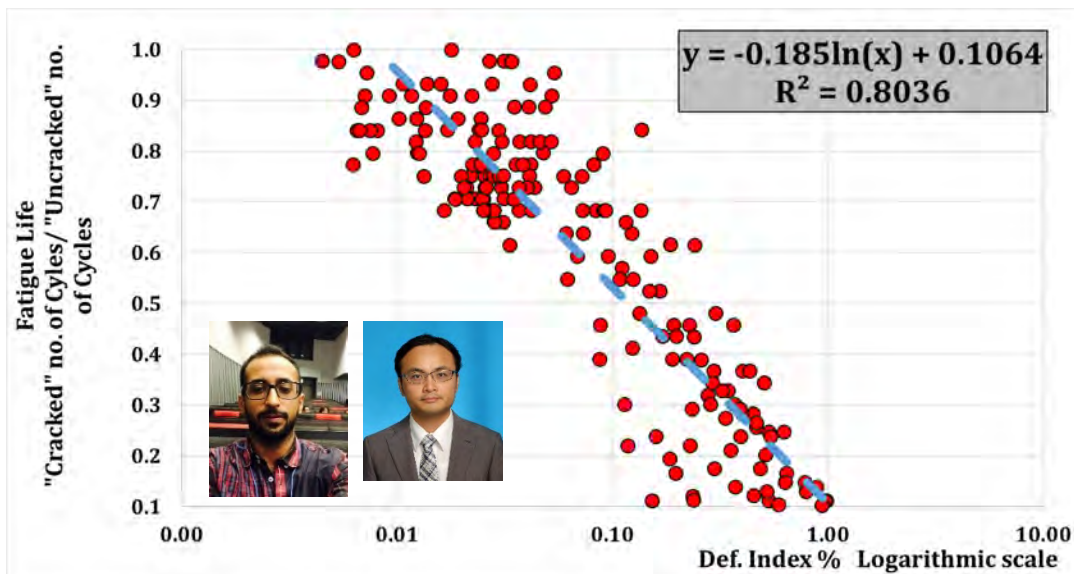
非直交ひび割れ群は、相互のひび割れ進展に相互に影響を及ぼす。

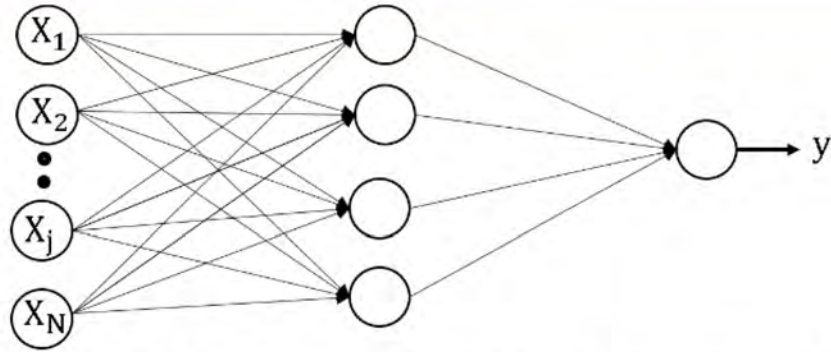


How about prediction by AI?



下面ひび割れと平均ひずみ

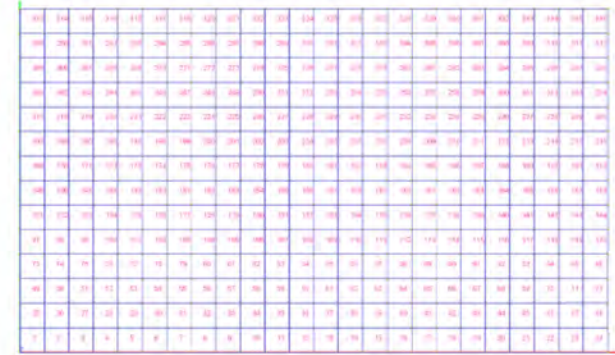
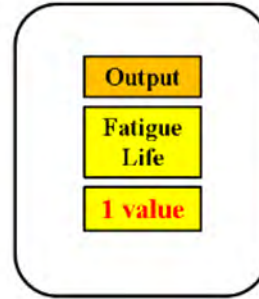
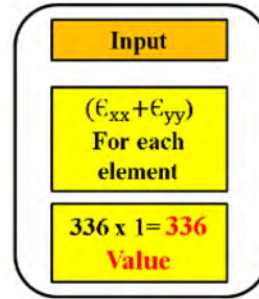




Input Layer

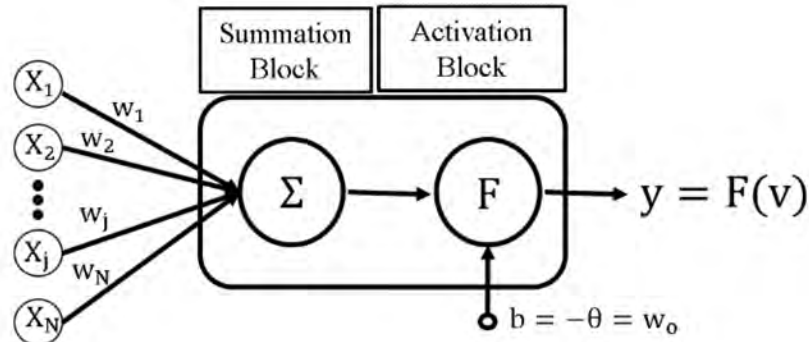
Hidden Layer

Output Layer

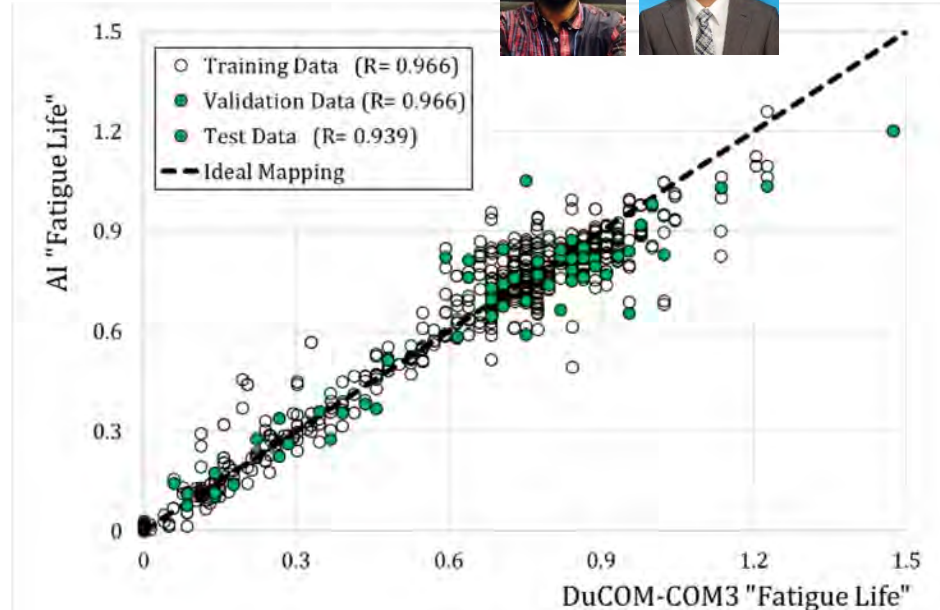


Plan View "Slab's bottom surface"  
Total no. of Elements= 336

入力層、隠れ層、出力層で構成。それぞれの層には複数のニューロンが存在し、各ニューロンは前後の層のすべてのニューロンとシナプスによって結合。入力層の数値に応じて信号がニューロンを伝わり、最終的に出力層に到達。



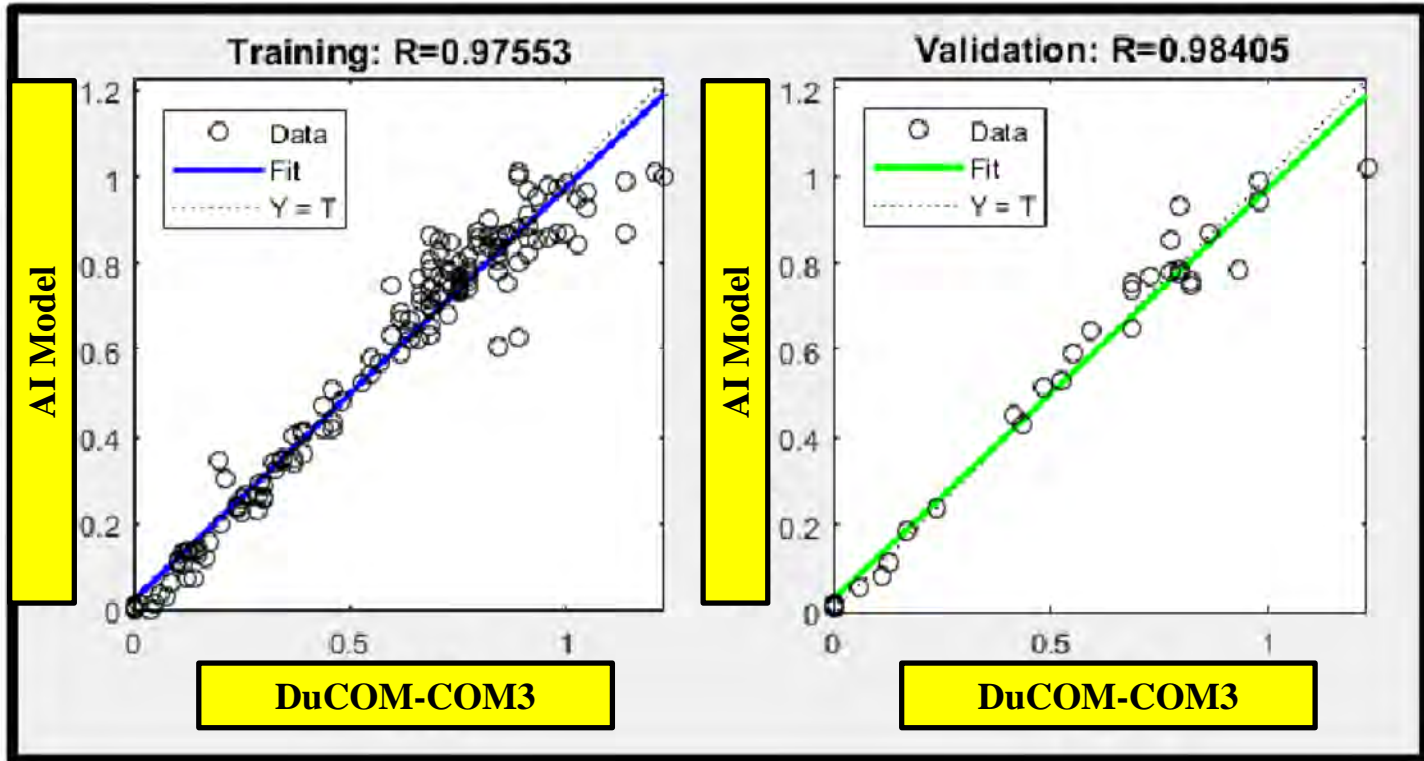
各シナプスは重み関数 $w_i$ を持ち、各ニューロンは活性化関数 $F(v)$ とバイアス $b$ を持つ。この構造で次の層への信号 $y$ の伝わり方が制御される。教師データをなるべく再現できるように定数を最適化。出力値の推定精度を高める。



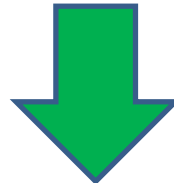


訓練データ  
70%のデータを使用

残りのデータに対する  
適合性



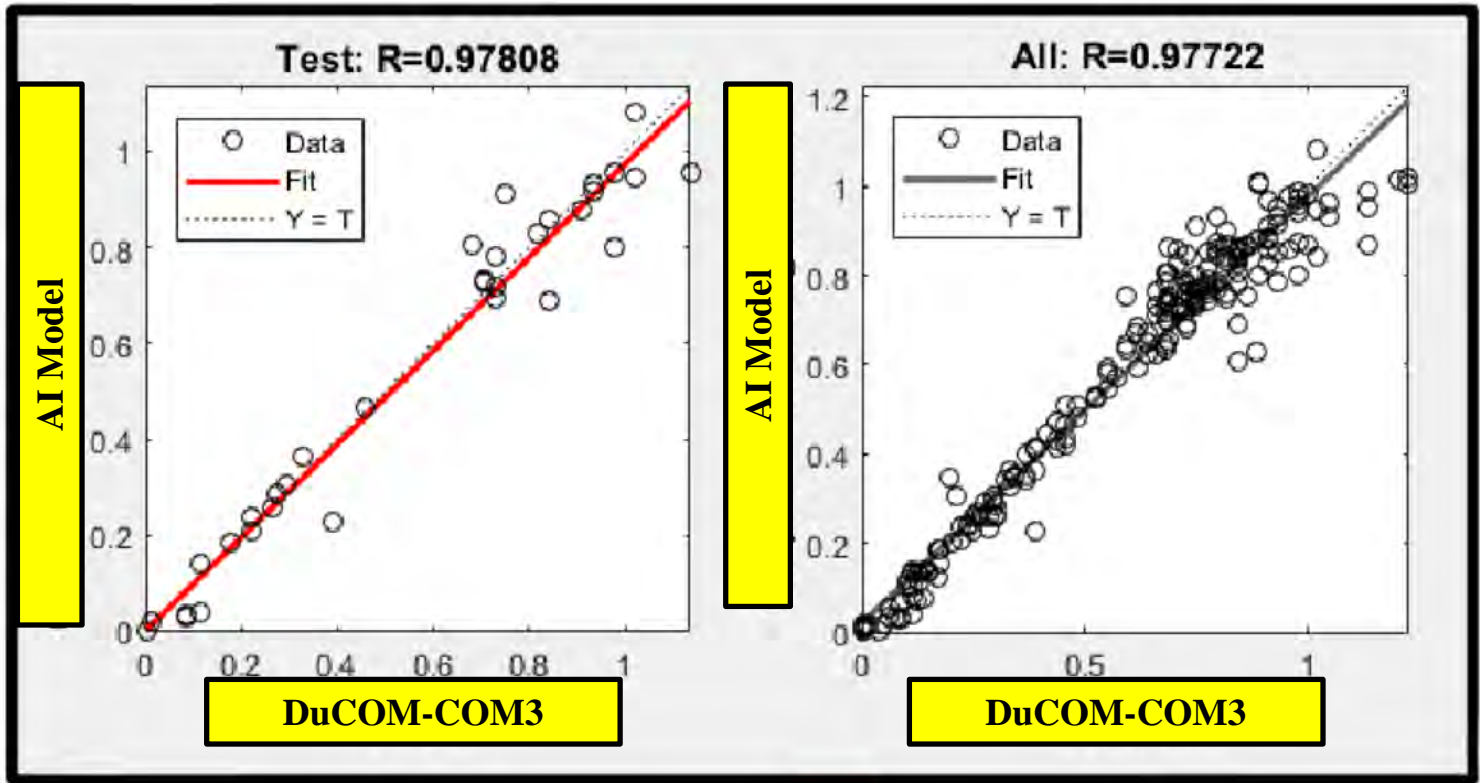
前川宏一、田中泰司、Eissa Fathalla (2017.12) :Society5.0時代における既設RC床版の疲労寿命評価,土木構造・材料論文集 第33号 2017年12月(予定)



今のところ、力学指標と比較して、適合性が高い

全体の15%のデータでトレーニング

全てのデータで検証



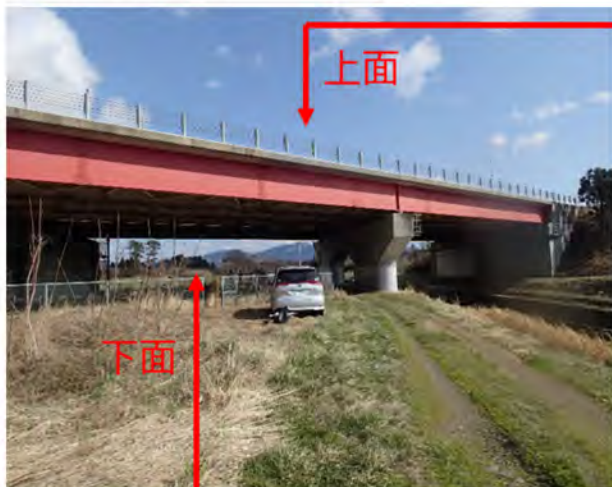
前川宏一、田中泰司、Eissa Fathalla (2017.12) :Society5.0時代における既設RC床版の疲労寿命評価,土木構造・材料論文集 第33号 2017年12月(予定)



今のところ、力学指標と比較して、適合性が高い

# 数値解析は人工知能を鍛え込む教師となる？

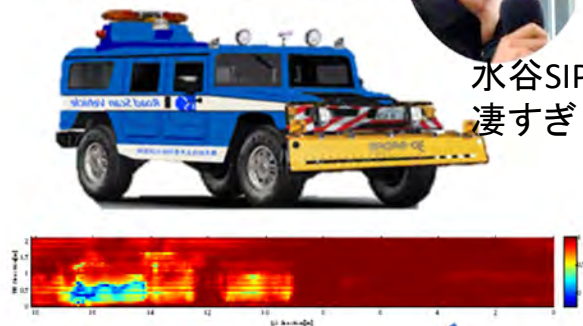
## 実橋梁床版



## 高精細ひび割れ画像

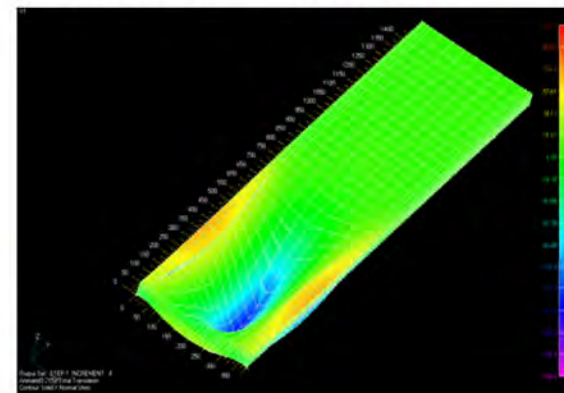


## 非破壊計測 (3次元レーダーなど)



水谷SIP  
凄すぎ！

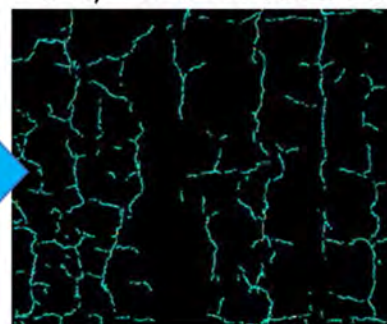
## マルチスケール解析



水, 土砂化,  
水平ひび割れ

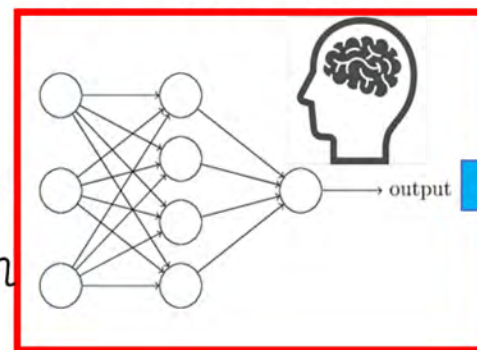
学習

## ひび割れ自動検出 (AI, ウェーブレット変換など)



ひび割れ

## AI (ニューラルネットワークなど)



余寿命評価



田中SIP大幹事

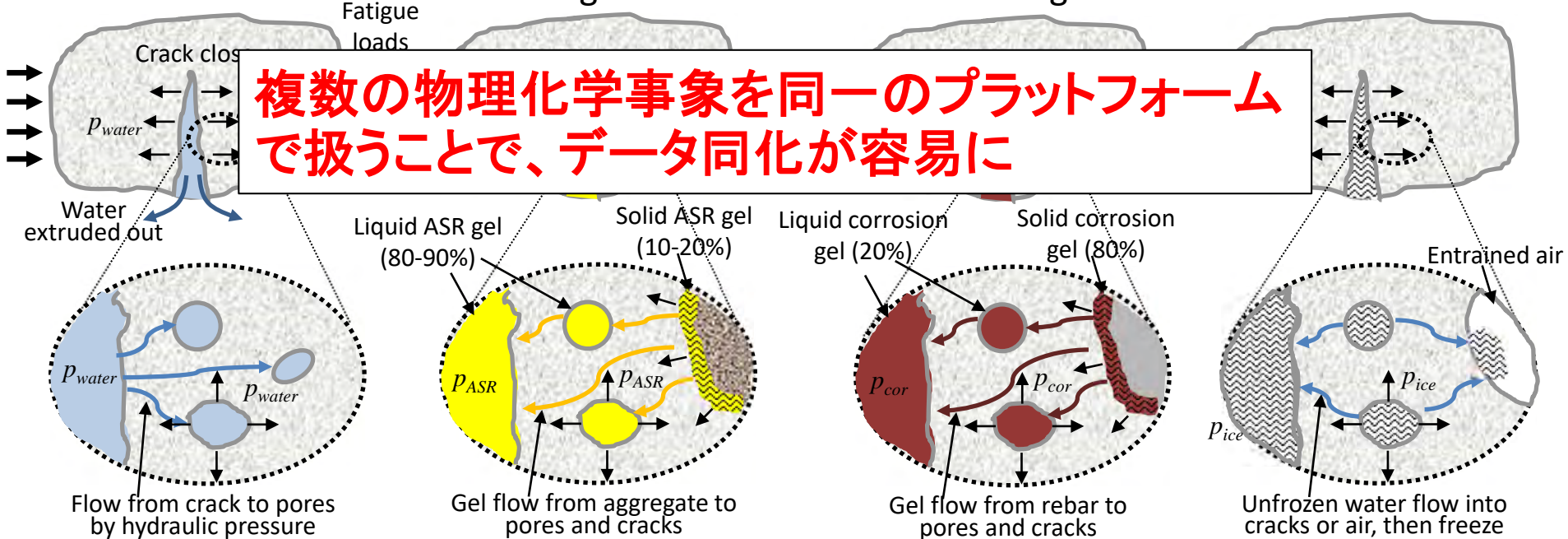
Condensed water

ASR gel

Corrosion gel

Frozen ice

複数の物理化学事象を同一のプラットフォームで扱うことで、データ同化が容易に



Crack open in water



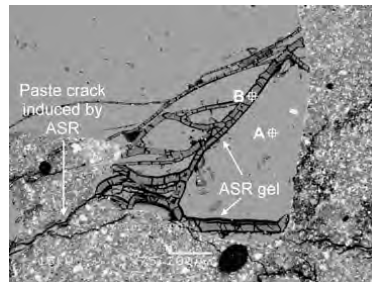
Crack closure with expelled water



Disintegrated concrete after fatigue + stagnant water



Discharged ASR gel through cracks: macroscopic motion



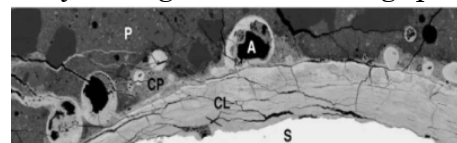
ASR gel ring and cracks



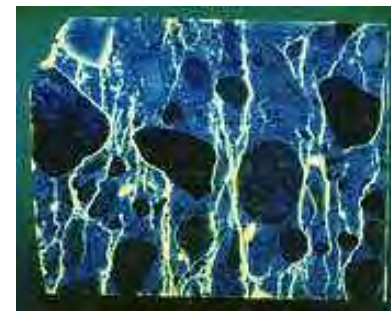
Injected and migrant of corrosion gel through cracks



Injected gels into crack gaps



S=steel CL=corrosion solidified gel, A=injected corrosion gel



Freeze-thaw damage



Ice formation inside entrained air space

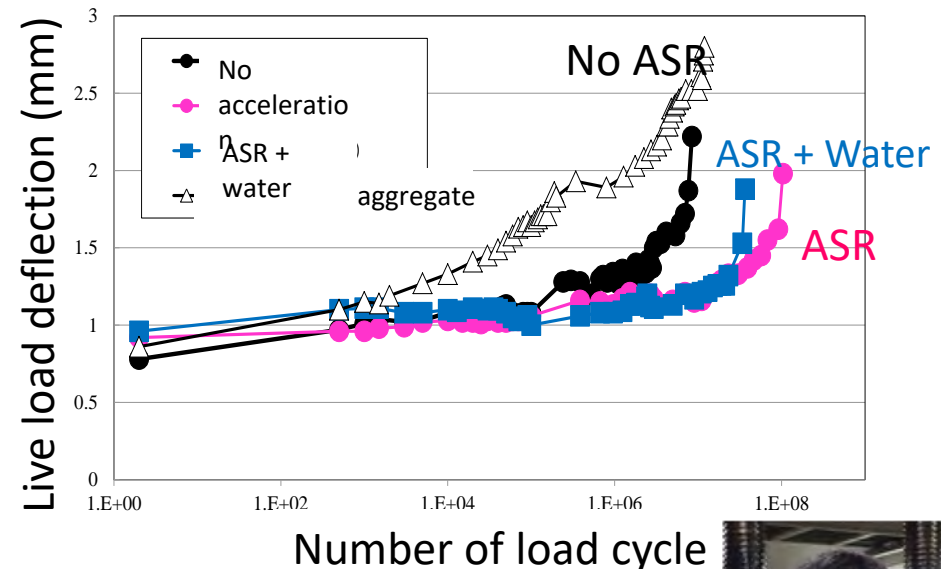
RC bridge deck deteriorated by ASR



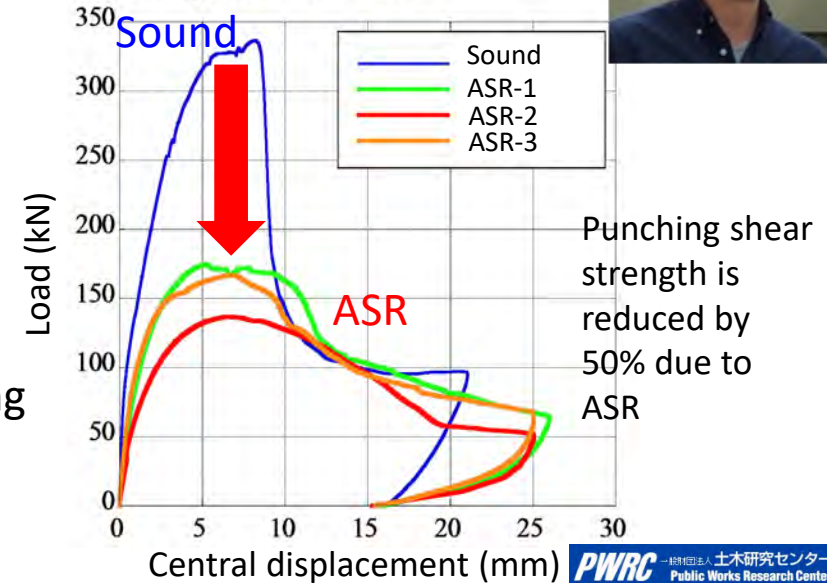
Sawn specimens



Loading



Punching shear test

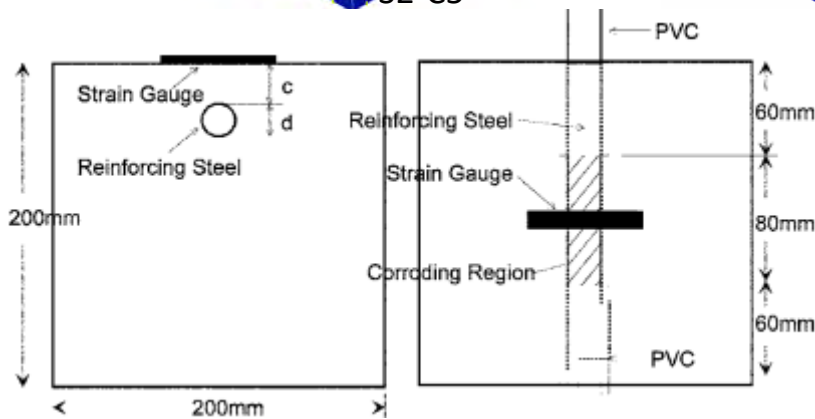
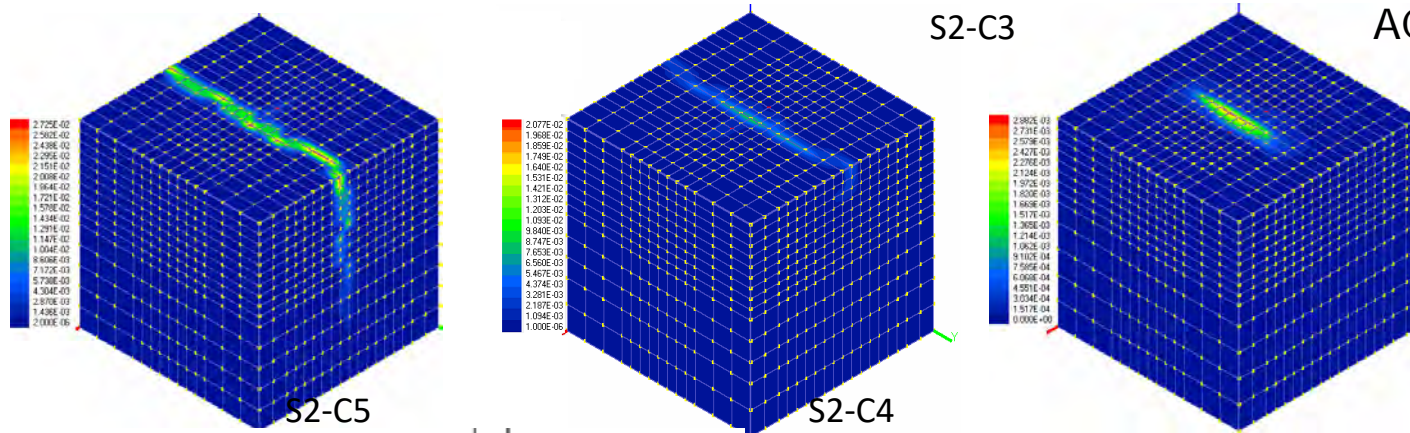


Punching shear strength is reduced by 50% due to ASR

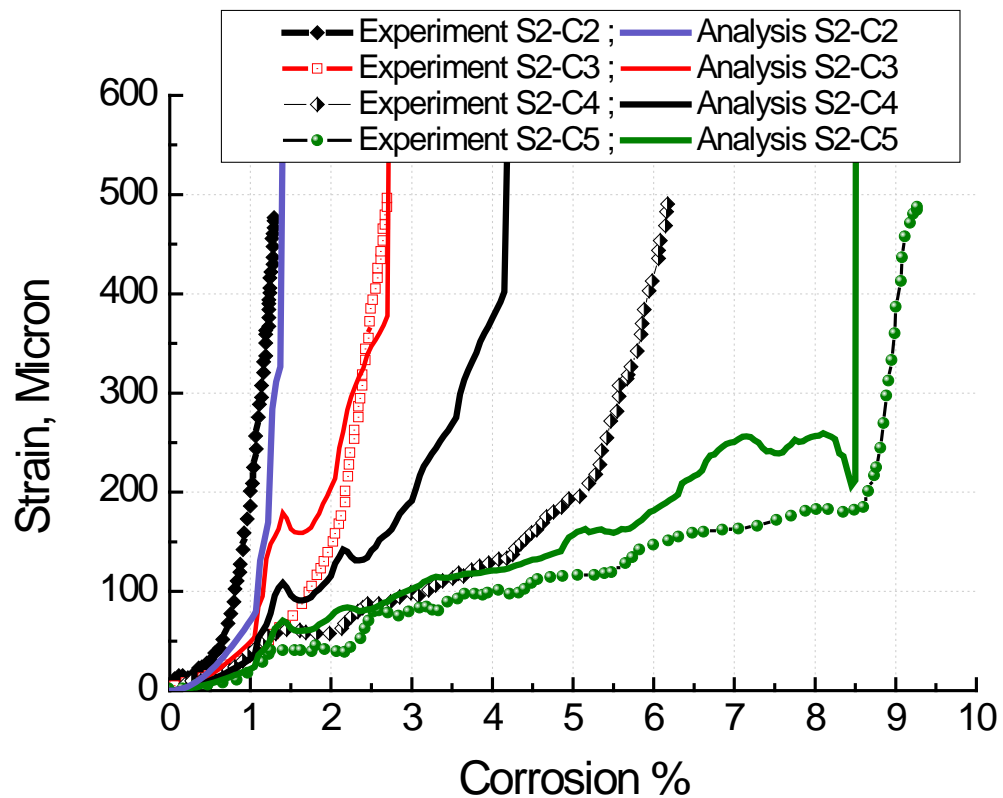
# 鋼材に酸化還元反応と腐食ゲルの生成移動

## 腐食ひび割れ幅と腐食量の関係に現れる時間依存性

Esayas, Maekawa  
ACT 2015



Experiment by Oh et al. 2008



# 水の相転換による氷生成と水の移動

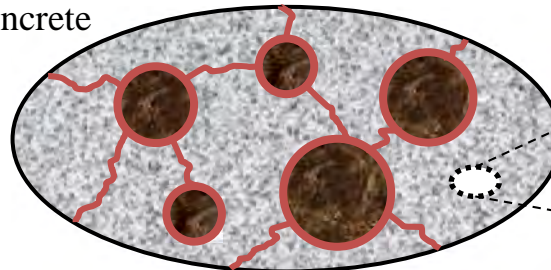
Gong, Takahashi, Maekawa (2017) Journal of Advanced Concrete Technology

ASR expansion generated

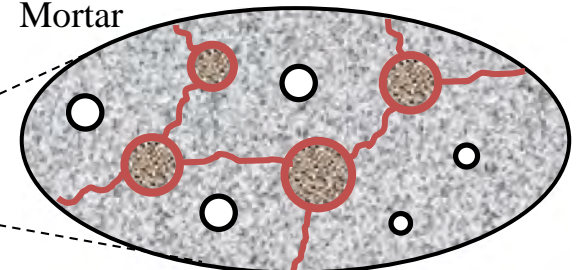
More micro-cracks by ice at mortar level

Empty remaining micro-cracks after thawing

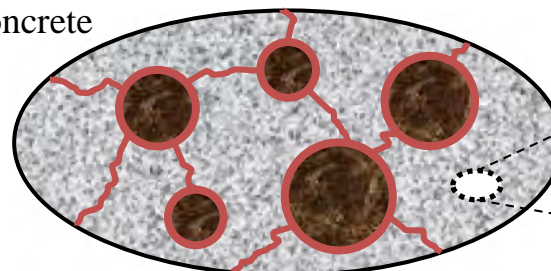
Concrete



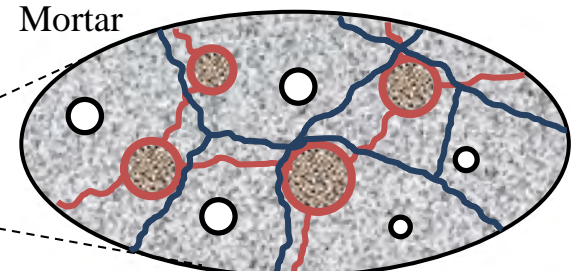
Mortar



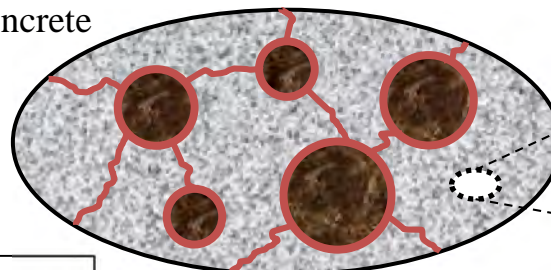
Concrete



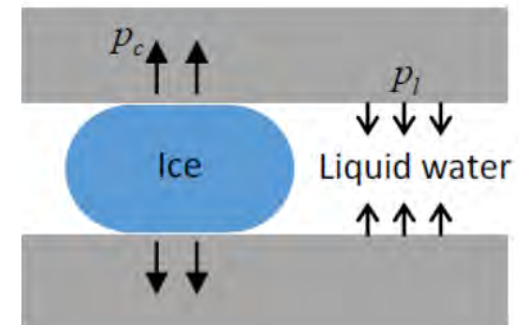
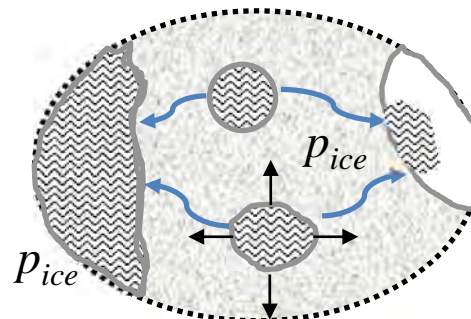
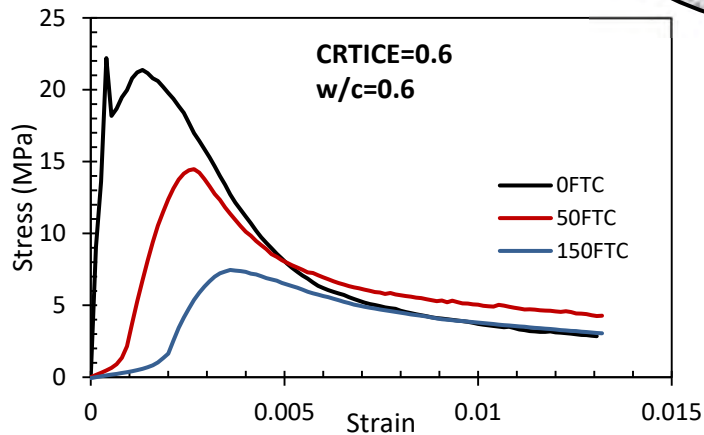
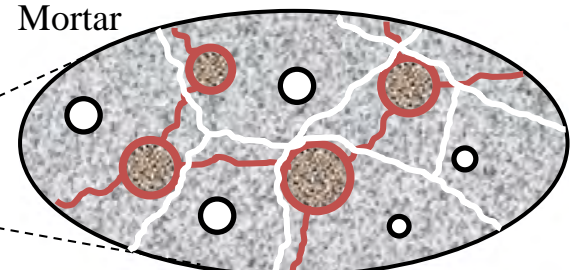
Mortar



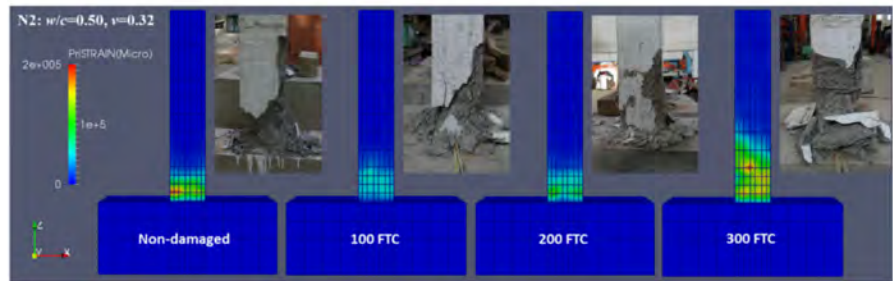
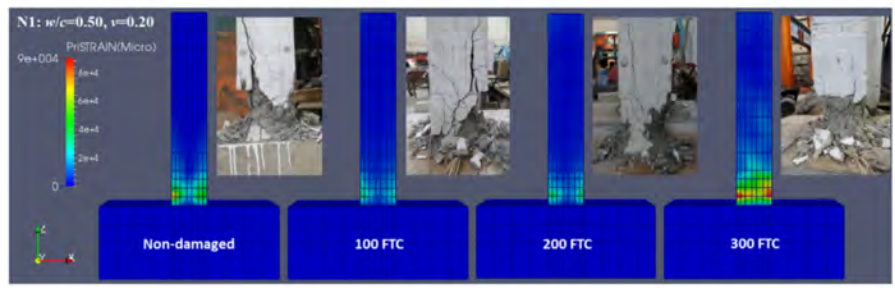
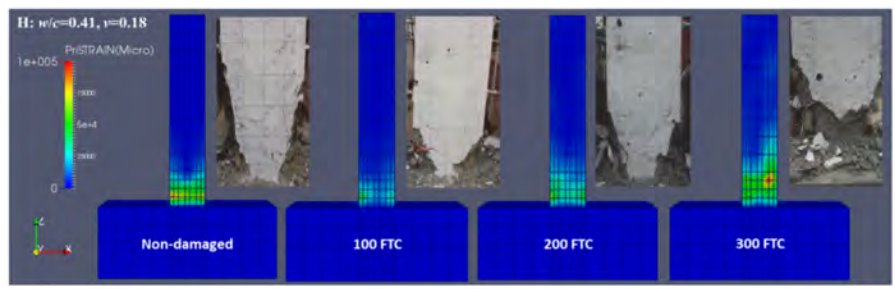
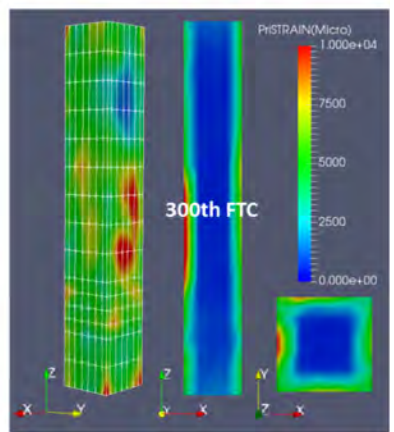
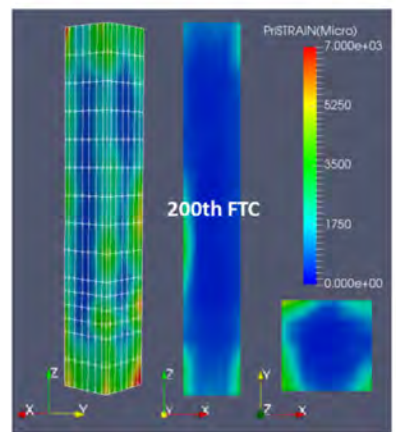
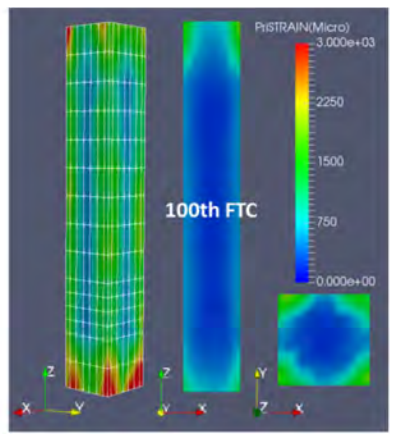
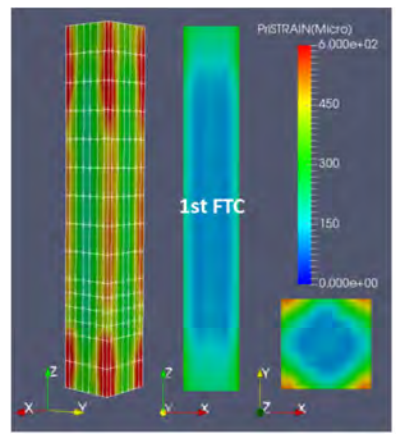
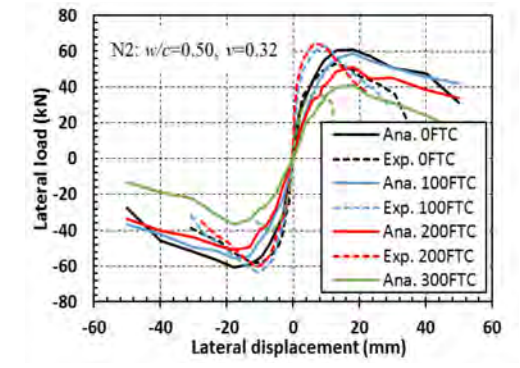
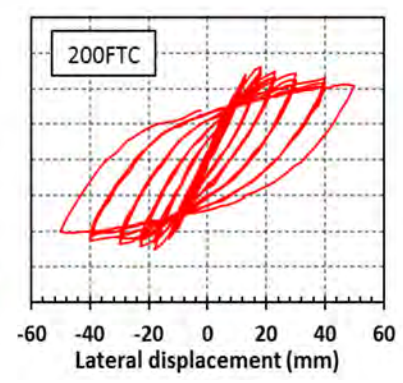
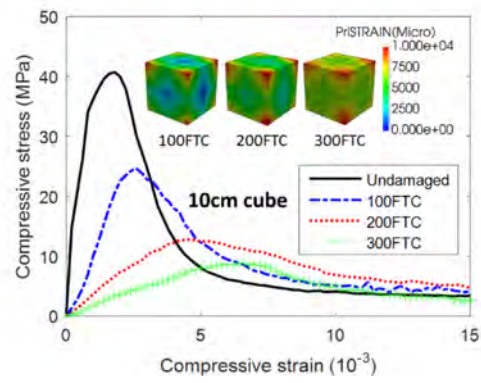
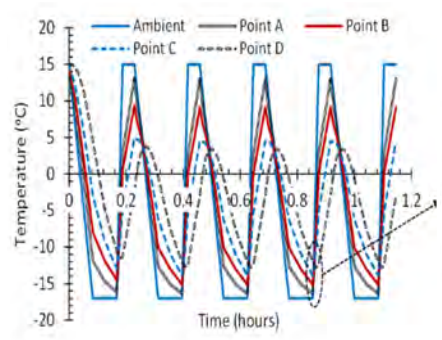
Concrete



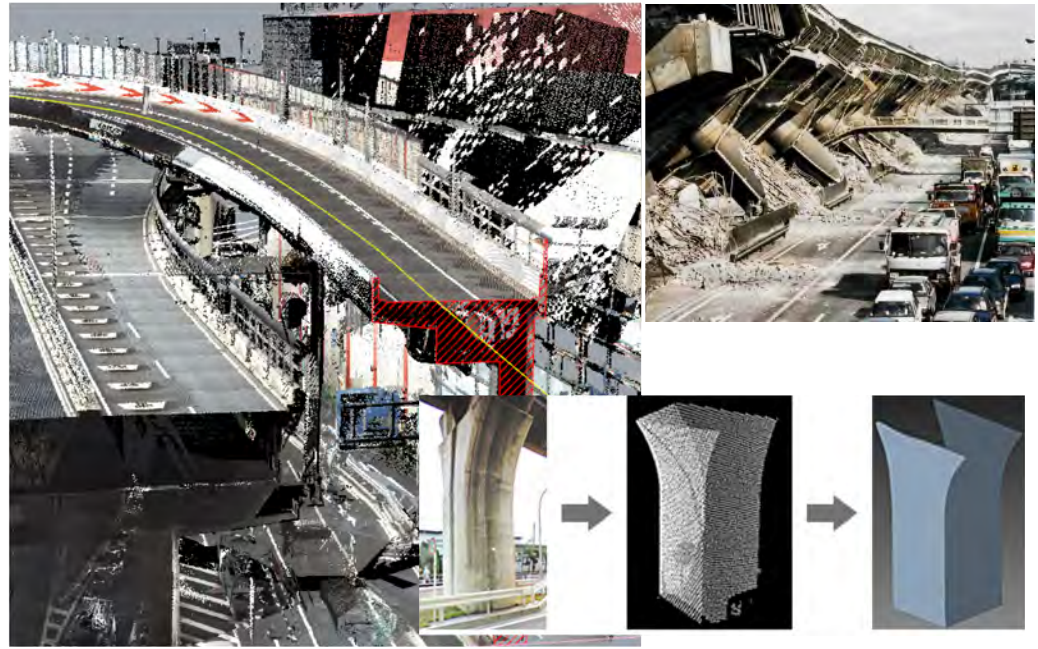
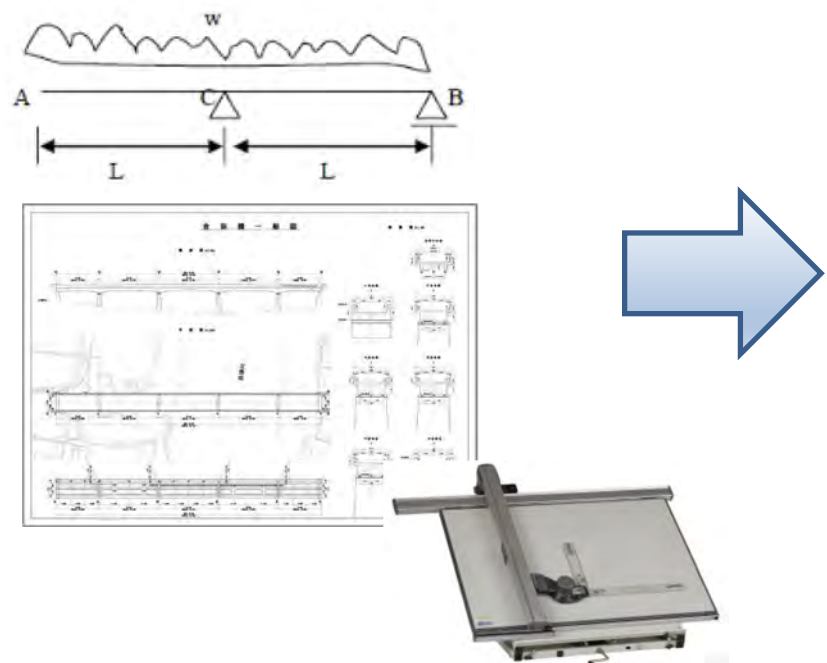
Mortar



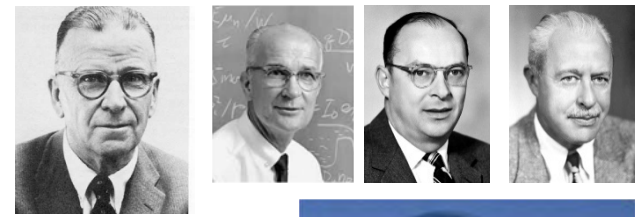
# 相間物質のミクロ挙動とRC構造のマクロ挙動が連結



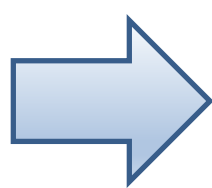




## Point contact transistor



1948



21th century