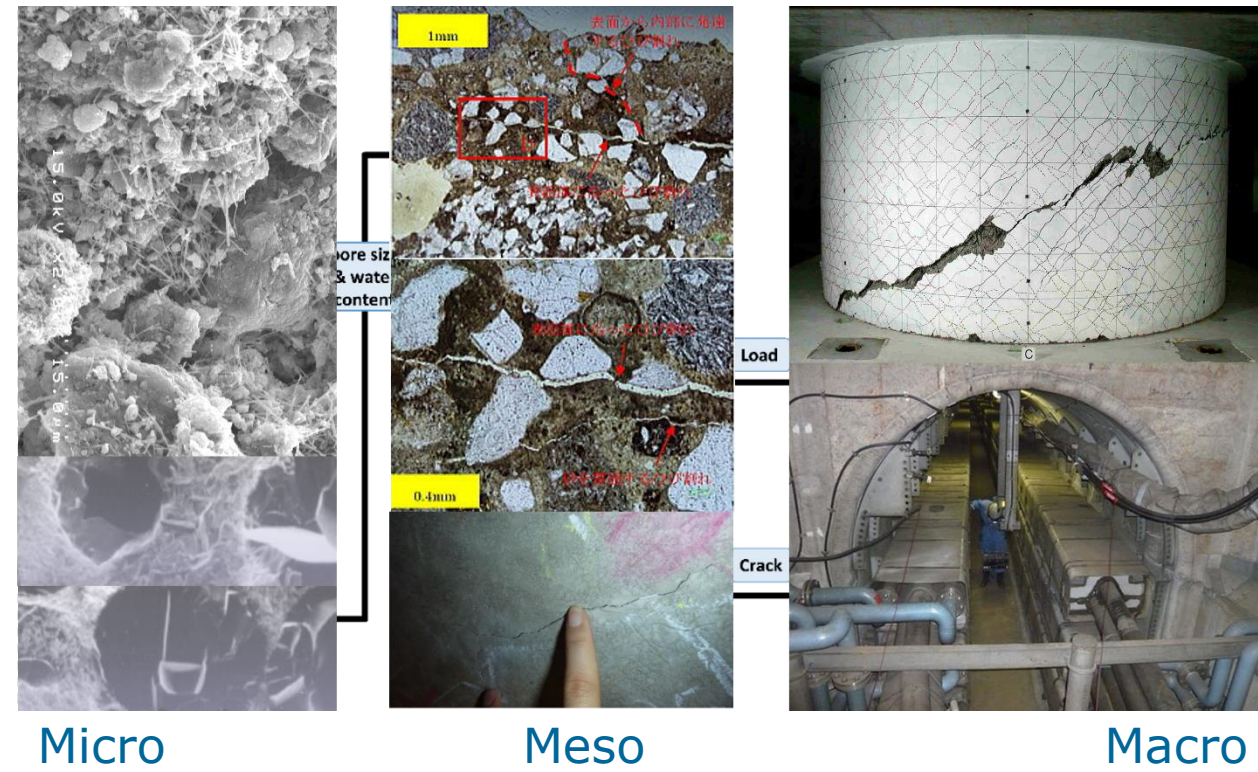


# RC構造の崩壊過程の数値解析と環境作用 — 崩壊過程と砂利化、火災高温履歴 —

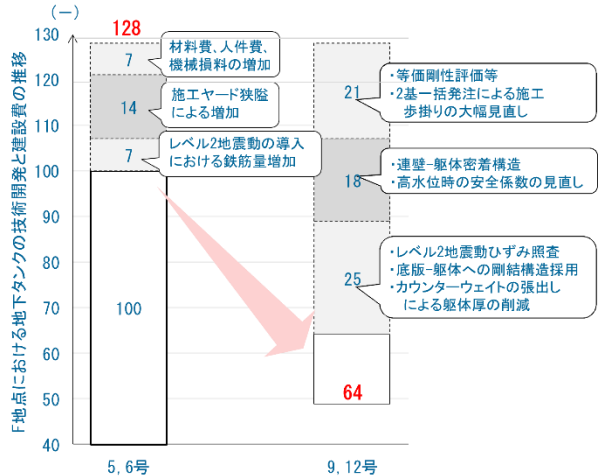
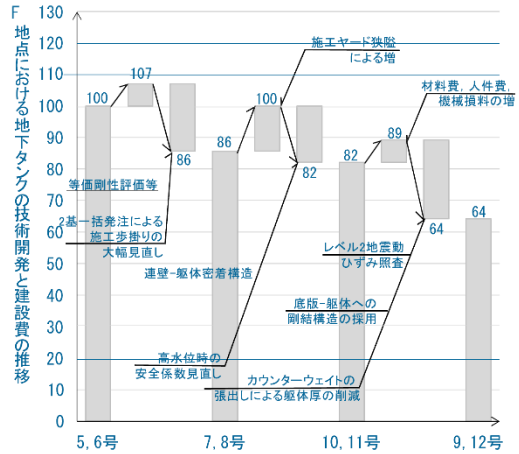
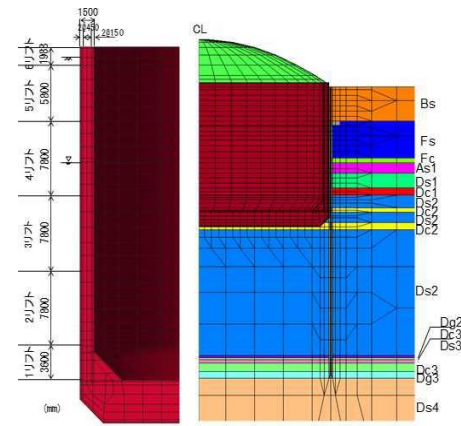
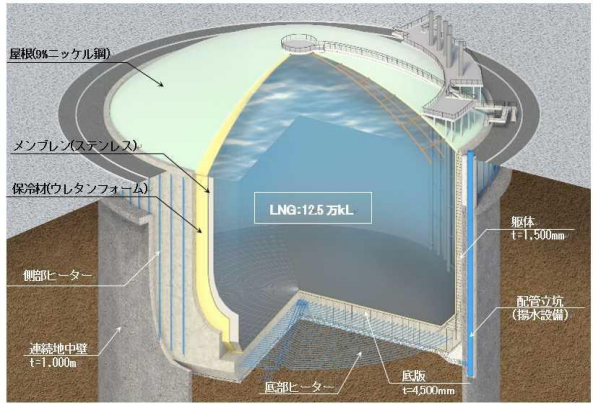
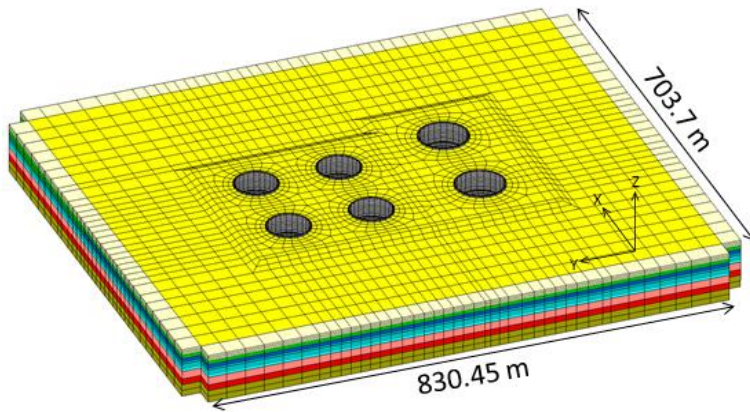


## **3次元非線形解析の応用：性能設計とハード技術開発**

**コンクリート構造と材料の崩壊過程：残余のリスク  
砂利化・土砂化、時間効果**

**高温履歴を受ける構造： 耐火、トンネル、環境**

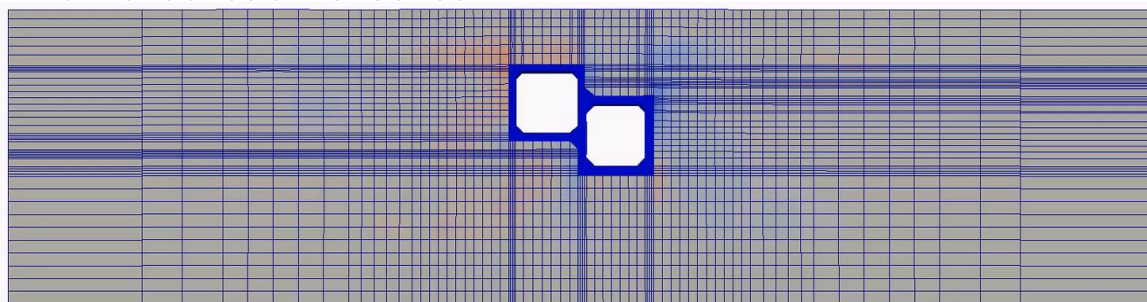
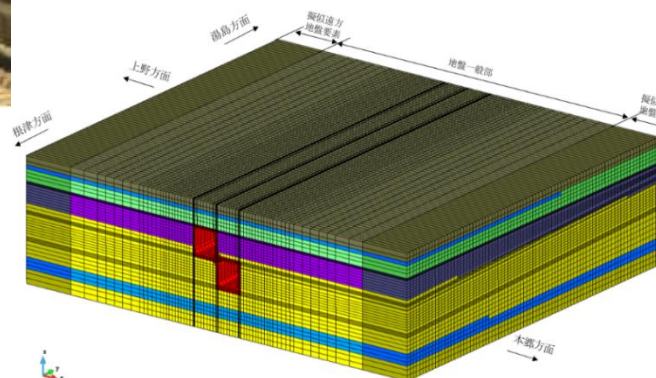
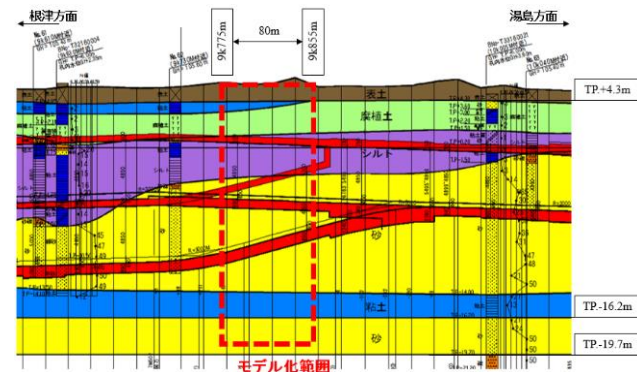
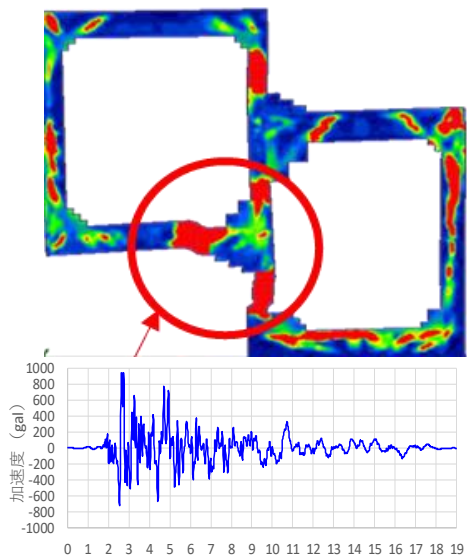
# LNG地下タンクの設計：限界状態設計法から性能設計：学位論文(東京大学) 高橋氏



**2021年土木学会技術賞**  
**RC非線形解析技術の実設計への高度利用(富津火力発電所9・12号 LNG地下タンク)**  
**30年で設計地震動約10倍：建設コスト半減強 構造+地盤+機器プラント全体を設計対象に。**

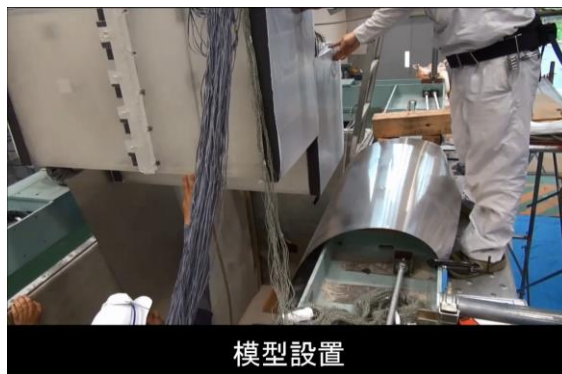


# 構造的な弱点ほぼ解明：異高型断面 2021年:学位論文（東京メトロ 大塚氏）



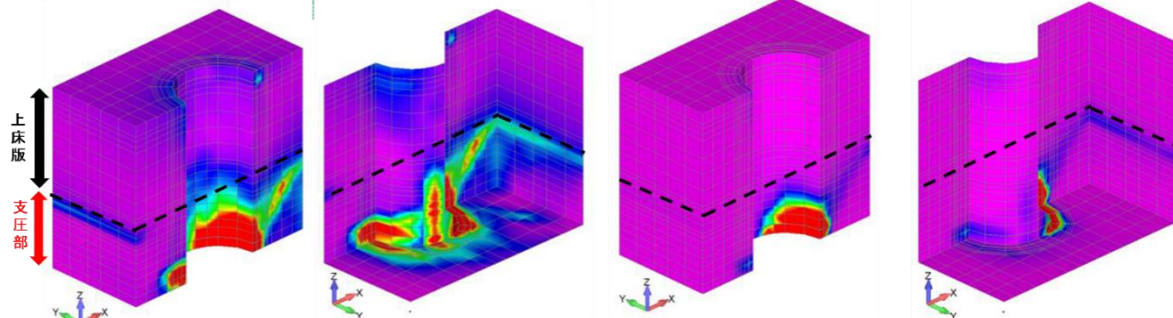
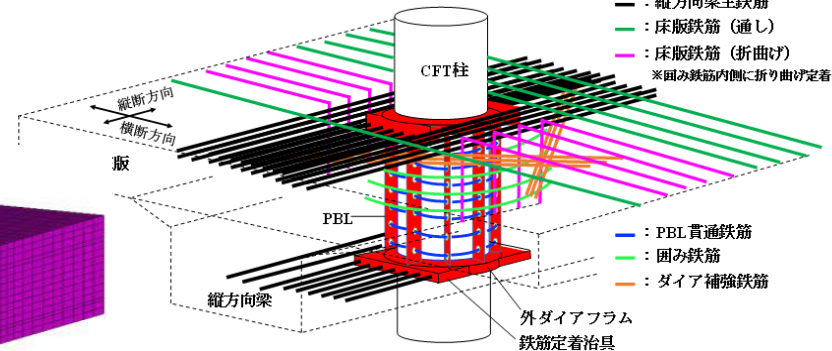
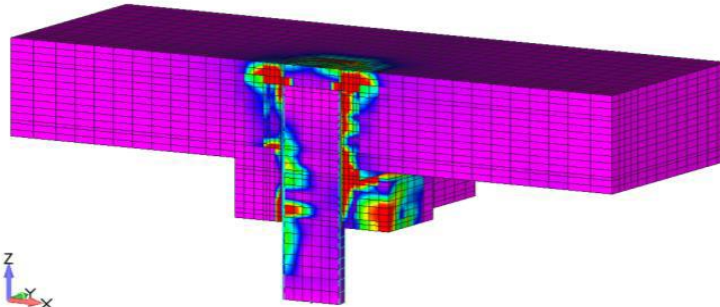
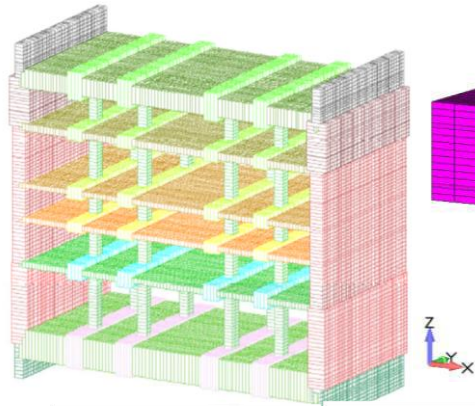
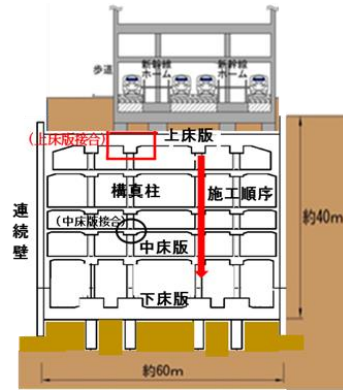
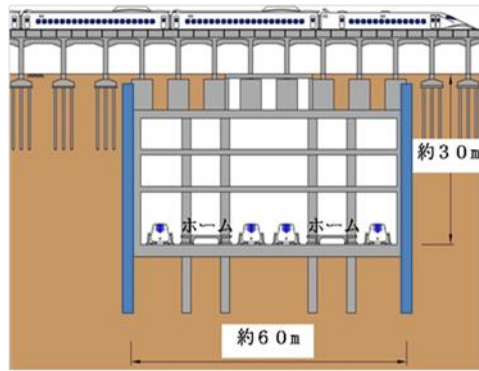
Otsuka, T., Sasaki, K., Nitta, H., Konishi, S., Tsuno, K., Sanagawa, T., Tsuchiya, S. and Maekawa, K. (2020). Research on earthquake dynamic behavior of uneven multi-section subway tunnel in transverse direction, *Soils and Foundations*, Vol.60, 1131–1150.

異高型断面を含むトンネル  
区間の耐震性能の評価  
(基準類の適用範囲外)  
地盤—構造の相互作用と破  
壊モード: 実験実証

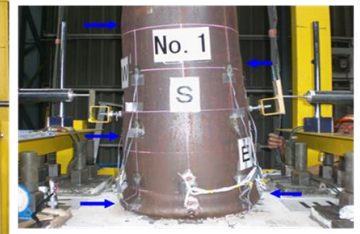




# リニア中央新幹線地下駅設計施工 (学位論文: 岩田 眞博士) 2021年



上部引張側状況  
完全に鋼管が割れ、内部コンクリートが見えている。

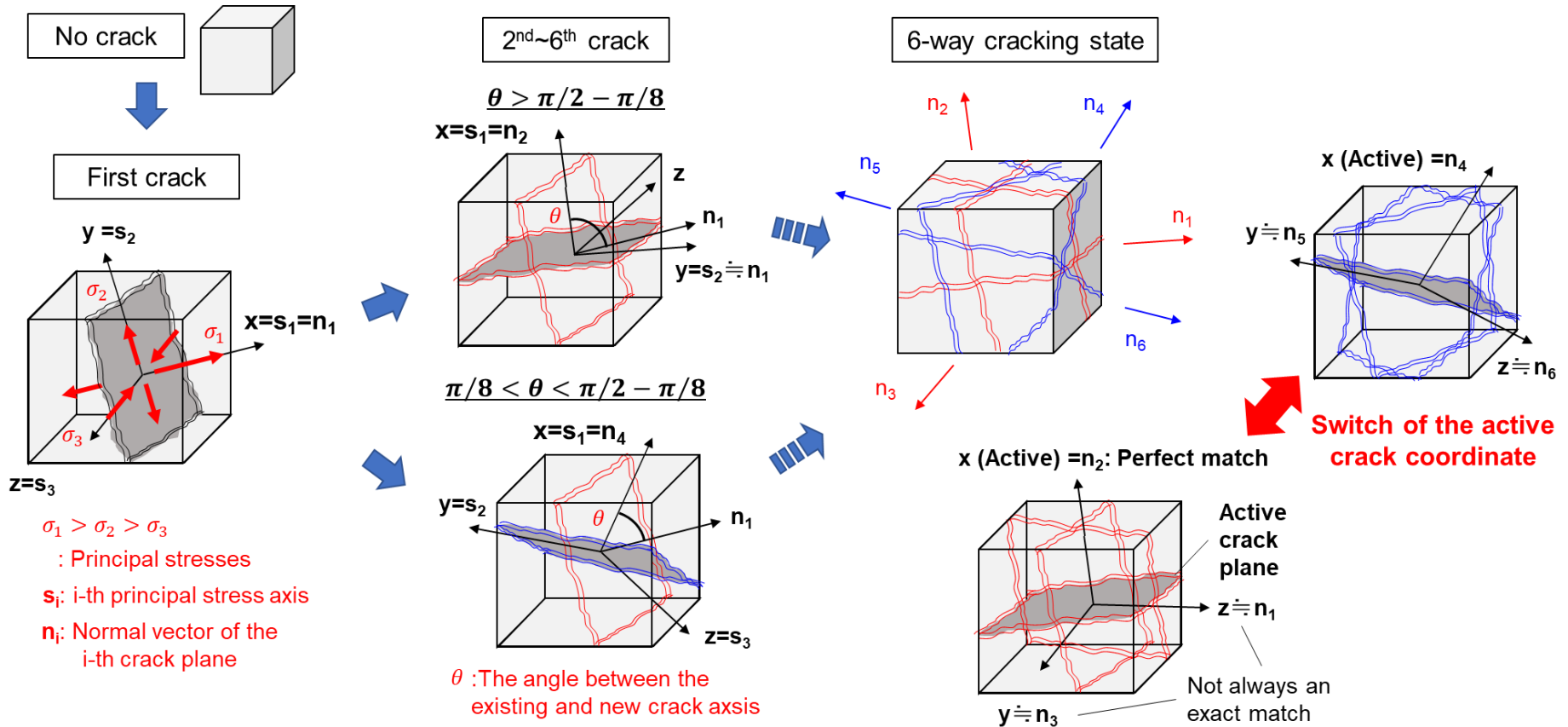


鋼管下部状況  
産屈箇所が増えた。目視で把握できる孕み箇所を写真内青矢印で示した。

岩田 眞, 戸崎 隆之, 安原 真人, 池田 学, 坂口 淳一, 前川 宏一(2022). 高軸力CFT柱-RC床版の埋込み接合部の耐荷性能に関する解析的検討, 土木学会論文集A1(構造・地震工学), 78(1), pp.17-33.

# 最もひび割れ直交方向の変形が大きい面が全体の非線形性を支配 (active crack) それ以外は休眠する(dormant crack)

## ◆ Active crack method

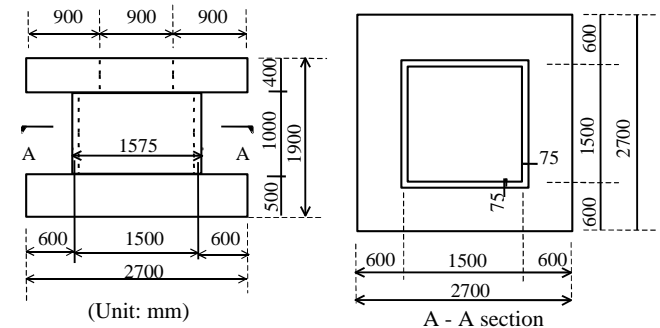
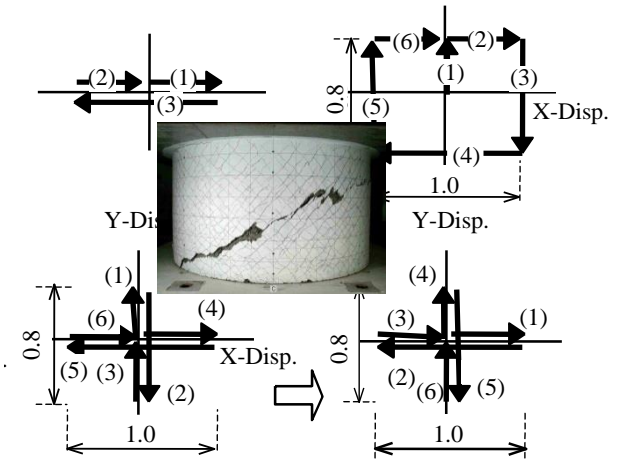
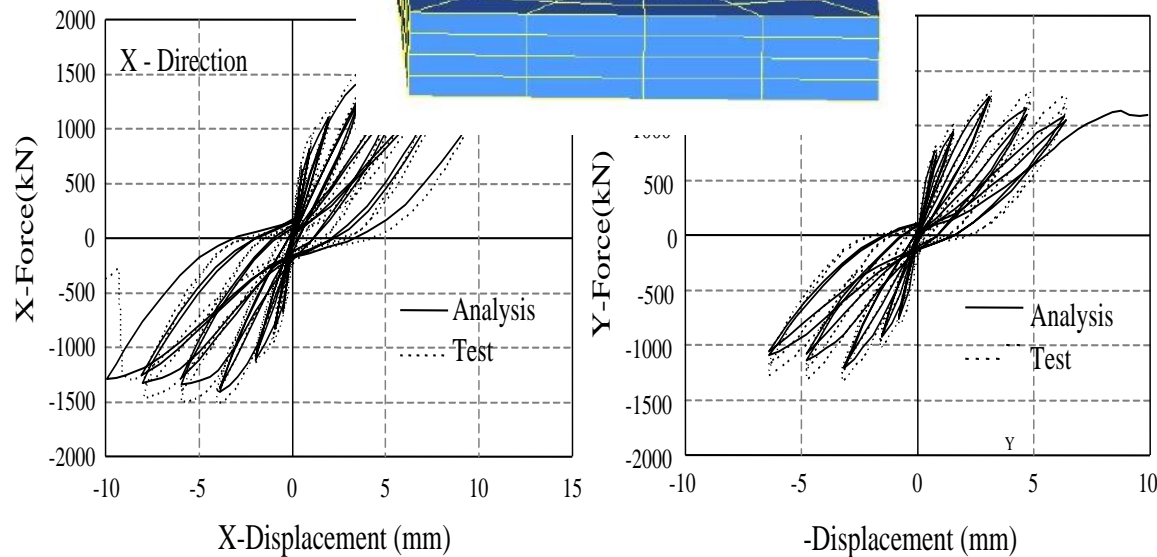
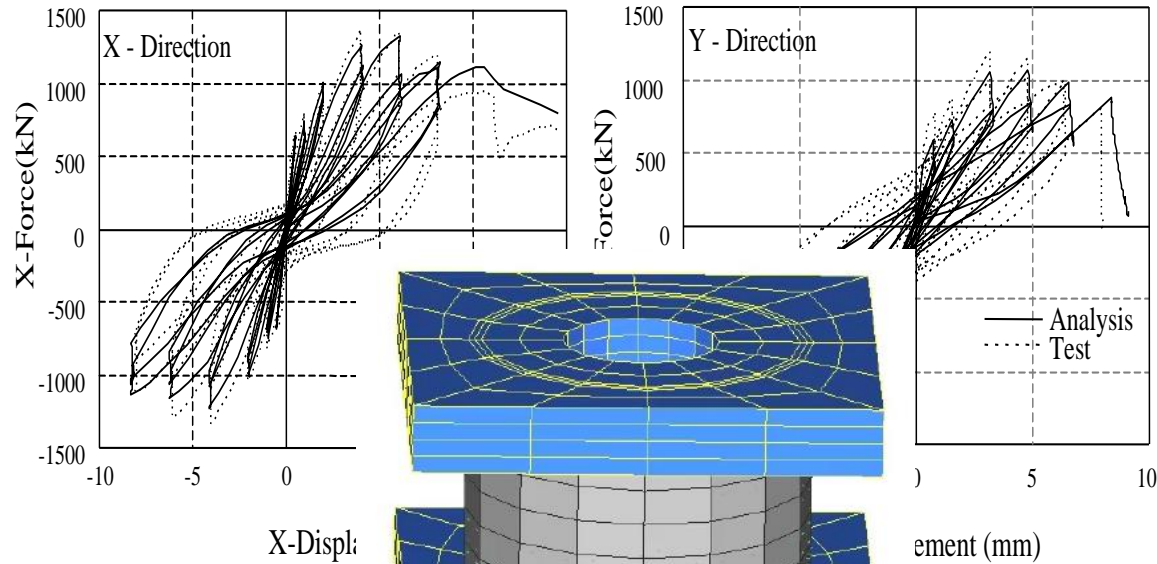


✓ 最大6方向の非直交ひび割れに対応：変形の履歴に応じてスイッチ



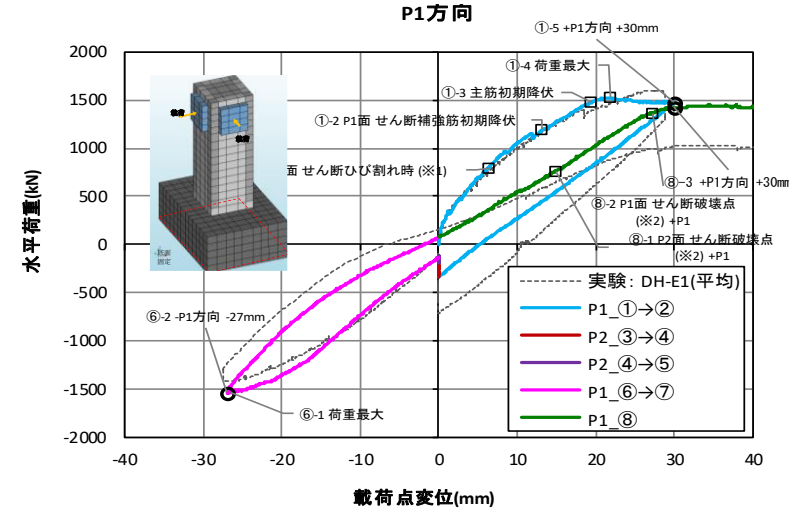
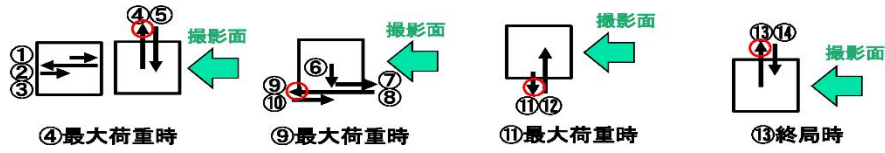
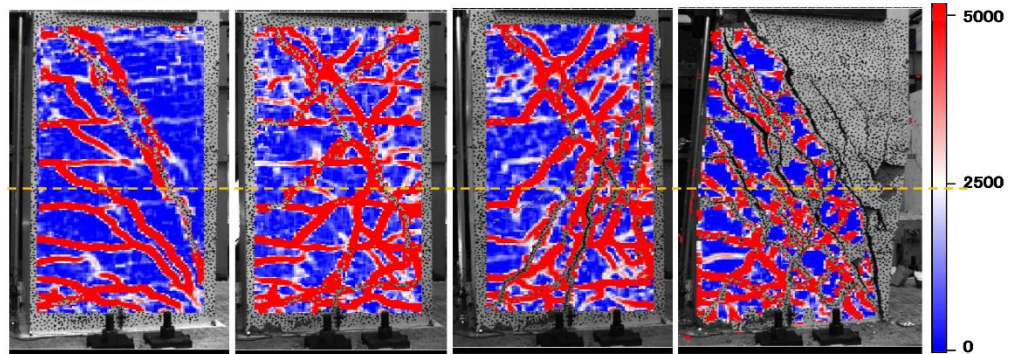
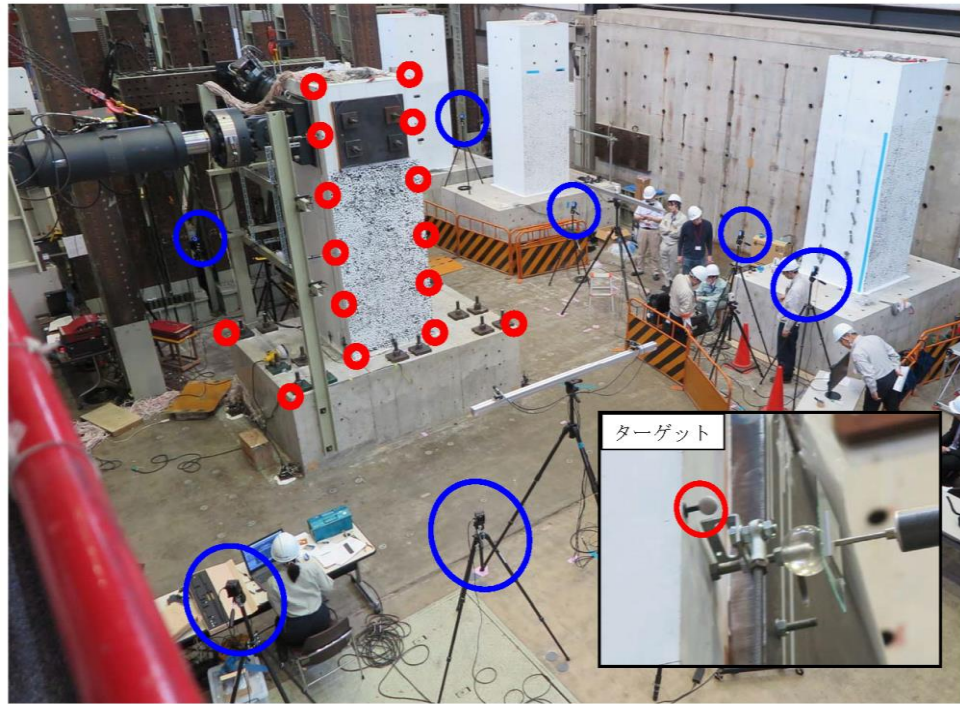
# 実験による検証 -主に面内せん断状態- validation 2000

Maekawa et al. (2003) Nonlinear Mechanics of Reinforced Concrete





# 実験による検証 一般化多方向ひび割れ- Validation 2021





**3次元非線形解析の応用：性能設計とハード技術開発**

**コンクリート構造と材料の崩壊過程：残余のリスク  
砂利化・土砂化、時間効果**

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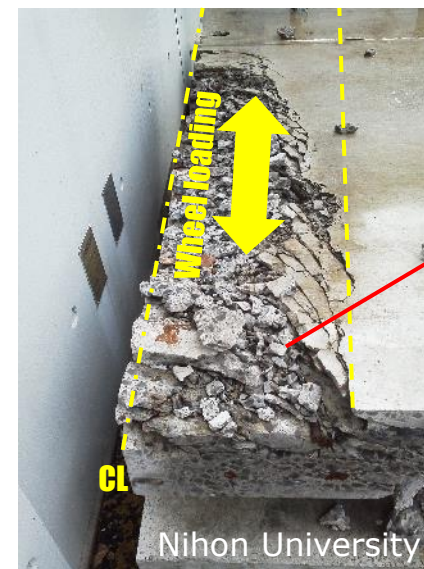
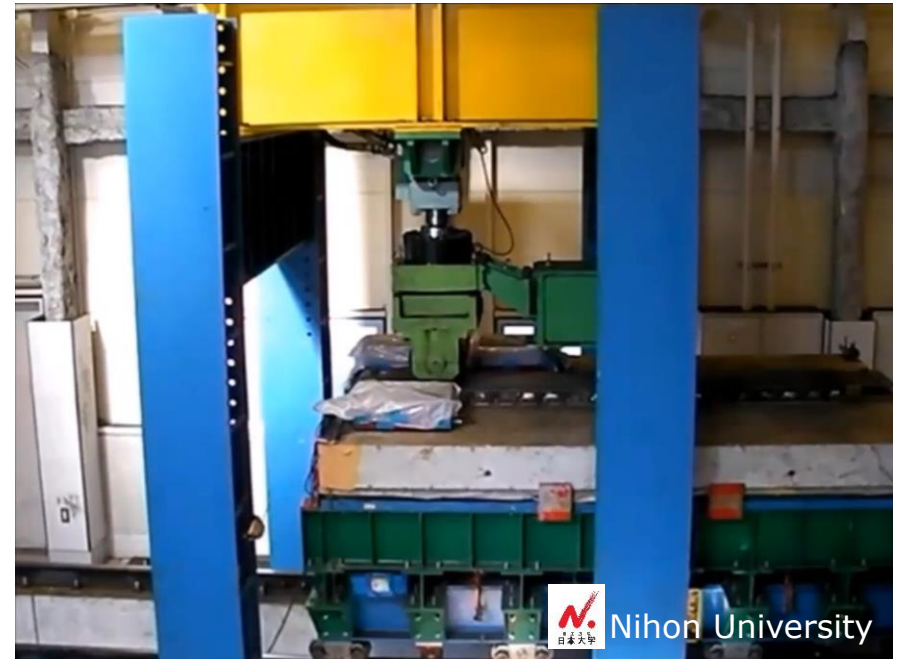
**高温履歴を受ける構造： 耐火、トンネル、環境**

# 砂利化—土砂化 : Graveling 崩壊の一つの姿

セメント硬化体の浸食  
と橋梁床版の劣化



輪荷重走行試験



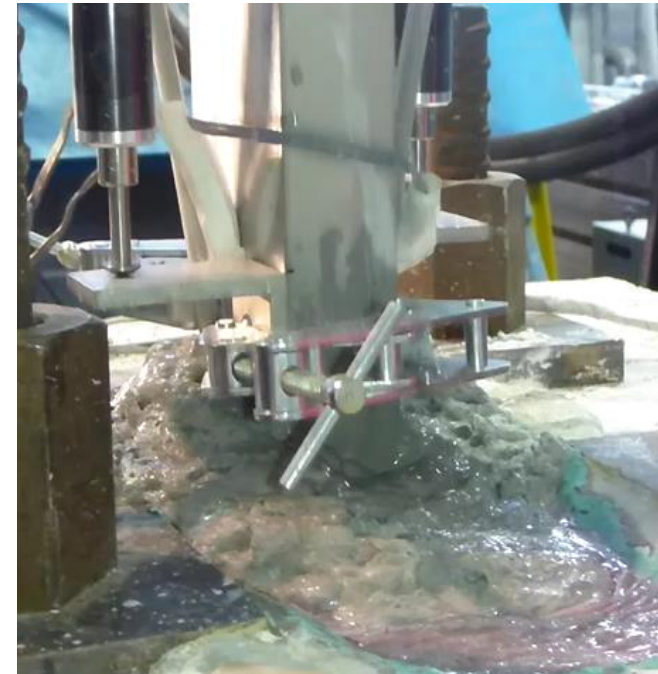
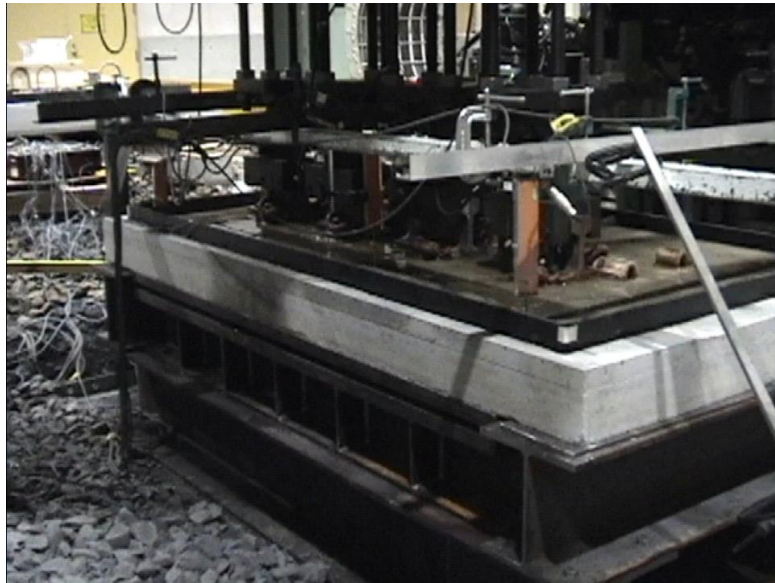
砂利化・土砂化は  
床版寿命を左右する  
要因

Maeshima, Iwaki (2014)  
J. JSCE

浸漬 + 繰り返し移動荷重  
が引き起こす砂利化



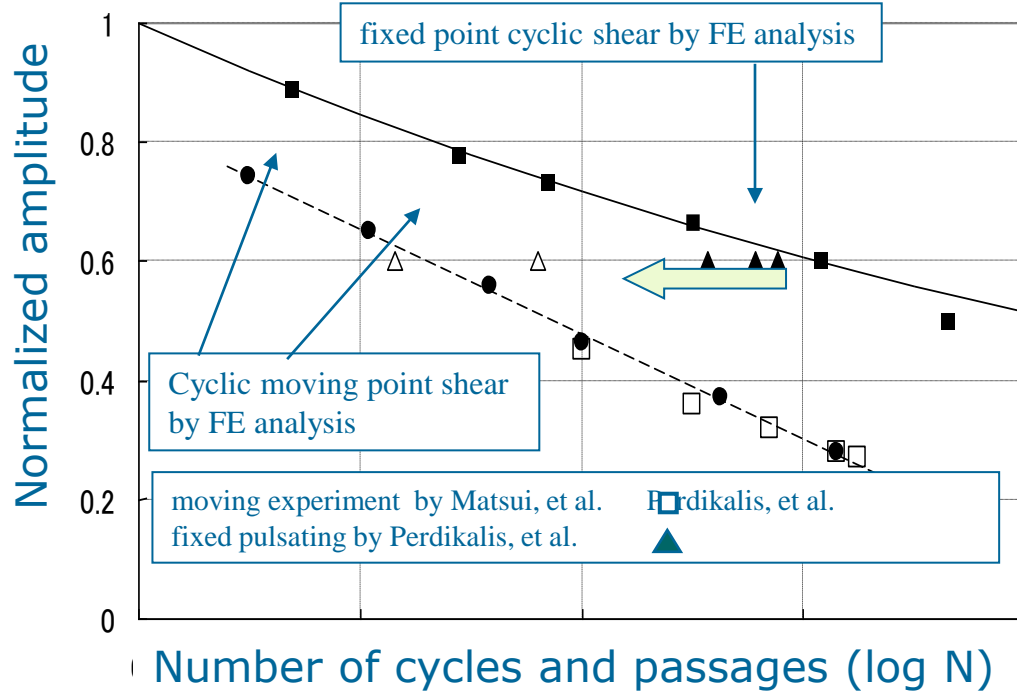
# 砂利化—土砂化 : Graveling 水が加速



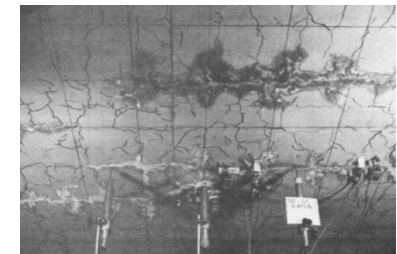
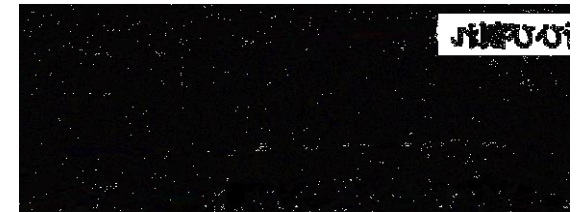
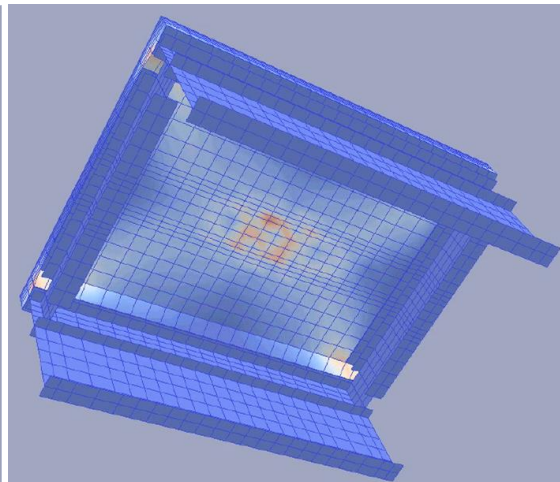
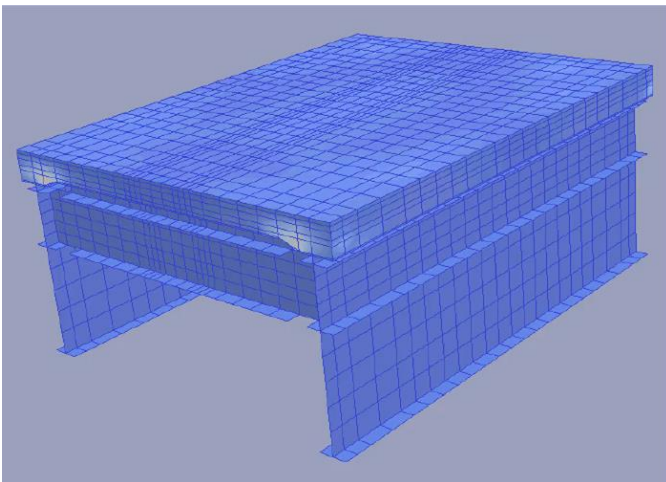
Fujiyama,C., Kobayashi,K., Zhan,JU. and Maekawa,K. (2011). Fatigue Life Simulation of RC Bridge Slab with Initial Defects under Water, *Procedia Engineering*, 14, 1897-1905.

Chijiwa,N., Hong,T.M., Iwanami,M., Saito,T., Yamaya,A., Motegi,H., Shinozaki,H. (2015). Rapid Degradation of Concrete Anchorage Performance by Liquid Water, *Journal of ASdvanced Concrete Technology*, 13(10)

# 砂利化、土砂化まで考慮が必要：体積剛性のみに収束(2004~2018)



Maekawa, K., Toongoenthong, K., Gebreyouhannes, E. and Kishi, K (2006) Direct Path-Integral Scheme for Fatigue Simulation of Reinforced Concrete in Shear, *Journal of Advanced Concrete Technology*.





# 滞留水の存在は、床版の寿命を決定的に縮める



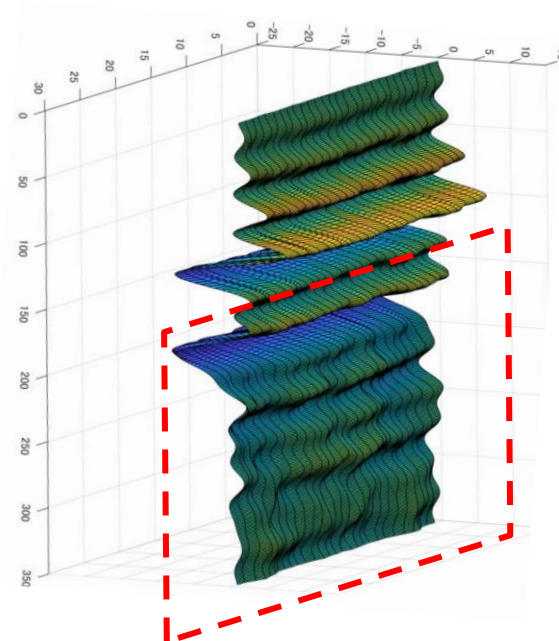
首都高速池袋近くで16万台/日



舗装の剥がしと床版  
本体の検査

打音検査  
検査の制約、安全、  
コスト

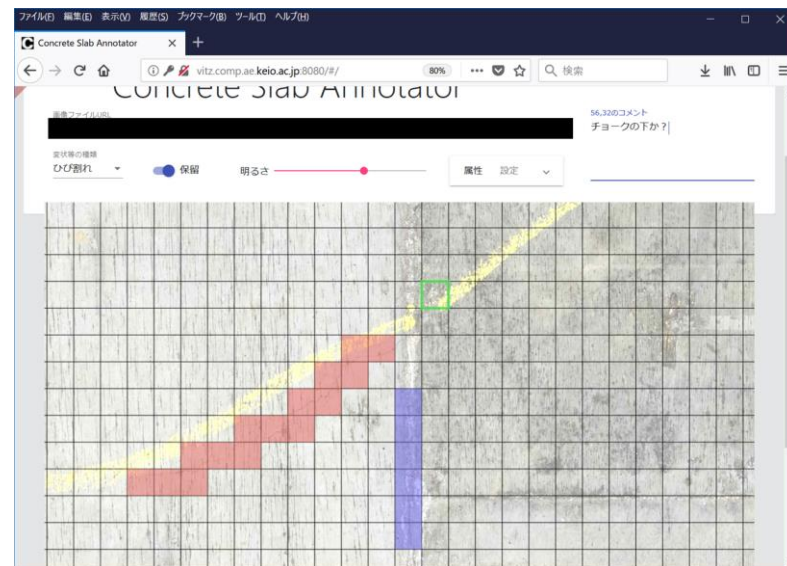
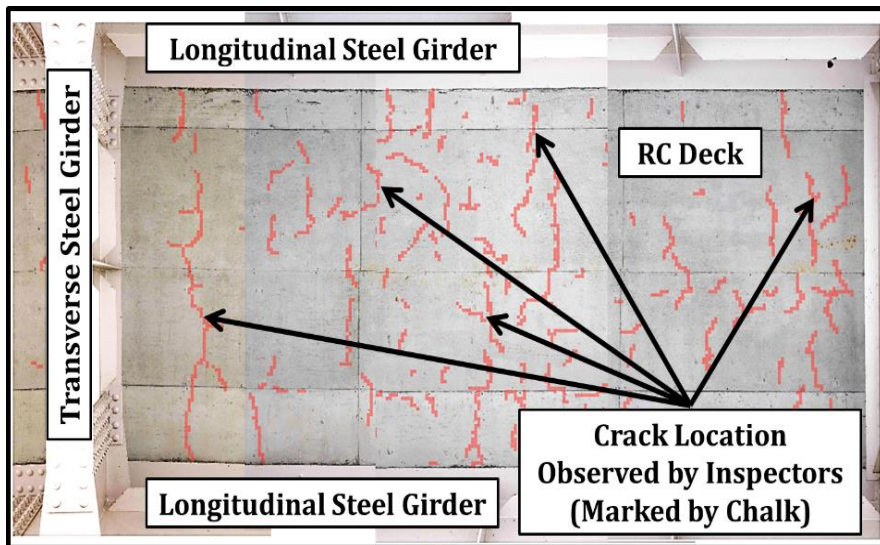
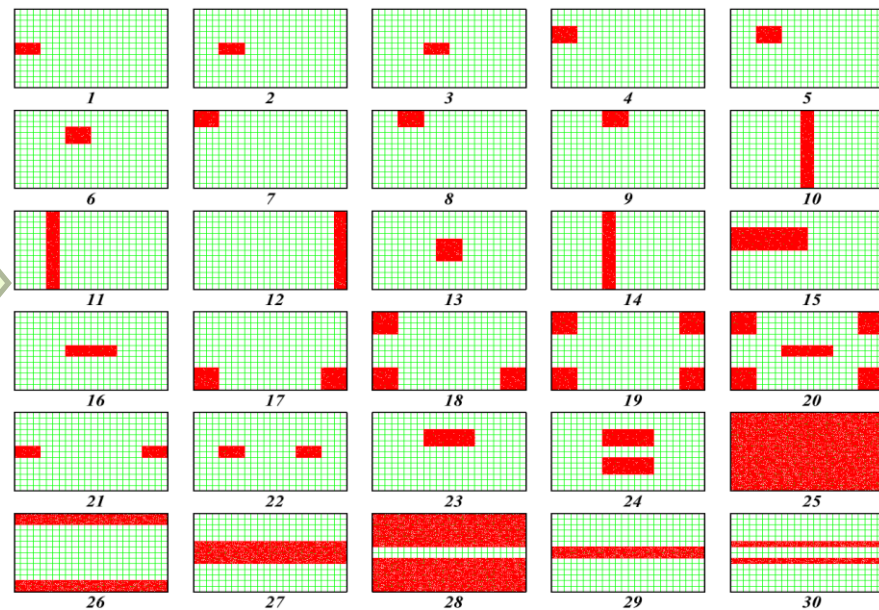
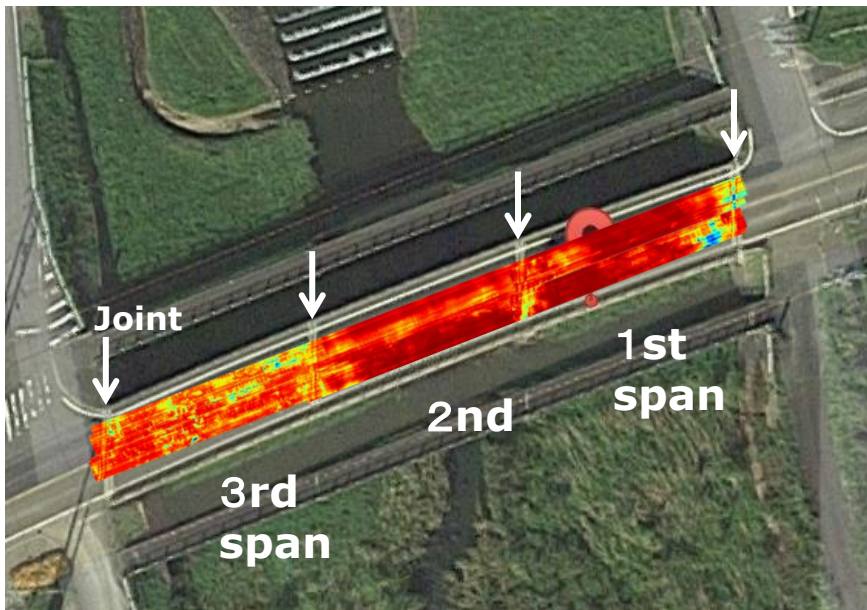
交通規制と時間制約、交通遮断は社会的コスト大



Presented by  
Prof. Mizutani, U.  
Tokyo

Yamaguchi, T. and Mizutani, T. (2019). Sensitive damage detection of reinforced concrete bridge slab by time-variant deconvolution of SHF-Band Radar Signal, *IEEE Transactions on Geoscience and Remote Sensing*, 57(3).

# 滞留水の存在を非破壊で見出し、寿命を推定する

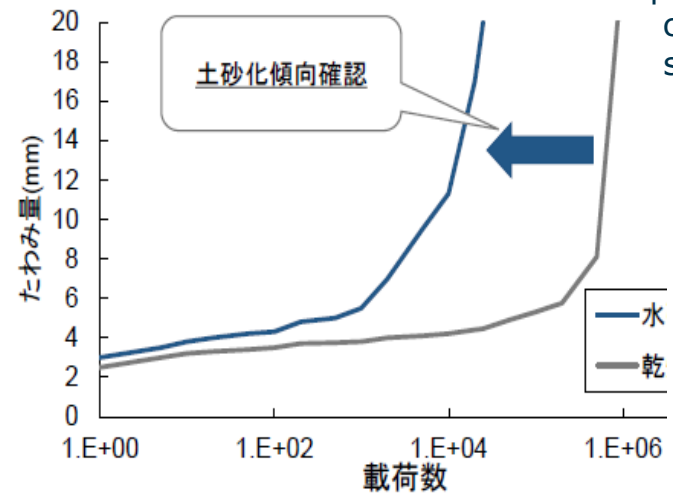
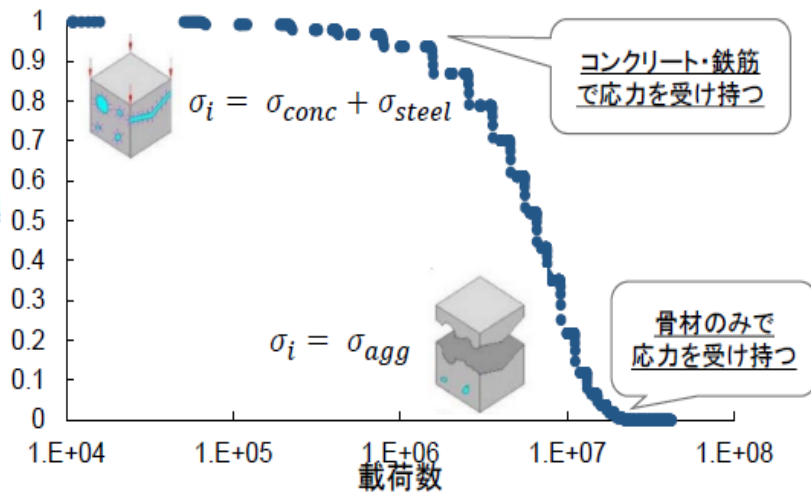




# 実世界の管理データから数理モデルを検証

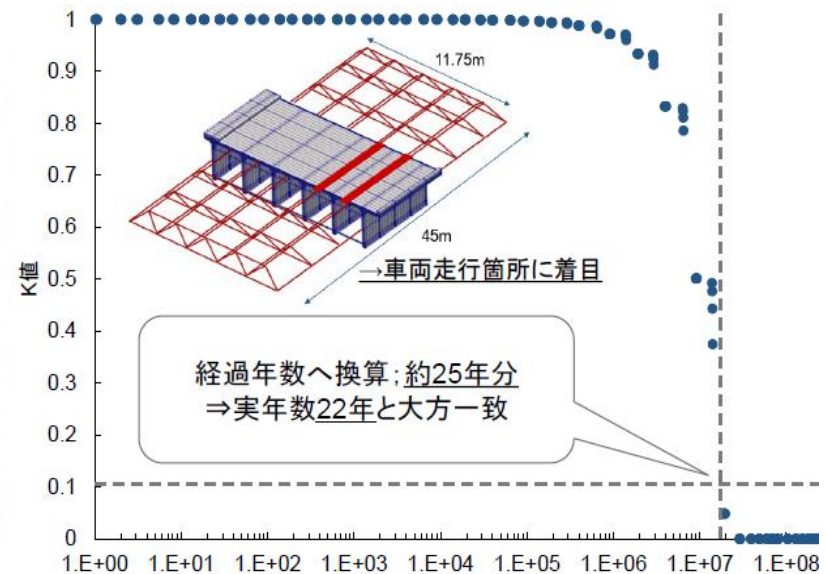
$$K = \exp(-Z), \quad \bar{p} = \frac{p}{f_{cd}}, \quad Z = 10^2 \int (1 + f_n) \cdot (|\bar{p} - \bar{p}_{pivot}|)^{f_n} \cdot |d\bar{p}|$$

K: degradation ratio  
 P: normalized pore pressure  
 f<sub>cd</sub>: compressive strength  
 F<sub>n</sub>: =4

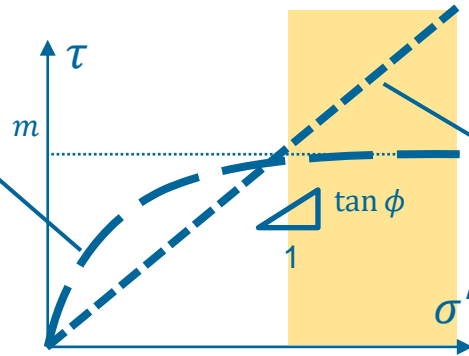
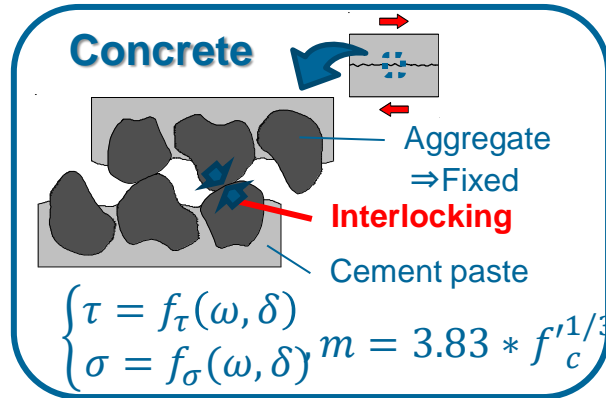


1 建設後22年程度で土砂化確認

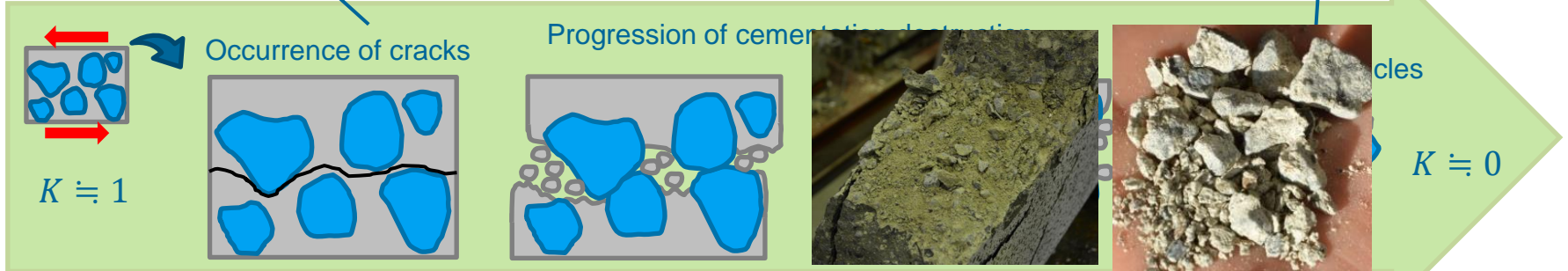
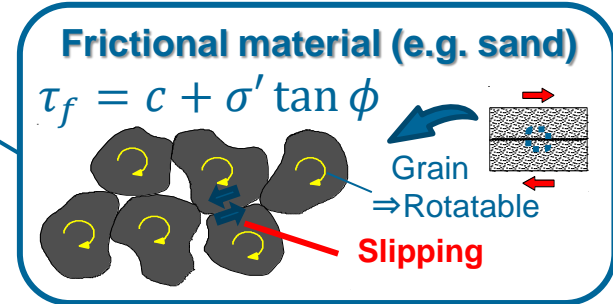
2 車両走行箇所で集中発生



# せん断伝達機構の崩壊過程：セメント硬化体が消失しても強い



$f'_c$ : Compressive strength,  
 $c$ : Cohesive strength,  $\phi$ : Frictional angle

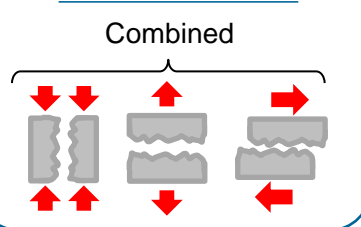


## Analytical Model

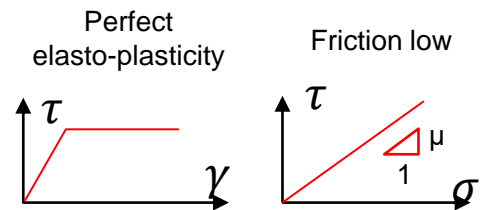
$$\sigma_{ij} = \sigma_{cij} (K) + (1 - K)(S_{ij} + \delta_{ij}I_1)$$

Total stress tensor

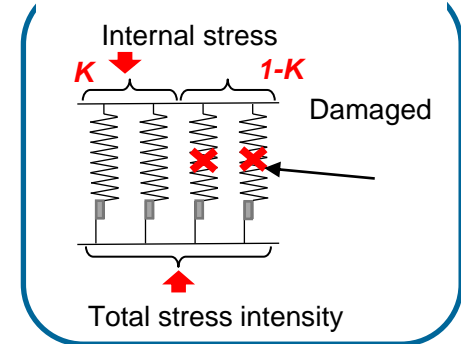
### Concrete Model



### Frictional material Model



### Fracture Parameter $K$

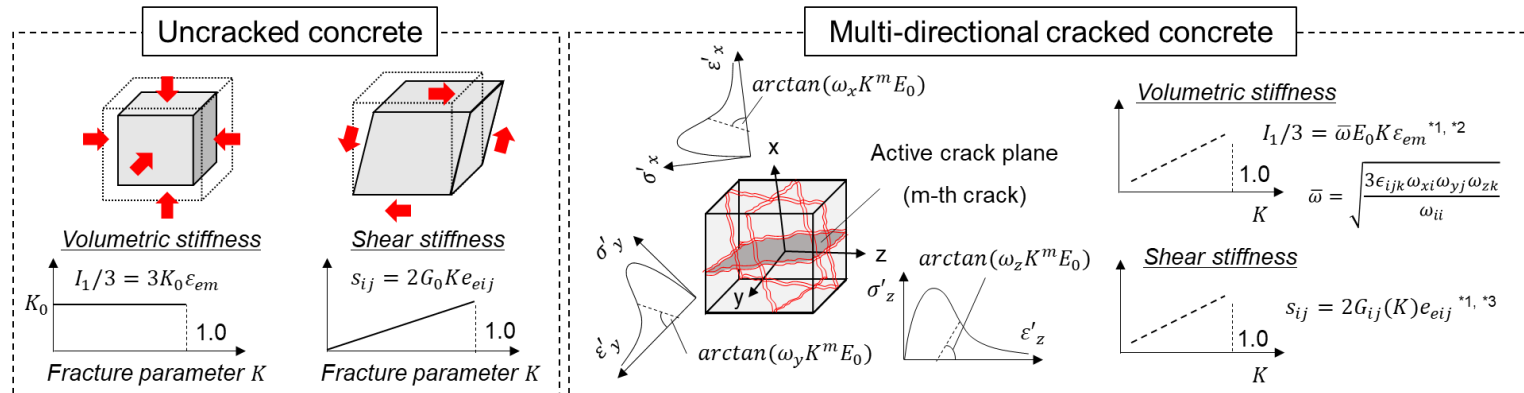




# コンクリートの損傷を代表するパラメータを使って砂利化を規定

## ◆ Fracture parameter $K$

せん断弾性エネルギーを保持できる体積の割合

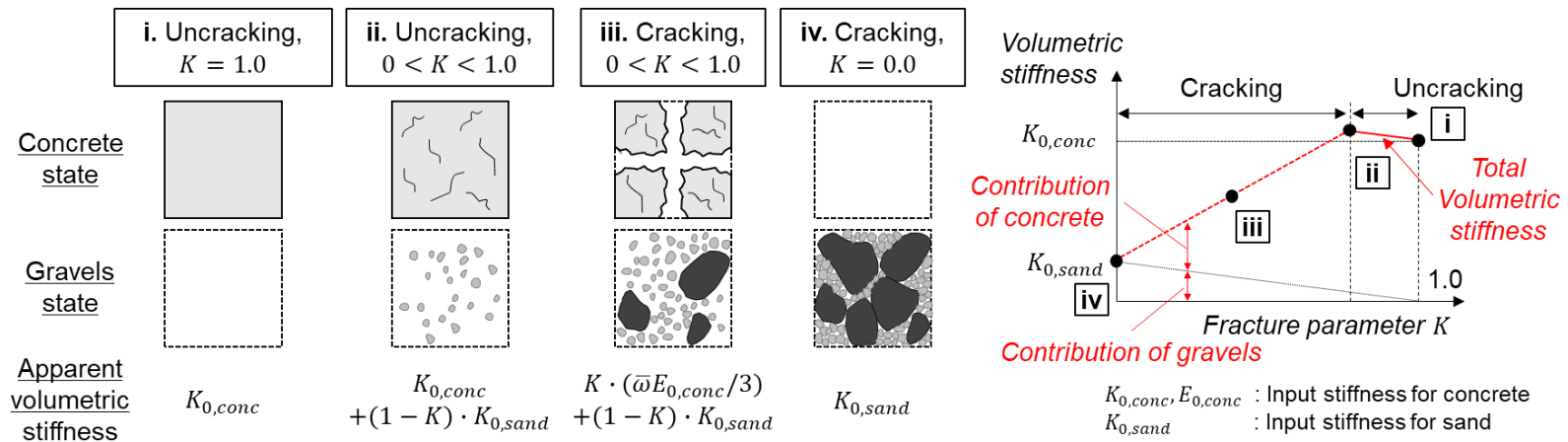


\*1:  $i, j \in \{x, y, z\}$

\*3:  $G_{ij}$  ... Anisotropic shear stiffness matrix related to normal strain

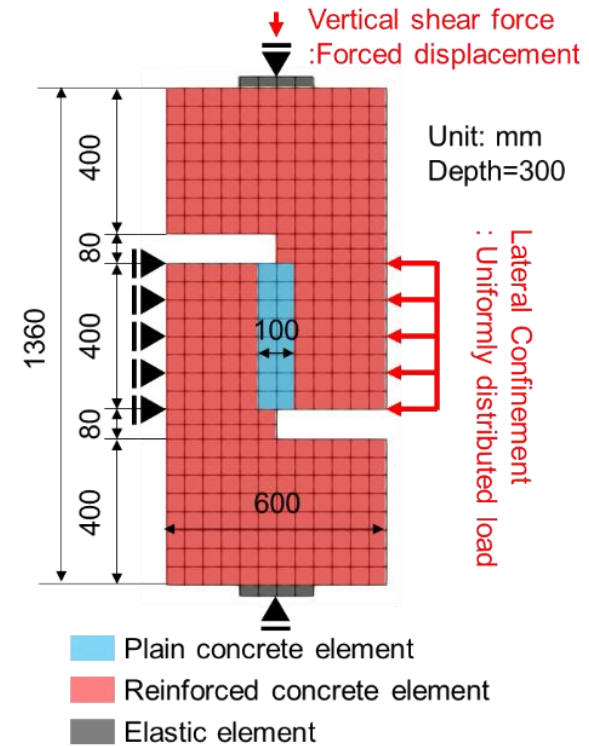
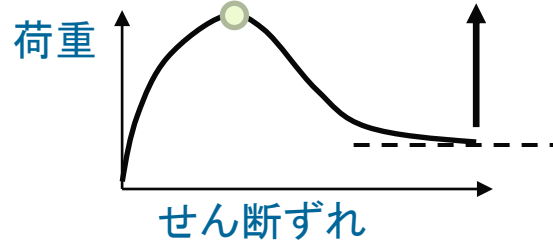
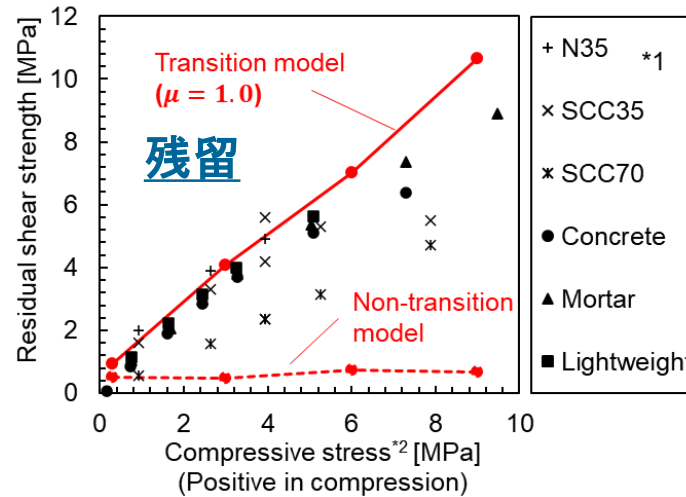
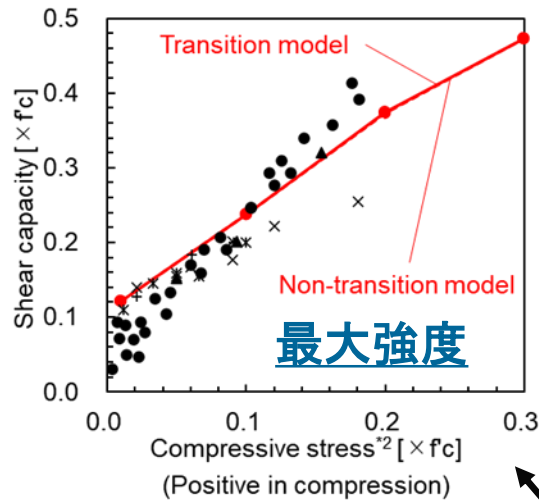
\*2: Ignore the re-contact stress,  $\omega_i, \dots$  Reduction factor according to the maximum tensile strain orthogonal to the  $i$  - direction

## ◆ Transition of volumetric stiffness according to $K$



# 摩擦面の劣化と砂利の集合への遷移

## ◆ プッシュオーバー試験：強度および残留応力

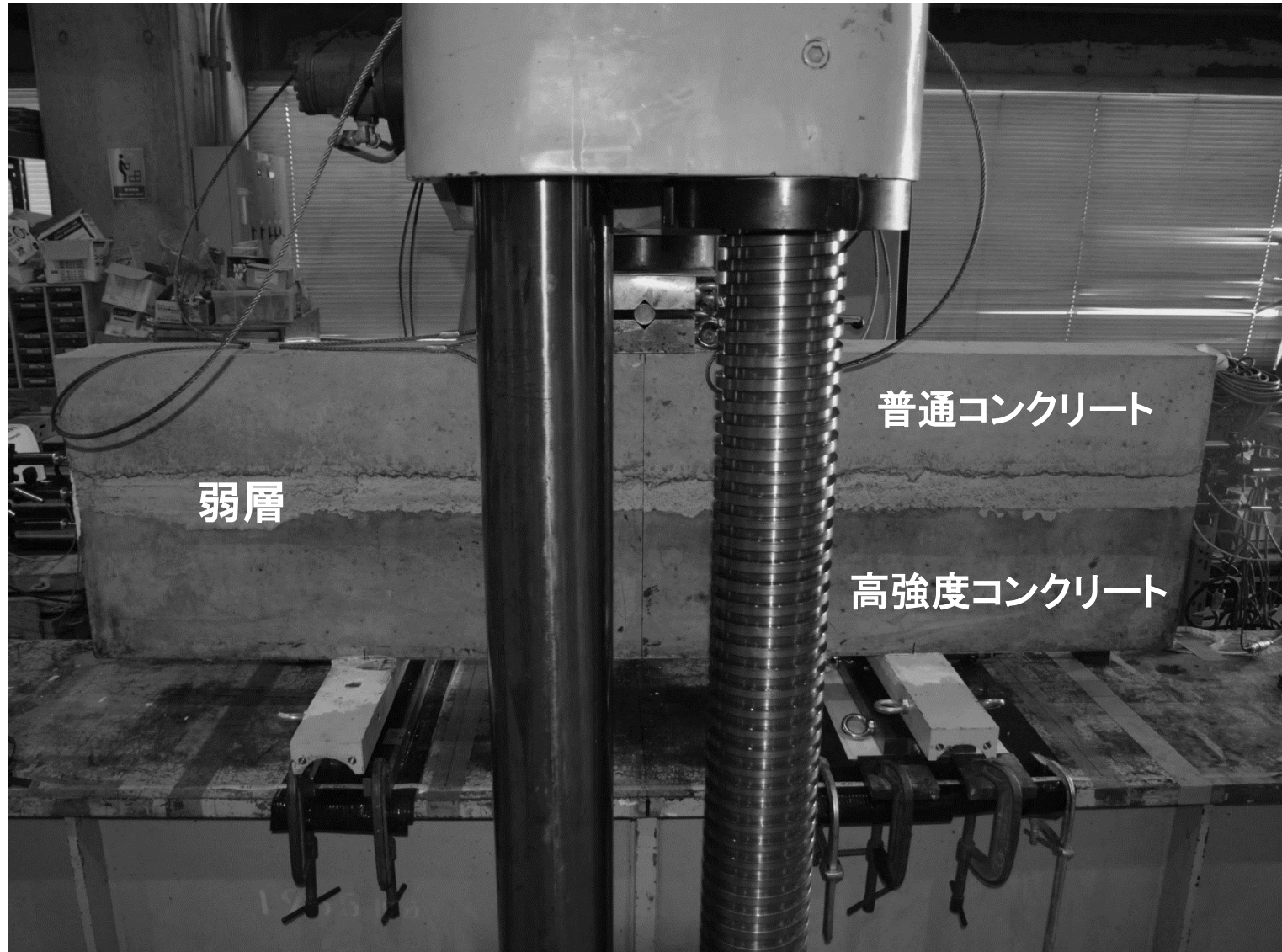


Test results by Lim et al. (1987) and Rahal et al. (2016)

- ✓ せん断強度はコンクリートのせん断伝達構成則で高精度で評価可能
- ✓ 大ひずみ域での残留強度は過少評価(実務上は安全側)
- ✓ 遷移モデルにより、大せん断変形時の力学挙動を従来より詳細に記述
- ✓ 高サイクル疲労のみならず、大せん断ひずみ領域にも拡張適用が可能



# 摩擦面の劣化と砂利の集合への遷移 実験でクローズアップ(定性的+定量的)

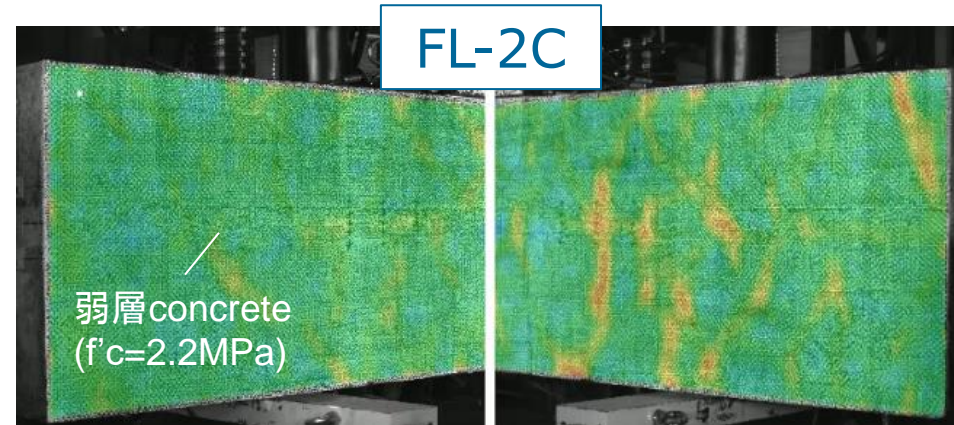


# 弱層を挟んだ2つのコンクリート 弱層にせん断集中—砂利化—それでも頑張る—コンクリート破壊

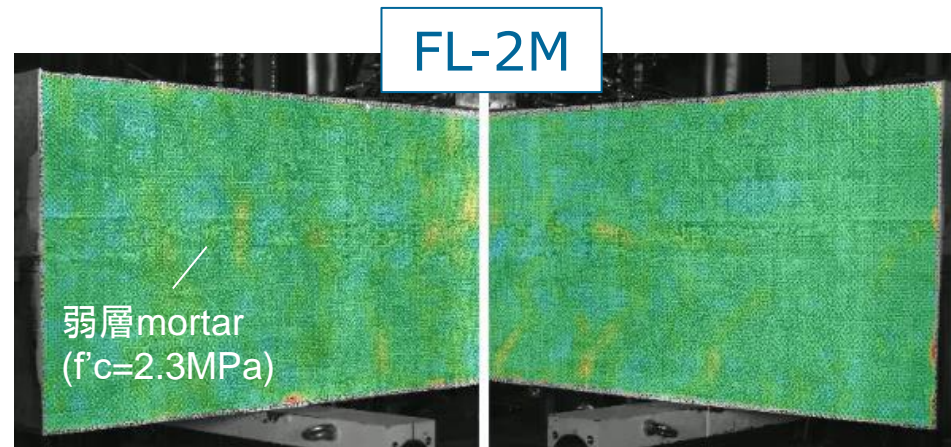
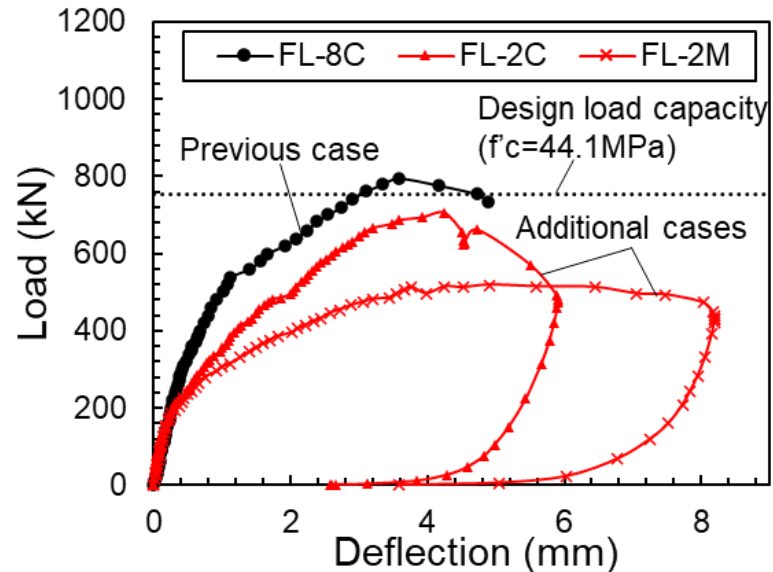
## ◆ 実験結果(コンクリート/モルタル)



FL-2C  
弱層コンクリート2MPa,  
梁上/下 45/100MPa



FL-2M  
弱層モルタル2MPa,  
梁上/下 45/100MPa





# 弱層を挟んだ2つのコンクリート

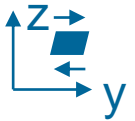
## 弱層にせん断集中—砂利化—それでも頑張る—コンクリート破壊

### ◆ 解析結果

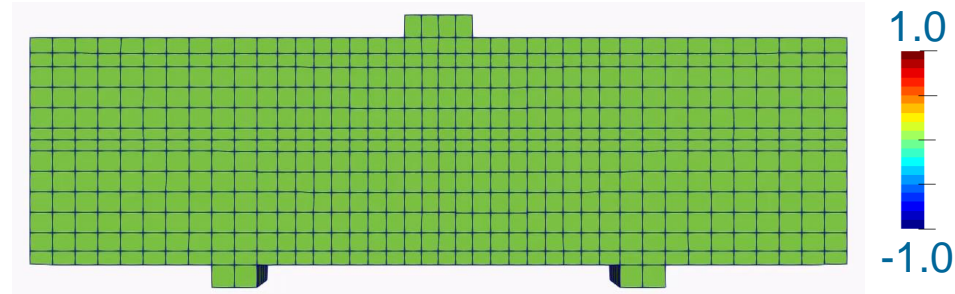
FL-2C

- ✓ 弱層はまず初めに損傷.
- ✓ 弱層は拘束下でせん断抵抗維持
- ✓ 上下側のはり部にせん断発生
- ✓ (普通と高強度コンクリート)

Shear strain:  $\gamma_{yz}$  (%)

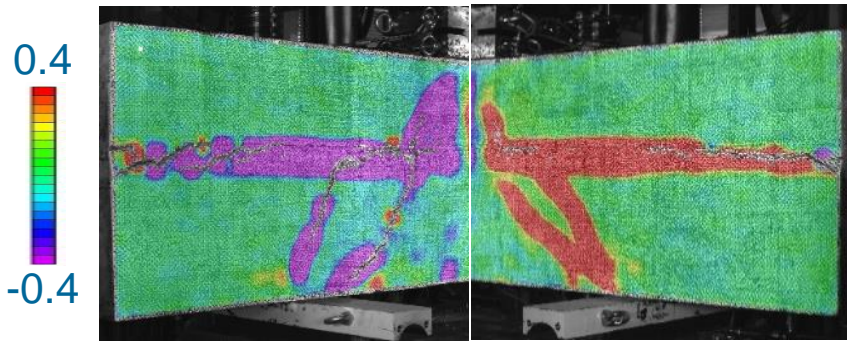


Analysis (animation)



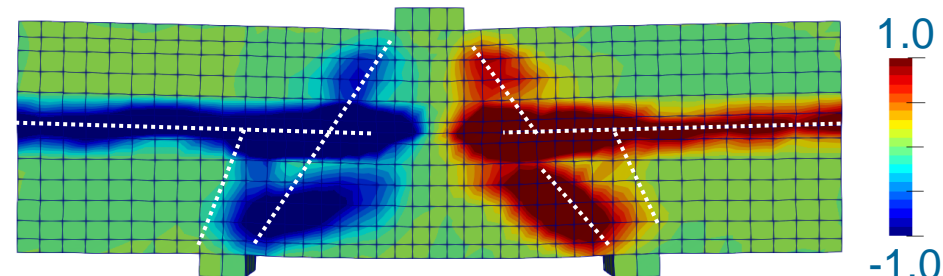
Experiment

u=4.0mm



Analysis

u=4.0mm



..... :Major crack paths in the experiment

\*Deformation magnification 3 times

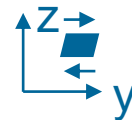
# 弱層を挟んだ2つのコンクリート 弱層にモルタルー砂利化ーコンクリート破壊へ

## ◆ 解析結果

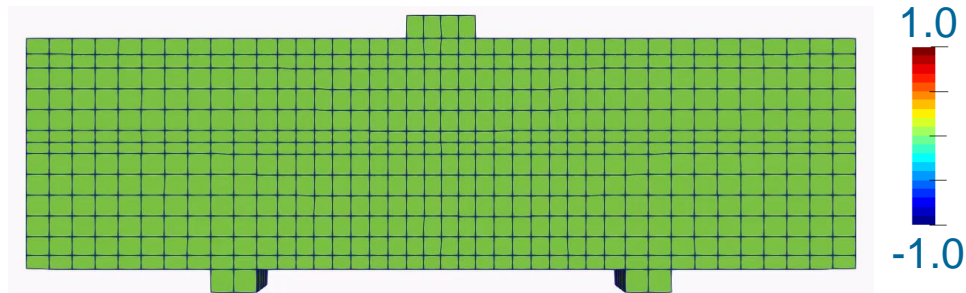
FL-2M

- ✓ 弱層がまず損傷.
- ✓ 弱層のせん断伝達機能は小さいが、なお梁下部高強度コンクリートにせん断
- ✓ 梁上部には曲げ損傷

Shear strain:  $\gamma_{yz}$  (%)

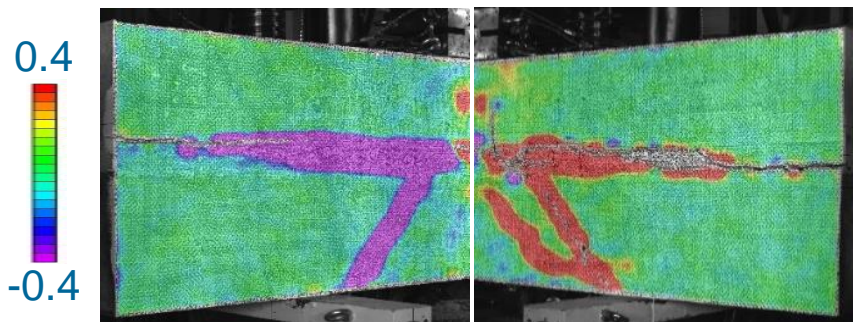


Analysis (animation)



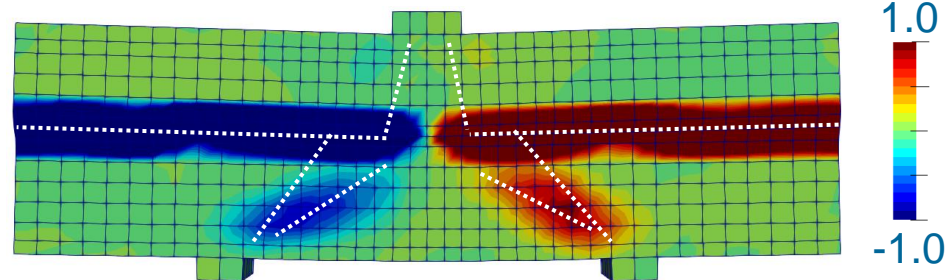
Experiment

$u=4.0\text{mm}$



Analysis

$u=4.0\text{mm}$



..... :Major crack paths in the experiment

\*Deformation magnification 3 times



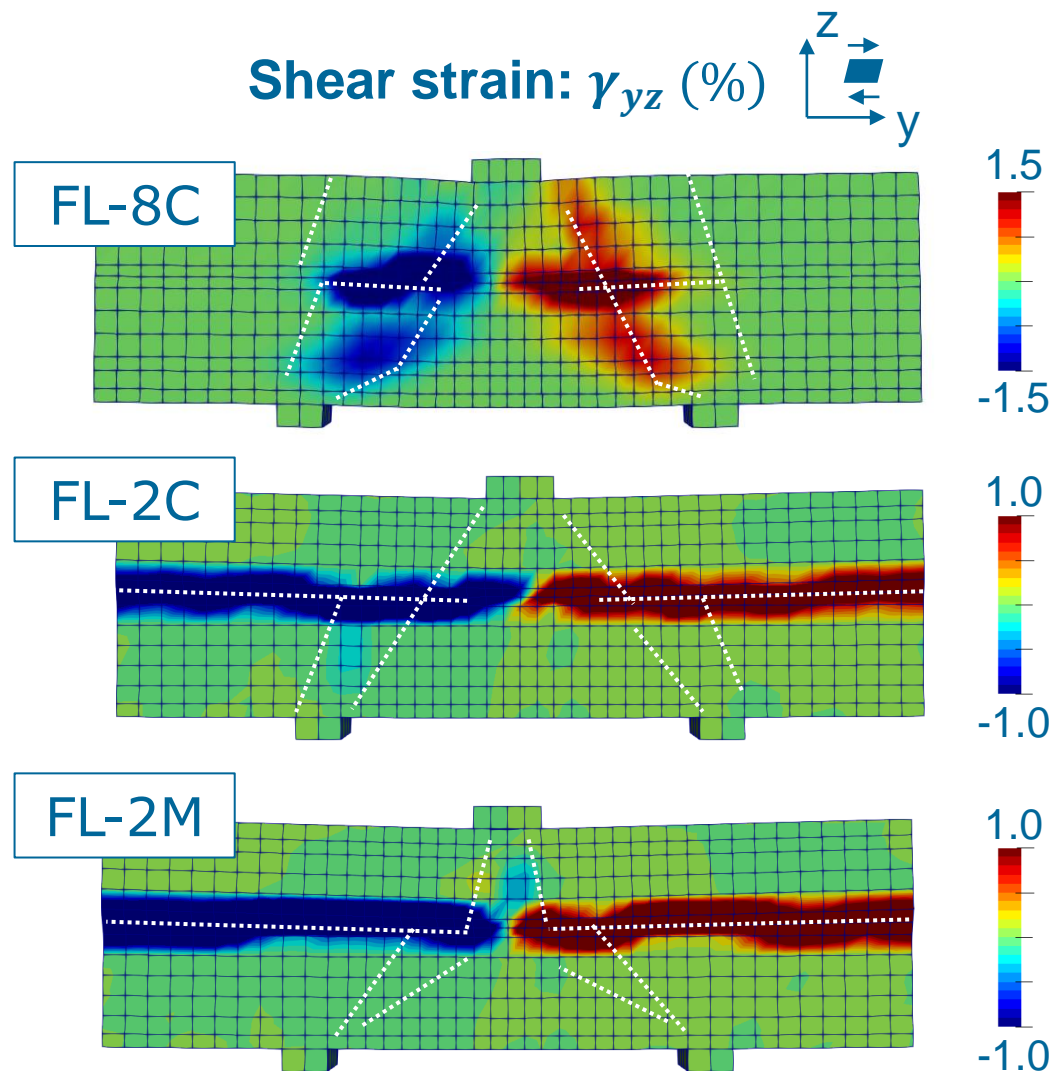
# 砂利化を考慮せず、初めから終わりまでコンクリートのせん断伝達が継続すると仮定すると、崩壊は早い(安全側)

## ◆ せん断遷移を考慮しないと...

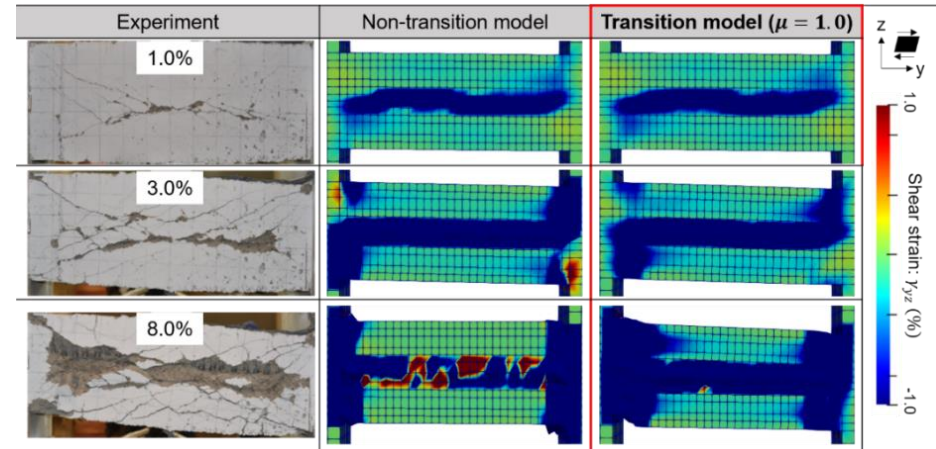
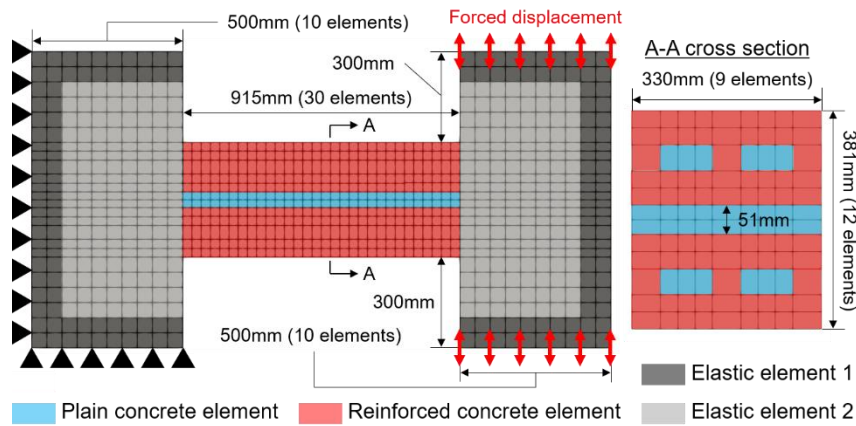
- FL-8Cの場合、砂利化モデル無しでも、悪くはない。
- (弱層は8MPa)
- FL-2C と FL-2Mでは、砂利化モデル無しでは、梁の全域でせん断変形(破壊)が現れない。
- せん断を導入できるだけのせん断力が伝えられないため(砂利であれば可能)



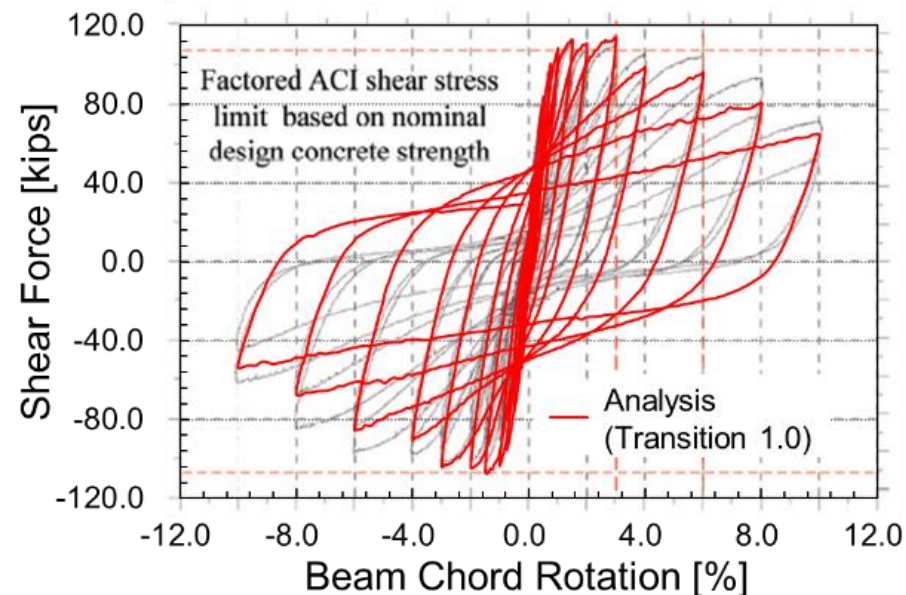
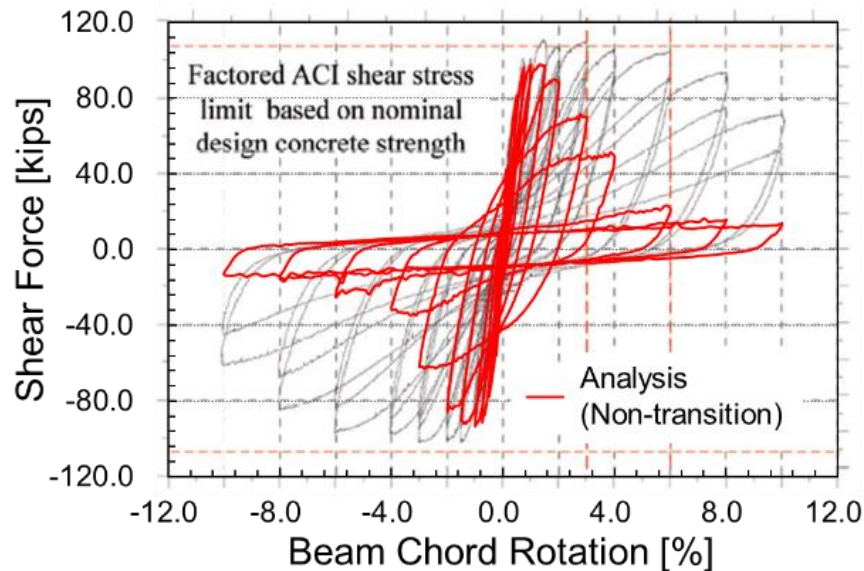
低強度であるほどに、砂利化のモデル化が有効



# 耐力以後の軟化と崩壊過程：砂利化の進行と同時に構造崩壊



Choi, Y., Chao, S.H., 2020. Analysis and design of double-beam coupling beams. ACI Structural Journal 117

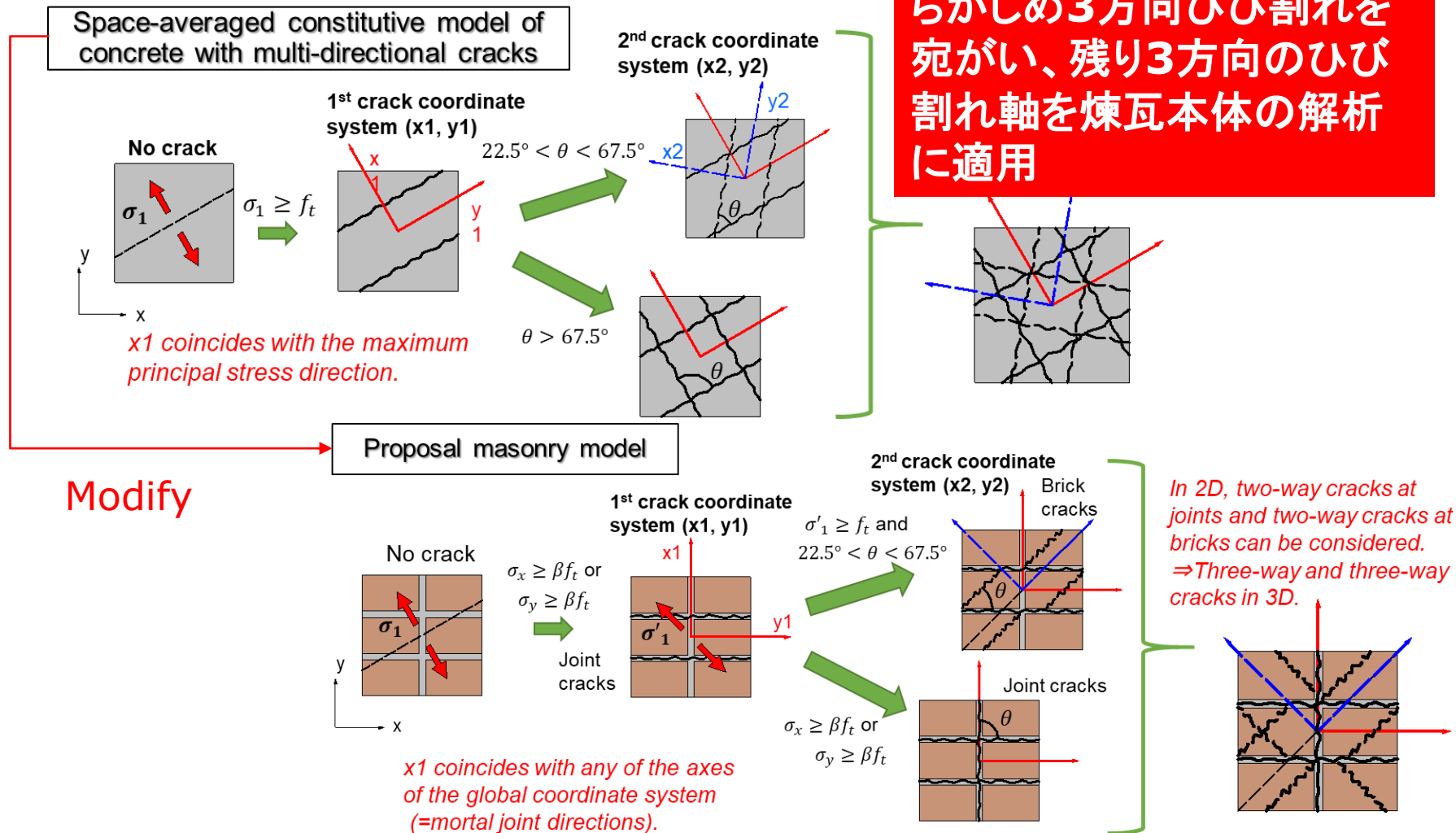


Yuto Yamanoi, Takashi Miura, Masoud Soltani, Koichi Maekawa (2021). Multi-directional fixed crack model extended to masonry structures, Journal of Advanced Concrete Technology, 19(9), 977-987



# 6方向ひび割れモデルのうち、3方向のメモリー領域を既存の煉瓦接合面に適用、残り3方向はレンガ自体の破壊に充当

## ◆ 煉瓦積み構造への拡張と砂利化モデル検証

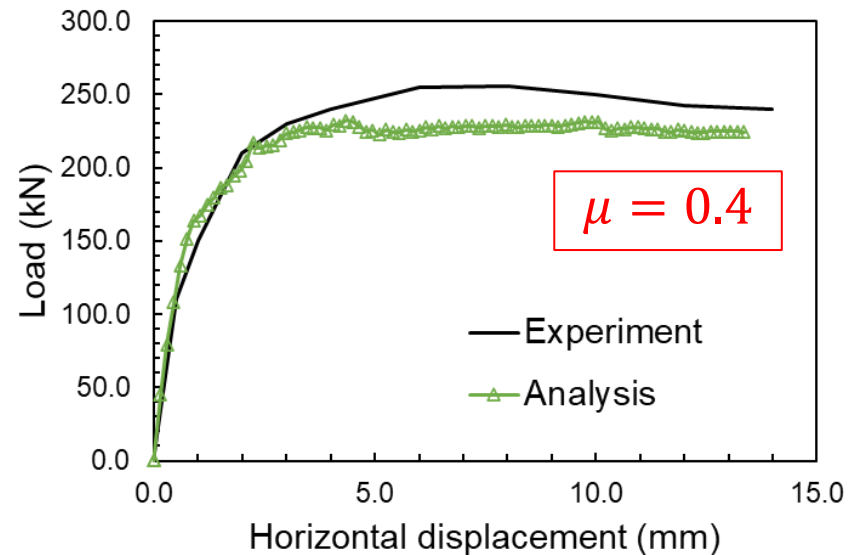


# モルタル接合面がレンガ本体より弱い場合

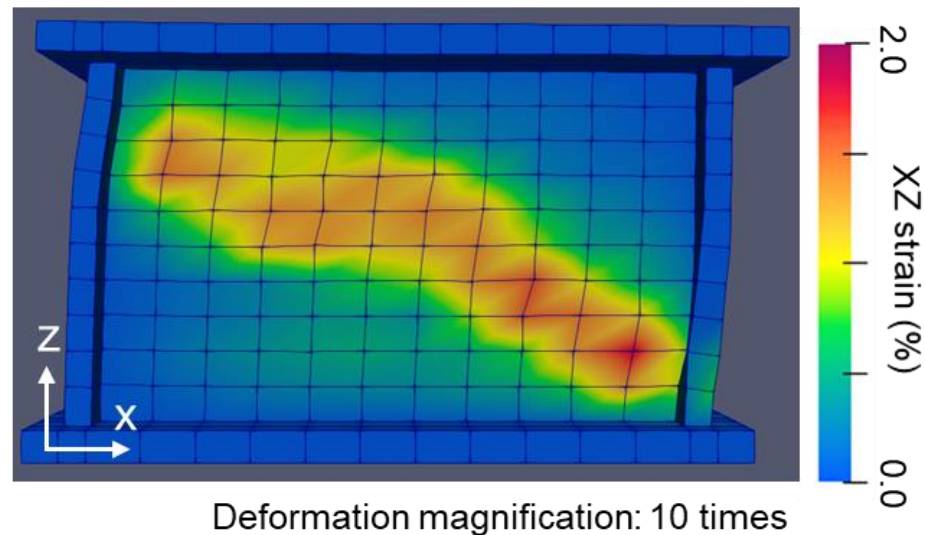
終局状態



Ganz, H.R., Thurlimann, B., 1984. Versuche an mauerwerksscheiben unter normalkraft und querkraft. Zurich, Switzerland.



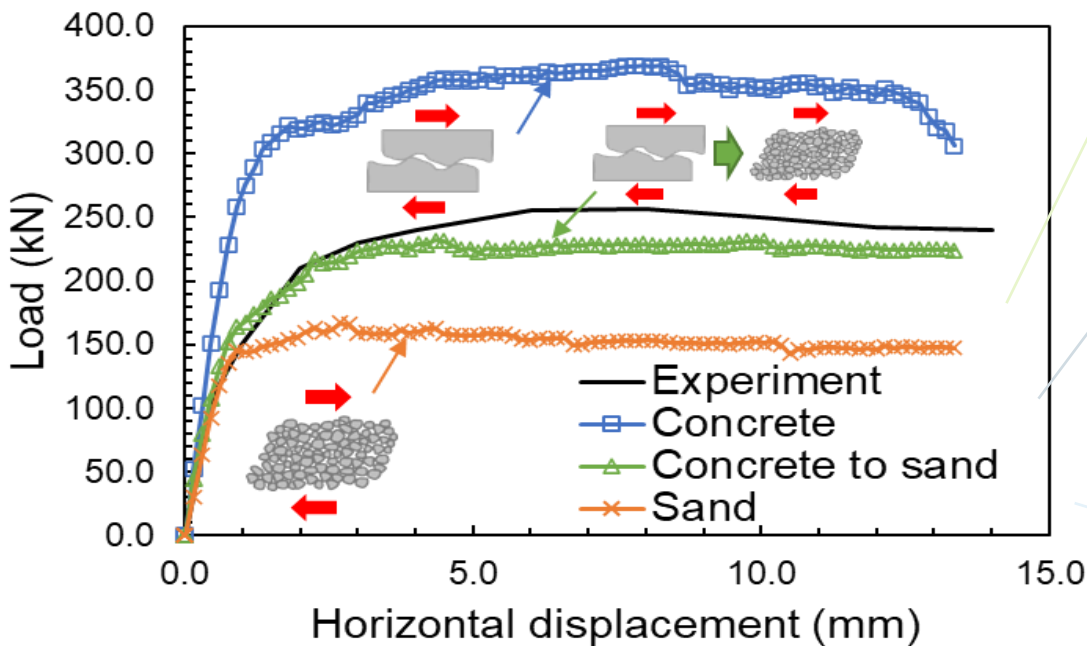
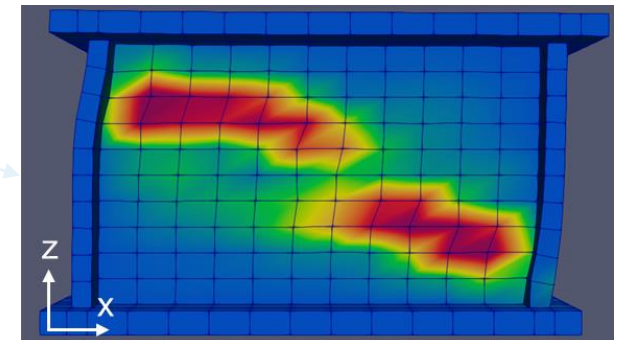
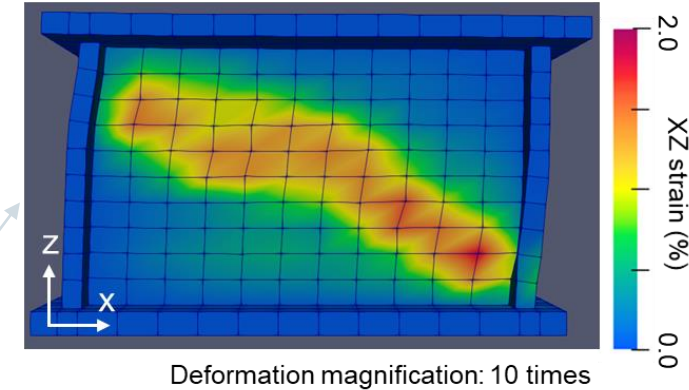
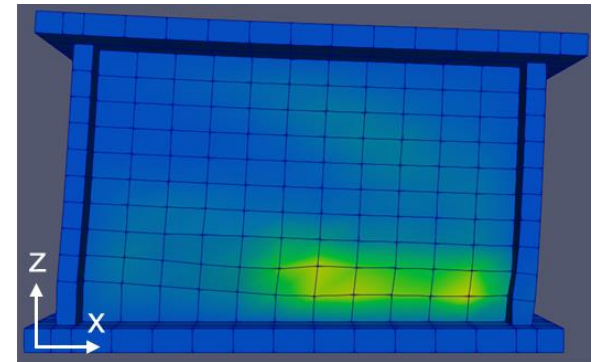
## Shear strain distribution





# モルタル接合面がレンガ本体より弱い場合

- ◆ せん断伝達の感度解析
- ◆ コンクリートモデル
- ◆ 砂利モデル(モールクーロン)
- ◆ 遷移モデル



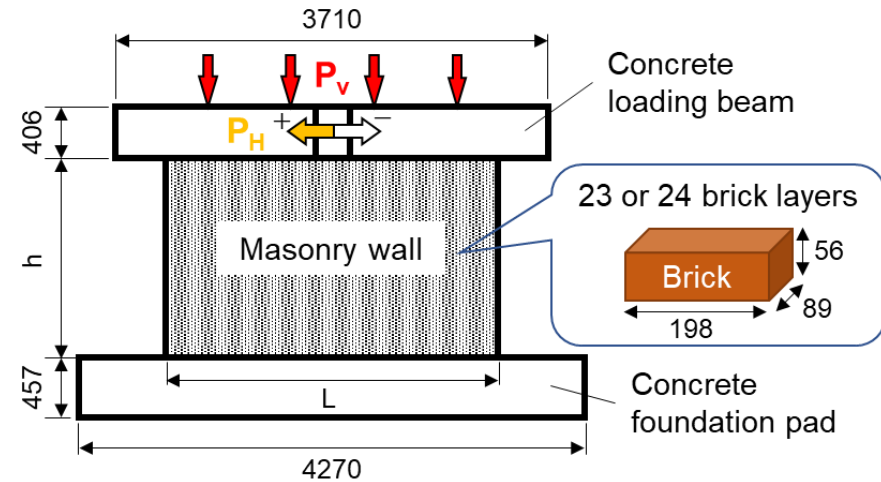
# モルタル接合面がレンガ本体より弱い場合

## Scale of each specimen

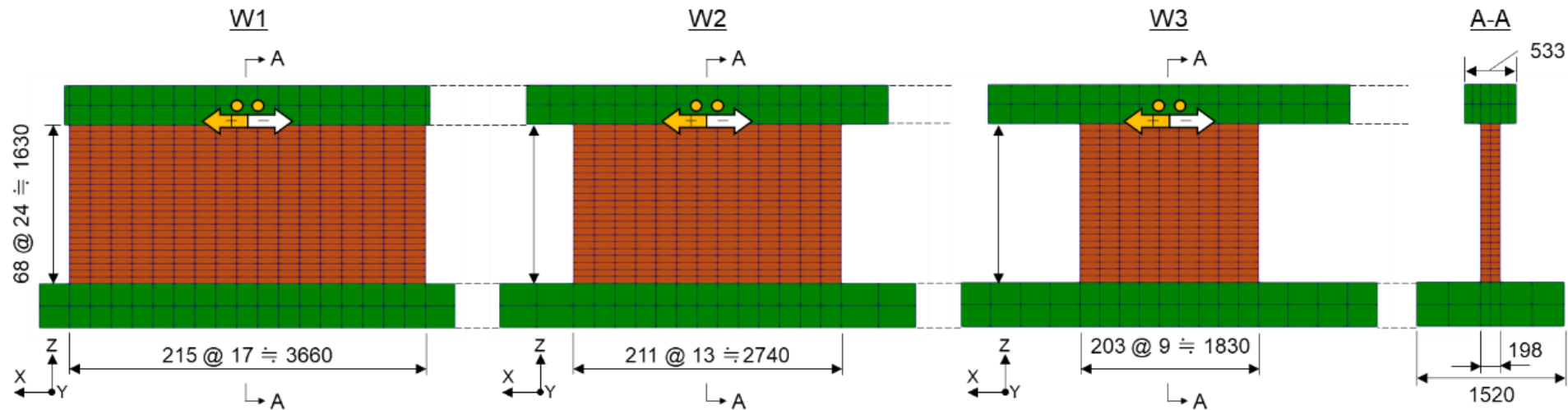
Specimen	L (mm)	h (mm)	L/h	$P_v^{-1}$ (MPa)
W1	3658	1626	2.25	0.52
W2	2743	1626	1.67	0.34
W3	1829	1626	1.12	0.34

\*1: Vertical stress

Material property value	unit	RC element (brick)	Elastic element
Young's modulus	MPa	4710	210000
Compressive strength	MPa	24.0	-
Tensile strength of concrete	MPa	1.91	-
Tensile strength of mortar	MPa	0.06	<a href="#">Input value</a>
Frictional coefficient	-	0.50	-



**Abrams, D.P., Shah, N., 1992.** Cyclic load testing of unreinforced masonry walls. University of Illinois, at Urbana-Champaign, Newmark Civil Engineering Laboratory, Advanced Construction Technology Center.

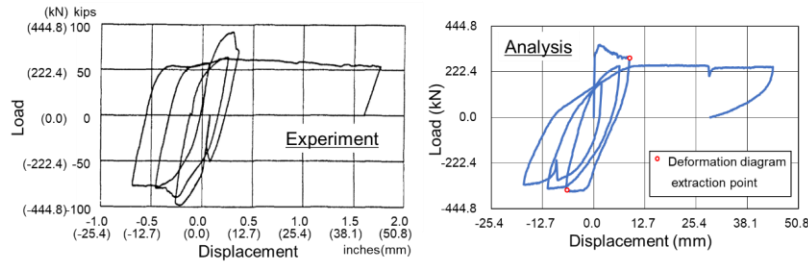


Yuto Yamanoi, Takashi Miura, Masoud Soltani, Koichi Maekawa (2021). Multi-directional fixed crack model extended to masonry structures, Journal of Advanced Concrete Technology, 19(9), 977-987

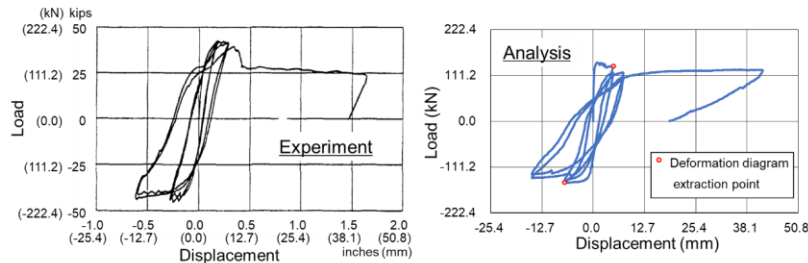


# モルタル接合面がレンガ本体より弱い場合

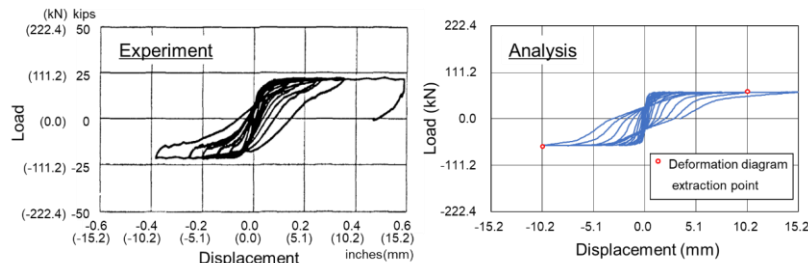
## 荷重-変位関係



(a) W1

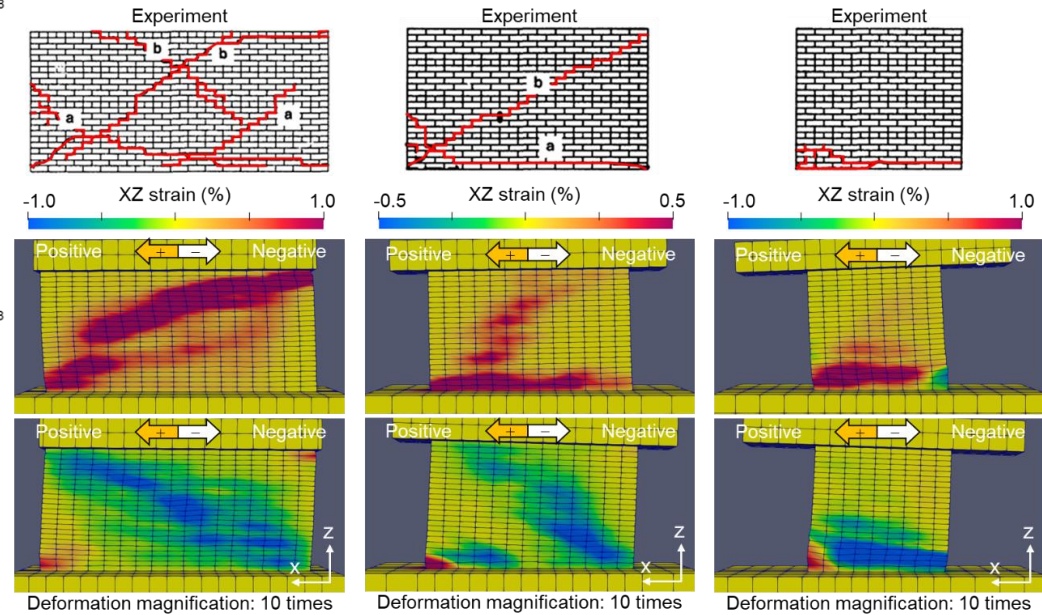


(b) W2



(c) W3

## 破壊モードとせん断ひずみの分布



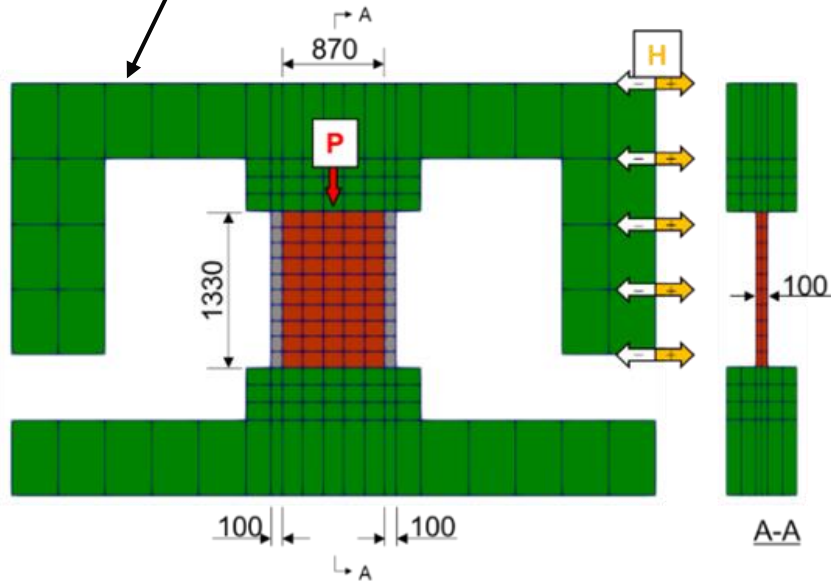
(a) W1

(b) W2

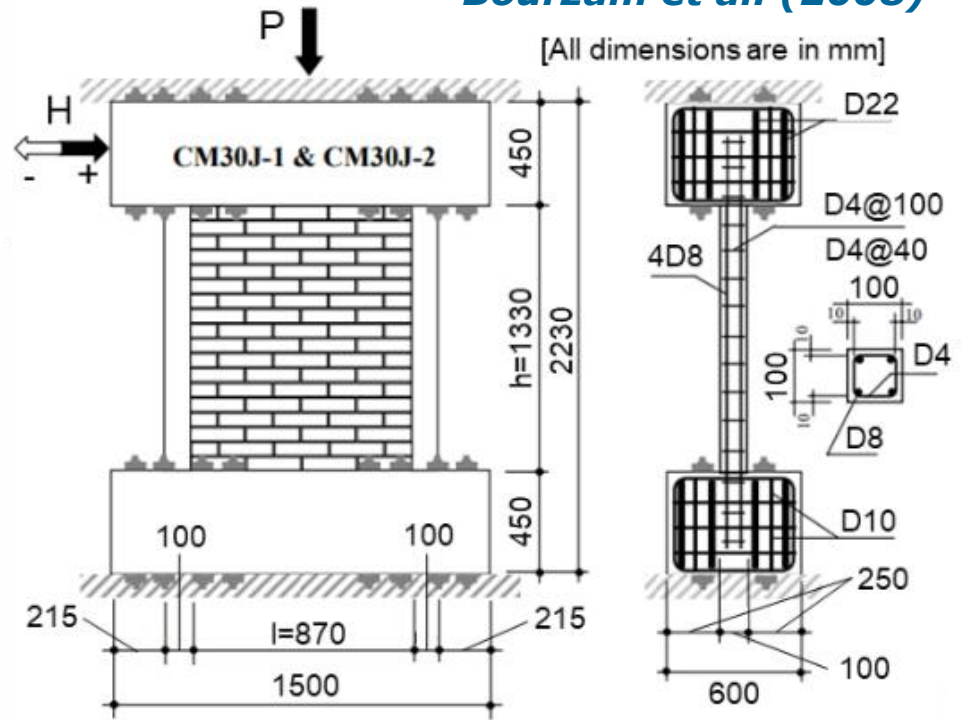
(c) W3

# モルタル接合面がレンガ本体とほぼ同じ場合

载荷フレーム



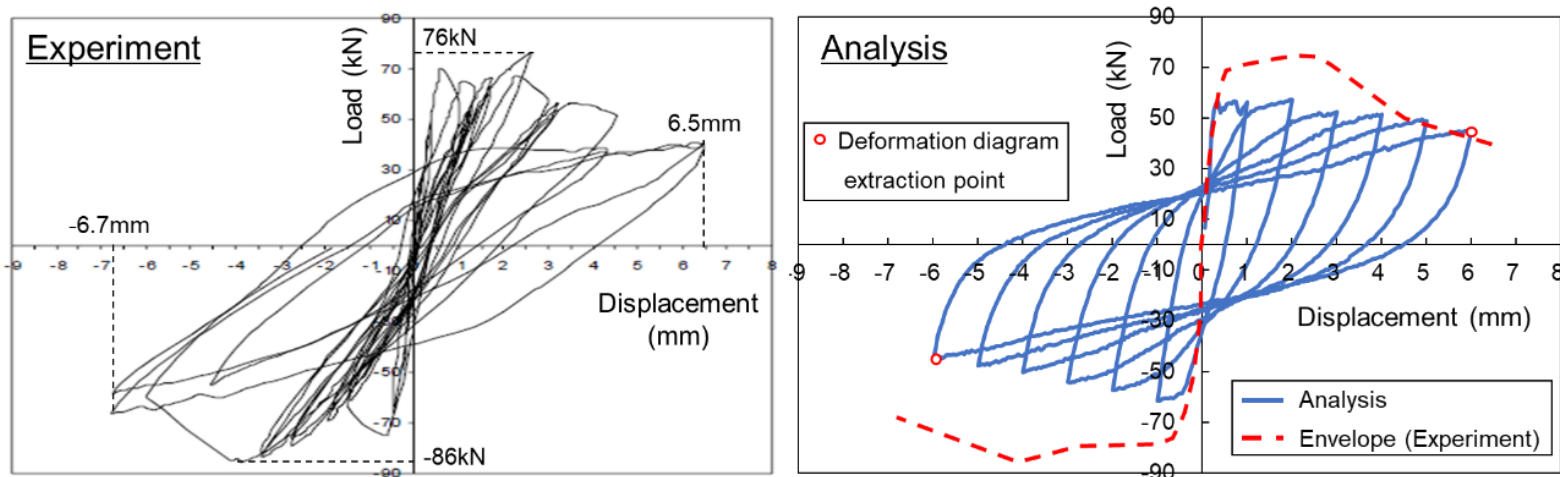
*Bourzam et al. (2008)*



Material property value	unit	RC element (brick)	RC element (RC pillar)	Elastic element
Young's modulus	MPa	8240	18300	210000
Compressive strength	MPa	30.0	20.0	-
Tensile strength of concrete	MPa	2.20	1.70	-
Tensile strength of mortar	MPa	0.27	-	-
Frictional coefficient	-	0.50	<u>Input value</u>	



# モルタル接合面がレンガ本体とほぼ同じ場合



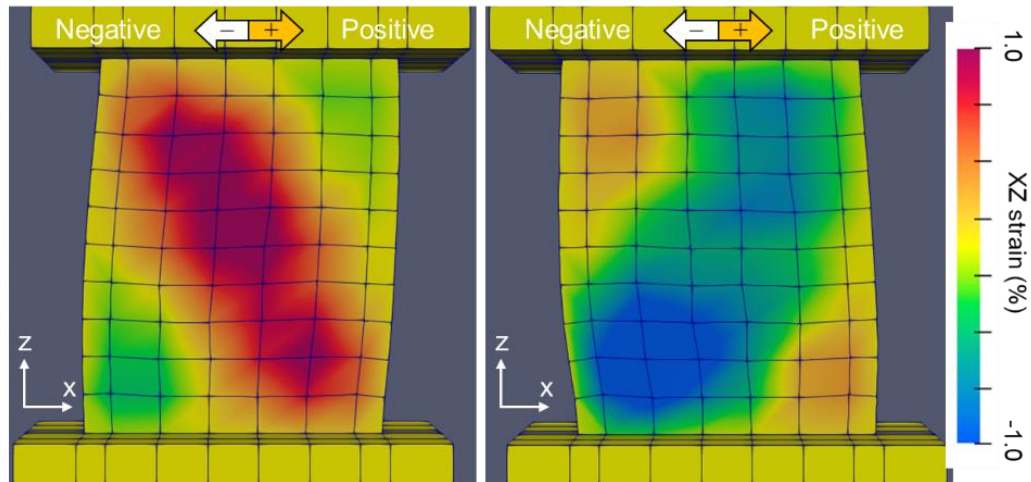
## Failure mode and shear strain distribution

Final crack pattern  
(Experiment)



Shear strain distribution (Analysis)

\*Deformation magnification: 10 times



# 砂利化モデルの応用: 断層、破碎帯と地下構造との相互作用

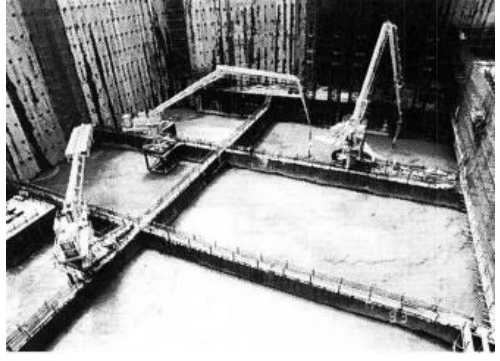
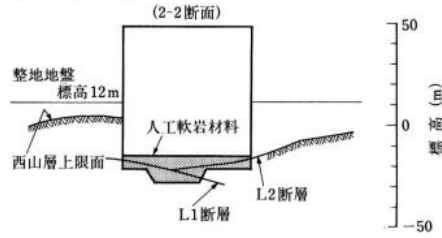
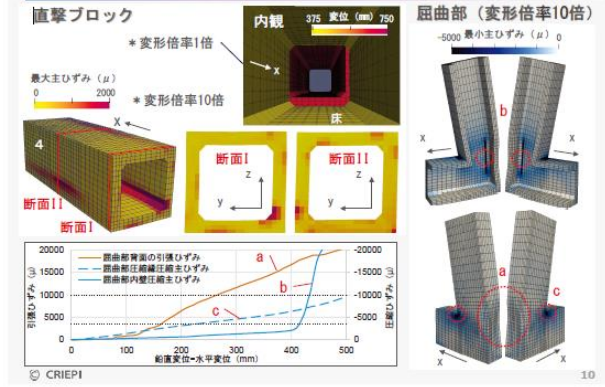
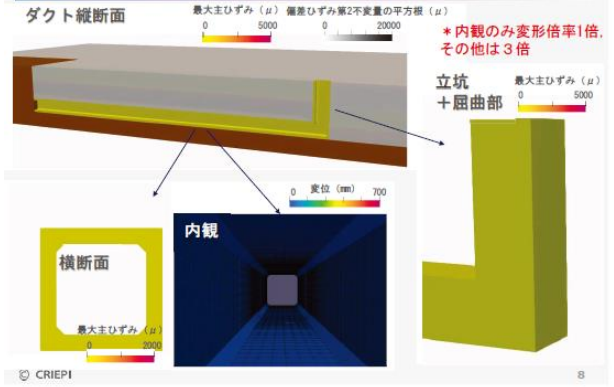
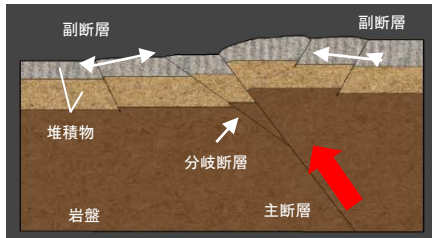
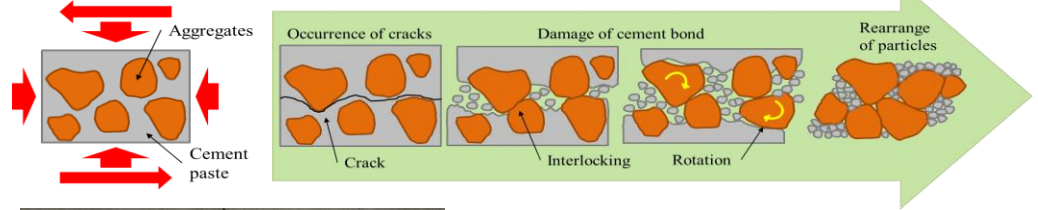
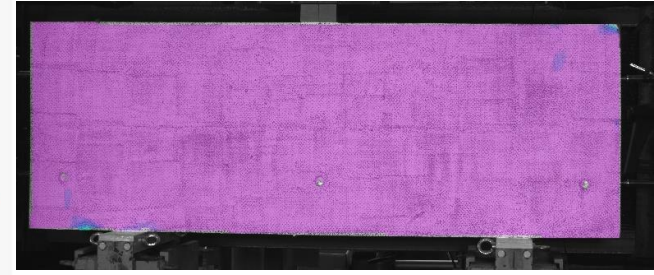
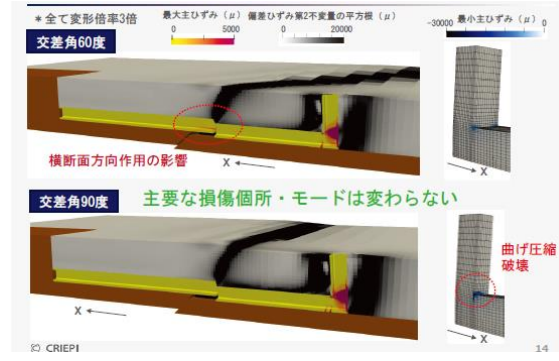
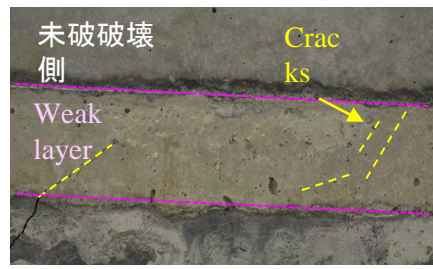


写真-2 人工軟岩材料の施工状況



岸 清:人工軟岩材料の開発:土木学会論文集/1995 巻 (1995) 522 号

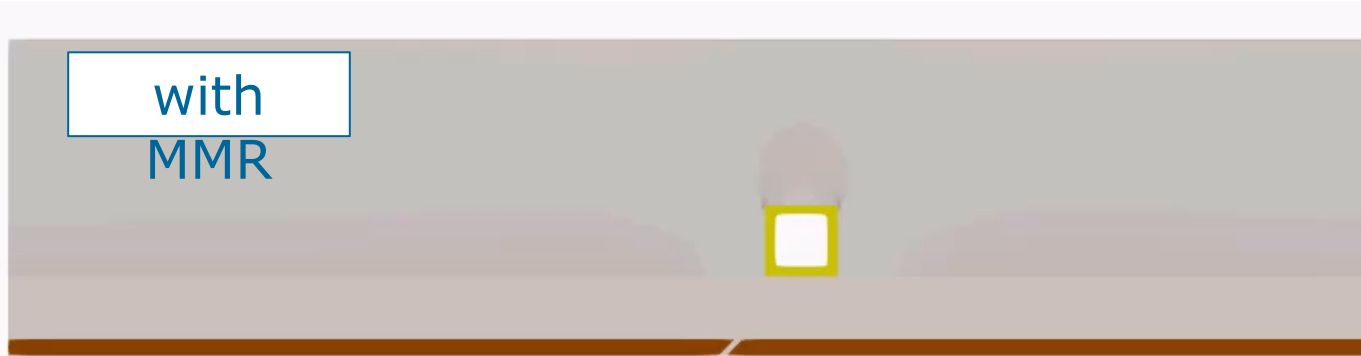
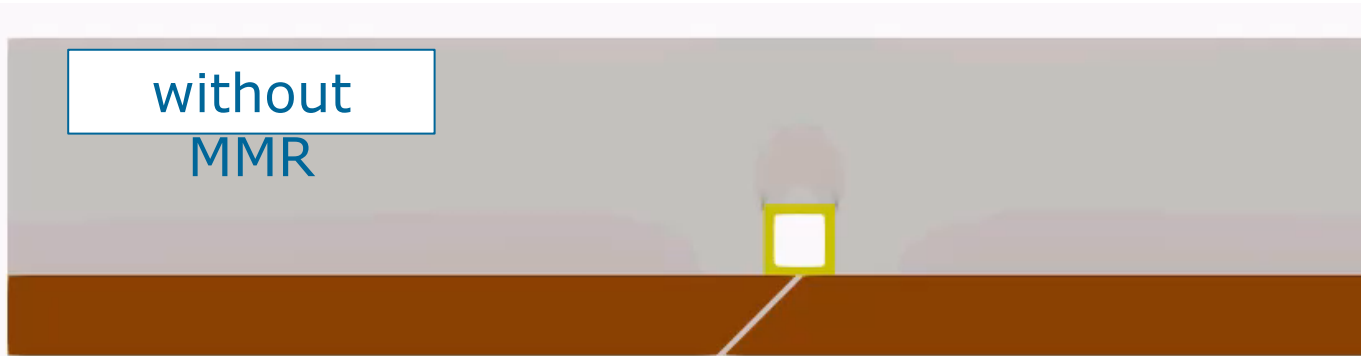
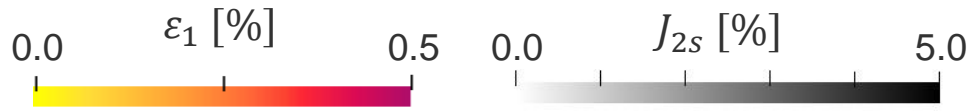
地盤と構造物の間に弱層がある場合、副断層(30cm程度)による変位を構造物と弱層の両方で受け止めることも可能では？



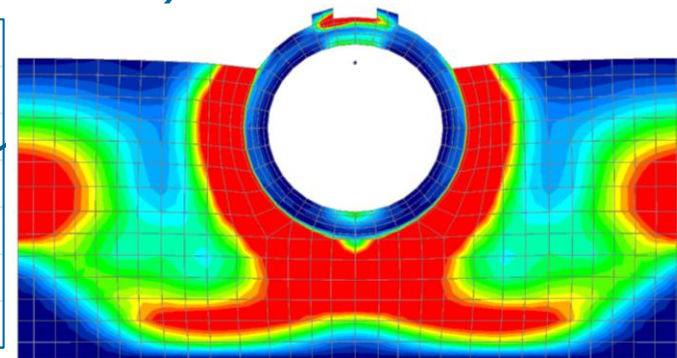
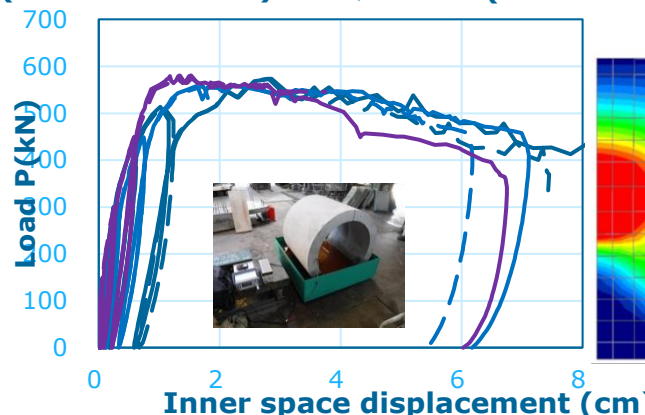
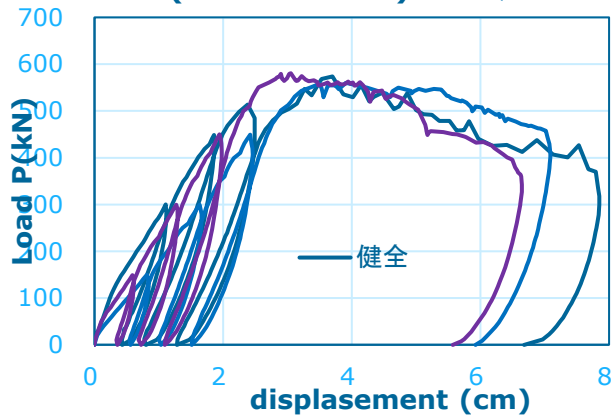
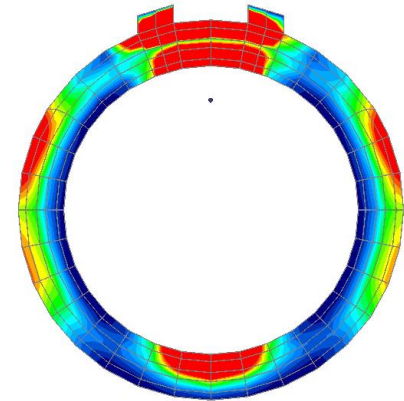


# 砂利化モデルの応用: 断層、破碎帯と地下構造との相互作用

## ◆ Strain distribution and deformation



# 地下構造の維持管理とも関連





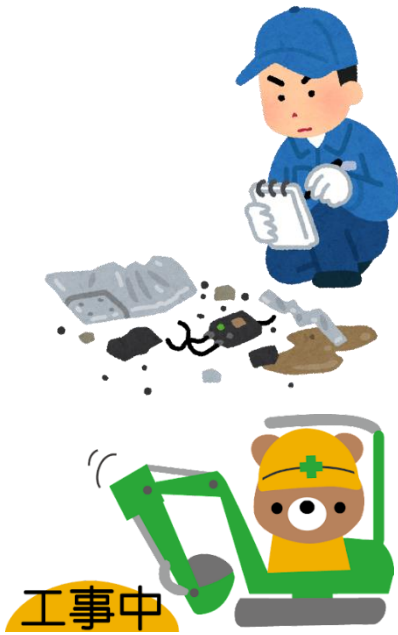
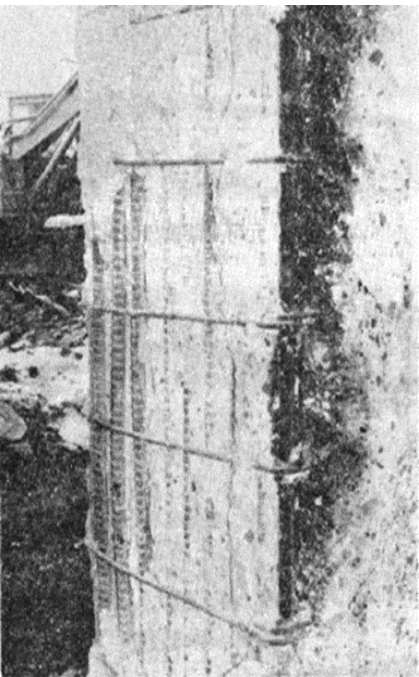
**3次元非線形解析の応用：性能設計とハード技術開発**

**コンクリート構造と材料の崩壊過程：残余のリスク  
砂利化・土砂化： 時間効果**

**高温履歴を受ける構造： 耐火、トンネル、環境**

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# 火災を受けたコンクリート構造の残存性能評価と早期復旧



首都高速池袋線火災:タンクローリー横転  
二か月強で全面復旧



JR武蔵野線火災:2日間に廃タイヤの燃焼:  
消火不能 1,200度に長期に暴露

日本坂トンネル火災事故(1979)





# 常温から1,200度へ

## 結晶変性、水蒸気爆裂、CO<sub>2</sub>固定と再解放、水蒸気再水和

火災を受けたインフラ構造の合理的な復旧方法選定  
残存性能の定量把握→更新計画設計施工



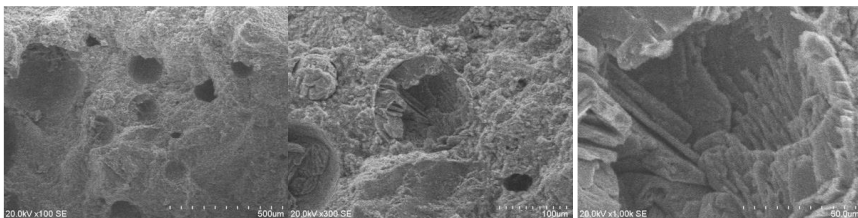
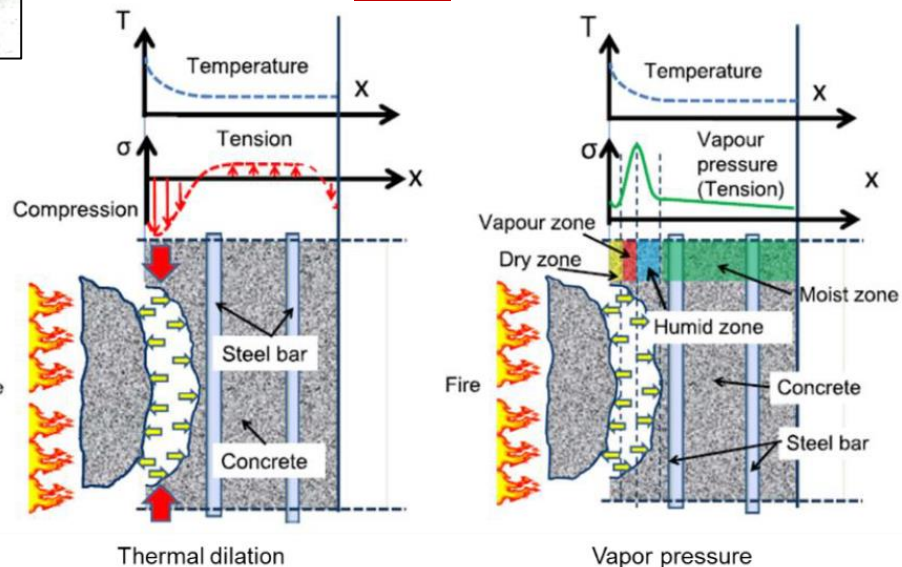
最高温度:  
約 1200 °C  
消火までの時間:  
約5時間

首都高  
5号線  
火災  
(2008)

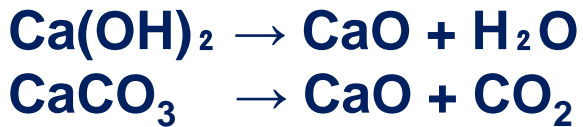
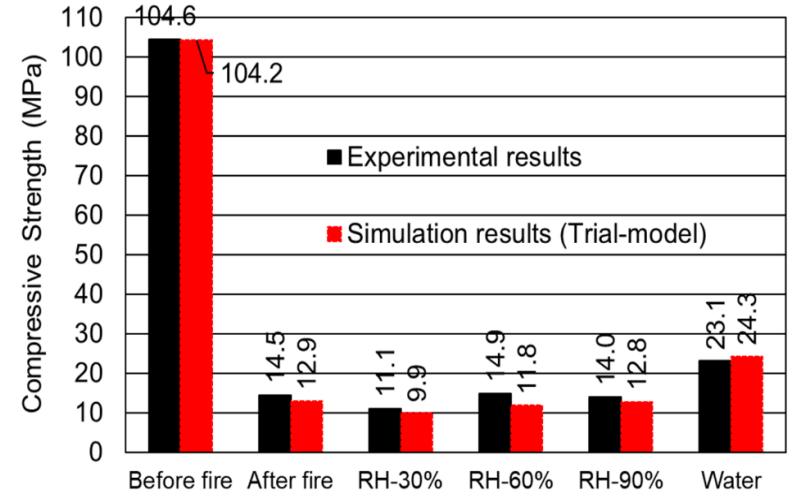


水和結晶構造の崩れ—結晶水から水蒸気—  
—高圧発生—**爆裂**—断面欠損—軸耐力減

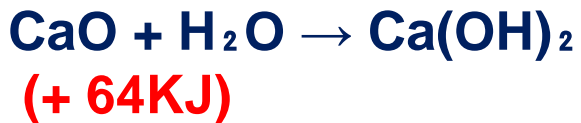
水和結晶構造崩れ—CO<sub>2</sub>取り込み—クリンカー再生—徐冷後に気中水蒸気とCO<sub>2</sub>固定—再結晶—細孔修復—強度回復—  
微細ひび割れ集合—高靱性構造転換



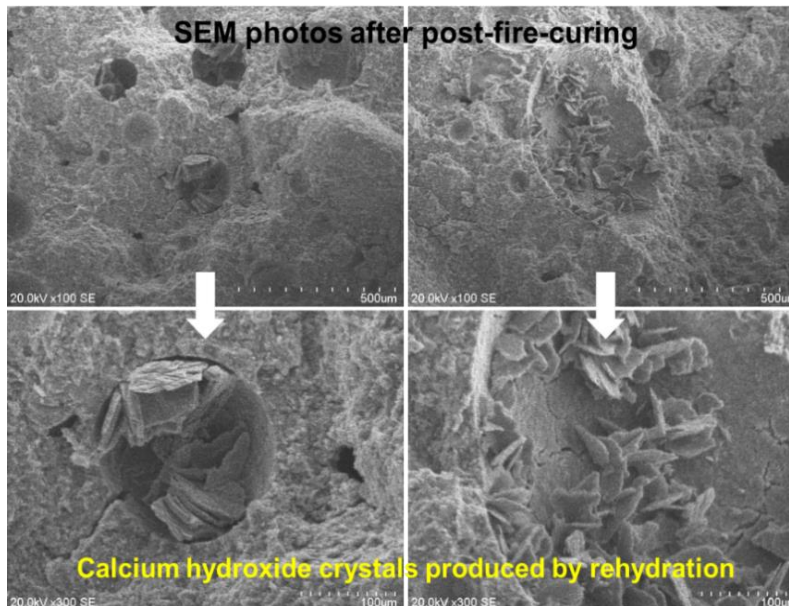
# 火災を受けて硬化体の先祖返りも



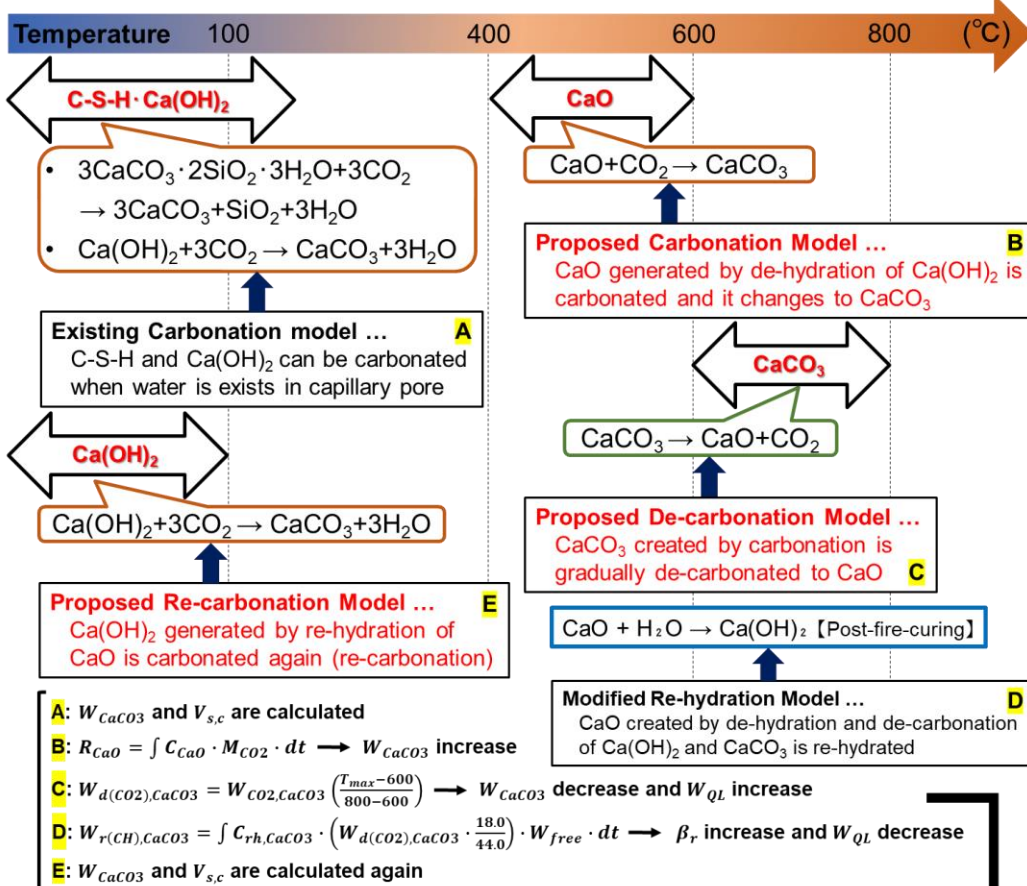
[Fire damage]



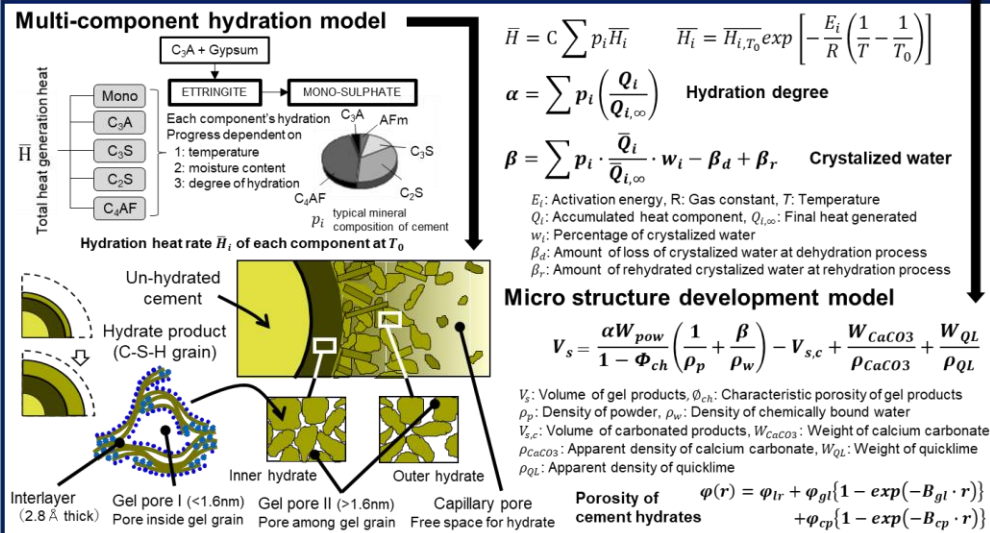
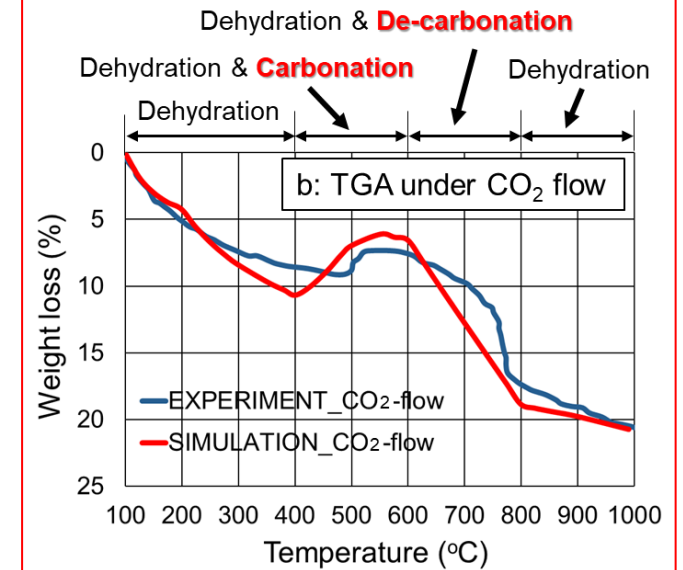
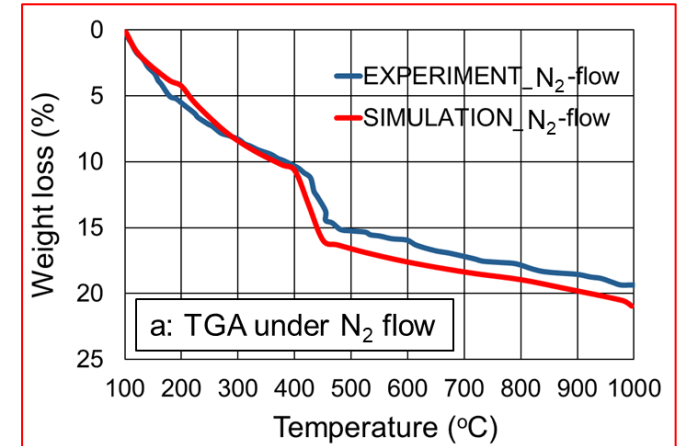
[quick lime, Post-fire-curing]



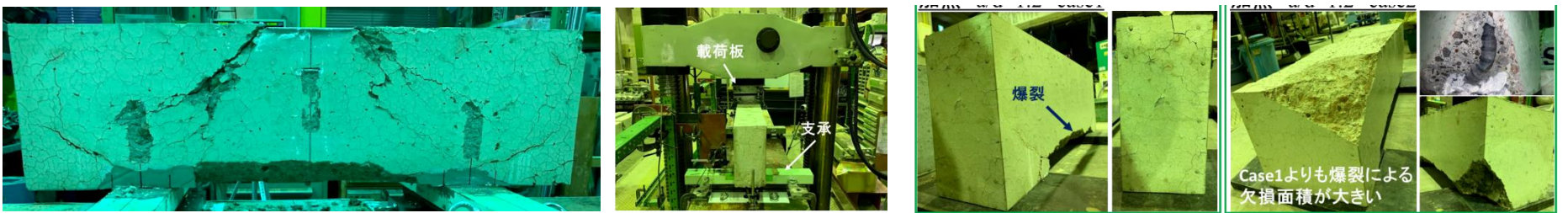
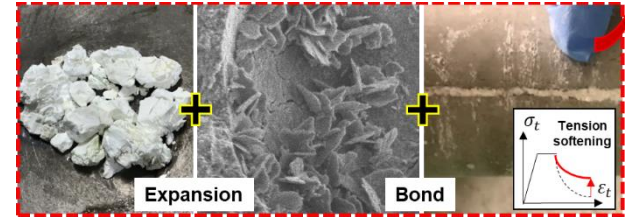
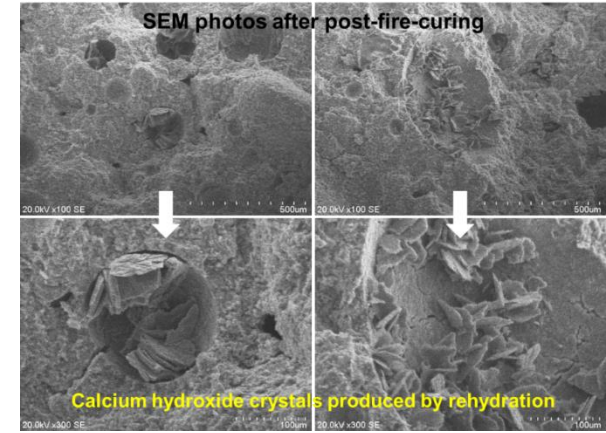
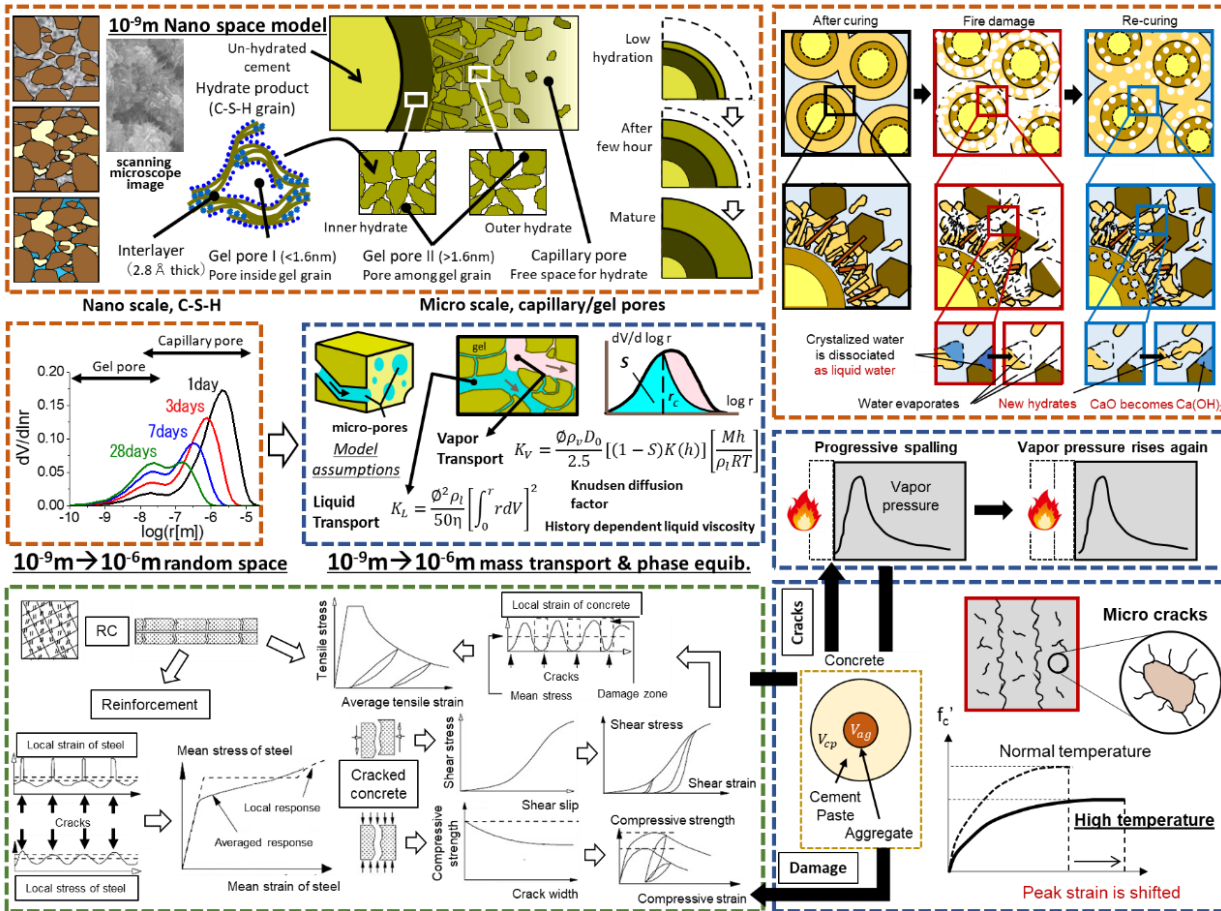




Keitai Iwama and Koichi Maekawa (2022). Modelling of carbonation, de-carbonation and re-carbonation processes of structural concrete subjected to high temperature heating, Cement and Concrete Composite,

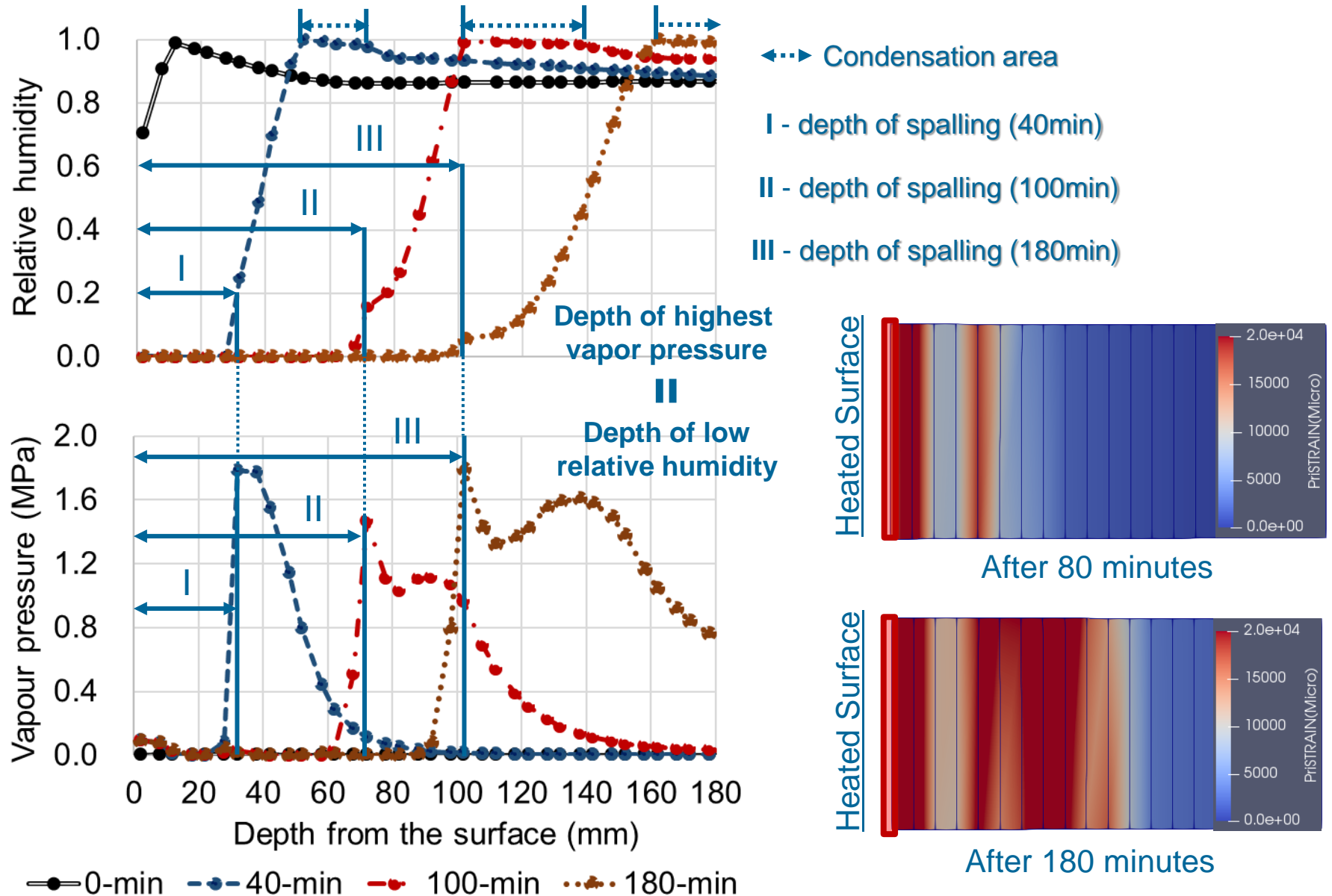


# DuCOM-COM3Dの構成





# 液相—気相の推移と水蒸気圧



# DuCOM-COM3Dの構成

Chemical substance field

Electrical potential field

①

②

③

④

⑤

⑥

⑦

Geochemical equilibria

Ion movement

Anodic/cathodic polarization

Electric current

**PHREEQC**

OH<sup>-</sup>, Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Al<sup>3+</sup>, SiO<sub>4</sub><sup>4-</sup>, Mg<sup>2+</sup>, HCO<sub>3</sub><sup>-</sup>

Calcium silicate hydrate [C<sub>3</sub>S<sub>H</sub>] [3(CaO)(Al<sub>2</sub>O<sub>3</sub>)<sub>2</sub>(CaSO<sub>4</sub>)<sub>2</sub>(32H<sub>2</sub>O)]  
 Portlandite [C<sub>2</sub>S<sub>H</sub>] [Ca(OH)<sub>2</sub>]  
 Monosulfo-aluminate [C<sub>4</sub>A<sub>1</sub>(OH)<sub>2</sub>SO<sub>4</sub>] [Ca<sub>4</sub>(Al<sub>2</sub>(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>2</sub>)<sub>2</sub>·26H<sub>2</sub>O]  
 Calcite [C<sub>1</sub>CO<sub>3</sub>] [CaCO<sub>3</sub>]  
 Gypsum [C<sub>2</sub>S<sub>H</sub>SO<sub>4</sub>] [CaSO<sub>4</sub>·2H<sub>2</sub>O]  
 Thaumassite [C<sub>4</sub>S<sub>2</sub>(OH)<sub>2</sub>(CO<sub>3</sub>)<sub>2</sub>(SO<sub>4</sub>)<sub>2</sub>·12H<sub>2</sub>O]  
 Brucite [Mg(OH)<sub>2</sub>]  
 Hydro-talcite [Mg<sub>3</sub>(Al<sub>2</sub>(OH)<sub>2</sub>(CO<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O)]  
 Friedel salt [C<sub>4</sub>A<sub>1</sub>(OH)<sub>2</sub>Cl<sub>2</sub>SO<sub>4</sub>]  
 Monocarbo-aluminate [3CaO·Al<sub>2</sub>O<sub>3</sub>·CaCO<sub>3</sub>·11H<sub>2</sub>O]  
 Hemicarbo-aluminate [Ca<sub>2</sub>Al<sub>2</sub>CO<sub>3</sub>·24H<sub>2</sub>O]  
 Bischofite [MgCO<sub>3</sub>·6H<sub>2</sub>O]  
 Halite [NaCl]

Concrete

Exposure solution

ION-ION interactions

Dissolution/precipitation

Minerals

Mass/energy balance

Mass action Mole balance

Law of Chemical Equilibrium Mass Actions

Before SO<sub>4</sub> equilibrium and transport model

SO<sub>4</sub> equilibrium and transport model

Hydrating OPC paste with W/C of 0.5

After OH equilibrium and transport model

OH equilibrium and transport model

**DuCOM**

Microstructure level 10<sup>-9</sup>m→10<sup>-6</sup>m

thermo-hygro-system

Multi-component hydration heat model

Microstructure development model

Capillaries, gel, and interlayer

Outer product

Inner product

Unhydrated core

particle radius

Mean separation

Representative CSM grain

Matrix micro pore structure

Moisture transfer and equilibrium model

Vapor transport

Liquid transport

Condensed water

Trapped water in inkbottle pores

log r

log r

**COM3**

Poromechanical approach 10<sup>-6</sup>m→10<sup>-3</sup>m

Thermodynamics of ice

Ice

surface tension

θ<sub>CL</sub> θ<sub>LV</sub>

P<sub>hydrau</sub>

P<sub>cryst</sub>

P<sub>vapor</sub> = 0

P<sub>cryst</sub>

Load

Effective internal stress

Skelton Pore

σ<sub>ij</sub> = σ<sub>ij</sub><sup>\*</sup> + δ<sub>ij</sub>p

viscosity

gravity force

viscosity

water

Water motion in pores and cracks

**COM3**

Material and member level 10<sup>-3</sup>m→10<sup>0</sup>m

Reinforcement

Local strain of steel

Mean stress of steel

Local response

Averaged response of steel in concrete

Mean strain of steel

RC

Local strain of concrete

Crack location

Mean stress

Damage zone

Average tensile strain

Cracked concrete

Shear stress transferred

Shear slip along a crack

Comp. strength reduction

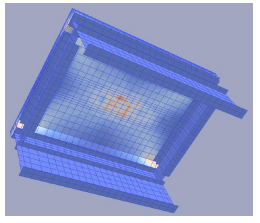
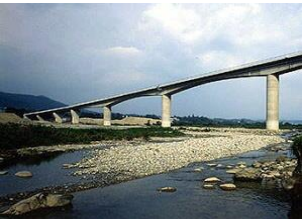
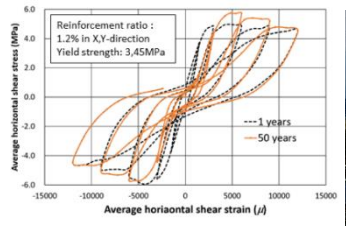
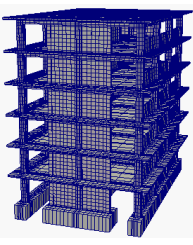
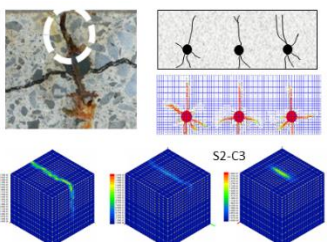
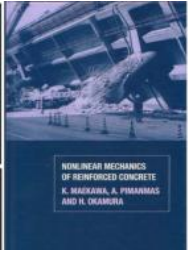
Mean shear strain

Crack width

Comp. strength reduction

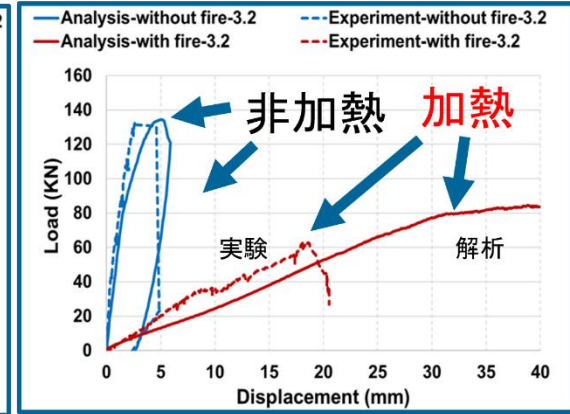
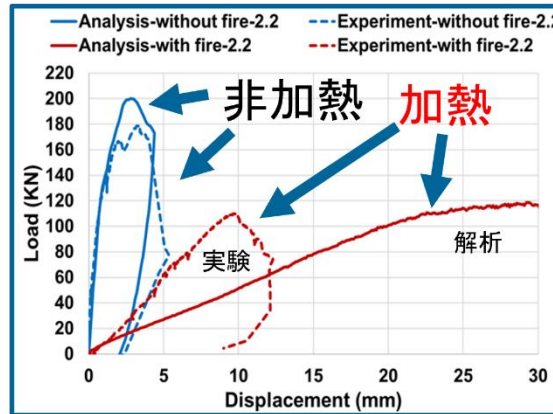
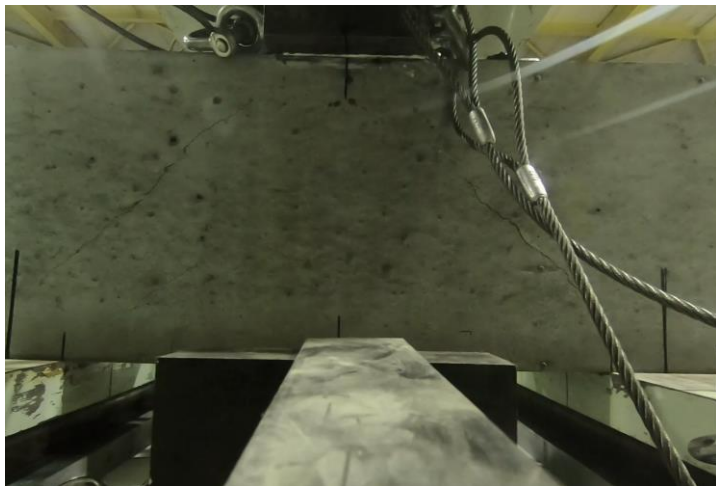
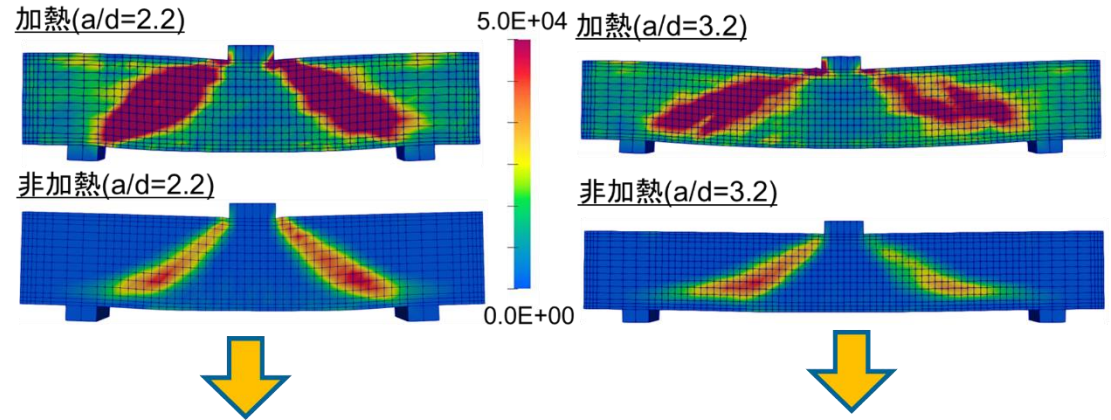
Mean normal strain in x-dir.

Multi-system LOCAL RESPONSE MEAN RESPONSE



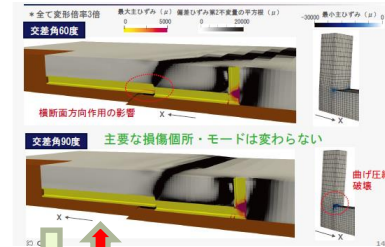
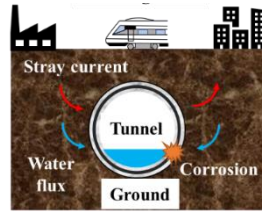


# 高温履歴を受けた残存構造性能→早期復旧→長期使用の可能性

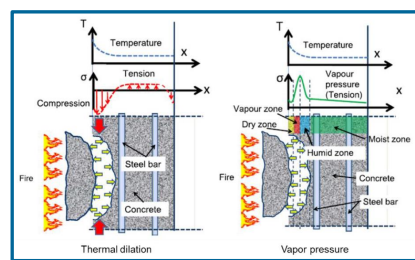
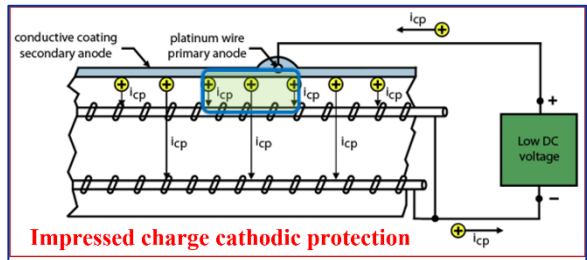
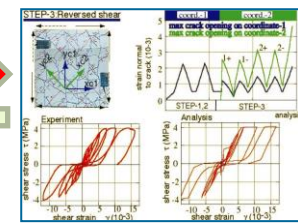
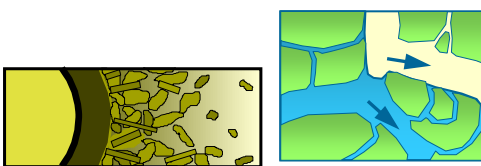
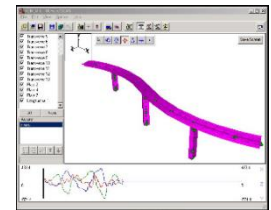
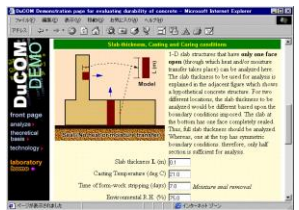
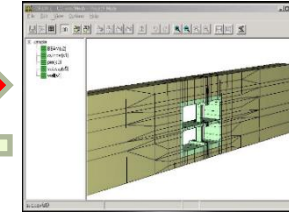
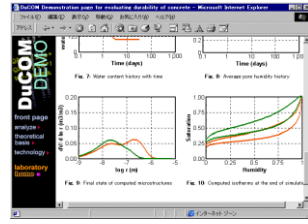


K.Higuchi,K.Iwama and K.Maekawa (2021).Remaining Shear Capacity of Fire-Damaged High Strength RC Beams after Moist Curing, J.of Adv.Concrete Tech.19(8)

# 複数の物理化学的な事象の重なりを、扱う基盤としてのDX



**data storage : DX**  
 temperature, humidity, micro-pore volume and size, surface area, hydration degree, water content, ions concentration, plastic strains, stresses, fracture parameter, crack direction and width, electric potential, CSH,  $\text{Ca}(\text{OH})_2$ , carbonation degree, pressure in crack spaces, corrosion degree, PH, saturation, gradient of dissolved ions, electric resistivity, .....



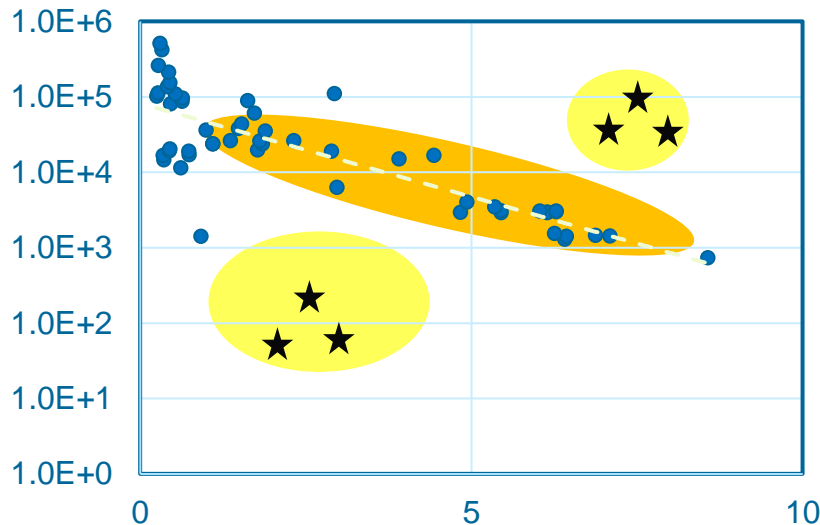


# 本日のまとめ : デジタル空間と実空間を重ねて解ること

## data storage : DX

temperature, humidity, micro-pore volume and size, surface area, hydration degree, water content, ions concentration, plastic strains, stresses, fracture parameter, crack direction and width, electric potential, CSH,  $\text{Ca}(\text{OH})_2$ , carbonation degree, pressure in crack spaces, corrosion degree, PH, saturation, gradient of dissolved ions, electric resistivity, .....

数値科学的方法による  
評価(寿命、強度等)



統計データ、過去の経験、記録等

