Multi-scale Modeling for Life-Cycle Management of Concrete Structures

1. Summary of multi-scale platform
2. Seismic response of multi-story RC building and impact of drying (weak coupling)
3. Long-term deformation of underground RC culverts and durability over 30 years (weak coupling)
4. Fatigue life assessment of bridge decks (strong coupling)
5. PDCA cycle for asset management

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Multi-scale modeling and simulation with regard to the space and the time domains

Size

km
- Reinforced Concrete

m
- Concrete

cm
- Aggregate, cement paste matrix, interfacial transition zone

mm
- Capillary water, C-S-H hydrate

µm
- Gel pores, water molecule, C-S-H layer structure

nm
- Capillary water, C-S-H hydrate

Shear failure of column

Fatigue of RC slab

Carbonation, Chloride Rebar Corrosion

Long-term deflection of PC bridge

Shear failure of column

Elapsed time from the completion (day)

Long-term deflection of PC bridge

Construction

Curing

In service

Deterioration

Long-term Durability

Time (Days)

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
10⁻⁹m nano space model

- **Unhydrated cement**
- **Hydrate product (C-S-H grain)**
- **Interlayer (2.8 Å thick)**
- **Gel pore I (~1.6nm)**: Pore inside gel grain
- **Gel pore II (1.6nm~)**: Pore among gel grain
- **Inner hydrate**
- **Outer hydrate**
- **Capillary pore**
- **Free space for hydrate**

Integration

- 10⁻⁹m to 10⁻⁶m space structures

Model assumptions

- Micro-pores

Vapor Transport

\[
K_V = \frac{\phi \rho_l D_o}{2.5} \left(1 - S\right) K(h) \left[Mh/\rho_l RT\right]
\]

Knudsen diffusion factor

History dependent liquid viscosity

Liquid Transport

\[
K_L = \frac{\phi^2 \rho_l}{50 \eta} \left[\int_0^r r dV\right]^2
\]

10⁻⁹m to 10⁻⁶m pore moisture state and motion
\[ F = \frac{\partial (\rho_l \phi S)}{\partial t} - \text{div}\{ \mathbf{J}(P_l, \nabla P, \nabla T) \} - Q_{\text{hyd}} = 0 \]

10^{-6} \text{m} \rightarrow 10^{-3} \text{m} \text{ scale potential} \quad \text{flux term} \quad \text{sink term}

10^{-9} \text{m} \rightarrow 10^{-6} \text{m} \text{ space structures} \quad \text{10^{-9}m \rightarrow 10^{-6}m pore moisture state and motion}

\[ K_V = \frac{\phi \rho V D_o}{2.5} \left[ (1 - S) K(h) \right] \left[ \frac{M h}{\rho_l R T} \right] \]

\[ K_L = \frac{\phi^2 \rho_l}{50 \eta} \left[ \int_0^{r_c} r dV \right]^2 \]

Model assumptions:
- Vapor Transport
- Liquid Transport

Integration

Capillary pore
Gel pore

1 day
3 days
7 days
28 days

10^{-9} \text{m} \rightarrow 10^{-6} \text{m} \text{ pore moisture state and motion}
10⁻⁹m nano space model

- Unhydrated cement
- Hydrate product (C-S-H grain)
- Interlayer (2.8 Å thick)
- Gel pore I (~1.6nm) Pore inside gel grain
- Inner hydrate
- Gel pore II (1.6nm~) Pore among gel grain
- Outer hydrate
- Capillary pore Free space for hydrate

Integration

- Micro-pores
- Seepage of water

10⁻⁹m → 10⁻⁶m cement + moisture system
Solidifying cluster of cement paste

Micro-pores
Seepage of water

$10^{-9}m \rightarrow 10^{-6}m$ cement + moisture binder system

$G_i = \sum_j \frac{\partial \sigma_{ij}(\varepsilon_{kl}, P, \phi, S)}{\partial x_j} + f_i + \rho \ddot{u}_i = 0$

$10^{-6}m \rightarrow 10^{-3}m$
stress gradient
gavity
acceeration term
$$F = \frac{\partial (\rho_l \phi S)}{\partial t} - \text{div}\{\mathbf{J}(P_l, \nabla P, \nabla T)\} - Q_{\text{hyd}} = 0$$

10^{-6}m \rightarrow 10^{-3}m \text{ scale potential} \quad \text{flux term} \quad \text{sink term} \quad \text{concrete composite section}

Integration

$$\iiint F(x,y,z) \cdot W_1(x,y,z) \, dv = 0$$
$$\iiint F(x,y,z) \cdot W_2(x,y,z) \, dv = 0$$
$$\ldots \ldots \ldots \ldots \ldots \ldots$$
$$\iiint F(x,y,z) \cdot W_k(x,y,z) \, dv = 0$$

10^{-3} \rightarrow 10^{-0}m \text{ scale integral over the structural element}

Weighted residual Function method

$$p = E_w \sum_{i=1}^{3} \left( \frac{\partial w_i}{\partial x_i} + \varepsilon_{ii} \right) / n$$
\[ G_i = \sum_j \frac{\partial \sigma_{ij}(\varepsilon_{kl}, P, \phi, S)}{\partial x_j} + f_i + \rho \ddot{u}_i = 0 \]

\( 10^{-6} \text{m} \rightarrow 10^{-3} \text{m} \) stress gradient

gravity acceleration term

\[ \iint G_i(x,y,z) \cdot W_1(x,y,z) \, dv = 0 \]

\[ \iint G_i(x,y,z) \cdot W_2(x,y,z) \, dv = 0 \]

\[ \cdots \quad \iint G_i(x,y,z) \cdot W_k(x,y,z) \, dv = 0 \]

\( 10^{-3} \rightarrow 10^{-0} \text{m} \) scale integral

over the structural element with crack stress transfer

\[ \begin{align*}
\int B^T \bar{\sigma} \, dv &= F \\
\int G_i(x,y,z) \cdot W_k(x,y,z) \, dv &= 0
\end{align*} \]

\[ p = E_w \sum_{i=1}^{3} \left( \frac{\partial w_i}{\partial x_i} + \varepsilon_{ii} \right) / n \]
\[ \int \iint \mathbf{F} \cdot \mathbf{W}_1(x,y,z) \, dv = 0 \quad \int \iint \mathbf{G}_i(\sigma) \cdot \mathbf{W}_1(x,y,z) \, dv = 0 \]

\[ \int \iint \mathbf{F} \cdot \mathbf{W}_2(x,y,z) \, dv = 0 \quad \int \iint \mathbf{G}_i(\sigma) \cdot \mathbf{W}_2(x,y,z) \, dv = 0 \]

\[ \ldots \ldots \quad \ldots \ldots \quad \ldots \ldots \quad \ldots \ldots \]

\[ \int \iint \mathbf{F} \cdot \mathbf{W}_k(x,y,z) \, dv = 0 \quad \int \iint \mathbf{G}_i(\sigma) \cdot \mathbf{W}_k(x,y,z) \, dv = 0 \]

Integration = assembly of elements over 10^{1-2} m

Nonlinear dynamic structural analysis

Reinforcement

Local strain of steel

Crack location

Mean stress

Yield level

Local stress of steel

Mean strain of steel

Averaged response of steel in concrete

Mean stress

Comp. strength reduction

Damage zone

Crack width

Average tensile strain

Comp. strain

Mean normal strain in x-dir.

Coupling

Multi-system LOCAL RESPONSE MEAN RESPONSE
weak coupling
Seismic full 3D analysis: disp. At the 2\textsuperscript{nd} floor

In consideration of drying experiment

Magnification of displacement=5
Effect of drying shrinkage on seismic performance

Ducom-COM3 link analysis

7~28 days drying
~28 days sealed

3rd floor (X – Y) displacement

E-defense
initial shrinkage cracking

~28 days sealed

10% 25% 50% 100%

~28 days sealed

10% 25% 50% 100%

~28 days sealed

10% 25% 50% 100%

~28 days sealed
Bažant et al. 1987 carried out experiment on the effect of cracking on diffusivity of concrete.
Background

Research object: Shallow underground RC culvert

Role keeping lifelines underground

Status of development

Many RC culverts constructed in urban areas

After a few decades, “Long-term excessive deformations” at the top slab are reported

Deflection excess 3~4 times of prediction

Unknown cause deformation ⇒ Future behavior is concerned about

Crack condition

Number of cracks

Deflection shape of top slab (30 years after completion)

Expected in design

Measured
Analytical results considering **interacting behavior of structures and soil** and **Drying shrinkage** show that long-term excessive deformation.
Destructive test: drilling and scanning inside

Shear path of inclined crack

Scan photos

1-2mm raised

(2) Use light to check the shadow
Life-Cycle Assessment and Inspection Data Assimilation for Concrete Bridge Deck Management

In design: fatigue life prediction
In maintenance: remaining fatigue life with and without damage

strong coupling
Seismic ↔ Fatigue
Numbers of cycles, strain levels, reversed/single sided cyclic

**FATIGUE**
- 10⁶-10⁷ cycles, lower stress level
- Single sided, 10-50 years

**EARTHQUAKE**
- 10-20 cycles, much high strain level
- Reversed cyclic, 10-60 sec
Extended to High cycle Fatigue Simulation

In the case of normal RC beams without any web reinforcement

\[
\frac{V_c}{V_\infty} = -0.036 \times (1 - r^1) \times \log N
\]

\[
r = \frac{V_{min}}{V_{max}}
\]

Time integration: \( \Delta t \)

Logarithmic time integration: \( t \Delta (\log t) \)

Evolution term: \( dK = F dt + G d\varepsilon \rightarrow F t d(\log t) + G d\varepsilon \)
Moving load $\rightarrow$ 2~3 order reduced life $\rightarrow$ stagnant water $\rightarrow$ 1~2 order

Fixed point cyclic shear by FE analysis

Cyclic moving point shear by FE analysis


Fixed pulsating by Perdikalis, et al. ▲

Normalized amplitude

Number of cycles and passages (log N)

Dry experimental results

Submerged experimental results

$S_P/P_0$ vs. Cycle
Aggregation (erosion) of concrete on bridge deck slab

Aggregation on Highway bridge deck

Wheel loading test of RC slab specimen

VTR ( Inspection )

Aggregation lead the failure of specimen

Aggregation on PC bridge deck

Sawn specimen after loading test
Erosion (disintegration) at the top surface of the slab

(Yokoyama et al. 2012)

Driving action of Erosion
(disintegration, freeze-thaw)

Closure

Positive pressure

Opening

Negative pressure

Fatigue amplitude

Compression

Erosion

Driving action of Erosion
(disintegration, freeze-thaw)
Erosion at the top surface of the slab

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>As above and Water compression and Reduction of Shear Transfer</td>
</tr>
<tr>
<td>Moist</td>
<td>As above and Erosion</td>
</tr>
<tr>
<td>Submerged</td>
<td>As above and Erosion</td>
</tr>
</tbody>
</table>

**Influence of water**

**Influence of erosion**

![Graph showing deflection over number of cycles](graph.png)

**Graph**

- Red: Dry 3km/hr
- Green: Moist 3km/hr
- Blue dashed: Submerged 3km/hr

**Images**

- N=1
- N=1000
- N=30000
Anisotropic pore pressure
\[ \sigma_{ij} = \sigma^*_{ij} + \delta_{ij} I_i \ p \]
l_i; unit vector normal to crack plane

\[ p = E_w \sum_{i=1}^{3} \left( \frac{\partial w_i}{\partial x_i} + \varepsilon_{ii} \right) / n \]

Gel production
\[ n\text{SiO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{O} \cdot n\text{SiO}_2 + H_2O \]

swelling
\[ \text{Na}_2\text{O} \cdot n\text{SiO}_2 + m\text{H}_2O \rightarrow \text{Na}_2\text{O} \cdot n\text{SiO}_2 \cdot m\text{H}_2O \]

Gel production
\[ R_{\text{ASR}\_\text{Na}^+} = k \cdot C_{\text{Na}^+} \cdot F_{\text{water}} \cdot \text{Gra} \cdot 1.0E \ - \ 9 \]

Gel generation
\[ \Delta Gel_{\text{Na}^+} = \frac{R_{\text{ASR}\_\text{Na}^+} \cdot \Delta t \cdot M_{\text{gel}}}{\rho_{\text{gel}}} \]

Rate of reaction
\[ R'_{\text{ASR}\_\text{Na}^+} = \exp(-1500.0 \times (1.0 - RH)^{5.0}) \cdot R_{\text{ASR}\_\text{Na}^+} \]

Dependent on alkalinity, moisture, and active silica

Consumed alkalinity
\[ \text{Solid}_{\text{Na\_ASR}} = 2.0 \cdot \Delta Gel_{\text{Na}^+} \cdot \rho_{\text{gel}} \cdot 1.0E + 6 / M_{\text{gel}} \]

Consumed water
\[ W_{\text{Na\_ASR}} = 8.4 \cdot \Delta Gel_{\text{Na}^+} \cdot \rho_{\text{gel}} \cdot 1.0E + 6 / M_{\text{gel}} \]

Linked with cement hydration and micro-pore formation model

By Micheal et al
C & CR, 2013
Uniaxial confinement test

**Mockup of footing**
- 30cm × 45cm × 60cm test body
- Cracking according to the rebar arrangement

**Beam model**
- 10cm × 18cm × 170cm
- Cracking at corners
- Cracking along main bars
- Cracking along ties

**Unconstrained expansion of ASR**
- Axial expansion (analysis)
- Axial expansion (exp)
- Confined expansion of ASR

**Cracking**
- Cracking along main bars
- Cracking at corners
- Cracking along ties

**Space discretization**
- 1/4

**DuCOM-COM3 – ASR reaction and expansion modeling verified**

**Figure**
- 10cm × 10cm × 40cm prism
- Confined by plates
- Cracking along steel bar
DuCOM-COM3 – Corrosion and expansion modeling verified

- Experiment S2-C2
- Analysis S2-C2
- Experiment S2-C3
- Analysis S2-C3
- Experiment S2-C4
- Analysis S2-C4
- Experiment S2-C5
- Analysis S2-C5

Strain, Micron

Corrosion %

Interface deformation (µm)

Time (days)

Node_1
Node_2
Node_3
Node_4
Node_5
Node_6
Node_7
Node_8

DuCOM-COM3 – Corrosion and expansion modeling verified

Experiment by Micheal et al. 2013

Experiment by Oh et al. 2008
Corroded bridge decks in lab. by Prof. Iwaki of Nihon Univ.

Equivalent repeated cycles

Deflection for live load (mm)

Normalized shear force

Equivalent number of cycle

strong coupling
Corroded bridge decks by analysis (Iwaki, Tsuchiya, Maekawa)
Data assimilation in terms of corrosion degree

**strong coupling**

a) 3億7800万回  
b) 27億8000万回

a) 112万回  
b) 2760万回

![Graph showing deflection vs. equivalent fatigue cycle](image)

![Graph showing corrosion rate vs. chloride concentration](image)
Wheel type moving Loads by Prof. Iwaki, Nihon University

- Live load deflection (mm)
- Number of load cycle

Graph: Live load deflection vs. Number of load cycle

- No acceleration
- ASR
- ASR + water
- No reactive aggregate

Expansion in each axis:
Vertical: 3000-5000μ
Fatigue analysis of ASR damaged decks (ASR+Force+water)

1800μ of free expansion

Graph showing material age (day) vs. length change percent.

Graph showing deflection in millimeters vs. number of cycles.

Images of damaged decks and laboratory setup.
FABriS software (2015 version) based on DuCOM-COM3
Cracks, water, NDT data, ambient states → future life (fatigue failure)

FABriS —— Fatigue Analysis for Bridge Slab
Limited Version of 3D Nonlinear Finite Element Analytical Software for Reinforced Concrete Structures

This product is designed to deal with the three-dimensional nonlinear FE analysis of existing reinforced concrete bridge slab structures to estimate residual fatigue life. For more information, please consult www.ducem.com. Concrete Laboratory, University of Tokyo and Waseda University, 2012. All Copyrights reserved.
Crack information is converted to digit dataset.

Digitalized crack location and the width can be a part of database for maintenance of RC decks.
Pseudo-Cracking Method

Crack maps by inspection

Converted field of Pseudo-cracking strain

Conversion of current cracking to strain field
Fatigue life is reduced by 2-3 order under the influence of water. We cannot describe the cave-in of the strengthened slab.
Steel Plate Bonding Method

- Steel plate bonding method has been applied in numerous bridges.
- Re-deterioration of strengthened slabs has been reported.
- Neither experiments nor analysis have systematically been made concerning the re-deterioration mechanism.

Make clear the process of re-deterioration and residual life
S-N curve of corrosion of the strengthened slab

<table>
<thead>
<tr>
<th>Case</th>
<th>Corrosion</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>0%</td>
<td>Dry</td>
</tr>
<tr>
<td>Wet</td>
<td>0%</td>
<td>Wet</td>
</tr>
<tr>
<td>Corr 50mg</td>
<td>1.60%</td>
<td>Dry</td>
</tr>
<tr>
<td>Corr 20mg</td>
<td>0.64%</td>
<td>Dry</td>
</tr>
</tbody>
</table>

Numerical analysis showed fatigue life deteriorated because of corrosion of the strengthened slab.

**Effects of corrosion**

Corrosion occur, rebar expand
- Concrete failed in layers
- Slab turned into a built-up beam
- Fatigue life deteriorated.
S-N curve of strengthened damaged decks
-Damaged concrete is not removed-

Steel plate bonded

Additional beam
S-N curve of strengthened damaged decks
-Damaged concrete is not removed-

Overlaid upper face

Overlaid bottom face
Remaining fatigue life assessment of existing RC bridge decks coupled with multi-scale platform

Combination of site inspection data and simulation platform

Knowledge of engineers

 Compile & link

computational platform

Pseudo-cracking method

Clear output $\equiv$ S-N diagrams

Knowledge of engineers

Advice etc.

users

「site inspection」
simple measurement

数値解析による推定寿命

知識のコンパイルと接続
Thank you for your kind attention.

U-Tokyo
2015