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Engineering Platform of Managing Huge Amounts of Knowledge for Simulation of Infrastructure Dynamics

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ABSTRACT

Multi-scale coupled analysis of mass transport and mechanistic damage with steel corrosion and cracking of concrete is presented for structural life-performance assessment of reinforced and prestressed concrete. Multi-scale models of micro-pore formation and transport phenomena of moisture and ion ingress are mutually linked for predicting the corrosion of reinforcement and its volumetric expansions. The interaction of crack propagation with corroded gel migration is simulated. Two computer codes for multi-chemo physical simulation (*DuCOM*) and nonlinear dynamics of structural concrete (*COM3*) were computationally combined. This system is verified by the laboratory scale experiments of damaged reinforced concrete members under static and dynamic loads, and has been applied to safety and serviceability assessment of existing infrastructures.

INTRODUCTION

In the scheme of performance-based design with more transparency to urbanized societies, performance assessment technology occupies a central position in the field of civil and structural engineering. This rational way of assuring the quality of infrastructures may lead to cost-beneficial design and construction that exactly satisfies several requirements on safety and serviceability. So called life-cycle performance of structures is required, and appropriate methods of design and maintenance for both materials and structures are being sought in several organizations. Needs to verify remaining functionality of existing facilities is rising for extending service life. To meet these challenges, keenly expected is an explicit prediction and simulation of long-term structural serviceability and safety under both specified loads and ambient conditions. It is also needed to examine the reliability of the simulation methods by comparing their computation with natural analogue of aged infrastructures.

In this paper, the author proposes an integrated platform of solid mechanics and thermo-hydro dynamics of materials and structures on the basis of the referential control volumes of multi-scales on which each chemo-physical event is scientifically formulated. Generally, the macroscopic responses of larger control volumes are reproduced by integral of more microscopic events. Here, the interaction among different chemo-physical events is to be formulated on the control volume of the same scale. In more detail, the constitutive model is discussed with regard to cracking in RC elements, and superimposition of thermo-hydro state variables is mathematically presented for multi-scale, multi-chemo mechanical coupling with soil foundation as well. Recent application of the multi-scale approach to practical problems is introduced and the future development is discussed as an integrated knowledge-basis of both structures and materials in civil engineering.

PLATFORM DESIGN OF MULTI-SCALE KNOWLEDGE

Overall scheme

A scheme of the integrated platform of huge accumulated knowledge on material and structure is simply illustrated in Figure 1. When we observe any event experimentally, the quantitative figures of measurement are associated with their specific sizes of volume of interest, and the macroscopic apparent events are the resultant or the integral of more microscopic ones. The cyclic shear deformation of RC panels (meter scale) derives from the shear transfer along crack planes, compression stress flow and the bond with reinforcement, which are regarded as more microscopic events (cm~mm scale). The compressive volumetric change of concrete composite is strongly linked with the pressure of moisture stored inside the micro-pores (nm~μm scale) as discussed in the next section.

The full nonlinear plastic-damage analysis can be thought to be an integrated mechanical platform to simulate both macro and microscopic mechanistic events of materials and structures [Maekawa et al. 1999, 2003, 2008]. This linkage of multi-scale knowledge is in a sequential mode. These serial linkages can be established with the same manner on the chemo-physical events, e.g., ion transport, phase equilibrium, reaction and electro-action as illustrated in Figure 1. The macroscopic events can be linked with the micro ones by numerically integrating the micro chemo-physics events with respect to the control volume [Maekawa et al. 1999, 2008]. Here, the author raises the point of "control volume consistency". The mutual interaction shall be formulated on the referential control volume of the same scale as shown in Figure 1. For example, the thermodynamic states of ion solution inside the capillary pores must be stated based on the pressure developing on the capillary pores, not on the space surrounded by crack planes. With this classification of modeled events on different scales, governing equations of mechanics and thermo-dynamic events can be consistently discretized to build up the finite element simulation [Maekawa et al. 2008].

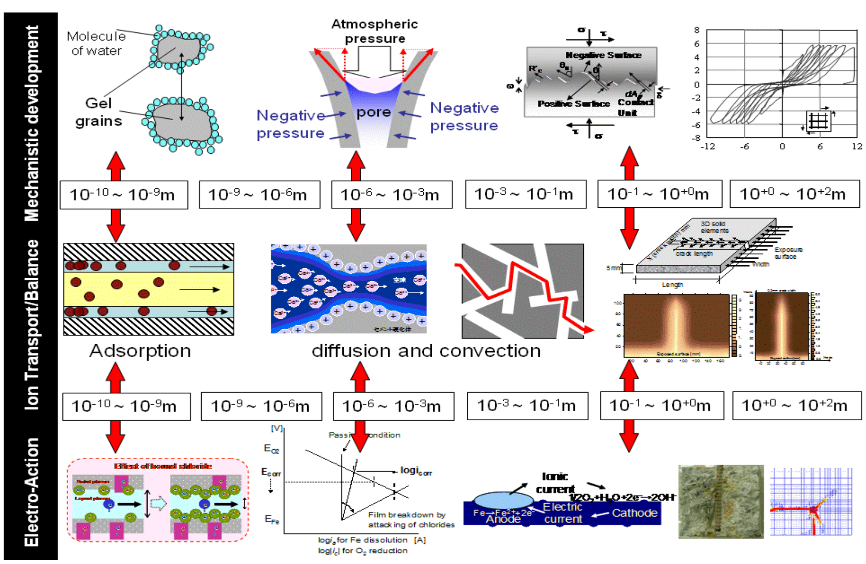

Fig. 1. Platform to Integrate Knowledge of Chemo-Physics and Mechanistic Events on Different Multi-Scales.

Multi-directional crack mechanics (meter-scale and cm~mm-scale)

Multi-directional cracking and its interaction are taken into account by the active crack approach [Figure 2: Maekawa et al. 2003] on the smeared compression stress field [Collins and Vecchio 1982]. All microscopic mechanical states (cracking, yielding, crack shear, remaining stiffness of fractured materials) are integrated for the macroscopic constitutive modeling. The primary crack to govern the nonlinearity of structural concrete is identical if some cracks intersect non-orthogonally. Here, path-dependent parameters are renewed only along the active crack in each load step of time. Plastic localization of reinforcement is of importance for rationally simulating macro-scale deformation of finite elements. The spatial averaging of local stress and strain along reinforcement is applied with finite elements as shown in Figure 2. As the steel yield is localized at concrete cracks, the space-averaged stress strain relation of deformed reinforcing bars differs from that of a single bare bar. The subsequent strain hardening is extended and the space-averaged hardening stiffness is computed [Maekawa et al. 2003]. When the load reversal is produced in a single direction, near orthogonal two-way cracking is experienced. Here, the crack-to-crack mutual interaction is not so great as to consider the shear transfer of each intersecting cracks. Then, the smeared crack methods that assume co-axiality of stress and strain fields (rotating crack) may function successfully. The multi-directional and non-proportional loading creates three and four directional cracking that intersects each other in finite element domain. When thermal and drying expansion and shrinkage would be coupled with seismic loads, principal stress directions considerably rotate. This situation tends to create multi-directionally intersecting cracking with strong interaction.

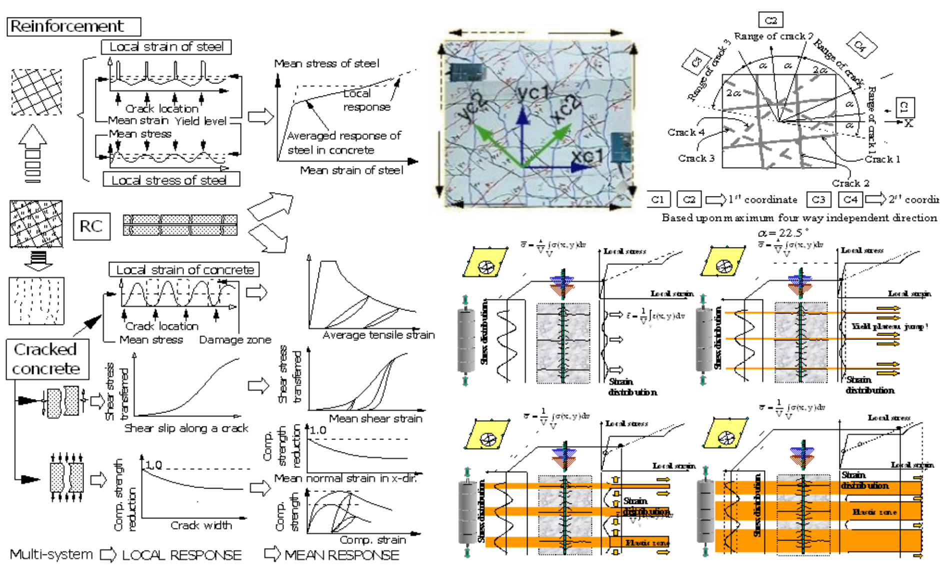

Fig. 2. Macro-Scale Element Derived from Micro-Mechanical Events

Constitutive models have to be verified on member/structural levels, because stress states and loading paths cannot be fully reproduced only by experiments at the specimen level under rather uniform fields of stress and strain. Figure 3 (left) shows the experimental verification by using the mock-up for tunnels and ducts. The shear capacity and ductility were carefully focused on. The multi-directional cracking model has been examined as well by reproducing alternate change of principal stress directions in 3D spaces. For practical use of the computational platform, the multi-plastic potential model for soil skeleton is included with the underground pore water to take into account liquefaction. Figure 3 (right) shows the soil container which includes the RC box culvert and was set on the shaking table. The soil pressure applied on the walls of the embedded RC duct and the average shear deformation of the structure was carefully compared with the analytical results. Right now, the nonlinear finite element analysis is authorized as a tool to examine the seismic safety performance in the scheme of designing LNG storage tanks and RC aqua-ducts for nuclear power plant facilities for practice in Japan [JSCE 1999].

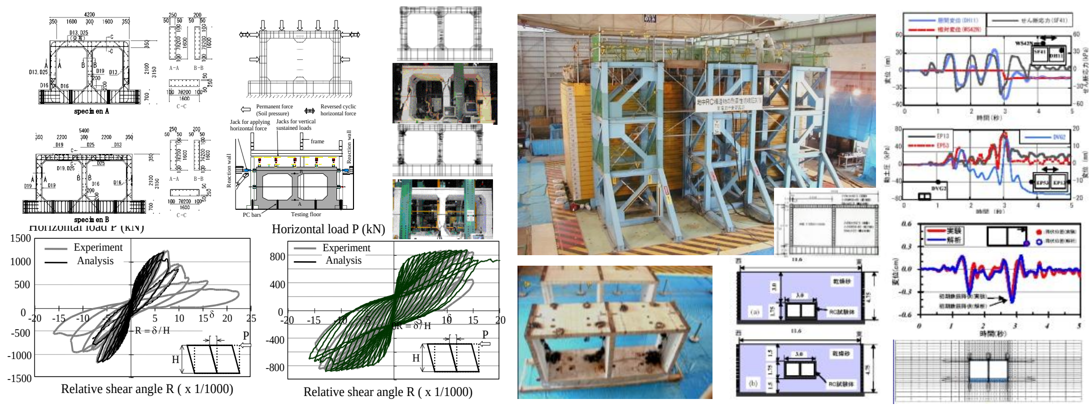

Fig. 3. Experimental Verification and Comparison with Experimental Facts.

Thermo-hydro chemo-physical modeling (mm-scale and nano-scale)

Thermo-hydro dynamics is further required for life-cycle assessment, especially for durability assessment. Volumetric change caused by temperature and long-term moisture equilibrium in micro-pores are greatly related to cracking and corresponding serviceability as well, and corrosion of embedded steel has much to do with migration of chemicals through micro-pores. Thus, the coupled system was proposed [Maekawa et al. 2003, 2008] to simulate the entire thermo-mechanical states of constituent material and structures. Here, micro-pore geometry and spaces are idealized by statically formulated pore distribution and internal moisture balance is simultaneously solved with the law of mass conservation. The moisture migration and diffusivity are computed based on the micro-pore size distribution and the linked condensed water channel (Figure 4).

Chloride ion migration and other chemical reactions such as carbonation and calcium leaching are mathematically superimposed on this system as discussed above. The conductivity and diffusion characteristics for mass transport are calculated based upon computationally formed micro-pore structure. The computation of multi-chemo-physical events is carried out by means of the sequential processing with closed-loop predictor-corrector method. The temperature dependent volume change is considered as an offset strain in constitutive modeling. But, concrete shrinkage associated with microclimate in CSH gel and capillary pores is directly linked with the macroscopic constitutive model (Figure 4) with regard to micro-pore pressure and disjoining pressure originated from Van del Waals and Coulomb forces. Corrosion rate is also computed by simulating migration of O_2-CO_2 gas and chloride ion [Maekawa et al. 2008], and the effect of corrosion is integrated in the structural analysis [Toongoenthong et. al 2004]. In this computation, the thermo-dynamic equilibrium requirements are simultaneously solved such as multi-ion balance, proton electro-balance, adsorption-desorption isotherm. Then, we have approximately 230 simultaneous equations to be solved numerically for chemo-physical and mechanical behaviors of different scales.

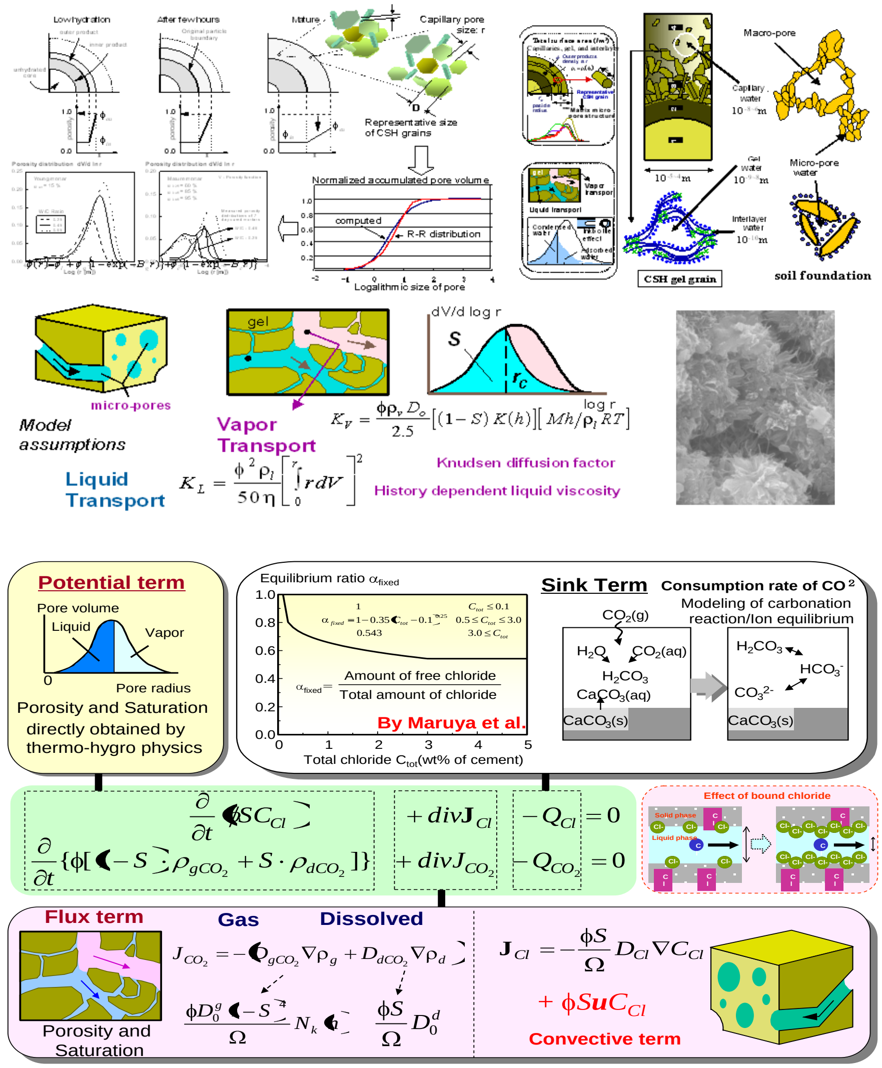

Fig. 4. Mass Conservation and Transport on Multi-Scale Micro Pores

INTEGRATED DAMAGE MECHANICS AND CHEMO-PHYSICS

Cracking as a macro-scale event is influential in mass transport of gases and dissolved ions. These cracks through which ion substances migrate are mutually coupled with thermo-hydro dynamic analysis by the hierarchy type of multi-scale modeling. This simulation will be useful for life-cycle assessment of structural concrete and examination of remaining functions of existing infrastructures. Cracking of concrete causes accelerated diffusion of chloride as well. It may allow deeper penetration of chloride and other substances. In the analysis, diffusivity of chemical substances is regarded as a variable in terms of computed averaged strain of concrete finite elements.

The corroded steel produces volumetric expansion and results in internal self-equilibrated stress, which may lead to additional cracking around reinforcing bars. Figure 5 illustrates the cracking induced by the volume expansion of generated corrosion gels. The effect of corrosion gel product formation is considered in the constitutive modeling of reinforcement in the transverse direction. The non-corroded core steel and the corroded clusters with different mechanical properties are treated as a fictitious aging material of varying volumetric stiffness and expansion according to the magnitude of corrosion. This growing steel is embedded in each finite element similar to smeared crack approach. If the corrosion is concentrated around the anchorage zone of main tension reinforcement, its structural capacity is degraded with the different crack propagation pattern from those of sound ones as shown in Figure 6. The diagonal crack which reaches the bending compression zone is initiated by the corrosion crack tip created along the longitudinal reinforcement. Finally, the diagonal crack is driven to the beam support. Apparently, the localized corrosion is seen to deteriorate the anchorage performance of longitudinal reinforcement. The acceleration test of corrosion of steel in RC beams by galvanostatic charge also substantiated this simulation result.

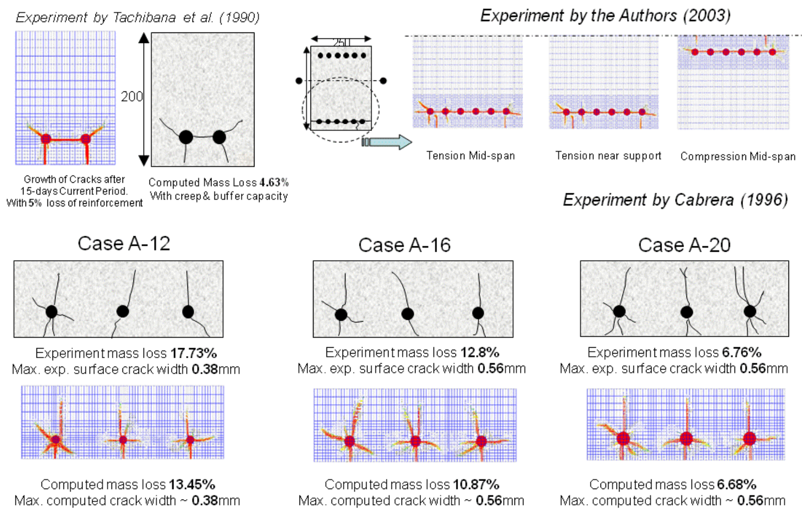

Fig. 5. Micro-Scale Cracking induced by Corrosion of Reinforcement

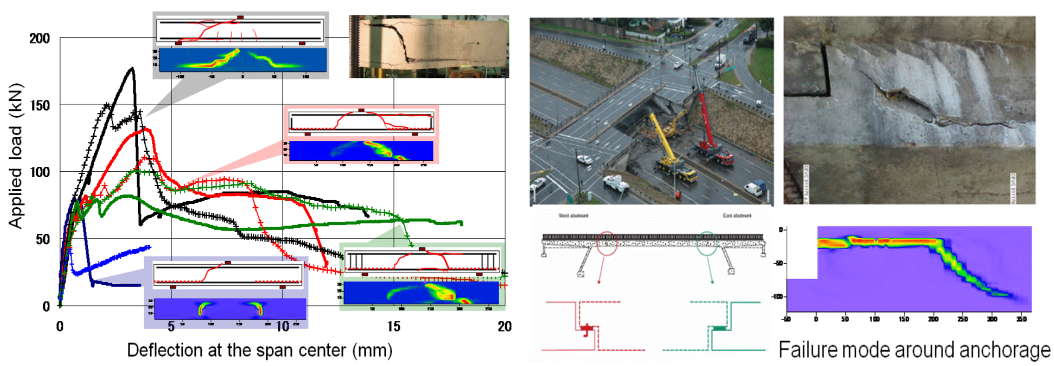

Fig. 6. Macro-Scale Cracking around Anchorage Zones and Mode of Collapse [Chijiwa 2008].

Autogenous/drying shrinkage, which is computed by solving the moisture migration under ambient conditions [Mabrouk et al. 2004], can be directly included in the constitutive modeling of concrete in each finite element as shown in Figure 7. The creep deformation of aging concrete is derived from the micro-scaled deformation of micro-pores which are related to the moisture micro-kinematics. The coupling of concrete creep in compression, shrinkage and post-cracking time-dependent tension stiffness models yields consistent behavioral simulation with reasonable accuracy for long-term deflections.

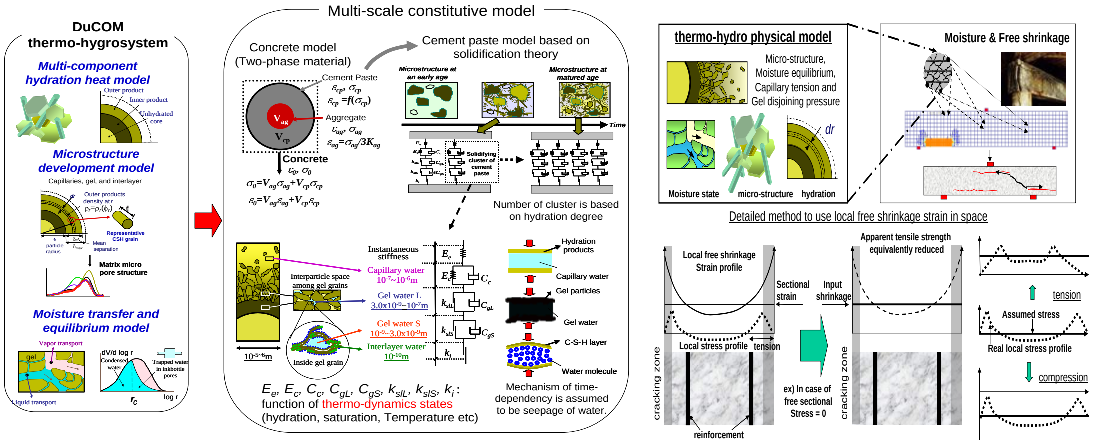

Fig. 7. Multi-Scale Creep Modeling derived from Micro-Scale Hygro-Dynamics of Pore Water [Asamoto et al. 2006, Maekawa et al. 2008].

Figure 8 shows one of practical applications for the seismic performance assessment of existing aqua-ducks of nuclear power plants and a 100-years old railway bridge in Tokyo [Sogano et al. 2001]. The point of discussion is the residual seismic performance after corrosive damages and uneven settlement of the soil foundation which took place in the past decades. Some initial damage remains in the form of cracking, and arch ribs were strengthened by additional RC arch inside layer in the past. The seismic ground motion was applied to the numerically aged structural concrete and the computed response was used for safety and serviceability assessment in practice. The seismic remaining performance was numerically investigated and the sustainable life with light retrofit was estimated for planning the maintenance schedule and the finances to be arranged.

The corrosion damaged RC underground box culverts shows reduced seismic performance as sown in Figure 9 although the static capacity does not decay. The coupled simulation re-produces the steel corrosion and associated cracking, which may influence on the dynamic responses having interaction with the soil foundation. If damaged structures are surrounded by soil foundation, sensitivity of damage and steel corrosion tends to be less compared to on-ground structures. In this case, the full 3D soil-structure system can be analyzed to assess the overall safety performance under traffic and seismic actions.

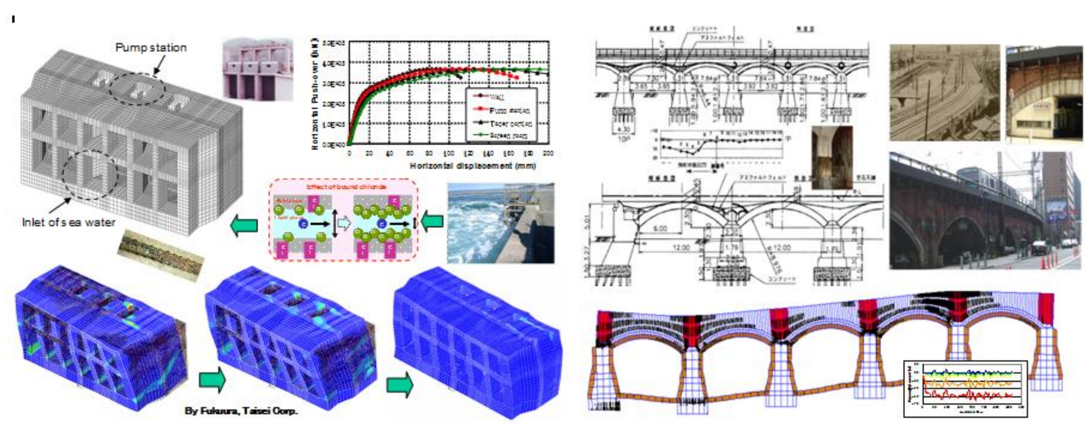

Fig. 8. Seismic Performance Assessment of Existing Aged Infrastructures.

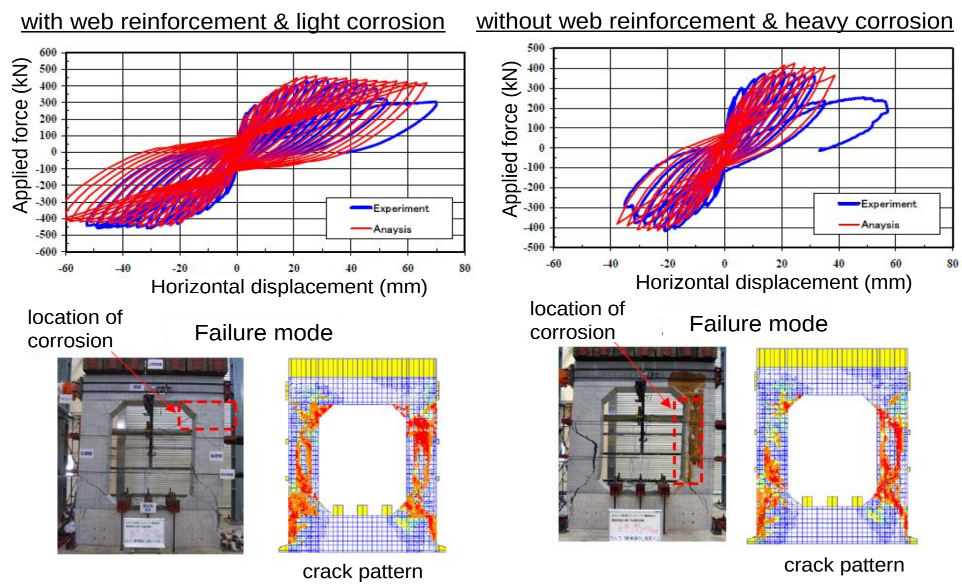

Fig. 9. Ductility Analysis of Corroded RC Box Culverts for Aqua-ducts.

Figure 10 shows the partial prestressed concrete (PRC) bridge in which plenty of cracks were induced to the viaducts due to excessive shrinkage of concrete and heavy reinforcement. The compliance of the viaduct in each span was reported to be much increased and the fatigue life was questioned. JSCE concrete committee (2005) investigated the detailed damage and corresponding remaining fatigue life by using the coupled chemo-mechanical simulation. For verification of the analysis method, the design live load (1500 kN) was applied on the deck and the incremental deflection was measured as shown in Figure 11. The simulation was reported to be closer to the reality of the damaged PRC bridge.

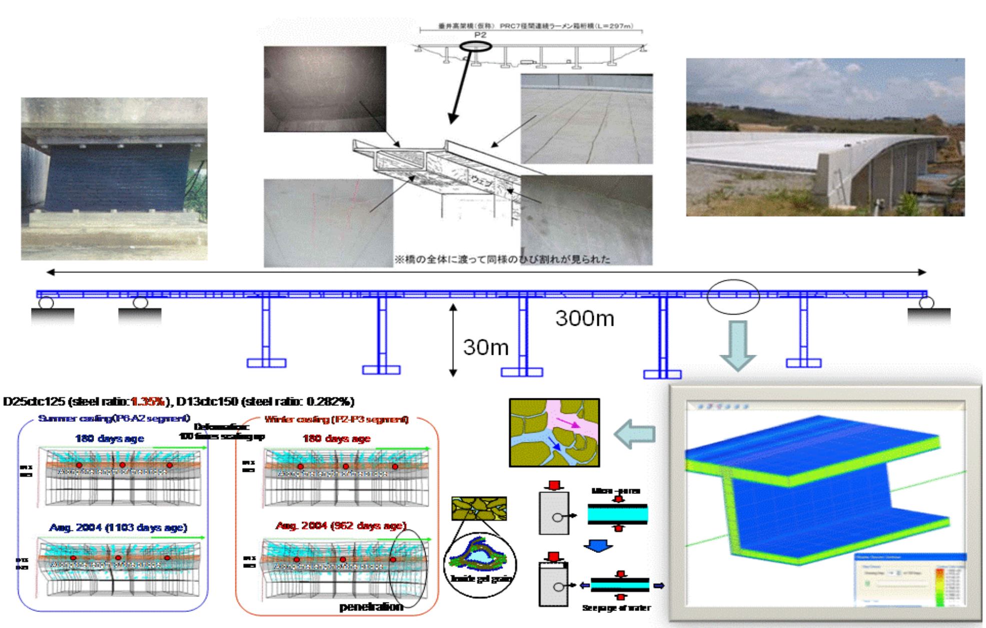

Fig. 10. Moisture Equilibrium and Migration of the Existing Bridge for Creep and Fatigue Simulation.

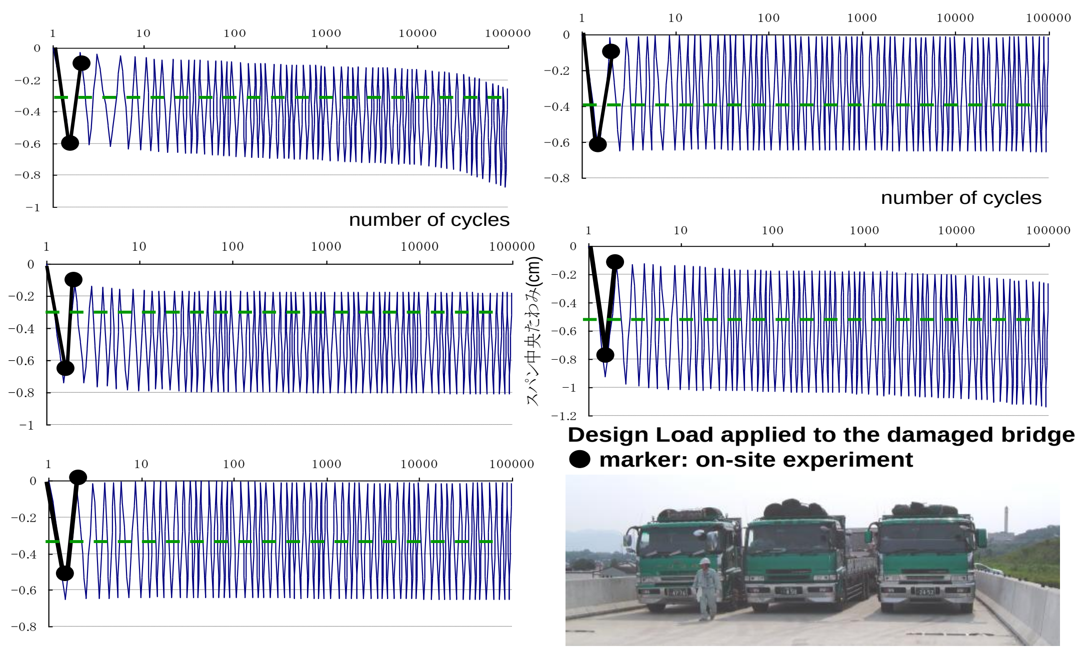

Fig. 11. Fatigue Simulation and Accelerated Deflection at Each Span of Bridge.

CONCLUSIONS

Chemo-physical and mechanical modeling of concrete with greatly different scales of geometry was presented, and synthesized on a unified computational platform, which may bring about quantitative assessment of structural concrete performances. The safety assessment method was extended to the life-cycle issue with multi-scaled information on microclimate states of cementitious composites under macroscopic ambient boundary conditions. Currently granted is a great deal of knowledge earned by the past development. At the same time, we face a difficulty to quantitatively extract consequential figures from them. The author expects that the systematic framework on the knowledge-based technology will be extended efficiently and may be steadily taken over by engineers in charge.

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