Transactions of the 17th International Conference on *Paper # A05*
*Structural Mechanics in Reactor Technology (*SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Computational Platform for Safety and Life-cycle Assessment of RC/PC shells

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ABSTRACT

The computational platform based upon structural mechanics of reinforced concrete and thermo-hydro dynamics of cementitious porous media is presented for engineering application to safety and life-cycle assessment of RC structures. Multi-directional fixed crack modeling of RC elements was formulated and consistently combined with thermo-hydro physics of concrete in terms of moisture/pore solution equilibrium and temperatures in micro-pores.

KEY WORDS: smeared crack, fixed crack approach, multi-directional cracking, seismic performance, life-cycle, performance based design, thermo-hydro dynamics

INTRODUCTION

In the scheme of performance-based design with more transparency to clients and taxpayers, performance assessment methods occupy a central position from a viewpoint of structural mechanics. This rational way of assuring the overall quality of infrastructures may creates cost-beneficial design and construction that exactly satisfies several requirements assigned to engineers. Life-cycle performance of structures is being explicitly requested and an appropriate design of materials and structures is sought after [8]. Furthermore, needs to verify remaining functionality of damaged existing facilities are rising for extending service life. To meet these challenges, explicit prediction and simulation of structural life span and safety under specified loads and ambient conditions are keenly expected. In this paper, the authors propose an integrated platform of solid mechanics and thermo-hydro dynamics of materials and structures with multi-scale of referential control volume on which each chemo-physics is applied. In-plane nonlinearity of RC shells is discussed with regard to cracking, and overlay of thermo-hydro state variables is presented for multi-scale coupling.

MULTI-DIRECTIONAL FIXED CRACK APPROACH

A scheme of in-plane RC modeling used for an integrated platform of both safety and life-cycle assessment is shown in Fig.1. Multi-directional cracking and their interaction are taken into account by the active crack approach [14]. All microscopic physical states (cracking, yielding, shear slippage, remaining stiffness of fractured materials) are inherently included in the scheme of stress-strain relation. The stress carrying mechanisms are composed of compression/tension parallel and normal to cracking and shear transfer. By the active crack method [5,14], the primary cracking of nonlinearity is identified and path-dependent parameters are renewed in each load step.

The plastic localization of reinforcement is of importance for simulating largely deformed elements. The spatial averaging of local stress and strain along reinforcement is applied for structural analysis with finite elements as shown in Fig.1. Since the local yield occurs at the crack location and the rest of domain remains elastic, the averaged stress strain relation of reinforcement differs from that of a single bare bar. The following hardening of the element is much associated with extension of plastic zones and the averaged hardening stiffness is computed by considering the reinforcement ratio, tensile strength of concrete and properties of reinforcing bars [14].

Verification of the in-plane RC constitutive modeling has been provided with systematically arranged experiments. Under monotonic loadings, highly reliable and accurate experiments have been reported by University of Toronto [3,22] and other institutes [1,16,23], and have served as a driving force of developing RC constitutive modeling. After 1990, the stress states concerned were extended to reversed cyclic paths of loading and multi-directional cracking was introduced into tested domains for the seismic analysis of RC shell structures [12,21].

When the load reversal is produced in a single direction, near orthogonal two ways cracking is experienced in finite elements. Here, the crack-to-crack mutual interaction is not so great as to consider the shear transfer of each intersecting cracks. Then, the rotating crack methods and other models that assume coaxiality of stress and strain fields function successfully for structural analysis, and the model of shear transfer does not play a central role of mechanics.

However, the multi-directional and non-proportional loadings may create 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 drastically rotate. This general situation tends to create multi-directionally intersecting cracking with strong mutual interaction. Fukuura and Maekawa extended the active crack approach [5] to these more general cases under reversed cyclic stresses. Figure 2 shows an example of experimental verification with three and four directional cracking in two-way reinforced RC panels under combined in-plane shear and normal stresses. The in-plane stresses were actively controlled by the internal hydraulic pressure, torsion moment produced by a couple of jacks and axial compression.

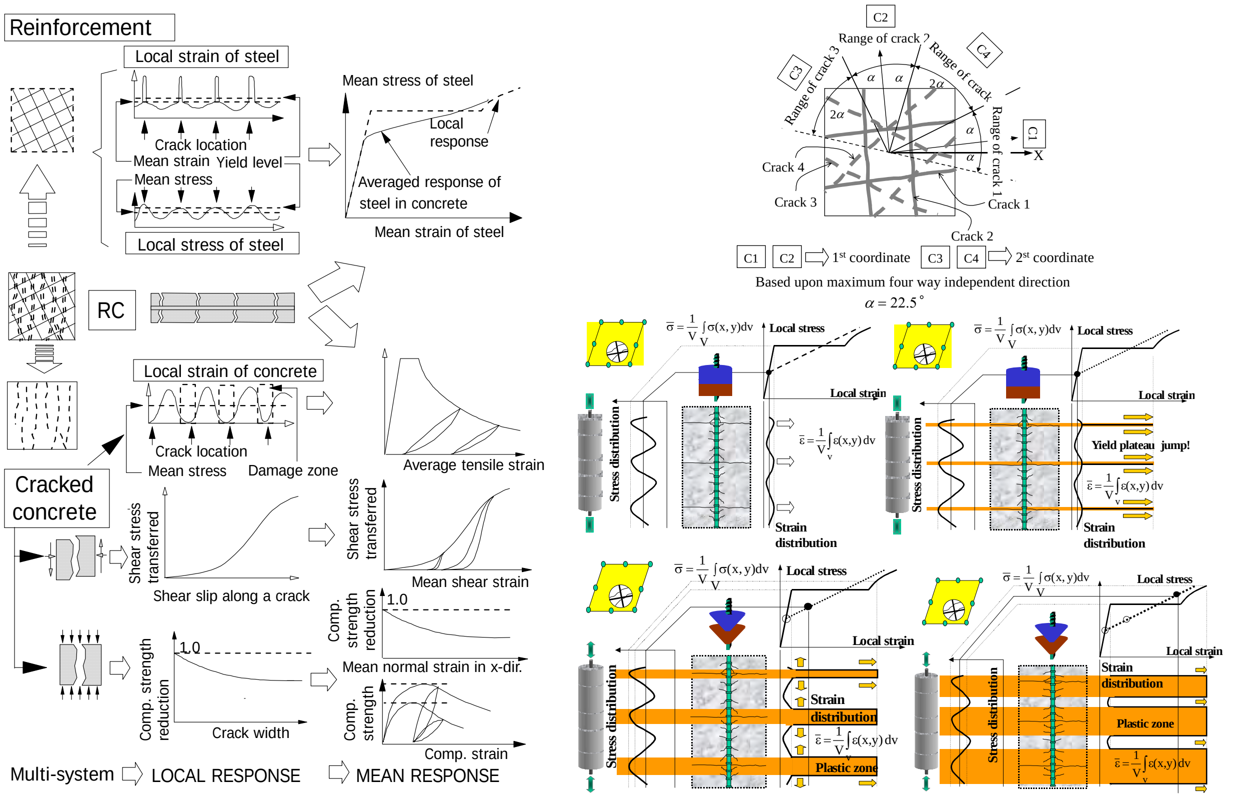
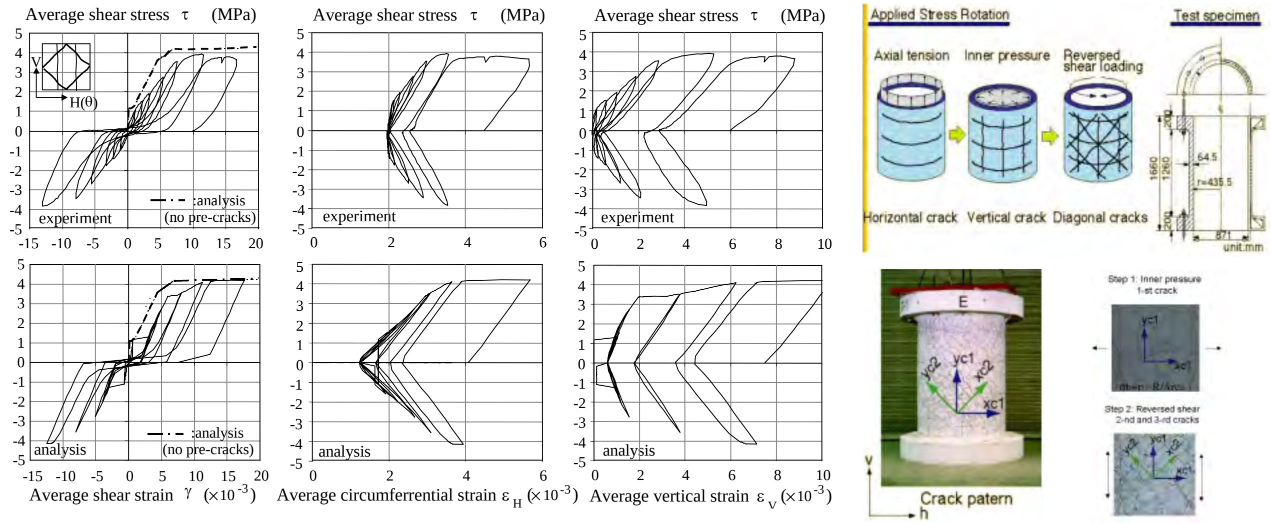
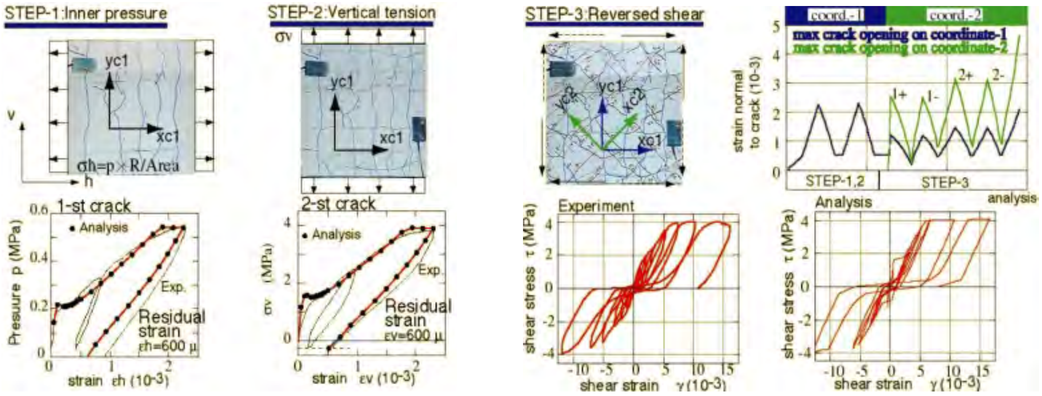


Fig. 1 Formulation of in-plane constitutive model with multi-directional cracking [14]



Specimen C-1 (3-way cracks introduced)



Specimen A-2 (4-way cracks induced)

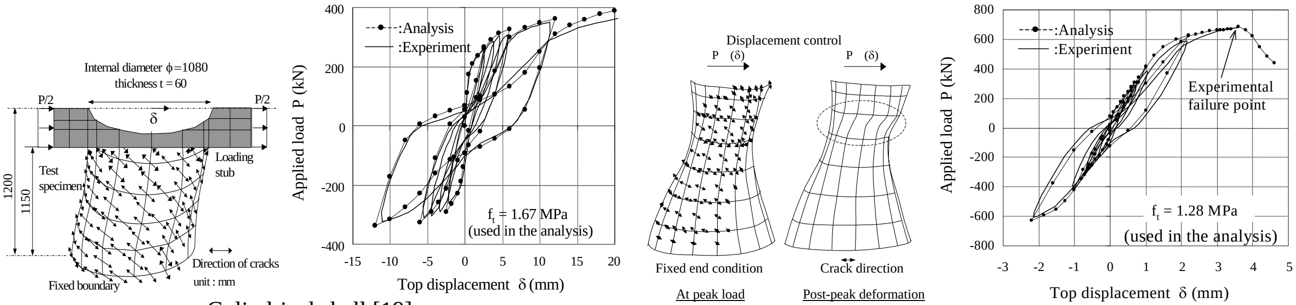
Fig. 2 Experimental and analytical behavior of specimens A-2 (4-way cracks) [5]

VERIFICATION –STRUCTURAL LEVEL-

Constitutive models have to be verified on member/structural levels, because stress states and loading paths cannot be fully reproduced only by experiments at element level. Shear wall experiments have been used for experimental verification of in-plane RC modeling under monotonic as well as cyclic loads. It is recognized that in-plane RC models is well applied under both static and dynamic excitation. Figure 3 shows cyclic responses of 3D shells subjected to reversed forces [17,19]. The layer integration procedure is applied for completing 3D shells applicable to out-of-plane bending and torsion, too. When compressive softening takes place, post-peak softening of restoring force appears and localization of deformation is seen as those in experiment. In these cases, nearly orthogonal cracking is introduced in RC finite elements.

For verification of multi-directional cracking more than 2-ways, box shells were tested under bi-directional horizontal forces combined as shown in Fig.4 [9]. In one direction of load, bending cracks are firstly formed in flange panels and diagonal cracks in the other two web panels. When the load turns orthogonally, two-way diagonal cracks are induced into the former flange panels in turn. Then, opening and closure of cracks intersecting each other occur in complexity of three and four-ways cracking. The horizontal restoring forces characteristics can be successfully reproduced up to the load carrying capacity.

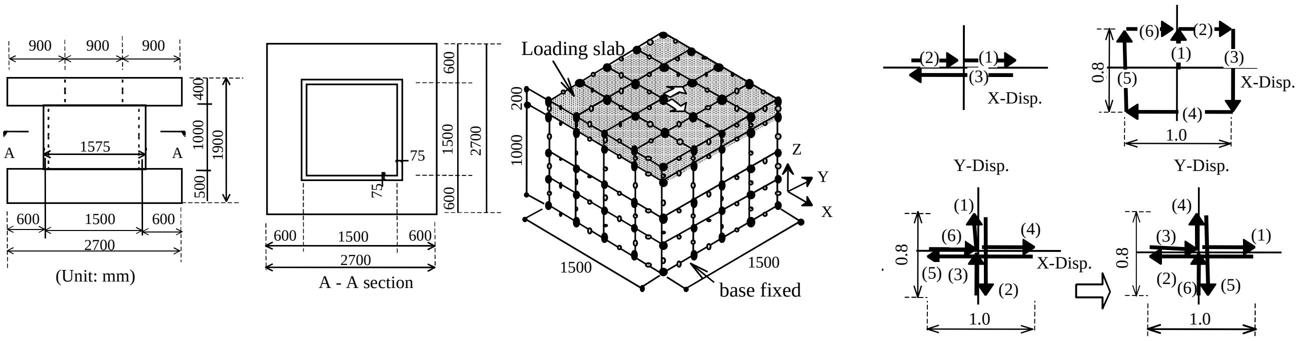
The multi-vent box culverts tested for check of seismic performance of underground aqua-duct for nuclear power plants are shown in Fig.5. The in-plane RC model was directly applied for these 2D problems. This experimental verification is oriented to the shear failure simulation of members under cyclic loads. In order to simply assume the soil pressure and the typical mode of deformation of RC vent in the ground, vertical loads and horizontal forces were mutually combined. The computation predicts shear failure mode after yield of main reinforcement consistently with the experimental report [20]. The ductility is much deteriorated due to the shear failure in compressed vertical members.



Cylindrical shell [19]

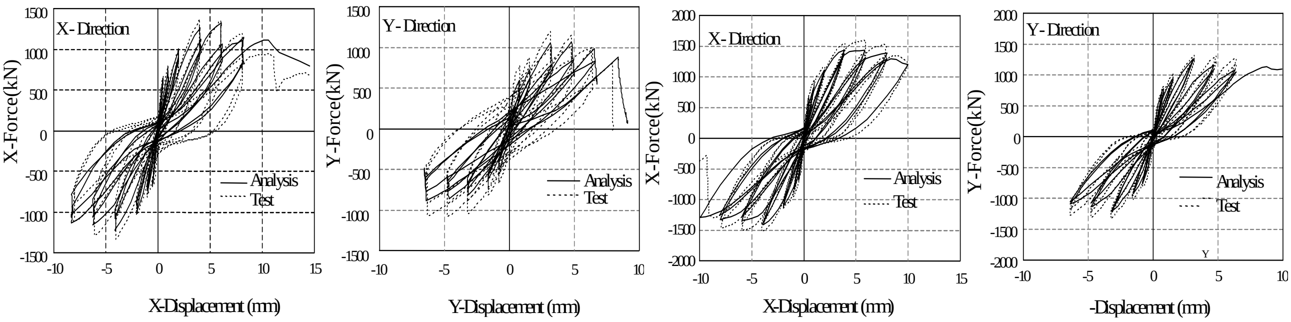
Hyperbolic shell experiment [17]

Fig. 3 Comparison and experimental verification under full 3D extent



(a) Specimen and analysis model (Box type)

(b) Loading pattern in the analysis



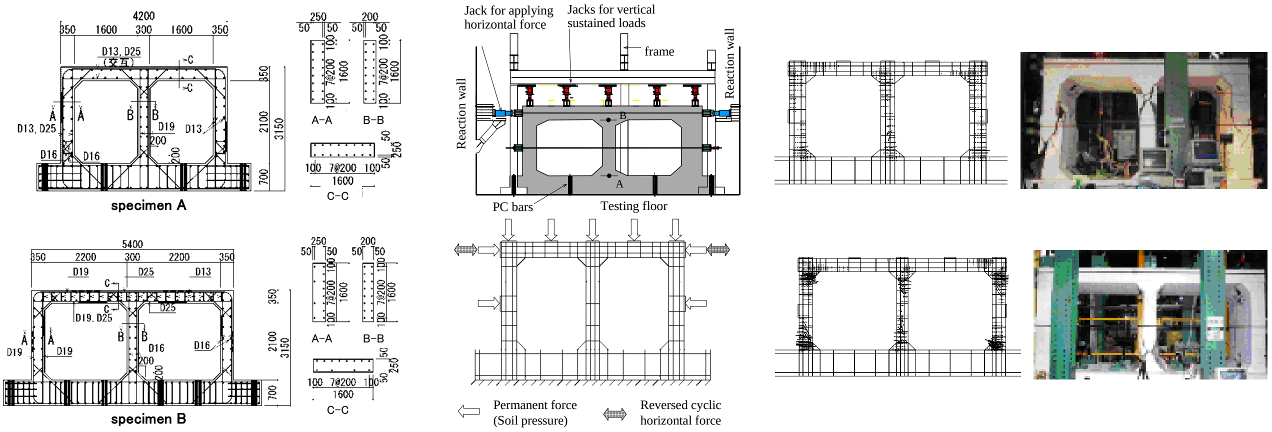
(1) Box-type wall rectangular loading

(2) Box-type wall cross loading

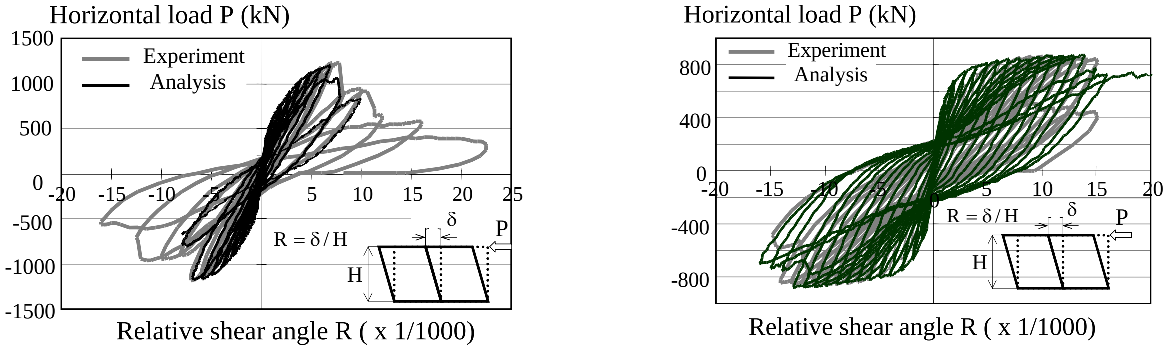
Fig. 4 Relations of shear force and multi-directional displacement [10]

Crack patterns are shown in Fig.5 for both experiment and analysis. The damage location and the direction of cracking can be well predicted. After diagonal cracks, the vertical displacement of the top slab turns to the downward direction under the sustained vertical loads that represent the dead weight of soil overlay. In analysis, the top slab starts to sink down, too. However, the rate of displacement was underestimated in post-peak region. Since the selected RC ducts have less amount of reinforcement, crack localization tends to occur. In analysis, the authors applied the zoning method [14] of tension softening and stiffening. It is concluded for shell structures that 2D/3D nonlinear structural analyses can be applied at least for the assessment of seismic performances level 1 and 2, which do not exceed the ultimate capacity of structural systems.

Experimental verification under dynamic ground motions was carried out by shaking table tests of middle-scale multi-story shear walls [4]. Analysis results were submitted by international participants including the authors to the organizer of the experiment and secondly, experimental facts were put on view afterward. As the size of specimen was small, the effect of drying shrinkage was taken into account by coupling the seismic analysis with thermodynamic one as discussed in the following section. The effect of shrinkage can be also seen in the loading tests of RC panels under in-plane actions. For the real scale structures with thick members, drying shrinkage effect can be ignored in the seismic performance assessment. The computed displacement is slightly less than the test values, but its discrepancy is limited within a small percentages. The location of concrete damage and the mode of deformation are well predicted.



Dimension of specimens, loading apparatus and finite element discretization



Specimen A　　　　Specimen B

Comparison of cyclic loops (analysis and experiment)

Fig. 5 RC underground box-vents subjected to shear [20]

DESIGN CRITERION – LNG STORAGE TANK –

Since underground RC storage tanks and soil foundation (Fig.6) have a strong interaction, full 3D domain including soil foundation is treated as a current design system [7]. It is known that the deformational mode of RC tank in the foundation is mainly controlled by shear and the main damage is appearing around the side web shells subjected to primary in-plane shear. From intensive collaborated research, a limit state of seismic performance level 2 (no collapse, possible reuse after earthquake without strengthening) is accepted in seismic design of underground RC tanks [7] as,

$$\varepsilon'_{p,comp} \le 2 \cdot \varepsilon'_{u} \qquad (1)$$

where $\varepsilon'_{p,comp}$ is the maximum principal compressive strain of all elements on the extreme outer surfaces and ε'_{u} is defined as the peak strain of concrete under uni-axial compression.

The larger reinforcement ratio brings about both higher stiffness and capacity, but ductility is sacrificed and sharp softening with localized in-plane shear is produced as shown in Fig.6. Provided that the lower reinforcement ratio is specified, the greater ductility after the initial yield of reinforcement is ensured. The criterion by Eq. (1) can be commonly used for any reinforcement ratio and the peak strain that is used as a limit value represents the concrete damaging related to compressive load-carrying mechanism. As stress and strain fields are rather uniform than the cases of beam/columns with slender geometry, the limit state of constituent elements is closely associated with the structural limit state of seismic performances. Out-of-plane shear failure shall be avoided for seismic performance level 2. To meet this requirement, shear force computed by the shell model should be suppressed within the transverse shear capacity estimated by the code empirical formula.

In order to check the validity of numerical simulation, the scale-down model of RC tank was constructed and the horizontal shear was applied beyond the limit state by Eq. (1) as shown in Fig.7. The analysis prior to the test was conducted in advance [6,9] and followed by the loading experiment. The load-displacement relation and the location of damage were reasonably predicted. Although the boundary condition of the experiment is not strictly the same as that of the real structures surrounded by the foundation, the mode of deformation is almost reproduced. For practical design, approximately 0.8% of the reinforcement ratio is chosen for necessary and sufficient ductility of RC shells so that the deformability of the main body becomes larger than that of the surrounding soil foundation. Under this situation, the soil foundation may fail before the failure of RC in-ground RC structures.

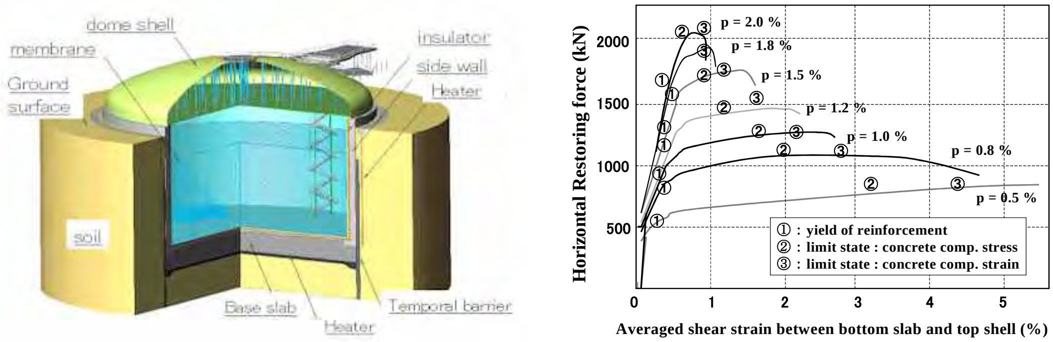


Fig. 6 Computed effect of reinforcement ratio on load-displacement relation of RC tank [9]

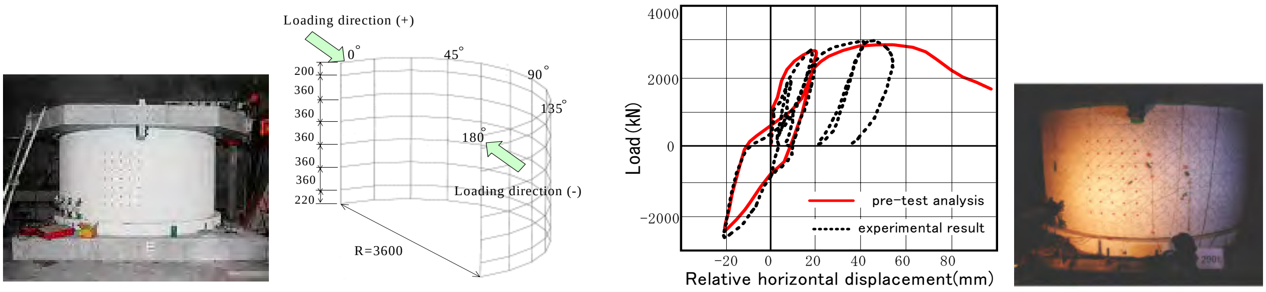


Fig. 7 Scale-down specimen of LNG storage tank models [6]

COUPLING WITH THERMO-HYDRO DYNAMICS

State variables of thermo-hydro dynamics are further required for life-cycle assessment. Volumetric change caused by temperature and long-term moisture equilibrium in micro-pores is associated with cracking and corresponding serviceability, and corrosion of reinforcement has much to do with migration of chemicals through micro-pores. Thus, the coupled system as shown in Fig.8 was proposed [13,15] to simulate the entire thermo-mechanical states of constituent material and structures. For computing the thermo hydro equilibrium, multi-scale analysis platform *DuCOM* [13,15] was used. Micro-pore geometry and spaces are idealized by statically formulated pore distribution and internal moisture balance is simultaneously solved with mass conservation requirement. The moisture migration and diffusivity are computed based on the micro-pore size distribution and the space of condensed water channel as illustrated in Fig.8. Chloride ion migration and other chemical reactions such as carbonation and leaching are overlaid on this system. The finite element scheme is applied to this multi-scale analysis and coupled with structural analysis program.

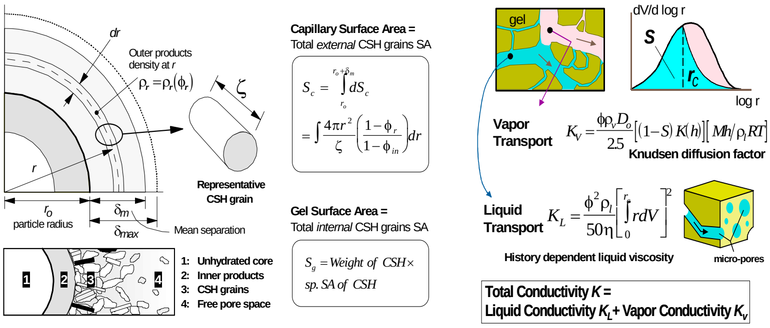


Fig. 8a Micro-modeling of CSH gel and capillary pores

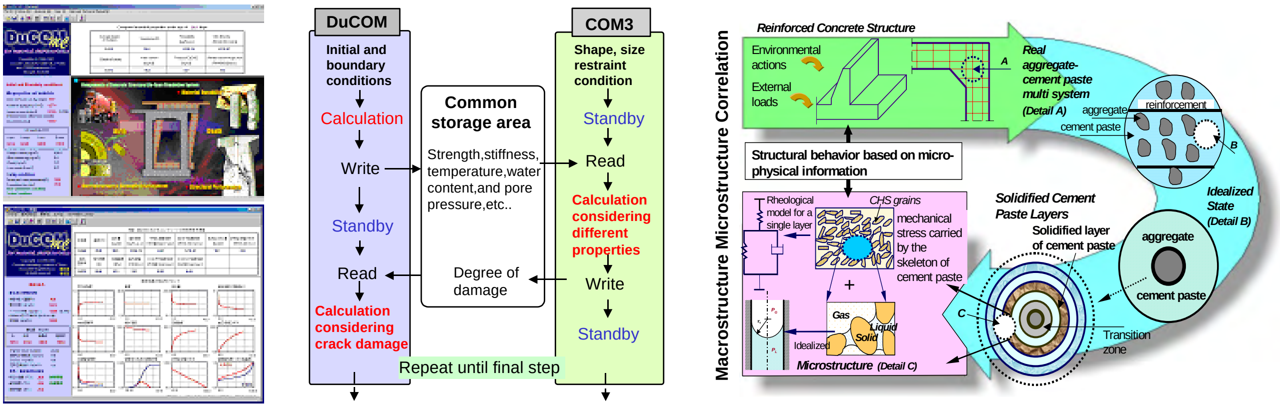


Fig. 8b Coupling with thermo-hydro dynamic analysis

The temperature dependent volume change and concrete shrinkage associated with micro-climate in CSH gel and capillary pores are considered as offset strain in constitutive modeling. Corrosion rate is also computed by simulating migration of O_2-CO_2 gas and chloride ion penetration, and the effect of corroded substances is integrated in the structural analysis. These thermodynamic state variables are incorporated into the constitutive modeling before cracking. Though the effect of volume change generally tend to disappear after single or multi-directional cracking, the effect of these microclimate states remain influential and is of importance to serviceability performance and durability. Spatially averaged stress-strain relation of cracked concrete under uniaxial tension was experimentally extracted as shown in Fig.9 under different moisture and temperature combinations. Here, the stress was initialized at the beginning of additional mechanical loads. Temperature ranged from 20 to 75 degree (C) and sealed wet and dry conditions (RH=100-50%) were reproduced. The apparent cracking strength is reduced according to the ambient conditions and the crack spacing and widths were largely changed in each case. It is still difficult to predict the particular crack width.

But, when we direct attention to the averaged stress-strain relation of cracked concrete with bond mechanics, it was empirically found that the post-cracking residual stress transferred by local bond between steel and concrete can be practically estimated by the same formula of tension stiffness [14] as,

$$\sigma_t = f_{t,crack}\left(\frac{\varepsilon_{t,crack}}{\varepsilon_t}\right)^{0.4} \qquad (2)$$

where, $f_{t,crack}$ and $\varepsilon_{t,crack}$ are tensile stress and strain when the first cracking occurs. The microclimate state and the effect of self-equilibrated stress are simply represented by $f_{t,crack}$.

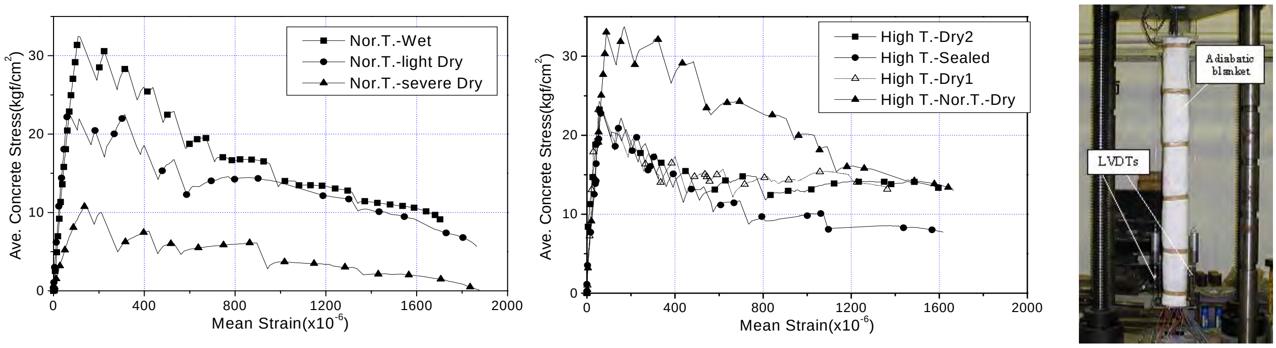


Fig. 9 Averaged tensile stress-strain relation of cracked structural concrete under different wet/dry and temperature [2]

Figure 10 shows load-deflection relations of plain concrete and RC members in flexure under coupled drying and sustained loads. Although pure drying induces no deflection but just contraction of volume, it accelerates the time-dependent deflection (curvature) so much in both plain and RC under long-term forces. The self-equilibrated stress induced by drying triggers the flexural crack propagation when mechanically loaded. The creep of concrete is here taken into account and the nonlinear interaction of creep and shrinkage is inherently involved [13]. It is clear that coupling of internal micro-pore states of thermodynamics is needed to predict the long-term structural performance.

The cracking is also influential in mass transport of gases and dissolved ions. This cracking effect is mutually linked with thermo-hydro dynamic analysis as shown in Fig.8. This simulation can be mainly used for life-cycle assessment. Figure 11 shows the simulation of corroded reinforced concrete beam subjected to shear and exposed to chloride [13]. Cracking of concrete causes accelerated diffusion of chloride and the larger crack region allows the deeper penetration of chloride and other substances. In the analysis, diffusivity of substances is regarded as a variable in terms of computed averaged strain of concrete elements.

The corroded steel produces volumetric swelling and results in internal self-equilibrated stress, which may lead to additional cracking around reinforcing bars. Figure 11 also shows the simulation results of corroded RC beams in shear. The referential case with no corrosion fails in shear accompanying sudden propagation of diagonal cracking in the web zone. In the case that corrosion is induced in the limited central span of the beam concerned, its capacity is simulated uninfluenced. As a matter of fact, experimental verification also reveals that we have the same result. On the contrary, if the corrosion is concentrated around the support of the beam, its capacity is simulated to be reduced with different crack propagation pattern. The diagonal crack which reaches the bending compression zone is initiated by the corrosion crack tip created along the longitudinal main reinforcement. Finally, the diagonal crack is driven to the beam support. Apparently, the concentrated corrosion is seen to deteriorate the anchorage performance of longitudinal reinforcement. The acceleration test of corrosion of steel in RC beam by electric charging also substantiated this simulation result.

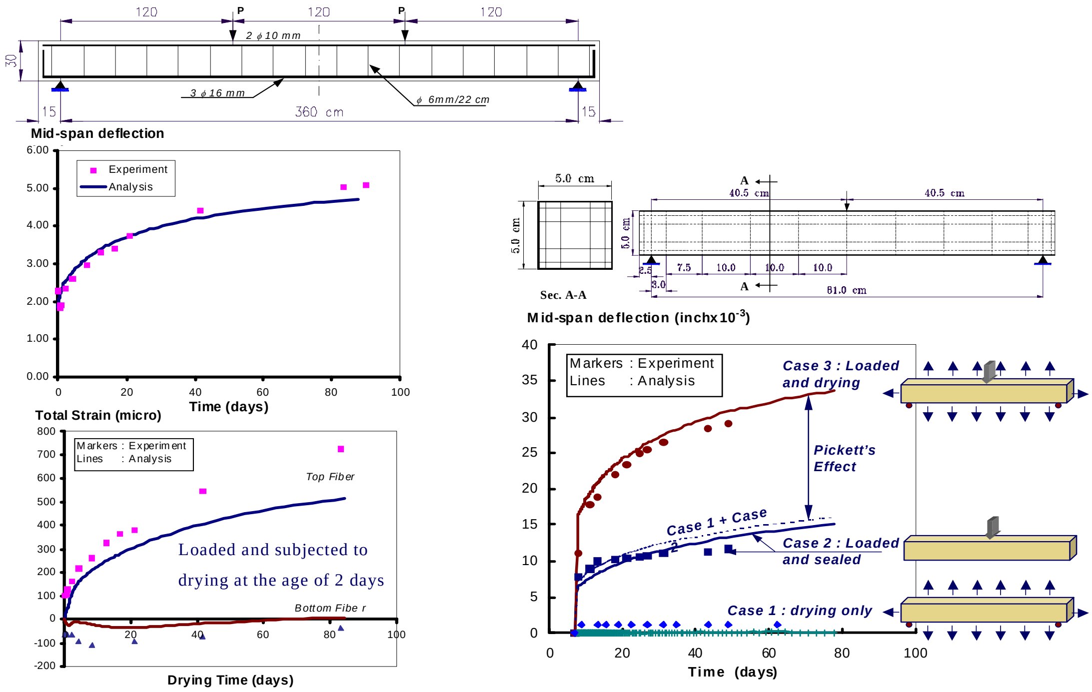
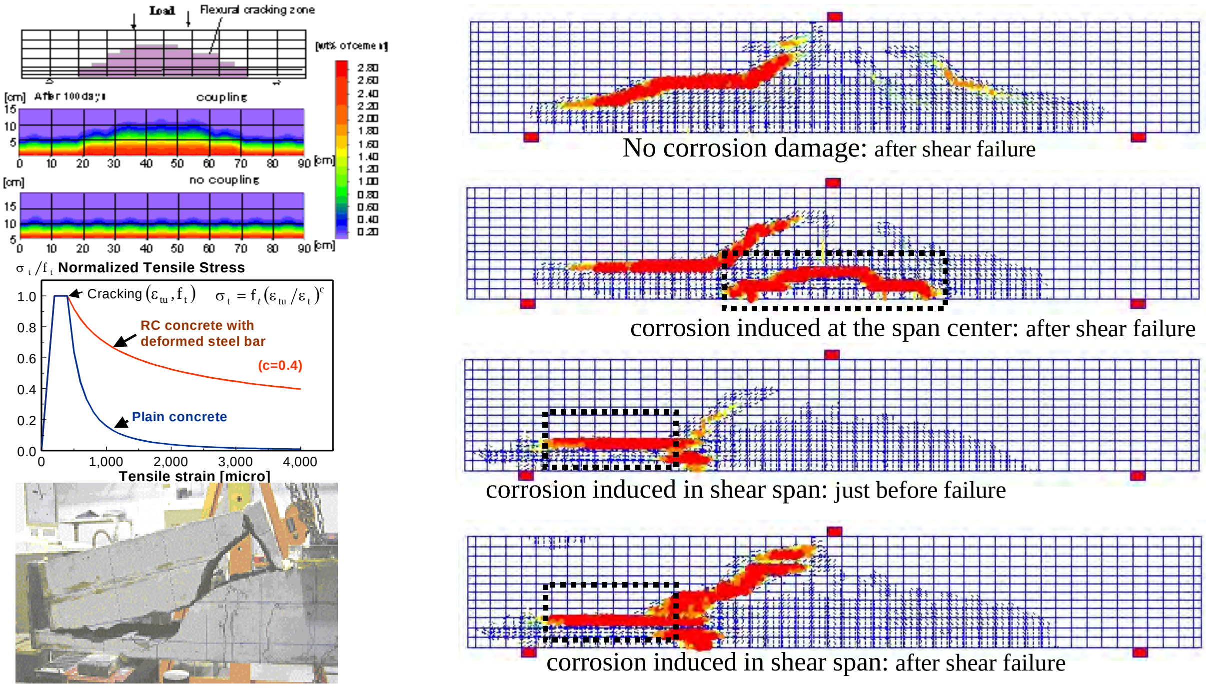


Fig.10 Nonlinear deformation of RC beams under coupled mechanical and whether actions [13]



(a) Crack-diffusion interaction (b) Shear and corrosion crack interaction

Fig. 11 Simulation of corrosion of reinforcing bars and structural performance assessment [13]

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. 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 authors expect that the systematic framework on the knowledge-based technology will be extended efficiently and can be steadily taken over by engineers in charge. This study was financially supported by JSPS Grant-in-aid for scientific research 14205065 and 14655160.

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