LIFE-SPAN SIMULATION AND DESIGN APPROACH FOR REINFORCED CONCRETE STRUCTURES

Xuehui An* · Koichi Maekawa** · Tetsuya Ishida***

ABSTRACT

This paper provides an introduction to life-span simulation and numerical approach to support the performance design processes of reinforced concrete structures. An integrated computational system is proposed for life-span simulation of reinforced concrete. Conservation of moisture, carbon dioxide, oxygen, chloride, calcium and momentum is solved with hydration, carbonation, corrosion, ion dissolution, damage evolution and their thermodynamic/mechanical equilibrium. Coupled analysis of mass transport and damage mechanics associated with steel corrosion is presented for structural performance assessment of reinforced concrete. Multi-scale modeling of micro-pore formation and transport phenomena of moisture and ions are mutually linked for predicting the corrosion of reinforcement and volumetric changes. The interaction of crack propagation with corroded gel migration can also be simulated. Two finite element codes, multi-chemo physical simulation code (*DuCOM*) and nonlinear dynamic code of structural reinforced concrete (*COM3*) were combined together to form the integrated simulation system. This computational system was verified by the laboratory scale and large scale experiments of damaged reinforced concrete members under static loads, and has been applied to safety and serviceability assessment of existing structures. Based on the damage details predicted by the nonlinear finite element analytical system, the life-span-cost of RC structures including the original construction costs and the repairing costs for possible damage during the service life can be evaluated for design purpose.

Keywords: life-span, performance verification, corrosion, cracking, mass transport, reinforced concrete

1. INTRODUCTION

Performance verification of reinforced concrete structures is one of the most important sustainable development topics, since concrete is the most extensively used construction material in the world. It is necessary to develop standard methods for predicting long term performances of infrastructures, including not only safety performance but also performance of durability. This paper provides an introduction to an integrated computational system for life-span simulation of reinforced concrete, developed to support the performance-based design processes of reinforced concrete structures.

In order to predict the durability performance of RC structures, such as carbonation, ion dissolution and steel corrosion, mass transport inside concrete has to be simulated, by solving thermodynamic equilibriums of hydration and conservation of moisture, carbon dioxide, oxygen, chloride and calcium. A durability simulation code of DuCOM has been developed for this purpose. Inside DuCOM, micro-pore formation and transport phenomena of moisture and ions are mutually linked for predicting the corrosion of reinforcement and volumetric changes. On the other hand, a nonlinear dynamic code of structural reinforced concrete (*COM3*) has been developed for years, capable of simulating cracking of concrete and yielding of reinforcement of RC structures. These two codes are combined together to form the integrated simulation system for prediction and simulation of structural life serviceability and safety of RC structures under specified loads and ambient conditions (Fig.1) (Maekawa *et al.* 1999, 2001, 2003). Furthermore, the damage details predicted by the integrated simulation system provides the necessary information to calculate the life-span-cost of RC structures, including the original construction costs and the repairing costs in case of possible damage during the service life, for cost-beneficial design and construction.

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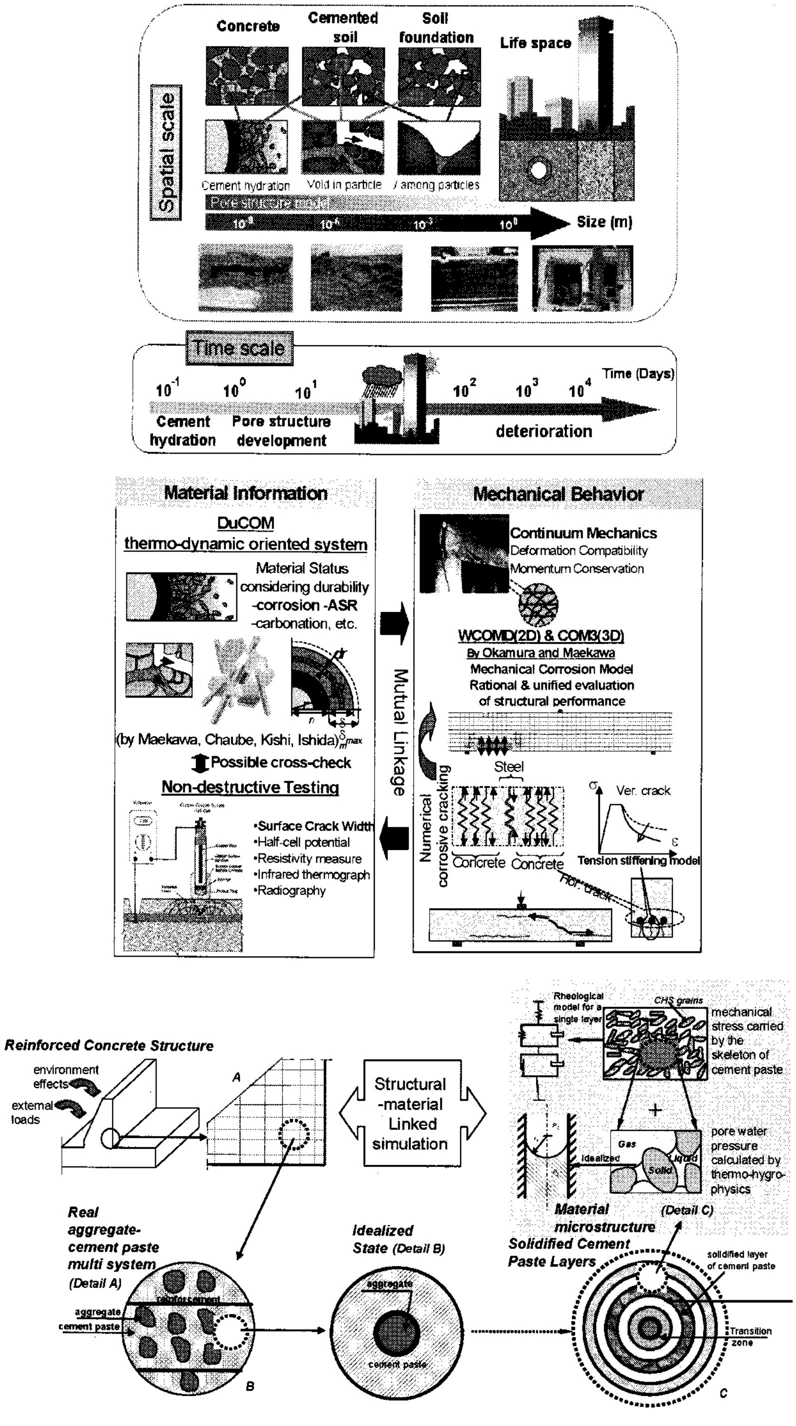


Figure 1 Coupling of thermo-hydro dynamics and damage mechanics for life-span simulation of RC structures based on micro-structure mechanics of cement paste

2. MECHANICS FOR STRUCTURAL PERFORMANCE SIMULATION

2.1 Basic constitutive models for structural mechanics of RC

Geometrically 3D behaviors of RC structures are able be simulated using 1D to 3D stress-filed finite elements (Fig.2). A scheme of RC modeling used for nonlinear simulation is simply illustrated in Fig.3 (Maekawa *et al.* 1999). Multi-directional cracking and its interaction are taken into account by the active crack approach (Maekawa *et al.* 2001) on the smeared compression stress field (Collins and Vecchio 1982), shown in Fig.4. All microscopic physical states (cracking, yielding, crack shear slip, remaining stiffness of fractured materials) are included in the constitutive modeling. The stress carrying mechanisms are composed of compression/ tension parallel and normal to cracking and shear transfer. By the active crack method (Maekawa *et al.* 2001), the primary cracking of governing nonlinearity of structural concrete is identified if some cracks intersect non-orthogonally. Here, path-dependent parameters are renewed only along the active crack in each load step during FEM calculation.

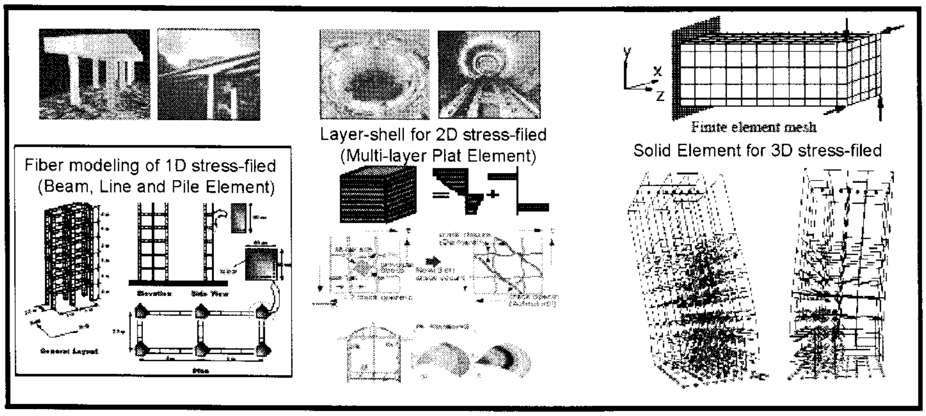


Figure 2 Finite element modeling for geometrically 3D simulation of RC structures

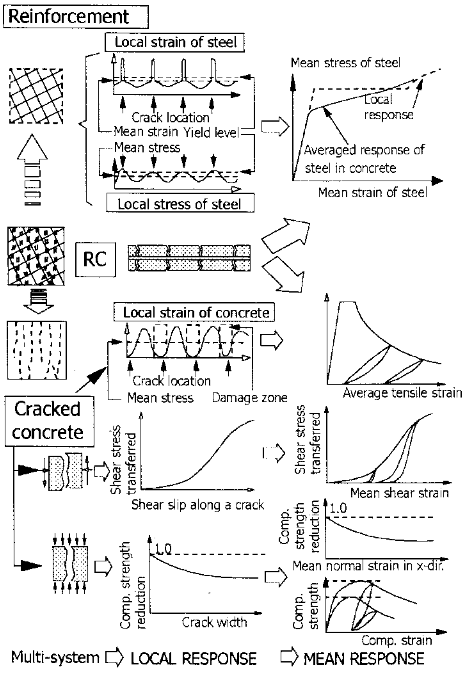


Figure 3 Constitutive model of reinforced concrete

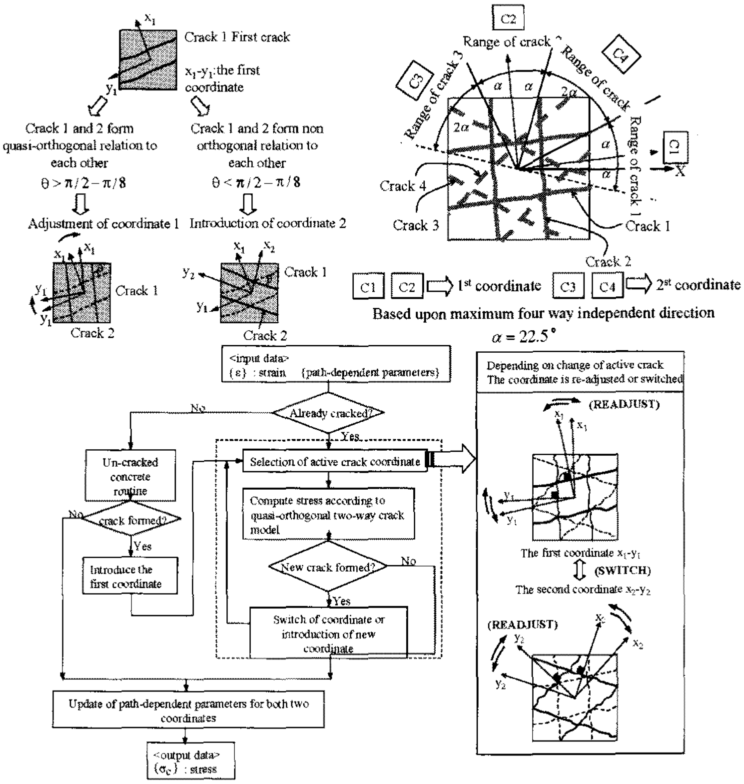


Figure 4 Formulation of in-plane constitutive model with multi-directional cracking scheme

The multi-directional fixed smeared crack model is applied on a 2D plane RC element. In order to apply this in-plane model to 3D FEM analysis, a 3D orthogonal coordinate system is introduced with principal axis (1) normal to the initially introduced crack plane and the remaining axes (2 and 3) within the crack reference plane (Maekawa *et al.* 2001). This establishes three sub-spaces defined by axes (1,2), (2,3) and (1,3), shown in Fig.5. The in-plane cracked concrete models are employed within these subspaces. The initial crack is contained in (1,2) and (1,3) planes, while plane (2,3) is orthogonal to the plane of the initial crack. Additional cracking is represented on the basis of the fixed two-dimensional sub-spaces. The partial stresses defined by the crack projection on (i, j) can be computed using of the in-plane RC constitutive law.

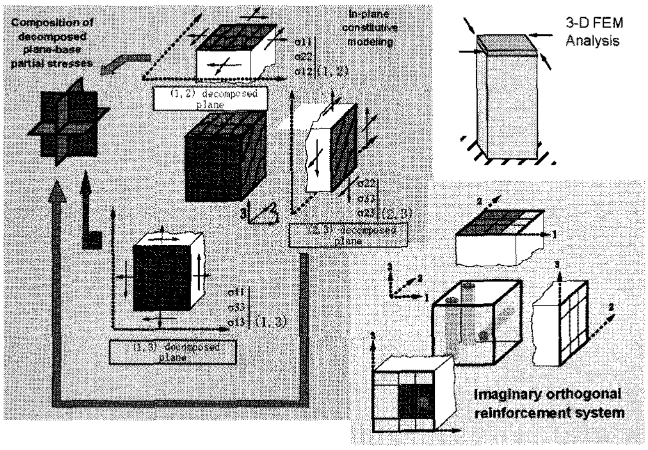


Figure 5 Composition of in-plane multi-directional cracking model for 3D cracked concrete

2.2 Multi-directional cracking simulation system

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 considerably rotate. This situation tends to create multi-directionally intersecting cracking with strong interaction. Fig.6 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 (Fukuura and Maekawa 1999). The in-plane stresses were actively controlled by the internal hydraulic pressure, torsion moment produced by a couple of jacks and axial compression. The non-orthogonal crack intersection frequently takes place when the principal direction of applied loads varies and/or external forces and ambient actions are coupled together.

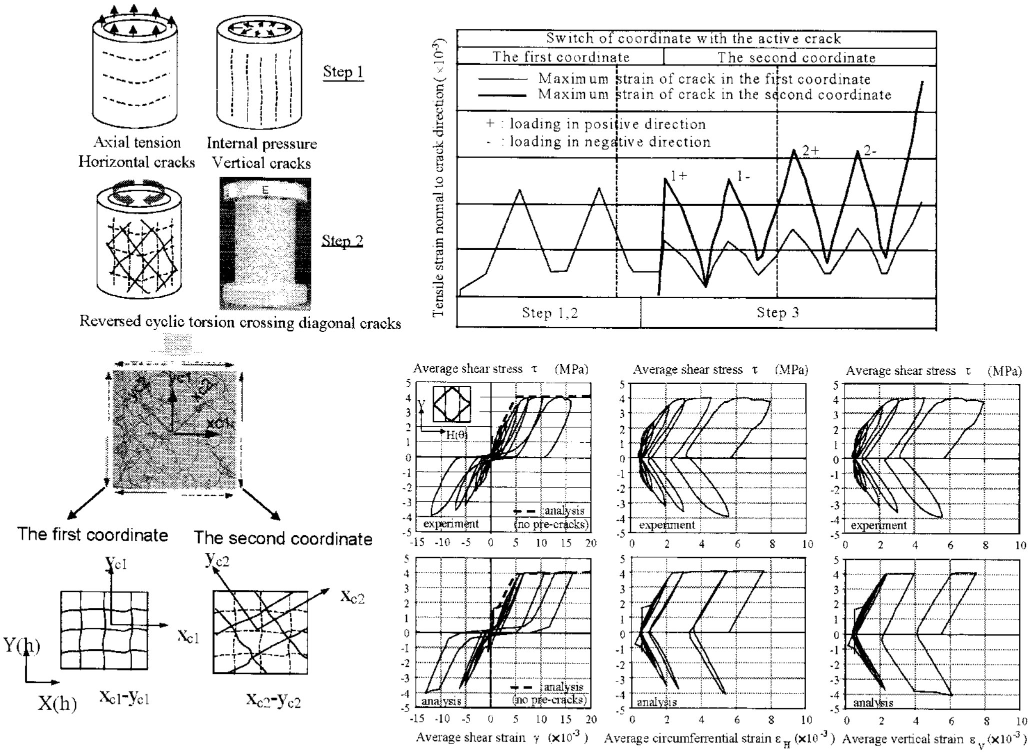


Figure 6 Fukuura's experiment for verifying four-way fixed crack model.

2.3 Shear capacity prediction including size effect

The RC constitutive models installed in the nonlinear FEM code COM3 include the smeared tension, compression and shear models for cracked concrete. The important points to consider are: the local behavior of reinforcing bars at the cracking section, the bonding effect of reinforcing bars and the deformation and failure of concrete between cracks.

Owing to bond of concrete to the reinforcing bars, the concrete continues to support a part of the tensile force even after cracking has taken place in the reinforced concrete. In order to consider the influence of bond effects, the relation between the average stress and average strain of concrete is given as a tension model for cracked concrete. This tension model shows tension stiffening due to the stress transferred from the steel bars by the bond effect being taken into account. The tensile model of cracked concrete with tension stiffening is shown in Fig.7a.

The concrete outside the bond effective zone is assumed to be the same as plain concrete, showing sharp strain-softening features as the tensile stress is transferred only through the bridging action at the crack surface. The numerical method for FEM computation can be applied by adjusting the strain-softening curve according the element size based on the fracture energy balance (Fig.7b), as in the finite element computation the crack width is replaced by element reference size (An *et al.*1997). In this case, the cracked band is assumed to be localized in an element and adjacent ones to be unloaded. Fig.7b shows a typical example that how to adjust the softening curve according the element size.

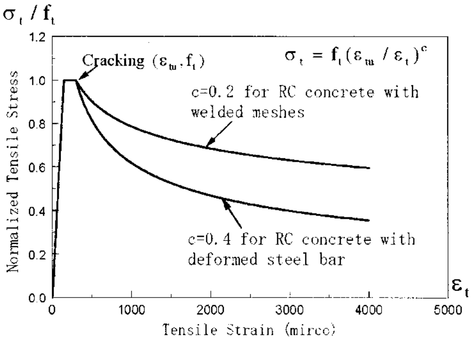


Figure 7a Tension stiffening model for RC

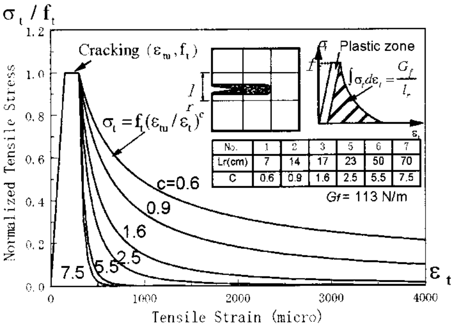


Figure 7b Tension softening model for plain concrete

In order to verify the application of the models for simulating the response of large-scale RC structures, the ability of the models to simulate shear failure and size effect is evaluated by analyzing a series of experiments for beams, with depths varying from 10cm to 300cm. The results of this simulation are summarized in Fig.8. Shear behavior is predicted effectively for even the largest beam, including the shear capacity, shear stiffness and shear cracking process. The sudden diagonal shear crack, observed during the experiment, is predicted in the final computational step in the analysis.

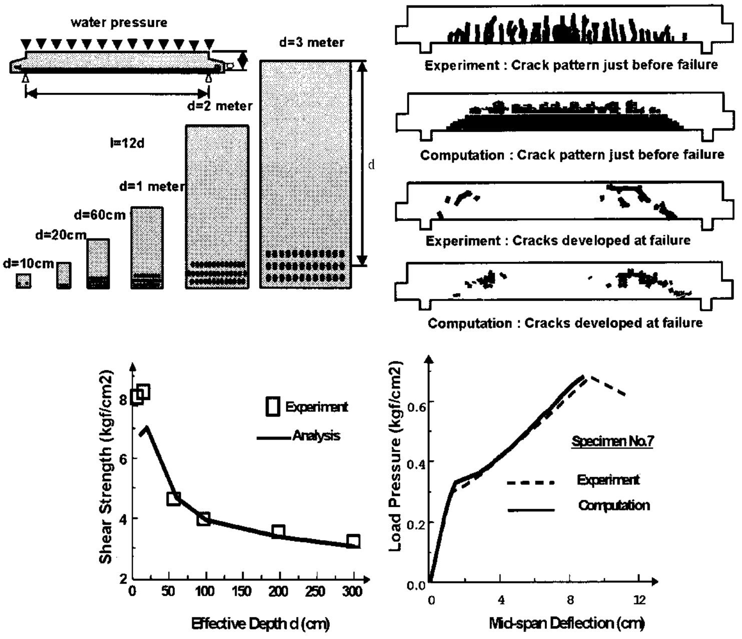


Figure 8 Computational results for size effect experiment

2.4 Seismic performance evaluation of real scale RC structures

In order to evaluate the ability of seismic performance prediction, COM3 were adopted for pre-test prediction in two benchmark tests. Fig.9 shows the experimental verification by using the real scale mockup for tunnels and ducts subjected to cyclic loads (Soraoka *et al.* 2001). Here, the shear capacity and ductility were carefully focused on. The prediction result of a real size shaking table experiment of RC wall is summarized in Fig.10 (Commissariat a l'Energie Atomique 1998). Without knowing the experimental results, COM3 is able to give good prediction only based on the input of real material properties.

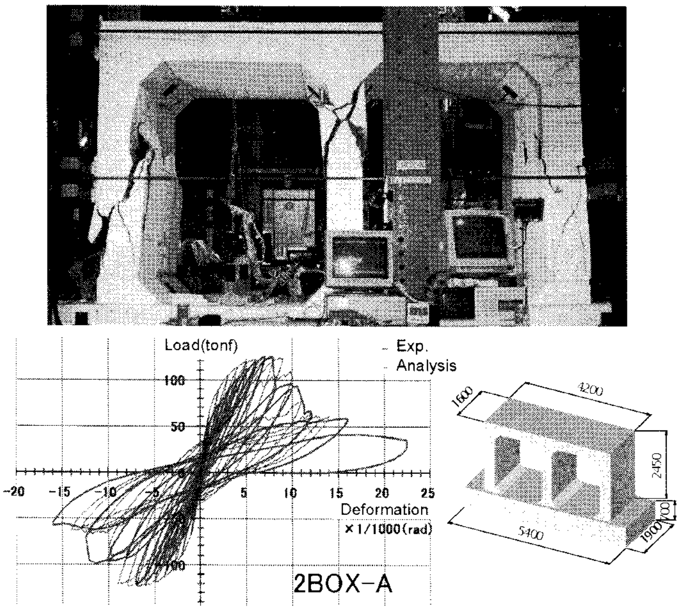


Figure 9 Computational results for large scale cyclic-loading experiment (Unit:mm)

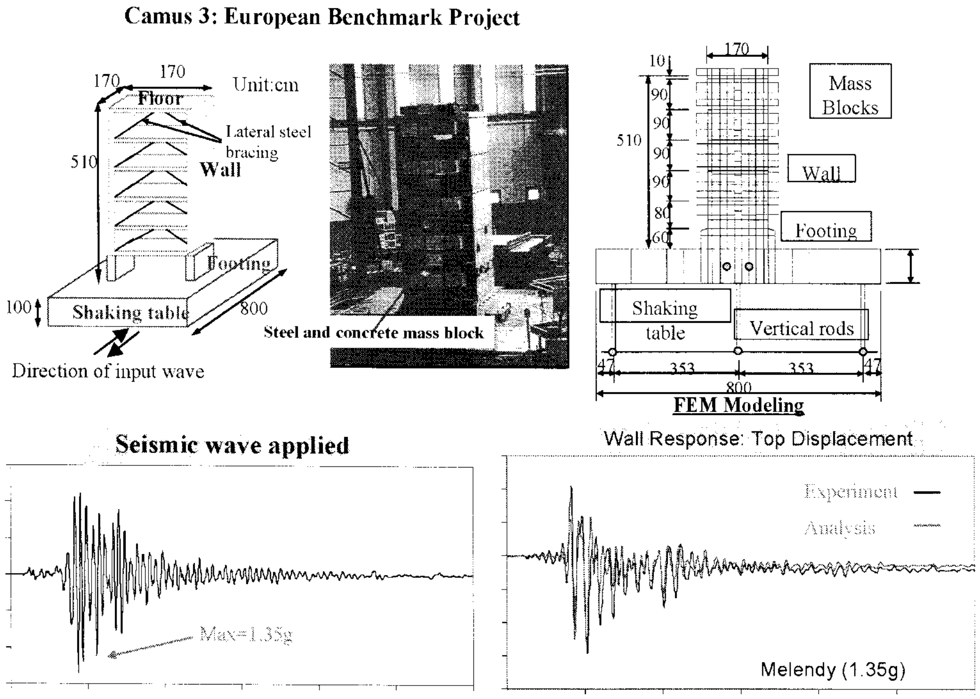


Figure 10 Benchmark prediction of RC wall subjected to seismic loading (CAMUS 3)

3. MECHANICS FOR MATERIAL PERFORMANCE SIMULATION

3.1 Thermo-hydro chemo-physical modeling for material performance simulation

State variables of thermo-hydro dynamics are further required for life-cycle assessment, especially for durability assessment related to material properties. Volumetric change caused by temperature and long-term moisture equilibrium in micro-pores are 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.11a was proposed (Maekawa *et al.* 1999, 2003) to simulate the entire thermo-mechanical states of constituent material and structures. For computing the thermo hydro equilibrium, multi-scale analysis platform *DuCOM* (Maekawa *et al.* 1999, 2003) was used (Fig.11d). 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.

Chloride ion migration and other chemical reactions such as carbonation and calcium leaching are overlaid on this system (Maekawa *et al.* 2003, Nakarai *et al.* 2005). 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 (Fig.11b and Fig.11c) (Maekawa *et al.* 2003). 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 with regard to micro-pore pressure and disjoining pressure originated from *Van del Waals* and *Coulomb* forces. Micro-corrosion rate is also computed by simulating migration of O_2-CO_2 gas and chloride ion (Maekawa *et al.* 2003), and the effect of corrosion is able to be integrated in the structural analysis (Toongoenthong and Maekawa 2005).

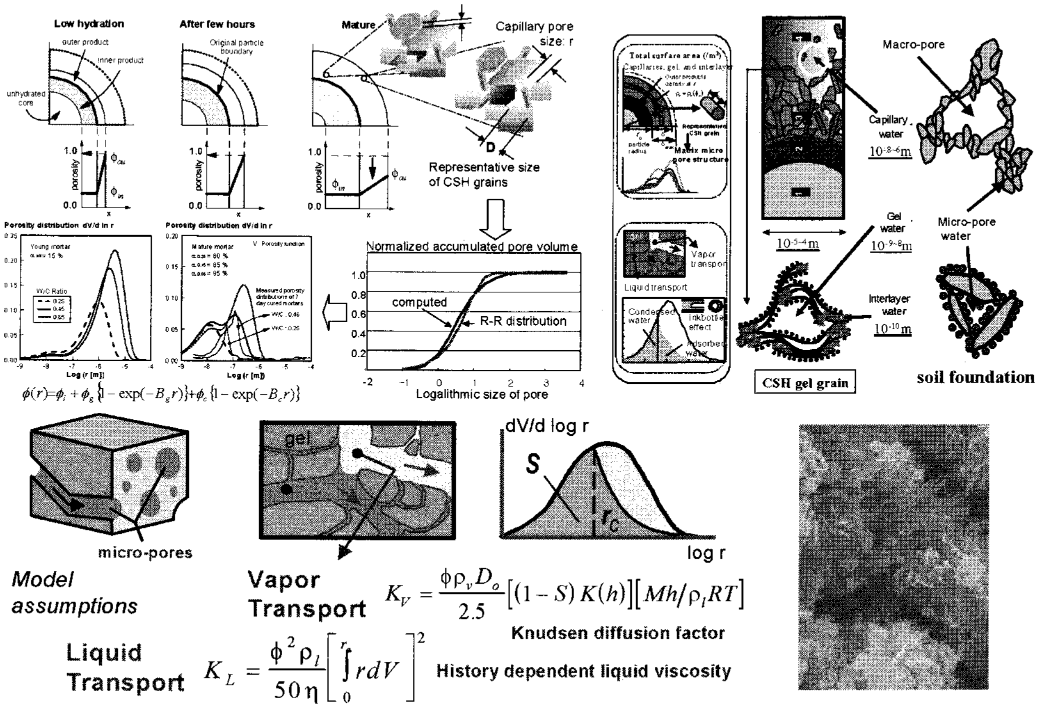


Figure 11a Statistical expression of CSH micro-porosity and the moisture equilibrium under pore moisture potential

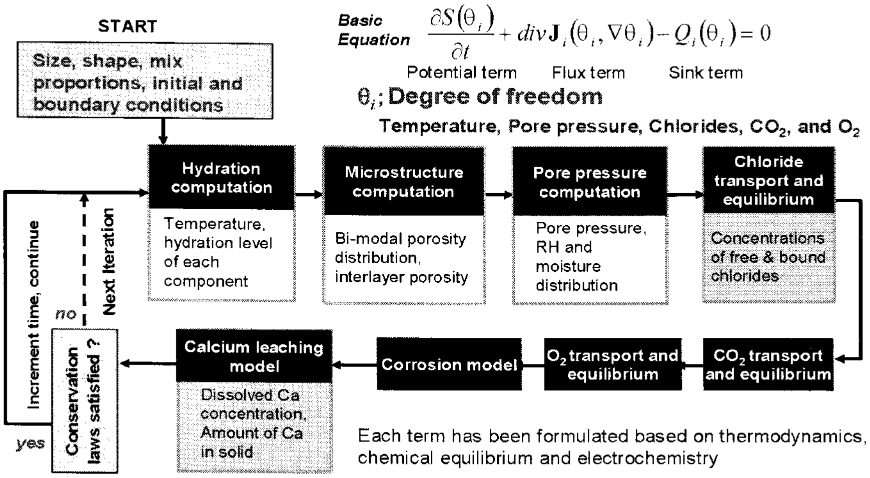


Figure 11b Flowchart of solving multi-chemo physical events

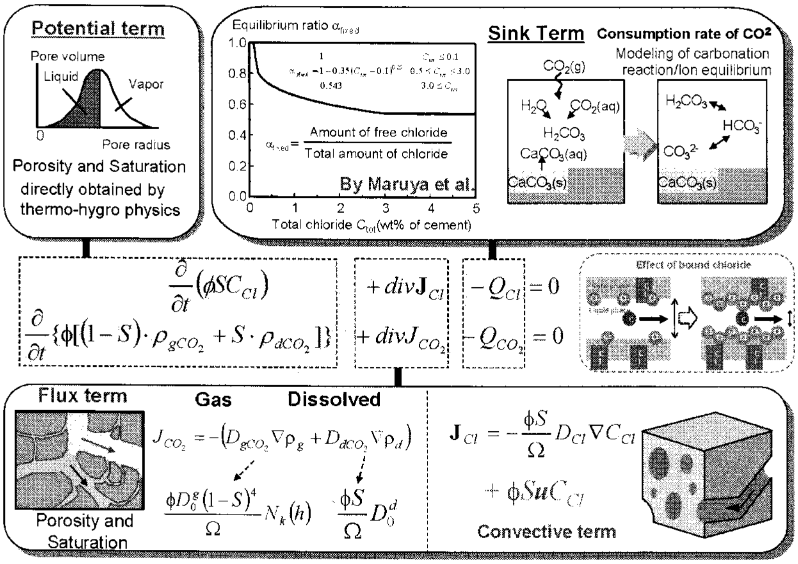


Figure 11c Micro-modeling of CSH gel and capillary pores and multi-chemo physics

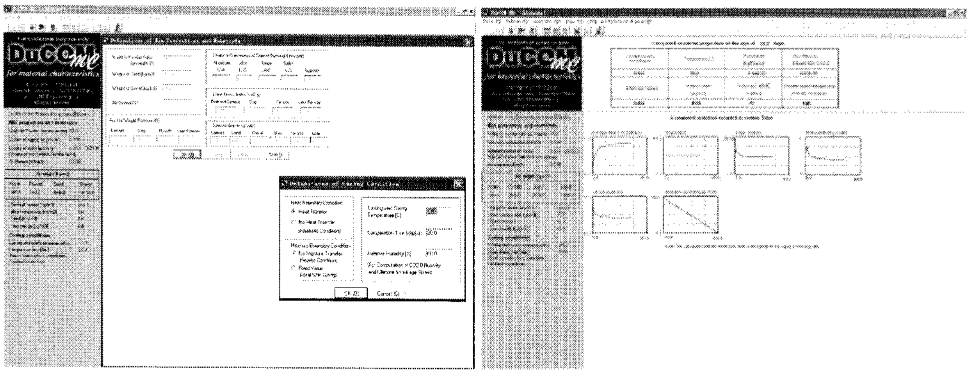


Figure 11d Typical input and output interface of DuCOM Code

3.2 Evaluation of chloride transport and carbonation phenomena in concrete

Using the proposed DuCOM code, transport of chloride ion under alternate drying wetting conditions is simulated here (Fig.12a). For verification, experimental data by Maruya et al.(1998) is used. In FEM analysis, mix proportions and chemical compositions of cements are given as input data. The curing and exposure conditions from experiment are also defined as boundary conditions for the target structures. Fig.12 shows the distribution of free and bound chlorides from the surface of exposure.

Computations were performed to predict the progress of carbonation for different CO_2 concentrations and water to cement ratio. The amount of $Ca(OH)_2$ existing in cementitious materials can be obtained by the multi-component hydration model as (Kishi and Maekawa, 1996 and 1997). Fig.12b shows the comparison of analytical results and empirical formula that was regressed with the *square root t equation*. Similar to the previous case, all of the input values in the analysis corresponded to the experimental conditions. Analytical results show the relationship between the depth of concrete in which pH in pore water becomes less than 10.0 and exposed time. The simulations can roughly predict the progress of carbonation for different CO_2 concentrations and water to powder ratios. Fig.12c shows the distribution of pH in pore water, CO_2, calcium hydroxide, and calcium carbonate inside concrete, exposed to the CO_2 concentration of 3%. Two different water to powder ratio, W/C=25% and 50%, were analyzed. It can be shown that higher resistance for the carbonic acid action is achieved in the case of a low W/C.

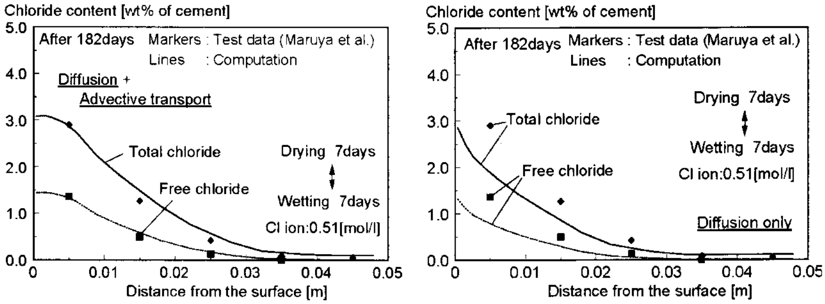


Figure 12a Chloride content profile in concrete exposed to cyclic drying wetting and drying

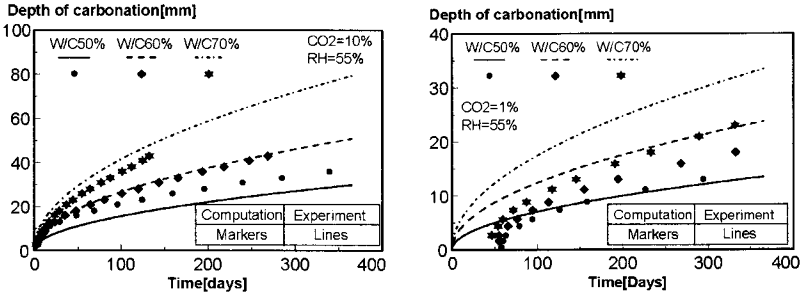


Figure 12b Carbonation phenomena for different CO2 concentrations and water-to-cement ratio

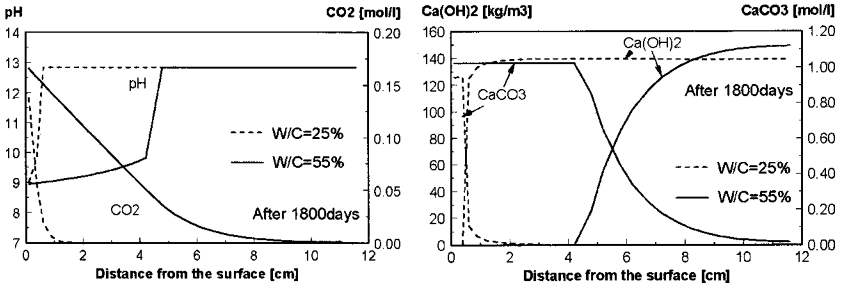


Figure 12c Distribution of pH, calcium hydroxide, and calcium carbonate under the action of carbonic acid

4. INTERGATED SCHEME FOR LIFESPAN PERFORMANCE SIMULATION

4.1 Integrated system of linked structural-material simulation

The material performance simulation code DuCOM is able to predict the durability information of RC through out the life-span. Using the information of durability as input data of material, such as strength varying and corrosion, structural performance simulation code COM3 is able to predict the mechanical behavior of the RC structure, giving the output of cracking of concrete or yielding of reinforcement (Fig.13).

Corrosion simulation can be mainly used for life-span assessment of RC structures, examining the remaining functional performance. The corroded steel produces volumetric expansion and results in internal self-equilibrated stress, which may lead to additional cracking around reinforcing bars. Cracking is also influential in mass transport of gases and dissolved ions. Cracking of concrete causes accelerated diffusion of chloride. It may allow deeper penetration of chloride and other substances. In the coupled system, diffusivity of substances is regarded as a variable in terms of computed averaged strain of concrete finite elements. This coupled system is able to run a life-span simulation of RC structures, by sharing the material and structural data, using each other's output as input information (Fig.14).

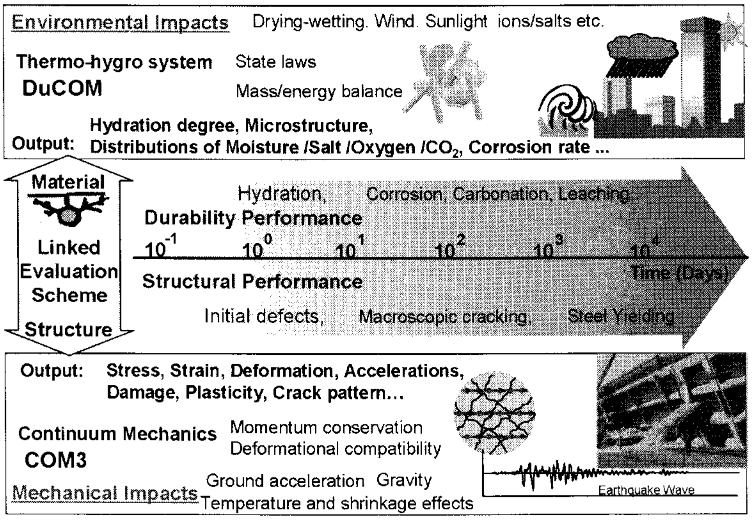


Figure 13 Coupling of material and structural mechanics for life-span assessment of RC structures

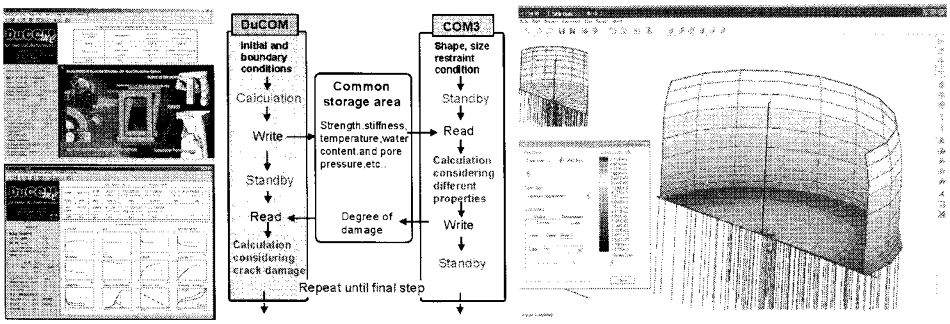


Figure 14 Linkage of DuCOM and COM3 codes through data sharing system during life-span simulation

4.2 Shear capacity evaluation of corrosion beam

Fig.15 shows the chloride ion penetration into the beam subjected to flexure. The information of bending cracks, calculated in code COM3, is transferred to code DuCOM. As the chloride ion diffusivity is formulated based upon both pore-structural characters (micro-information) and crack strain (macro-information) dependent on applied loads, the deep penetration is seen at the center span of the beam.

Fig.16 shows the corrosion crack propagation in experiment and simulation. The corrosive mass loss can be computed by *DuCOM*. The corrosion gel product is assumed to be created around the steel bars and the transverse stress normal to the reinforcement axis is computed. The crack patterns of the same surface crack width and the corresponding corrosion mass loss are compared with each other. The crack orientation and ligaments are fairly simulated.

The structural cracking pattern of an RC beam subjected to shear and flexure is illustrated in Fig. 17. As the shear capacity is less than the flexural one, a localized shear crack band can be seen after failure. The tension-stiffness defined in finite elements with corroded steel is reduced to plain concrete softening since the bond is thought deteriorated. If the corrosion induced cracking is located around the center span, no interaction of shear and flexural cracks is seen and shear capacity of the beam is computed unchanged. When it is placed around the shear span close to the support, diagonal shear crack joins this pre-cracking and early penetration of the diagonal crack is computed.

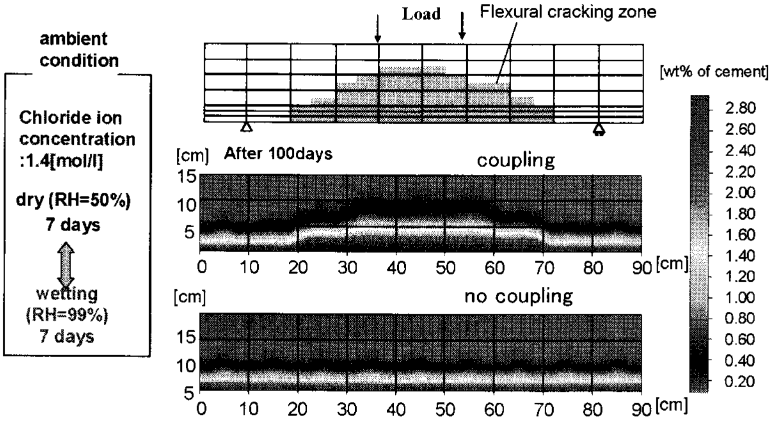


Figure 15 Coupling of thermo-hydro dynamics and damage mechanics for life cycle assessment of structures with soil foundation interaction

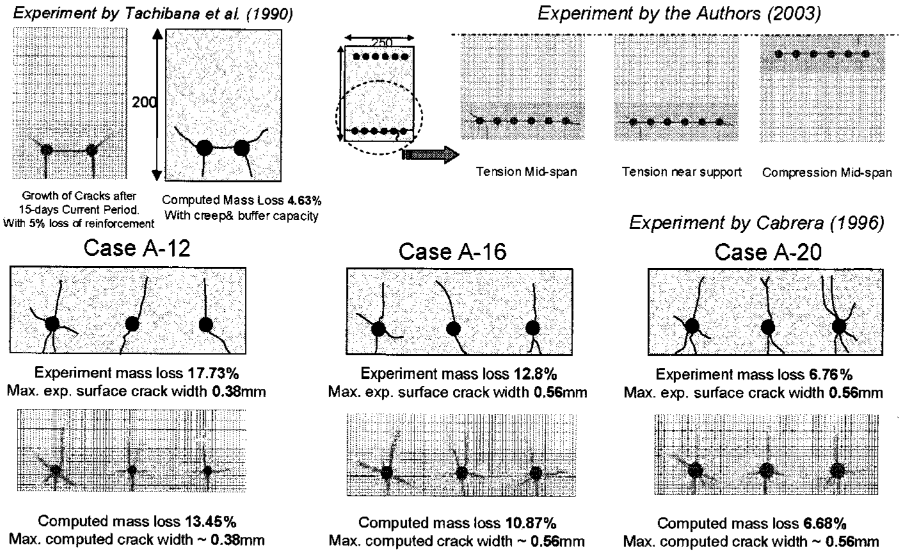
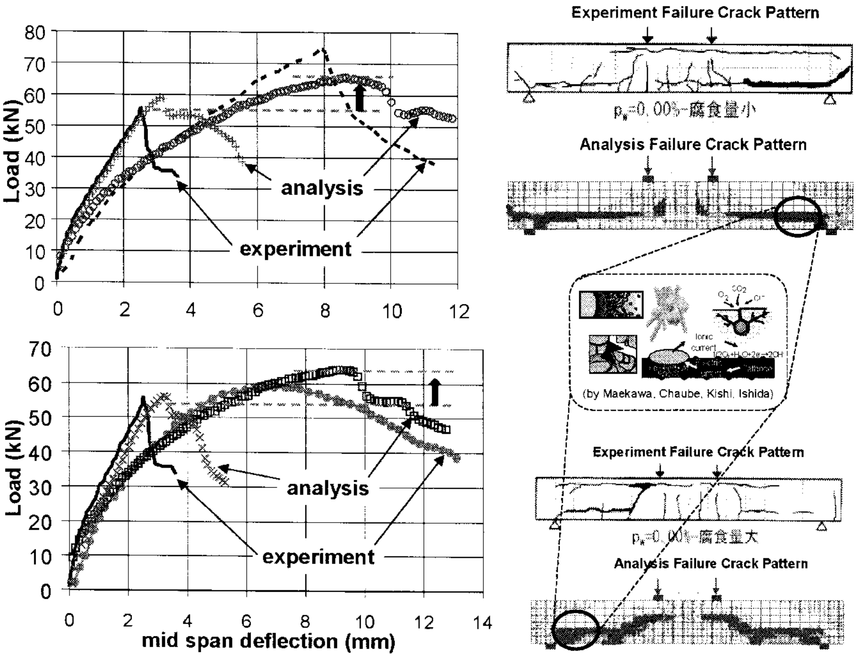


Figure 16 Corrosion crack propagation in experiment and simulation



a) Load-displacement relation b) Failure crack pattern

Figure 17 Simulated shear capacity and cracking of corrosion beam

5. LIFE-SPAN COST EVLATATION FOR DESIGN PURPOSE

Usually, the design service life of RC structure is about 50 years or even longer. Life-cycle-design method is proposed to consider economical efficiency of the structure during whole service life compared with traditional method. Life-span cost is a key index of economical efficiency in life-cycle-design. Optimization of the design schemes can decrease repair cost caused by possible damage, accordingly total life-span cost can be economized. The aim of life-cycle-design is to minimize life-span cost under the condition of satisfying bearing capacity. Two main factors should be taken into consideration in life-cycle-design: life-cycle cost and bearing capacity. In recent research, durability index and damage index are used to denote the bearing capacity and damage level respectively. The flowchart of the life-cycle-design based on nonlinear finite element analysis is shown in Fig. 18 (Han and An, 2006).

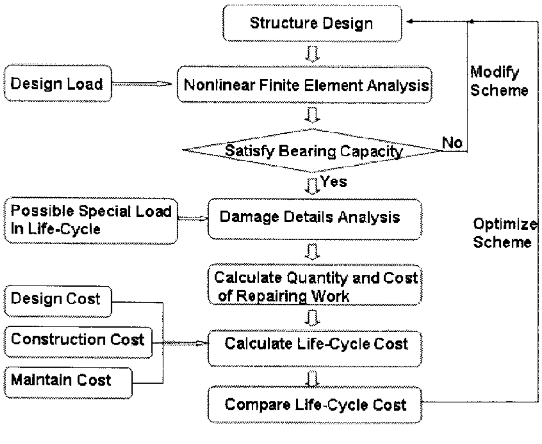
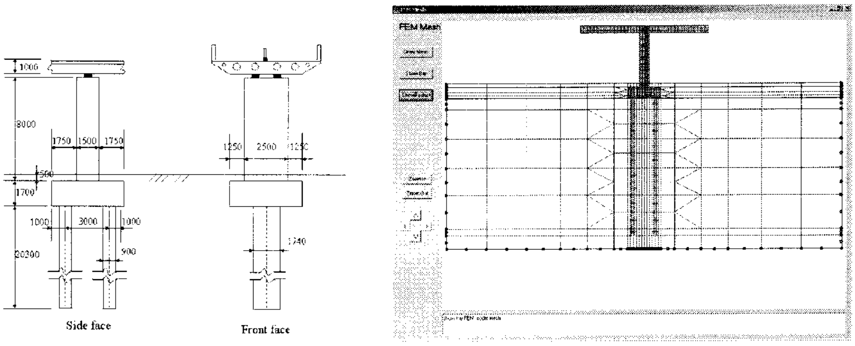


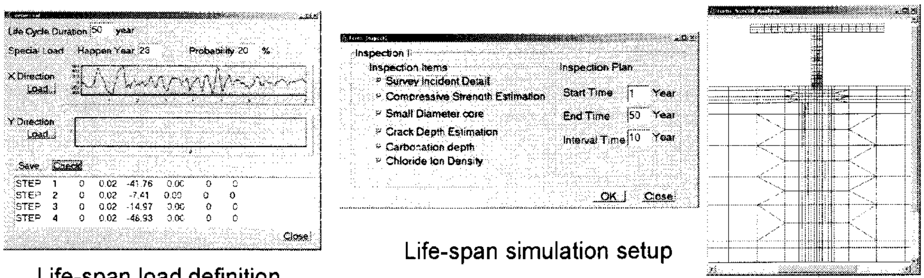
Figure 18 Flowchart of the life-cycle-design using the proposed system for damage details analysis

The damage details analysis results mainly include structure deformation, cracking of concrete and yielding of reinforcement bar. These damage details are shown in finite element mesh, so the repair zone can be easily identified. Also bearing capacity and damage level (in good condition, slight or serious damage) could be calculated or determined.



Design Target

FEM Model



Life Cycle Duration 50 year

Special Load Happen Year 23 Probability 20 %

STEP 1	0	0.02	-41.76	0.00	0	0
STEP 2	0	0.02	-7.41	0.00	0	0
STEP 3	0	0.02	-14.97	0.00	0	0
STEP 4	0	0.02	-46.93	0.00	0	0

Inspection I

Inspection Items
- ☑ Survey Incident Detail
- ☑ Compressive Strength Estimation
- ☑ Small Diameter core
- ☑ Crack Depth Estimation
- ☑ Carbonation depth
- ☑ Chloride Ion Density

Inspection Plan

Start Time 1 Year

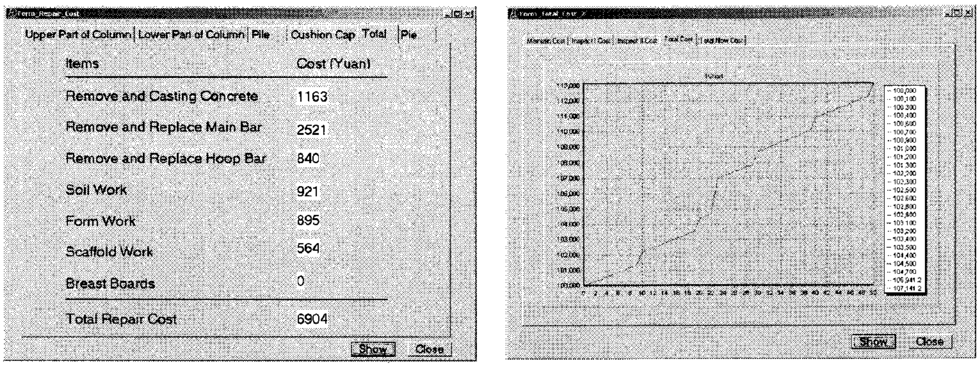
End Time 50 Year

Interval Time 10 Year

Life-span load definition

Life-span simulation setup

Damage simulation



Upper Part of Column | Lower Part of Column | Pile | Cushion Cap | Total | Pie

Items	Cost (Yuan)
Remove and Casting Concrete	1163
Remove and Replace Main Bar	2521
Remove and Replace Hoop Bar	840
Soil Work	921
Form Work	895
Scaffold Work	564
Breast Boards	0
Total Repair Cost	6904

Repairing cost calculation

Life-span cost calculation

Figure 19 Example of life-span cost evaluation based on nonlinear performance simulation of RC structures (Bridge Pillar based on Chinese Design Code)

Main processes of the life-cycle-design include constituting of FEM model, inputting other necessary information, exerting analysis under design load and special load, performing calculation of repair quantity and cost, and comparing life-span cost of different design schemes (Fig.19). By using the coupled material-structural performance simulation scheme introduced in this paper, the damage details of different design schemes can be predicted through out the life-span of the target RC structure. This makes the life-span cost evaluation reasonable.

6. COLCLUSION

Life-span performance simulation system of RC structures is introduced here, including two sub-systems, material durability performance simulation code of DuCOM, and structural performance simulation code COM3. By combining these two sub-systems together, the life-span performance data of RC structures are able to be exchanged and predicted. Experimental verifications show its possibility as a holistic approach, while individual modeling of chemical-physical events is required to be enhanced in the future with continuous effort.

Based on the damage simulation results from the proposed system, a life-cycle-design system is also introduced for life-span cost evaluation. It may be expected that practical uses of the proposed system would spread gradually according to the revision to performance based design cords or specifications.

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