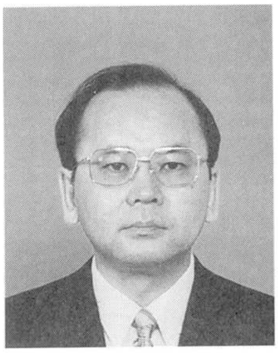
Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 81 (1999)

Artikel: Design strategies for concrete structures
Autor: Sakai, Koji
DOI: https://doi.org/10.5169/seals-61420

Design Strategies for Concrete Structures

Koji SAKAI
Kagawa University
Takamatsu, Japan



Koji Sakai is Head of Department of Safety Systems Construction Engineering, Kagawa University.

Summary

It is presumed that the next century will be the century of the environment. Concrete technology will not be an exception in this regard. Recently, there were two important meetings in which author was involved. One is International Workshop on Concrete Technology for a Sustainable Development in the 21st Century , which was held in Norway in June 1998. The other is JCI TC 961 (Technical Committee on Interface Problem between Structural and Durability Design of Concrete Structures) Symposium, which was held in Japan in July 1998. In the meetings, the new target which we should direct was definitely established. In this paper, the essences from the events are described.

1. Introduction

A workshop on "Concrete Technology for a Sustainable Development in the 21st Century" was held at Lofoten Islands, Norway, during 24 - 27 June 1998. This Lofoten workshop is on the extension of the workshop on "Rational Design of Concrete Structures" at Hakodate, Japan, in 1995 in which it was emphasized that next century will be the century of the environment. There were two significant points in the Hakodate Workshop (1). One was integration of structural design and durability design as a rational method of design. The other was concrete technologies in relation to global environmental issues. Based on the discussions in the workshop, the following "Hakodate Declaration" was adopted:

1. We, concrete experts, shall place environmental consciousness at the center of concrete technology towards the 21st century.
2. We, concrete experts, shall change the framework of concrete technology by integrating structural design and durability design and by considering planned maintenance.

It can be said that the Hakodate Workshop showed the direction of concrete technology in the century of the environment. However, it was just a beginning of introducing a new concept into the field of concrete technology.

Twenty nine papers were presented in the Lofoten Workshop (2), which led to fruitful discussions. Based on the discussion, the following "Lofoten Declaration" was adopted:

> We concrete experts shall direct concrete technology towards a more sustainable development in the 21st century by developing and introducing into practice:
> 1. Integrated performance-oriented life cycle design
> 2. More environmental-friendly concrete construction
> 3. Systems for maintenance, repair and reuse of concrete

structures
In addition, we will share information on all these issues with technical groups and the general public.

On the other hand, in the JCI TC 961 Symposium, the committee Report of JCI TC 961 and three papers by Dr. Corley, Dr. Litzner and Dr. Somerville who have been involved in making major codes were presented.

In this paper, the essences from both meetings are reviewed.

2. Design systems and strategies

There is no doubt that rational design of concrete structures is the key for a sustainable development in the 21st century. Although we have different types of design method, most of them are strength-oriented design. It means that durability or long term performance of concrete has not been incooperated into the codes or specifications in rational shapes.
Sakai et al. (3) proposed an integrated design method which include structural design and durability design and described the direction of technology development in the scope of the integrated design. Fig.1 shows the framework of integrated design. The characteristics of the proposed framework are as follows:

(1) Basic design concept is "performance-based evaluation."
(2) Final goal ia to grasp the behavior of structure accurately.
(3) Technologies developed in the future are easily incorporated into the design, or in other words it enables rational design according to the development level of the technology.
(4) Safety and durability can be integrated rationally, or in other words it becomes integrated design.

As shown in Fig.1, two extreme cases were considered. One is the method to grasp the behavior of a structure, based on a model in terms of the material properties as a function of time and their relationship with the mechanical properties of a cross section, an element or a structural member and to verify whether they fulfill the required performances (Flow B). This method would be difficult at present and should be established in the future. The other case is to examine mechanical and durability aspects separately, and to fulfill the required performance for each aspect (Flow A2). An intermediate method between the two will be also possible (Flow A1). Although the examination for mechanical behavior is not necessarily at a satisfactory technological level, it can be regarded as usable as a whole, as seen in the limit state design. However, there is no doubt that durability design is at an extremely primitive design level.

In the paper, they concluded as follows: "Technology is the reflection of a social system. That is to say technology develops in the framework of the social system of an era, therefore, the direction of development of technology changes when the value standards of people change along with their social environment. The situation surrounding concrete structures has also changed greatly. First, the myth that concrete is maintenance-free was proven untrue. Second, because of the serious economic situation, a tight control over construction costs and gurantees of longer life have been strongly demanded. This means that a structure must be designed taking cost-performance into consideration. The direction in which we have to proceed is obvious." It is also quite obvious that longer life or cost-performance is a very important aspect in realizing a sustainable development.

The outline of provisions made based on the above framework is as follows (4):

1. General

2. Required performance and load and environmental actions
 2.1 General requirements
  (1) Constructability, serviceability, safety, durability, aesthetics/landscape

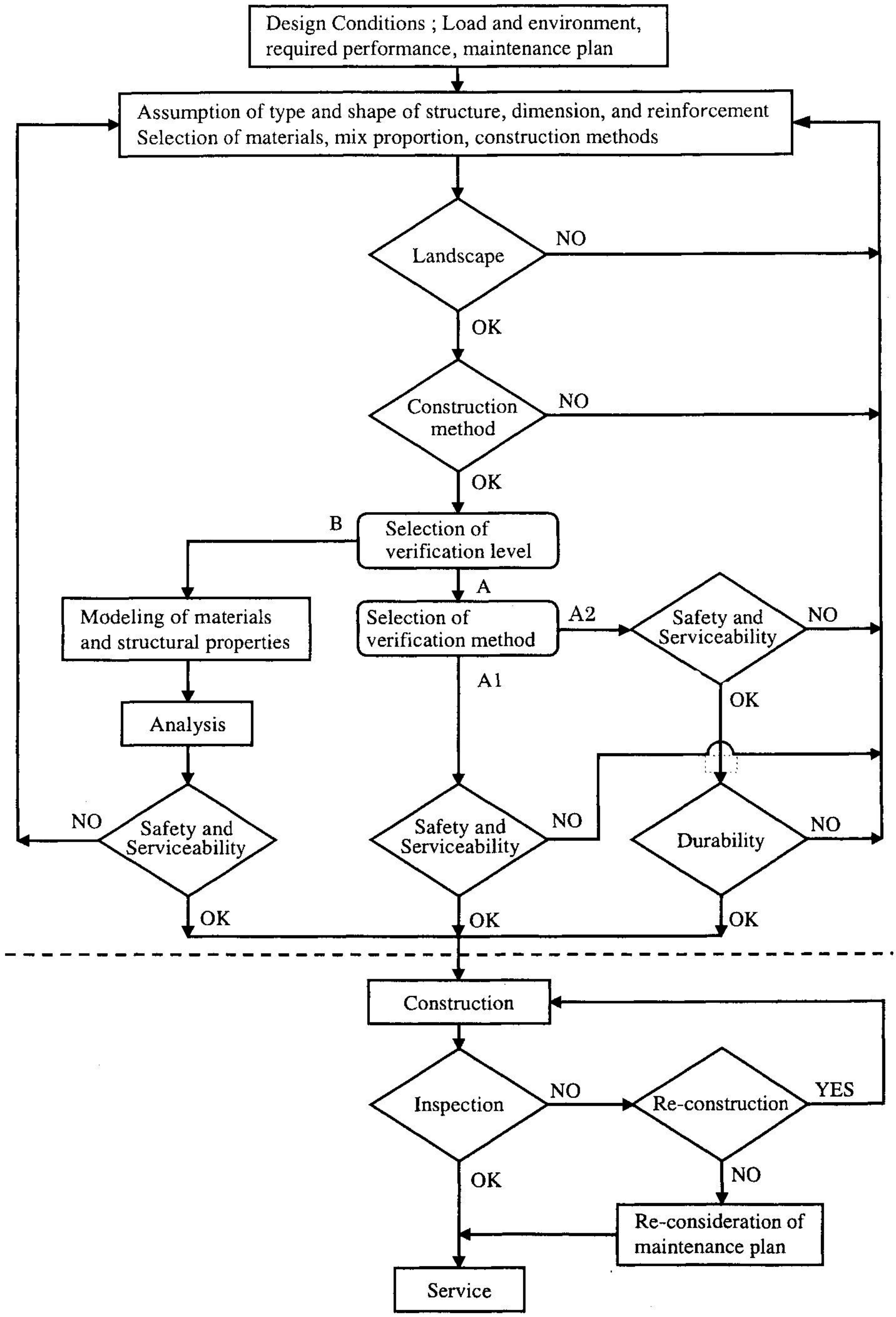


Fig. 1 Framework of integrated design(3)

(2) Environmental load, effect of society, culture and economy
2.2 Constructability
2.3 Serviceability
(1) Performances which satisfy the five senses of the user (comfortable ride, vibration, aesthetics/landscape, uneasiness caused by the view, smell), water-tightness, sound isolation.
2.4 Safety
2.5 Aesthetics/landscape
2.6 Environmental load
2.7 Conditions from the viewpoint of society, culture and economy

3. Performance verification and inspection
3.1 General
(1) It is important to quantitatively evaluate the behavior of structure, considering the properties of materials and structure, as well as load and environmental actions, and the required performance shall be verified based on these results.
- To quantitatively evaluate the behavior of structure, appropriate models, includind structural, material models and mass transfer model shall be determined.
- The following models can be utilized for the penetration of chloride ions, oxygen, water, carbon dioxide into concrete and subsequent chemical reactions.
- The following models can be utilized for the deterioration of the concrete (crack or disintegration) due to freeze-thaw or chemical actions, and loss of material (scaling or spalling).

(2) When required performance can be checked by the appropriate performance test or inspection, they can be converted to verification of the design conditions.
(3) When it is difficult to trace time-dependent structural behavior, the limit states can be set properly according to the required performance, and the verification of the performance can be deemed to have been conducted by confirming that the material, member or structure do not reach their respective limit states.
(4) Appropriate safety factors shall be included in performance verification process considering the reliability of the verification and inspection.
3.2 Verification of constructability
3.3 Verification of serviceability
(1) The verification of serviceability shall be conducted based on quantitative evaluation considering variable load and environmental actions, as well as regular load and environmental actions on the structural system in the life span.
(2) When it is difficult to conduct the methods described in (1), some appropriate limite states for materials, member or structure shall be set and the verification of serviceability performance shall be conducted.
(3) When the quantitatively evaluation of the behavior of the structure due to the environmental action is difficult, durability performance to consider the effect of the environmental action can be set as the required performance and the verification shall be conducted based on this requirement. It is possible to set the durability performance where the structure maintains the situation at the beginning of service life as durability performance 1, and the durability performance where the deterioration is such that no loss of function is allowable and no strengthening work is necessary as durability performance 2. In this case, appropriate safety factors shall be taken into account for the mechanical evaluation of serviceability.
(4) In the verification of each durability performance, an appropriate durability index can be set in accordance with the environmental actions to be considered.
(5) In calculation of each durability index, effect of mechanical cracks of concrete and combined effect due to different environmental actions shall be appropriately incoperated.
(6) The following eqations can be used regarding accumulation of chloride ions, progress of carbonation, corrosion of steel, and initiation and progress of cracking in the concrete.
(7) Appropriate methods can be used to evaluate the degree of deterioration or damage of concrete due to freeze-thaw or chemical action.

(8) The amount of permeable water in concrete shall be calculated by using an appropriate permeability model.

3.4 Verification of safety

(1) The verification of safety shall be conducted with quantitative evaluation considering variable load and environmental actions, as well as regular load and environmental actions on the structural system in the life span.

(2) When it is difficult to conduct the methods described in (1), some appropriate limite states for materials, members or structures shall be set and the verification of safety performance shall be conducted.

(3) In the calculation of limit state index of materials, members or structures, the effect of earthquake and environmental actions shall be appropriately incorporated.

(4) In the verification of safety against earthquakes, it is possible to set the seimic performance where the structure can function properly after the earthquake without any repair work (Seismic performance 1), the structure can recover the function in a short period of time without any strengthening works (Seimic performance 2), and the structure as a whole system does not collapse (Seimic performance 3).

(5) The verification for each seismic performance shall be conducted using appropriate ground motion.

(6) When the effect of environmental action cannot be evaluated along with the mechanical behavior in a combined manner, the durability performance can be set as durability performance 3 which implies large scale repair or strengthening work. In this case, appropriate safety factor shall be considered in the evaluation of the safety of mechanical behavior.

(7) The verification of durability performance 3 shall be achieved by evaluating properly the deterioration due to the environmental action.

The concept in which design of structure is conducted according to the required performance, is not necessarily a new idea, but it should basically be the origin of the design. From the immaturity of technology and the demand of efficiency, the design specification based on prescriptive provisions has gradually increased. This is frequently seen in durability design. Ultimate limit design for structural design implies basically "performance-based design." However, in most codes, the whole framework is not well defined, and the prescriptive provisions are mixed up as typically shown in the structural details. Therefore, it can be said that the ultimate limit state design is not really equal to a unified performance-based design. This kind of design framework has hidden the problematic place and the future direction where we should aim. The framework proposed covers all situations. There is no barrier. Engineers can choose any method depending their technical level and other conditions.

Maekawa et al. (5) showed a challenge to make the above-mentioned Flow B possible. Their fundamental standpoint is that the unified approach of mechanics which governs stress and strain fields and thermo-hygro phisics ruling mass and energy transport associated with thermo-dynamic state equilibrium would serve as a technicality of ensuring total performances of concrete structures as well as structural concrete performance over the life span of concrete structures. Their approach covers (a) the hydration of cement in concrete volume, corrosion of steel, moisture migration and associated transport of solved ion ingress and micro-pore structural formation (thermo-hygro physics:DuCOM sub-system) and (b) structural behaviors expressed by displacement, deformation, stresses and macro-defects of materials in view of continuum plasticity, fracturing and cracking (continuum mechanics of materials and structures: COM3 and sub-system of mechanics). For solving two sub-systems as for micro structural by DuCOM and macro structural performances by COM3 with mutual interaction, complete amalgamation of these dual systems in a single processing was considered. An example was shown on the process.

They concluded that if we may simulate cyber materials and structural behaviors in a virtual world under artificial environments and mechanical actions, we could see what happens within shortened period. If this becomes practical in the future, it means that a design for a really sustainable development will be accomplished.

Gjørv (6) emphasized that appropriate programs for life cycle management should be established because an incresing spending of recources for repairs , rehabilitation and premature demolition which is based on an uncontrolled service life is poor utilization of natural resources. The current experience on field performance and engineering practice was outlined. In Norwegian coastline bridges, more than 50% of the larger bridges have a varying extent of steel corrosion or has been repaired due to steel corrosion. Most of these bridges have been buit during the last 25years. In Norwegian harbor structures, although, based on improved technology, new harbor structures appear to perform much better, it was found that corrosion problems still occur on several new structures already after a service period of less than 10 years. For most of these structures, current standard requirements to both concrete quality and thickness of concrete cover have been fulfilled. In offshore structures in the North Sea, most of them have been in good condition without any visible sign of deterioration. However, it was demonstrated that the chloride penetrate the high quality concrete only at a slower rate. In the Oseberg A platform, where the concrete cover has partly been less than prescribed, corrosion has already occured, and cathodic protection is currently being installed. Good performance of concrete platform comes from the increased concrete quality requirements. On the contrary, in the land-based concrete structures, the traditional requirement to compressive strength was almost the only concrete quality requirement until the late 1980's.This descriptive approach has shown to yield insufficient and unsatisfactory results. In addition, he pointed out that although several numerical models for chloride penetration are available, these models do not yet seem to have any satisfactory and practical validation.

Based on this histrical background, he suggests that it may be better to have a strategy for a more controlled prevention of chloride penetration based on an appropriate program for life cycle management. As a strategy to obtain a more controlled chloride penetration, protective surface treatments or coating were recommended. It was also emphasized that a regular monitoring of the chloride penetration provide a most reliable basis for the preventive maintenance. It can be said that this is the most practical way until more sophisticated methods are available in the future.

Sarja (7) described that sustainable building is defined as a technology and practice which meet the multiple requirements of the people and society in an optimal way during the life cycle of the build facility, and the most important sustainability factors in performance for structures with long target service life can therefore generally be defined as flexibility towards functional changes of the facility and high durability, while in the case of the structures with moderate or short target service life changeability and recycleability are dominating.

It is valuable to cite his comment that ecology can be interpreted as the ecomomy of the nature. Namely, the application of this aspect to materials and structural engineering can be concretized in the life cycle methodology in design, manufacturing, construction , maintenance and management. It was described that the multiple requirements optimisation is needed using appropriate index. In addition, the following equation to calculate the life cycle cost was shown:

$$E_{tot}(t_d) = E(0) + \sum[N(t) \bullet E(t)]$$

where E_{tot} is the design life cycle cost, E(0) is construction cost, N(t) is coefficient for calculation of the current value of the cost at the time t after construction, and E(t) is cost to be born at time t after construction.

Somerville (8) presented a holistic approach to structural durability design which comes from an idea that good performance-in-service-with time ia a sustainability issue, i.e. a structural design approach to durability is the best means of achieving that. The holistic approach here means a durability design embracing material, design and construction matters, although it seems that this is an origin of concrete technology. The keys he suggested to realize the holistic approach are as follows:

(1) The establishment of performance requirements, in practical whole life terms, including the future operation of the structure, and its management and maintenance.
(2) How to deal with relevant environments, in a design context.
(3) Variations in construction quality, as influenced by design detail, construction method and workmanship.
(4) The precise make up of the design framework, which simultaneously

embraces all relevant factors and provides the required reliability.

Mehta (9) described that infrastructural needs in our rapidly industrializing world will have to be balanced against another equally important human need, namely the preservation of the life-sustaining environment on the planet earth, which is being threatened by the uncontrolled use of natuaral resources and increasing amounts of environmental pollution. In addition, it was emphasized that, being an important player in the infrastructural development and a major consumer of natural resources of the earth, the concrete industry needs to be reoriented through the adoption of environment-friendly technologies. Crucial key elements were identified as follows:

(1) Conservation of concrete-making materials.
(2) Enhancement of durability of concrete structures.
(3) A paradigm shift from reductionistic to a holistic approach in concrete technology research and field practice.

It was emphasized that the goal of sustainable development of the cement and concrete industries is the complete utilization of the cementitious and pozzalanic by-products produced by thermal power plants and metallurgical industries. Concerning the enhancement of durability, it was described that the challenge lies in making the ordinary concrete a highly durable, high-performance building material for the future structures. He also commented that the prevailing reductionistic approach is, in fact, responsible for many wasteful practices in concrete technology today because according to this approach all aspects of a complex system can be fully understood and controlled by reducing it to parts and considering only one part at a time, and as a result, test methods for concrete durability, materials specifications, and codes of recommended practice have failed to consider that durability ia a holistic (pertaining to the whole structure) performance criterion which must take into consideration many factors including weather conditions, structural design, and concrete processing. It was concluded that as long as the concrete community continues to pursue reductionistic solutions to major technological and societal problems confronting us, it will neither attract highly motivated researchers nor the financial support needed for suatainable development.

Moksnes (10) discussed a sustainable development in concrete from the completely different angle. A number of international associations are active in the field of promoting research and development and in the dissemination of knowledge related to concrete and concrete structures. As the relationship between the individual engineers and scientists, their employers, national associations and the international umbrella associations, Fig. 2 was shown. Loop 1 is the vast majority of engineers. Loop 2 embraces the National Associate which companies, institutions and individuals join and support through activities on committees and commissions. Loop 3 brings in the voluntary international association and their interrelations with their Member Groups. Loop 4 is the problem and the main challenge when examining the role of the voluntary international associations, namely the interaction and efficient cooperation between the different associations and the interaction with society (politicians, planners, authorities, customers, media). It was pointed out that when concrete people get together in committees, for meetings or for Congresses and Symposia, they talk to themselves and very seldom are society or people issues addressed. This means that even if we discussed the sustainable development in concrete technology without a strategy to the public, it does not work.

3. Repairs/rehabilitations and retrofitting

From environmental considerations and shrinking public budgets, it will become more significant to prolong the life span of existing structures by repairs or rehabilitations and retrofitting. Horrigmoe (11) emphasized that we should consider the solution to the problems of deteriorating infrastructure as a part of the challenge of creating a sustainable development in the 21st century and there is a need for significant improvements and innovations of existing repair techniques to meet future demands of costs and performance. As a numerical simulation, nonlinear finite element analysis of damaged and repaired concrete beams was shown. It was also described that the use of externally bonded carbon fiber reinforced plastics for strengthening and repair is a promising new technique.

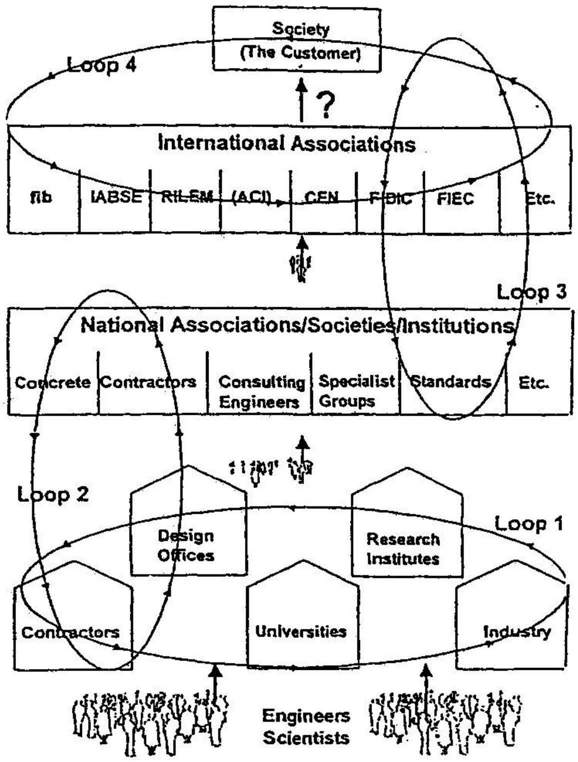


Fig. 2 Concrete networks(10)

Sheikh et al. (12) discussed the advantages of using fiber reinforced plastics (FRP) for construction, strengthening and repair from the technical as well as the economical point of view. As the advantages of FRP, high strength-to-weight ratio, much better fatigue performance, ease of transport and installation, low maintenance cost, durable, minimum disruption of structure use during rehabilitation, no measurable loss of overhead or side clearance were raised. Many applications of FRP to beams, columns, slabs, and walls were reviewed. From their own tests, it was found that the response of the FRP-repaired specimen resulted in much larger energy dissipation. The economical advantages of using CFRP was also concretely shown.

Ueda (13) described that the 21th century is the century in which infrastructure has been constructed and stocked, the 21st century, however, is the century in which we will be asked how to hand the infrastructure as the property of human being to the next generation, and retrofitting seems to be the best solution for that. He introduced the performance-based design system for retrofitting proposed by Sub-Committee on Retrofitting Design of JSCE Concrete Committee, in which design methods for major retrofitting methods, such as external cable method, wrapping (or jacketing) method and concrete wrapping (or jacketing) method, were shown for the first time. The retrofitting design methd consists of (a) investigation of existing structure, (2) examination of performances of existing structure, (3) selection of retrofitting method, and (d) examination of performances in retrofitted structure. It was concluded that further study is still needed especially on how to predict the time dependency of structural performances.

4. Eurocode 2

Accoding to Litzner (14), for the realization of the European single market, the Commission of the European Communities has initiated the work of establishing a set of unified technical rules for the designof building and civil engineering works which will gradually replace the different rules in force in the various EC-Member States. The design concept of Structural Eurocodes are as follows:

1. With acceptable probability, they will remain fit for the use for which they are required,

having due regard to their intended life and their cost.
2. With appropriate degrees of reliability, they will sustain all actions and influences likely to occur during execution and use and have adequate durability in relation to maintenance costs.

The verification of the performance of concrete structures will be conducted in the following condition:

$$Sd \leq Rd$$

where Sd is actions due to load and environment and Rd is corresponding resistances.

Thus, it may be said that the Eurocode 2 is a partially performance-based design code, because it actually contains many practical descriptive rules. This comes from the fact "the structual Eurocode have to provide the technical tool for their achievement(14)." Although Eurocode 2 does not provide an integrated design approach, performance -based design on durability will be applied to the practical level for the first time. It will be not so difficult to modify the whole framework in due process in the future depending on the development of concrete technologies.

5. ACI Building and ISO Codes

In the JCI Tokyo symposium, Corley (15) addressed a proposed framework for future codes in his paper. As a future format of ACI building codes, the following was proposed:

Chapter X
- X.0 -- Notation
- X.1 -- Scope
- X.2 -- General requirements
- X.3 -- Minimum reinforcement
- X.4 -- Design procedures
  - X.4.1 -- Direct design
  - X.4.2 -- Rigorous design
  - X.4.3 -- Performance design

Direct design is the simple approach with a simple calculator. Rigorous approach mostly the body of ACI 318-95. However, according to his understanding, performance design is limited only by statics, compatibility, and serviceability, in which computer assistance is mandatory.
A framework of ISO code on "Performance Requirements for Structural Concrete"was also proposed as follows:

1. Scope
2. General Principles
3. Requirements
   3.1 Structural safety, ultimate limit states
   3.2 Serviceability limit states
   3.3 Durability limite states
   3.4 Fire resistance limit states
   3.5 Fatigue
4. Criteria
   "Criteria shall be established so that resistance exceeds actions by a suitable margin"
5. Assessment
   5.1 Material properties/5.2 Analysis of concrete structures/ 5.3 Strength calculations/
   5.4 Discontinuity regions/5.5 Bond,anchorage, and splices/5.6 Stability/5.7 Bearing/
   5.8 Two-way slabs/5.9 Precast concrete and composite action/5.10 Prestressed concrete/
   5.11 Design for earthquake resistance/5.12 Detailing requirements/5.13 Construction requirements/5.14 Quality control
6. Standards Deemed to Satisfy
   "Any standard in the following list is deemed to satisfy this ISO Standard:
      1. XXX

2. YYY
For a standard to be added to the list of "deemed to satisfy; it must be approved by letter ballot of ISO TC/71"

It will be valuable to compare this framework and Japanese one on the advantages for the future development of concrete technology.

6. Concluding remarks

We are now in a turning point in the history of design of concrete structures. Technology is the reflection of social system. Th drastic change of every systems have been required all over the world. It means that we need to establish a new framework of concrete technologies which meet the requirements from the new sophisticated systems. The level of development in design methods of concrete structures will depend on the comprehensiveness of the design framework. From the above-discussion, the points which we have to direct is quite obvious. The final target is to grasp the performance of a structure as it is. Based on this fundamental concept, the information s on the performance of concrete structures should be steadily accumulated.

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