Extending the lifespan of nuclear power plant structures

Extending the Lifespan of Nuclear Power Plant Structures
Prolongement de la durée de vie des structures de centrales nucléaires
Verlängerung der Lebensdauer von Kernkraftwerksbauten

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SUMMARY

Reinforced concrete structures play a vital role in the safe operation of nuclear power plants. Isolated incidences of degradation indicate that there is a need for improved quantitative evaluation methods and surveillance. inspection/testing, and maintenance activities to ensure continued safe operation. The Structural Ageing Program has addressed these issues through development of an ageing management methodology that encompasses a materials property database, inspection and repair technologies, and reliability-based techniques to indicate the current and future condition of these structures. Although aimed at nuclear power plant concrete structures, program results are equally applicable to the general civil engineering infrastructure.

RÉSUMÉ

Les ouvrages en béton armé jouent un rôle vital dans la fiabilité du fonctionnement des centrales nucléaires. Des cas isolés de dégradation partielles montrent l'importance de l'amélioration des méthodes d'évaluation, de surveillance, d'inspection, d'essais et de maintenance, afin d'assurer le fonctionnement et la sécurité fonctionnelle de tels ouvrages. Une procédure systématique a été mise en place pour la gestion du vieillissement, comportant une banque de données sur les propriétés des matériaux, des techniques d'inspection et de réparation, toutes basées sur la théorie de fiabilité, qui permet de visualiser les états actuels et futurs de ces structures. Bien que prévue pour des centrales nucléaires, il est possible d'appliquer cette méthode à des ouvrages de génie civil.

ZUSAMMENFASSUNG

Stahlbetonbauten spielen eine lebenswichtige Rolle für den sicheren Betrieb von Kernkraftwerken. Vereinzelte Verfallserscheinungen deuten darauf hin, dass verbesserte Erfassungsmethoden, Ueberwachungs-, Inspektions- und Testverfahren benötigt werden, um einen anhaltend sicheren Betrieb zu gewährleisten. Im "Structural Ageing Program" wurde daraufhin eine Methodik zum Alterungsmanagement entwickelt, die eine Datenbank mit Werkstoffeigenschaften, Inspektions- und Reparaturtechniken und Verfahren auf Grundlage der Zuverlässigkeitstheorie umfasst, um den gegenwärtigen und zukünftigen Zustand dieser Tragwerke anzuzeigen. Obwohl auf Kernkraftwerksbauten ausgerichtet, sind die Ergebnisse des Programms auch auf allgemeine Bauten anwendbar.

1.   INTRODUCTION

By the end of this decade, 63 of the 111 commercial nuclear power plants in the United States will be more than 20 years old, with some nearing the end of their 40-year operating license term. Faced with the prospect of having to replace lost generating capacity from other sources and substantial shutdown and decommissioning costs, many utilities are expected to apply to continue the service of their plants past the initial licensing period. In support of such applications, evidence should be provided that the capacity of the safety-related systems and structures to mitigate potential extreme events has not deteriorated unacceptably due to either aging or environmental stressor effects during the previous service history.

2.   REINFORCED CONCRETE STRUCTURES EXPERIENCE

Reinforced concrete structures are important to the overall safety of nuclear power plants in that they provide foundation, containment, support and shielding functions. Aging of these structures occurs with the passage of time and has the potential to degrade strength and increase the risk to public health and safety. Degradation mechanisms that can impact the performance of these structures include corrosion of the steel reinforcing systems, chemical attack, alkali-aggregate reactions, sulfate attack, frost attack, leaching, salt crystallization, and microbiological attack. When structural degradation has occurred, it primarily has done so early in life and has been corrected. Causes were related to either improper material selection, construction/design deficiencies, or environmental effects. Examples of some of the more serious instances include voids under vertical tendon bearing plates resulting from improper concrete placement; cracking of post-tensioning tendon anchorheads due to stress corrosion or embrittlement; containment dome delaminations due to low quality coarse aggregate material and absence of radial reinforcement or unbalanced prestressing forces; reinforcing steel corrosion in water intake structures; leaching of concrete in tendon galleries; and low prestressing forces [1-2].

3.   CONCRETE STRUCTURAL AGING PROGRAM

Experiences summarized above indicate the possibility that degradation effects may reduce the margin that concrete structures have to accommodate loadings beyond the design basis. There is a need for improved quantitative evaluation methods and surveillance, inspection/testing, and maintenance to ensure continued safe operation of nuclear power plants. Guidelines and criteria for use in evaluating the remaining structural margins (residual life) have been developed under the Structural Aging (SAG) Program [3]. These activities were conducted under three major technical task areas — materials property data base, structural component assessment/repair technology, and quantitative methodology for continued service determinations.

3.1   Materials Property Data Base

A reference source containing data and information on the time variation of material properties under the influence of pertinent environmental stressors or aging factors has been developed. The data base, in conjunction with service life models, has application in the prediction of potential long-term deterioration of reinforced concrete structural components and in establishing limits on hostile environmental exposure for these structures. The results also have application to establishment of maintenance and remedial measures programs that will assist in either prolonging component service life or improving the probability of the component surviving an extreme event such as an earthquake. The data base has been developed in two formats — a handbook and an electronic data base.

The *Structural Materials Handbook* is an expandable, four volume, hard-copy reference document containing complete sets of data and information for each material. Volume 1 contains performance and analysis information (i.e., mechanical, physical, and other properties) useful for structural assessments and safety margins evaluations. Volume 2 provides the data used to develop the performance information in Volume 1. Volume 3 contains material data sheets (e.g., constituent materials, general information, and material composition). Volume 4 contains appendices describing the handbook organization and revision procedures. The *Structural Materials Electronic*

Data Base is an electronically-accessible version of the handbook that has been developed on an IBM-compatible personal computer. It provides an efficient means for searching the data files.

Two approaches have been utilized to obtain the data and information contained in the data base — open-literature information sources and testing of prototypical samples. A total of 143 material data bases have been developed addressing concrete and steel reinforcing materials. Examples of concrete material property data and information files currently available include compressive strength, modulus of elasticity and flexural strength versus time for several concrete materials cured under a variety of conditions (i.e., air drying, moist, or outdoor exposure) for periods up to 50 years; ultimate compressive strength and modulus of elasticity versus temperature at exposures up to 600°C for durations up to four months; and compressive strength versus time for concrete materials obtained from prototypical nuclear power facilities. Metallic reinforcement (ASTM A 615 and A 15) performance curves are available for fatigue, and ambient and temperature-dependent (A 615 material only) engineering stress versus strain. Temperature-dependent engineering stress versus strain, and tensile yield strength, ultimate tensile strength, and ultimate elongation versus temperature performance curves are available for both prestressing tendon (ASTM A 421, Type BA) and structural steel (ASTM A 36) materials. A more detailed description of the data base and the files it contains is provided elsewhere [4].

Also under this activity, methods for predicting the service life or performance of reinforced concrete have been assessed [5]. Models for each of the environmental degradation processes noted earlier were established and evaluated. A major conclusion of this study was that theoretical models need to be developed, rather than relying solely on empirical models. Predictions from theoretical models are more reliable, far less data are needed, and they have wider application. Purely stochastic models have limited application because of the lack of adequate data to determine statistical parameters. The best approach to providing realistic predictions of the service life of an engineering material is to combine deterministic and stochastic models.

3.2   Structural Component Assessment/Repair Technology

A methodology has been developed that provides a logical basis for identifying the critical concrete structural elements in a nuclear power plant and the degradation factors that can potentially impact their performance [6]. Numerical ranking systems were established to indicate the relative importance of a structure's subelements, the safety significance of each structure, and the potential influence of the particular environment to which it is exposed. Results of this activity can be utilized as part of an aging management program to prioritize in-service inspection activities.

Direct and indirect techniques used to detect degradation of reinforced concrete structures have been reviewed [7]. Capabilities, accuracies, and limitations of candidate techniques were established (e.g., audio, electrical, infrared thermography, magnetic, stress wave reflection/refraction, radioactive/nuclear, rebound hammer, and ultrasonic). Information was assembled on destructive (e.g., coring, probe penetration, and pull-out) and emerging (e.g., leakage flux, nuclear magnetic resonance, and capacitance-based) techniques. Recommendations were developed on application of testing methods to identify and assess damage resulting from typical factors that can degrade reinforced concrete. Also, statistical data were developed for nondestructive testing techniques commonly used to indicate concrete compressive strength (i.e., break-off, pull-out, rebound hammer, ultrasonic pulse velocity, and probe penetration) [8]. This information is required where destructive and nondestructive tests cannot be conducted in tandem at noncritical locations to develop a regression relation between the technique parameter measured and the structure parameter of interest. The methods developed can be used to estimate variance in strength or to yield information about distribution of strength population that is required to calculate the characteristic strength for use in structural integrity assessments .

As corrosion resulting from either carbonation or the presence of chlorides is the dominant type of distress that impacts reinforced concrete structures, corrosion mechanisms and types (e.g., uniform, pitting, bimetallic, crevice, etc.) were identified as well as conditions that affect the corrosion rate (e.g., oxygen, electrolyte conductivity, ion concentration, temperature, etc.). Methods available to detect corrosion occurrence include visual observations, half-cell potential measurements,

delamination detection, electrolyte chemistry, corrosion monitors, acoustic emission, radiography, ultrasonics, magnetic perturbation, metallurgical properties, and electrical resistance. Remedial measures include damage repair, cathodic protection, inhibitors, chloride removal, membrane sealers, stray current shielding, dielectric isolation, coatings, and environmental modifications. Stray electrical current resulting from any of a number of sources (e.g., cathodic protection systems, high voltage direct current systems, and welding operations) could also lead to corrosion. Techniques to detect stray current include half-cell potential versus time measurements, half-cell potential versus distance measurements, and cooperative (interference) testing. Mitigation measures for stray current include prevention or elimination of the current source, installation of cathodic protection, draining the current from the source, and shielding the structure from the source. Use of sacrificial or impressed current cathodic protection systems as both a rehabilitation technique for corroding structures and a corrosion prevention technique for steel that may lose its inherent passivity at a later date was investigated. Design considerations, advantages and disadvantages, and commentary on when cathodic protection should and should not be used were also addressed [9].

Damage repair practices commonly used for reinforced concrete structures in both Europe and North America have been reviewed [10–11]. Basic repair solutions for corrosion of steel reinforcement in concrete include: (1) realkalization by either direct replacement of contaminated concrete with new concrete, use of a cementitious material overlay, or application of electrochemical means to accelerate diffusion of alkalis into carbonated concrete; (2) limiting the corrosion rate by changing the environment (e.g., drying) to reduce the electrolytic conductivity; (3) steel reinforcement coating (e.g., epoxy); (4) chloride extraction by passing an electric current (DC) from an anode attached to the concrete surface through the concrete to the reinforcement (chloride ions migrate to anode); and (5) cathodic protection. Repair strategies and procedures were developed in the form of flow diagrams. Information specifically addressing inspection, degradation, and repair of reinforced concrete structures in light-water reactor plants was assembled through a questionnaire sent to U.S. utilities. Responses provided by 29 sites representing 42 units indicate that the majority of the plants perform inspections of concrete structures only in compliance with integrated-leak-rate test requirements (visual inspections), and surveillances of the post-tensioning systems of prestressed concrete containments. The most common deterioration causes were drying shrinkage, acid/chemical attack, thermal movement, freeze-thaw cycles, and sea water exposure. Most of the repair activities were associated with problems during initial construction (cracks, spalls, and delaminations), with the repairs performed on an as-needed basis. When the performance of a repair was evaluated, visual inspection was used.

3.3   Quantitative Methodology for Continued Service Determinations

Structural loads, engineering material properties, and strength degradation mechanisms are random in nature. The strength, R(t), of a structure and the applied loads, S(t), both are random (or stochastic) functions of time. At any time, t, the margin of safety, M(t), is

$$M(t) = R(t) - S(t).$$ (1)

Making the customary assumption that R and S are statistically independent random variables, the (instantaneous) probability of failure is,

$$P_f(t) = P[M(t) < 0] = \int_0^\infty F_R(x) f_s(x) dx.$$ (2)

in which $F_R(x)$ and $f_s(x)$ are the probability distribution function of R and density function of S. Equation 2 provides one quantitative measure of structural reliability and performance, provided that P_f can be estimated and validated.

For service life prediction and reliability assessment, the probability of satisfactory performance over some period of time, say (0, t), is more important than the reliability of the structure at the particular time provided by Eq. (2). The probability that a structure survives during interval of time

(0, t) is defined by a reliability function, $L(0, t)$. If n discrete loads $S_1, S_2,..., S_n$ occur at times $t_1, t_2, ...,t_n$ during (0, t), the reliability function becomes,

$$L(0,t) = P[R(t_1) > S_1,..., R(t_n) > S_n].$$ (3)

If the load process is continuous rather than discrete, this expression is more complex.

The conditional probability of failure within time interval (t, t+dt), given that the component has survived during (0, t), is defined by the hazard function:

$$h(t) = -d[\ln L(0,t)] / dt$$ (4)

which is especially useful in analyzing structural failures due to aging or deterioration. For example, the probability that time to structural failure, T_f, occurs prior to a future maintenance operation at t+Δt, given that the structure has survived to t, can be evaluated as,

$$P[T_f \le t + \Delta t \mid T_f > t) = 1 - \exp\left[-\int_t^{t+\Delta t} h(x)dx\right].$$ (5)

The hazard function for pure chance failures is constant. When structural aging occurs and strength deteriorates, h(t) characteristically increases with time.

Intervals of inspection and maintenance that may be required as a condition for continued operation can be determined from the time-dependent reliability analysis. When a structure is inspected and/or repaired, something is learned about its in-service condition that enables the density function of strength, $f_R(r)$, to be replaced by the (conditional) density $f_R(r|B)$, in which B is an event dependent on what is learned from the in-service inspection. The updated density of R following the inspection is,

$$f_R(r|B) = P[r < R \le r+dr, B]/P[B] = c\, K(r)\, f_R(r)$$ (6)

in which K(r) is denoted the likelihood function and c is a normalizing constant. The time-dependent reliability analysis then is re-initialized using the updated $f_R(r|B)$ in place of $f_R(r)$. The updating causes the hazard function to be discontinuous in time and lowers the failure probability in Eq. (5).

Uncertainties in methods of in-service inspection/repair affect the density $f_R(r|B)$. A combination of methods is usually more effective from a reliability point of view than using one method. When there are limited resources, it is most effective to select a few safety-critical elements and concentrate on them [5,12]. Optimal intervals of inspection and repair for maintaining a desired level of reliability can be determined based on minimum life cycle expected cost considerations. Preliminary investigations of such policies have found that they are sensitive to relative costs of inspection, maintenance and failure. If the costs of failure are an order (or more) of magnitude larger than inspection and maintenance costs, the optimal policy is to inspect at nearly uniform intervals of time. Additional information on application of the methodology to investigate inspection/repair strategies for reinforced concrete elements in flexure and shear is presented elsewhere [13-14].

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5.   ACKNOWLEDGMENT