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Structural aging issues and research

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ABSTRACT: As nuclear plants continue to operate incidence of degradation of structures, systems and components caused by aging becomes of more concern. Questions often arise when evaluation of the safety significance of aging degradation is considered. The Structural Aging Program addressed these questions through the development of guidelines and criteria for use in evaluating the remaining structural margin of aged concrete containments.

1. INTRODUCTION

As of June 1996, 110 nuclear reactor units are licensed and operating in the United States. The 110 containments consist of 38 steel, 31 reinforced concrete, and 41 prestressed concrete units, see Table 1. By the end of this decade, 63 of the 110 nuclear power plants in the U.S. will be more than 20 years old, with some nearing their 40-year operating license term. Some 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.

This paper describes and highlights the findings of a multiyear research program on concrete containments conducted by the Oak Ridge National Laboratory for the United States Nuclear Regulatory Commission (NRC). Aging issues and recommendations for future activities are also discussed.

CONTAINMENT TYPES				
PLANT	CONTAINMENT DESIGNATION	STEEL	REINFORCED CONCRETE	POST-TENSIONED CONCRETE
BWR	PRE-MARK	-	-	-
	MARK I	20	2	-
	MARK II	1	5	2
	MARK III	2	2	-
PWR	LARGE DRY	7	20	39
	ICE CONDENSER	8	2	-
TOTAL		38	31	41

Table 1. Operational U.S. Containments [NRC Information Digest, 1996].

2. STRUCTURAL AGING EXPERIENCES

As operating plants grow older, the NRC staff are seeing more aging-related structural problems such as the deterioration of concrete water intake structures at seawater locations. 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; leaching of concrete in tendon galleries; and low prestress forces [Ashar, et al, 1994].

Some of the degradation occurred early in the plant life and was corrected. But with the passage of time the experiences noted above have the potential to degrade strength and increase risk to public safety and health. Thus methodologies and criteria are needed to evaluate aging.

3. STRUCTURAL AGING PROGRAM

The need for evaluation methods and surveillance, inspection/testing, and maintenance to ensure continued safe operation of nuclear power plants has been the basis for work developed under the Structural Aging (SAG) Program. Guidelines and criteria for use in evaluating the remaining structural margins have been developed under the SAG program. These activities were conducted under three major technical task areas -- materials property data base, structural component assessment/repair technology, and reliability-based methodology for continued and future 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 was developed under this task. 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 and displaying information in a graphic format.

Two approaches were utilized to obtain the data and information contained in the data base-- open-literature information sources and testing prototypical samples. A total of 145 material data bases have been developed addressing concrete and steel reinforcing materials. A more detailed description of the data base and the files it contains is provided elsewhere [Oland and Naus, 1994].

It should be noted that before a material was considered suitable for entry into the Structural Materials Handbook, certain types of general and compositional information about the material had to be available so that a unique identifier (material code) could be established and its characteristics and features could be adequately represented and accurately reported. In addition, baseline properties or reference values had to be reported and at least one set of time- or environment-dependent data or values had to be available.

The quality of time and environment-dependent material properties ranged from extremely high to very low, depending on the information source, extent of reported data and values, and type of testing methods involved in the experimental investigation. In order to provide a meaningful way to compare the relative quality of one property to another, five quality levels were established. Each quality level was represented by a one-character letter designation that ranged from A (highest to E (lowest). Although the criteria for assessing the relative quality of data and values are somewhat subjective, an evaluation of each time and environment-dependent material property was performed and included in the handbook for reference and consideration.

3.2 *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 [Hookham, 1991]. 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 [Refai and Lim, 1991]. 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)[Snyder et al, 1992]. 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.

3.3 *Reliability-Based Methods for Condition Assessment*

The performance of a structure inservice is assessed by comparing its state of behavior to one of several limit states. When a structure or structural component becomes unfit for its intended purpose, it is said to have reached a limit state. In the reliability-based condition assessment methodology developed subsequently, structural performance in the presence of uncertainty is measured in terms of a limit state probability. Ultimate limit states relate to safety under extreme conditions. A concrete structure is considered to have failed when a load effect (e.g., axial force, moment, shear or some combination of these effects) to which it is subjected exceeds its available capacity at that time. Such an event should have a low probability of occurrence. Serviceability limit states relate to disruption of function under conditions of normal usage. Excessive deflections or crack widths under normal service loads are examples of serviceability limit states in concrete structures.

Aging and durability issues introduce the time factor into limit states design. One cannot deal with durability issues rationally without introducing the notion of design or service life [Somerville, 1986]. The limit state probability must be determined with respect to service life in order to be useful as a decision variable. The service life is defined as that period during which the structure is able to withstand all loads safely. A design service life (or maintenance interval) is that period during which the probability of the structure performing its intended functions is acceptable.

Time-dependent reliability analysis and service life predictions for reinforced concrete structures require time-dependent stochastic models of the structural strength. In concept, stochastic strength models can be derived from: (1) mathematical models describing the effects of the aging process resulting from service and environmental factors on steel and concrete materials and component geometry; (2) accelerated life testing; or (3) a combination of the two. At the current state of the art, these effects are often known qualitatively; however, quantitative models that describe material degradation processes often are empirical in nature [Clifton, 1991]. The service life determinations often require that these models by extrapolated outside the range of experimental data.

In NUREG/CR-6424, "Report on Aging of Reinforced Concrete Structure." primary degradation mechanisms and models for service life estimations are presented. Also, NUREG/CR-6424 gives several examples where the time-dependent reliability analysis concept is used.

4. AGING ISSUES

Issues identified related to age-degraded passive structures and components can be summarized as below.

(1) *The lack of requirements and programs for conducting inservice inspections.*

Lessons learned by the NRC staff while visiting 9 pilot NPPs for the implementation of the maintenance rule NUREG-1526 indicated that most licensees considered the monitoring of structures required by the rule to be a low priority. Some licensees assumed that many of their structures are inherently reliable without justification. The performance criteria for monitoring some structures were not predictive and did not include adequate examination/inspection of structures. For passive structures and components, the inspection programs in practice and the current

underlying state of knowledge is mixed.

(2) ***The lack of reliable inspection techniques especially for areas difficult to access or heavily reinforced:***

In the SAG program, it was pointed out that nondestructive evaluation techniques were found in large measure to be more qualitative than quantitative. Developments in non-destructive evaluation techniques are required with respect to two specific areas related to inspection of NPP structures. Specifically, they are (1) massive, heavily-reinforced concrete structures such as basemats, and (2) inaccessible regions.

(3) ***License renewal considerations:***

The final license renewal (10 CFR Part 54) rule of 1995 was clarified to indicate that "only long-lived passive structures and components are subject to an aging management review for license renewal." In addition, "the second and equally important principle of license renewal holds that the plant-specific current licensing basis (CLB) must be maintained during the renewal term in the same manner and to the same extent as during the original licensing term." In other words, the foundation of license renewal rests on the determination that currently operating plants were initially shown to have adequate levels of safety and this level has been enhanced through maintenance of the licensing bases, with appropriate adjustments to address new information from industry experience over the plant life. A license renewal applicant must demonstrate that effects of aging will be managed such that the intended functions of structures and components within the scope of license renewal will be maintained for the period of extended operation.

(4) ***Seismic responses and resistance of age-degraded structures and components:***

While the objective is to maintain the plant-specific CLB, the interim safety and regulatory consideration may require evaluation of degraded civil structures and containments subjected to seismic loads. The evaluation of seismic loading is important because the degraded structures are more vulnerable to the seismic loads which affect the entire structure or components. The aging or degradation may affect dynamic properties, structural response, resistance or capacity, failure modes, and locations of failure initiation. To this end, the program should build upon past and current NRC research programs and address issues such as: the cause and mechanisms of age-related degradation, inspection techniques and how to implement them, when, where and how correction actions such as repairs should be conducted, the assessment (either by test, analysis, or a combination of both) of age-degraded material properties, and the effects of all these on the seismic margins [Shao, et al, 1996].

5. CONCLUSIONS AND RECOMMENDATIONS

This research has led to the following conclusions:

1. The performance of the reinforced concrete structures in NPPs has been good. However, as these structures aged, incidences of degradation due to environmental stressor effects are likely to increase.

2. Techniques for detecting the effects of environmental stressors are sufficiently developed to provide qualitative data.

3. Methods for conducting condition assessments of reinforced concrete structures are fairly well established and generally start with a visual examination. To be of most use, the condition assessments should be conducted at regular intervals.

4. Techniques for repair of concrete structures are well established and when properly selected and applied are effective. At present, no codes and standards are available for repair of reinforced concrete structures, although some are being developed.

5. A reliability-based methodology has been developed that can be used to facilitate quantitative assessments of current and future structural reliability and performance of reinforced concrete structures in NPPs.

This research has led to the following recommendations:

- Review guidelines and acceptance standards need to be established.
- Better Non-destructive examination techniques are needed, especially in the software area.
- The inspection/detection of aging occurrences in non-accessible areas needs to addressed.
- Causes for the loss of prestress needs to be examined in more detail.
- Seismic Performance of a degraded or aged structure needs to be evaluated.

DISCLAIMER

The findings and opinions expressed in this paper are those of the authors and do not reflect the views of the USNRC or Oak Ridge National Laboratory.

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