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Long-term reliability evaluation of nuclear containments with tendon force degradation

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HIGHLIGHTS

- A probabilistic model on long-term degradation of tendon force is developed.
- By using the model, we performed reliability evaluation of nuclear containment.
- The analysis is also performed for the case with the strict maintenance programme.
- We showed how to satisfy the target safety in the containments facing life extension.

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ABSTRACT

The long-term reliability of nuclear containment is important for operating nuclear power plants. In particular, long-term reliability should be clarified when the service life of nuclear containment is being extended. This study focuses not only on determining the reliability of nuclear containment but also presenting the reliability improvement by strengthening the containment itself or by running a strict maintenance programme. The degradation characteristics of tendon force are estimated from the data recorded during in-service inspection of containments. A reliability analysis is conducted for a limit state of through-wall cracking, which is conservative, but most crucial limit state. The results of this analysis indicate that reliability is the lowest at 3/4 height of the containment wall. Therefore, this location is the most vulnerable for the specific limit state considered in this analysis. Furthermore, changes in structural reliability owing to an increase in the number of inspecting tendons are analysed for verifying the effect of the maintenance program's intensity on expected containment reliability. In the last part of this study, an example of obtaining target reliability of nuclear containment by strengthening its structural resistance is presented. A case study is conducted for exemplifying the effect of strengthening work on containment reliability, especially during extended service life.

1. Introduction

Nuclear containments not only act as important safety barriers between nuclear reactors and the surrounding environment but also protect the reactor from external accidents. Therefore, the primary aim of nuclear containment design is to ensure tightness against overpressure, which may occur owing to a reactor accident. The most common type of containment is a concrete structure prestressed with hoop-shaped horizontal tendons and inverted U-shaped vertical tendons. These tendons are designed to keep the containment concrete in a compressed state in the event of a design-based accident for avoiding tensile failure of the concrete. Thus, degradation of the prestressing system directly affects the integrity and tightness of the nuclear containment. Mechanisms such as creep and shrinkage in the concrete and relaxation in the tendons gradually deteriorate the prestressing system's performance (Anderson, 2005a). These mechanisms are influenced by various parameters and are difficult to predict. In particular, attempts have been made for extending the service life of nuclear power plants because decommissioning a nuclear reactor is difficult. Therefore, it is crucial to evaluate the long-term reliability of nuclear containments, considering prestressing system degradation. Additionally, a degradation model for prestressing systems should be formulated for obtaining reliable analytical results.

This study focuses on ensuring the reliability of nuclear containments while considering the gradual loss of tendon force. The tendons in nuclear containments are checked regularly during in-service inspections (ISIs) to ensure that prestressing system's performance is satisfactory. The gradual loss of containment tendon force is estimated from ISI data on nuclear containments in Korea, which are prestressed using unbounded tendons (Hahm

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Table 1
Probabilistic characteristics of tendon force evaluated from ISI data.

Characteristic value	Time after pressure initial structural integrity test (ISIT) [Number of ISI data/number of inspected tendons]					
	0-year	1-year [9/78]	5-year [8/70]	10-year [2/9]	15-year [2/6]	20-year [2/12]
Tendon force at inspected year/initial tendon force	1.000	0.937	0.918	0.933	0.892	0.090
C.O.V.	0.033	0.033	0.034	0.030	0.025	0.024

et al., 2011). Based on this data, in this study, a degradation model of prestressing system applied to Korean nuclear containments (for those having unbounded or ungrouted tendons) was developed. Using this model, reliability analyses were conducted for estimating the annual reliability of a typical nuclear containment. For satisfying the service life extension plan of the Korean government, 60-year reliability of the nuclear containment was considered. Additionally, this study carried out a reliability analysis of the performance-improved nuclear containment. Although the nuclear containment performance can be enhanced using several methods, two alternatives are considered in this study: (1) performing a strict inspection and (2) strengthening the prestressing system of a nuclear containment.

2. Gradual loss of tendon force in nuclear containments

Similar to other concrete structures, prestressed containments undergo long-term degradation mainly because of the creeping, shrinkage and relaxation of tendons. For avoiding unexpected tendon force degradation in a nuclear containment, tendons are inspected thoroughly during an ISI. ISIs are performed according to Regulatory Guide 1.35.1 (USNRC, 1990). This guide prescribes the methodology for inspecting concrete containments with unbounded tendons. It stipulates that the ISI should be performed at 1, 3, and 5 years after a structural integrity test and at 5-year intervals thereafter. Tendon force is measured by the lift-off test. This test measures tendon force by lifting an anchor head using a hydraulic jack, and the result is contingent on the movement of the anchor head (Lundqvist and Nilsson, 2011). Measurements are performed for both hoop- and meridional-directional tendons. Nuclear containments have numerous tendons; therefore, only a few parts can be checked during each inspection. The guide suggests that 4% of the randomly selected tendons (minimum of 4 and maximum of 10 tendons) should be tested during the 1-, 3-, and 5-year inspections. After 10 years, the number of tendons to be inspected is reduced to a minimum of 3 and a maximum of 5 (2% of each of the directional tendons). A strand of wires in some of the selected tendons is to be removed and checked over its entire length to inspect for corrosion or other types of material degradation.

In Korea, tendon force data measured during ISIs have been collected since 1978, when the Kori nuclear power plant began generating power commercially. This study used 23 ISI datasets recorded at 12 Korea-based nuclear containments. The measured containments are from several units in the Kori, Yonggwang, and Ulchin power plants, each having three buttresses and prestressed by unbonded tendons. These data include the tendon forces measured from a year after the commencement of operation until the 20th year of operation. However, interpretation of the recorded data is not obvious. Difficulties arise from both uncertainties in the measurement process (i.e., reading accurate tendon force during lift-off tests) and external environmental conditions, which varied across ISIs (Anderson, 2005a). Therefore, the measured loss of force does not always represent all tendons in a containment (Watanabe et al., 2000). Additionally, this study confirmed that the expected tendon force in each service year does not decrease monotonically; however, a unilateral decrease will be indicated if all tendons are considered. Table 1 lists the average values of tendon force evaluated from ISI data.

In this study, the measured data was fitted to a curve such that the tendon force decreased monotonically. Assuming no loss in tendon force in the 0th year, the expected tendon forces from the 1st year to the 20th year were curve-fitted logarithmically (Anderson, 2005b), as shown in Fig. 1(a). For comparison, the tendon force data for Swedish containments (three containments prestressed using unbonded tendons, 13 ISI data) are shown in Fig. 1(b) (Anderson, 2005b). From these figures, it can be seen that data measured in two countries show similar degradation characteristics.

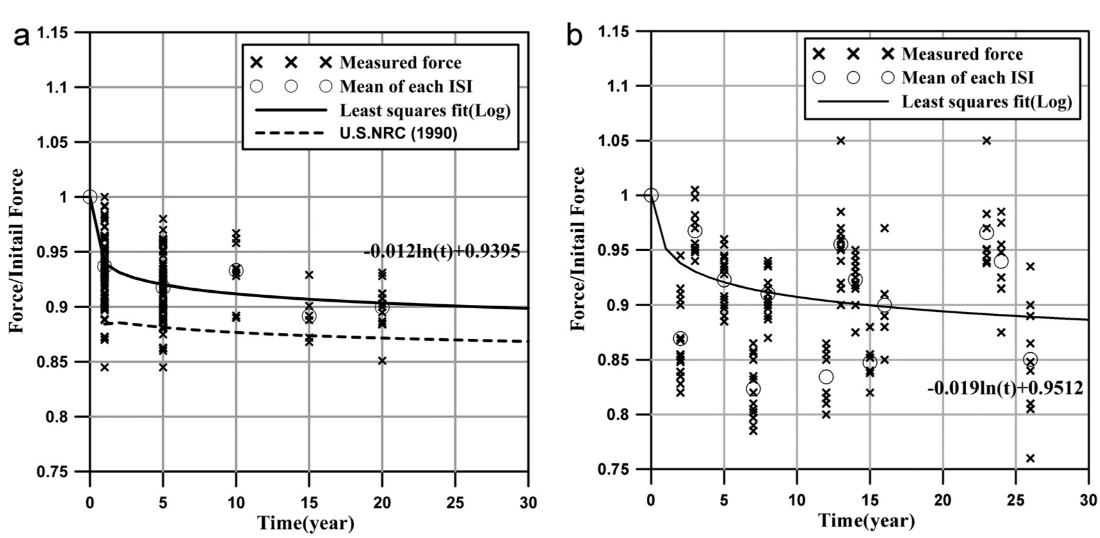

Fig. 1. Loss of tendon force measured from ISI data: (a) Korean nuclear containments, (b) Swedish nuclear containments (Anderson, 2005b).