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Probabilistic finite element investigation of prestressing loss in nuclear containment wall segments

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HIGHLIGHTS

- Probabilistic finite element framework for assessing concrete strain distribution.
- Investigation of prestressing loss based on concrete strain distribution.
- Application to 3D nuclear containment wall segments.
- Use of ABAQUS with python programing for Monte Carlo simulation.

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ABSTRACT

The main function of the concrete containment structures is to prevent radioactive leakage to the environment in case of a loss of coolant accident (LOCA). The Canadian Standard CSA N287.6 (2011) proposes periodic inspections, i.e., pressure testing, in order to assess the strength and design criteria of the containment (proof test) and the leak tightness of the containment boundary (leakage rate test). During these tests, the concrete strains are measured and are expected to have a distribution due to several uncertainties. Therefore, this study aims to propose a probabilistic finite element analysis framework. Then, investigates the relationship between the concrete strains and the prestressing loss, in order to examine the possibility of estimating the average prestressing loss during pressure testing inspections. The results indicate that the concrete strain measurements during the leakage rate test may provide information with respect to the prestressing loss of the bonded system. In addition, the demonstrated framework can be further used for the probabilistic finite element analysis of real scale containments.

1. Introduction

Nuclear power plants (NPPs) play a major role for the global energy supplies, while in the province of Ontario (Canada) 50% of the electricity is generated by NPPs (Mirhosseini et al., 2014). The CANDU (CANada Deuterium Uranium) nuclear reactors are housed by the Gentilly-2 type secondary containment structures (Elwi and Murray, 1980). This containment structure is circular and consists of a concrete base, a cylindrical perimeter wall, a ring beam and a dome (Simmonds et al., 1979), while its basic dimensions are shown in Fig. 1 (Murray and Epstein, 1976a; Murray et al., 1978). The main function of the containment is to prevent any radioactive leakage to the environment, if a serious failure occurs to the process system (Pandey, 1997). Thus, the containment is designed to withstand the loss of coolant accident (LOCA), where both temperature and pressure are increased inside the containment due to steam release, leading to increased tensile stresses in the concrete walls (Lundqvist and Nilsson, 2011). Therefore, the containment is made of prestressed concrete, either using bonded or unbonded tendons (Anderson et al., 2008), in order to ensure integrity and tightness in case of an accident (Anderson, 2005). However, the reliability of the containment is significantly affected by the degradation of the tendon force (Kim et al., 2013). Thus, the containment integrity is vulnerable to prestressing losses due to actual material deformations, i.e., creep and shrinkage of concrete and relaxation of tendons, and due to corrosion of the tendons (Pandey, 1997).

For the evaluation of the bonded prestressing system, Appendix A of the CSA N287.7 (2008) provides three types of tests on both bonded and unbonded test beams, namely flexural tests, lift-off tests and a destructive test, while a more detailed review on the above inspection procedures can be found in literature (Pandey, 1996a). In general, flexural tests involve testing of at least 12

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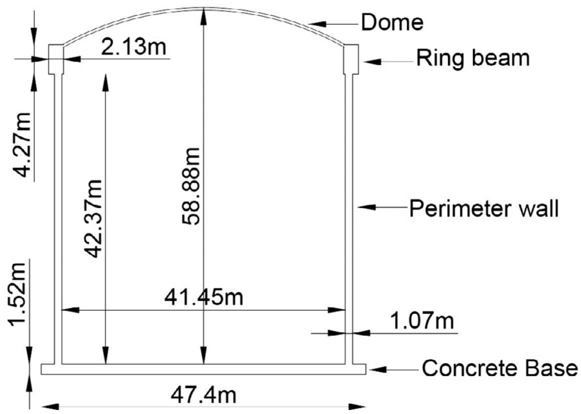

Fig. 1. Sketch of the prototype containment structure.

bonded beams to evaluate the concrete cracking but do not quantify the prestress losses. Lift-off tests require the testing of at least 4 unbonded beams to measure the prestressing loss at the end of the tendon but cannot detect corrosion, since the tendons are permanently greased, and cannot evaluate the prestressing loss of bonded systems. Destructive tests use a sample from the previous flexural test bonded beam to detect corrosion through visual examination of the tendon. Thus, a direct assessment of the prestressing loss of the bonded tendons it is not possible. For containments with unbonded tendons, the lift-off technique is general used during regular in-service inspections, in order to assess the prestressing loss at the end of the tendons (Anderson et al., 2008), where it was found that the average prestressing loss along the tendon is smaller compared to the measured prestressing loss in the end of the tendon (Anderson et al., 2005).

On the other hand, Clause 6 and 7 of the CSA N287.6 (2011) provide the proof test and the leakage rate test requirements, respectively. These are non-destructive techniques, which involve the pressurizing of an existing containment structure. This predefined pressure is equal to 1.15 times the design pressure for the proof test and equal to the design pressure for the leakage rate test (CSA N287.6-11). Under this load the stress–strain is measured in order to be assessed the strength and design criteria of the containment (proof test) and the leak tightness of the containment boundary (leakage rate test), where a more detailed review can be found in literature (Pandey, 1996b). Concrete wall strains have been measured during pressure tests (using SOFO fiber-optic gauges), where these measurements were in general consistent (Hessheimer et al., 2003). However, the measured strains during a pressure test will still have a distribution due to uncertainties, where this distribution is expected to change due to prestressing losses. Therefore, there is a need to investigate this change in the distribution of the concrete strain with respect to the prestressing loss in tendons. Thus, this study first proposes an easy to implement probabilistic finite element analysis framework. Then, examines if concrete strain distribution changes can provide information with respect to the prestressing loss in bonded prestressing systems.

2. Wall specimens

2.1. Test description

The selected wall specimens (Fig. 2) are part of a research program at the University of Alberta, which was sponsored by the Atomic Energy Control Board of Canada. The main objective of the research program was to investigate the overpressure effect on the Gentilly-2 type secondary containment structures (Elwi and Murray, 1980). The first report of the series is divided in two volumes (Murray and Epstein, 1976a, 1976b) and provides the description of the prototype containment structure together with the main objectives of the research, followed by a second report (Murray et al., 1977) and a third report (Murray et al., 1978).

A series of tests were conducted on reinforced concrete wall segments (specimens 4 and 7) and on prestressed concrete wall segments (specimens 1–3, 5 to 6 and 8–14), leading to 14 tested specimens in total. All tested specimens except specimen 7, have dimensions which correspond to a 1:4 scale of the prototype containment. Thus, each specimen has a width of 266.7 mm, i.e., almost one-fourth of the wall thickness, and a tendon duct size almost one-fourth the size of ducts used in the prototype. Specimen 7 was considered in order to be evaluated the scale effects. Thus, the thickness of specimen 7 was increased 1.5 times, i.e., 400.05 mm, which corresponds to a 1:3 scale of the prototype containment, while its reinforcement size, reinforcement spacing and concrete cover was also increased proportionally. The lateral dimensions were chosen as three times the wall thickness ($3 \times 266.7 = 800.1$ mm), due to laboratory restrictions regarding the total lateral applied force and due to crack observations regarding allowing the formation of more than one through the wall crack. The technical report No. 81 (Simmonds et al., 1979) provides a detailed description and the test results of the specimens 1–9 and 11–13, while the technical report No. 80 (Rizkalla et al., 1979) provides a detailed description and the test results of the two additional specimens involving air leakage, i.e., specimens 10 and 14.

Specimens 1 and 2 are selected in this study, which represent the prestressing conditions and loading of the cylindrical wall of

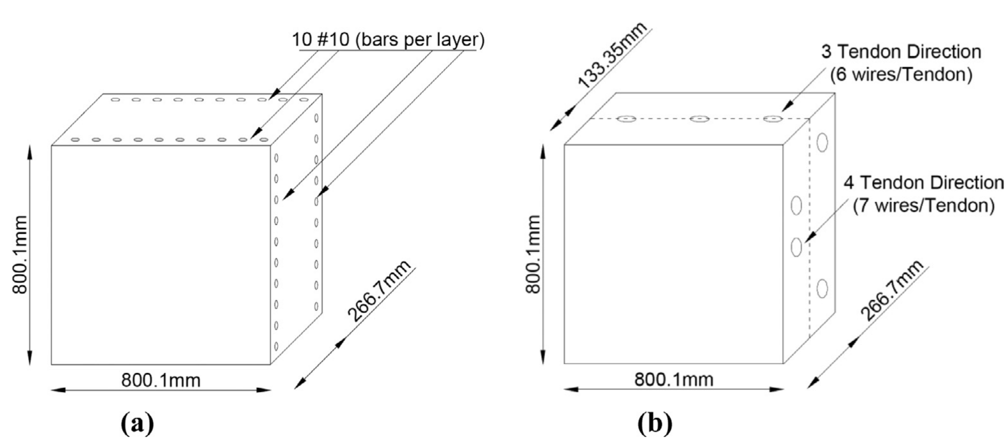

Fig. 2. Sketch of the wall specimen with: (a) non-prestressed reinforcement; (b) prestressed reinforcement (tendon orientation in the containment structure).