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Leakage Rate of Containment Structure Based on Damage Using Abaqus CDP Model

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1. Introduction

During the Fukushima nuclear accident, the containment structure, which serves as the final barrier to prevent the release of radioactive materials, was damaged. This resulted in the release of a large amount of radioactive material, causing damage to the surrounding area. As a result, it has become crucial to accurately assess the ultimate pressure capacity (UPC) of the containment structure and the amount of radioactive material released during severe accidents.

Sandia National Laboratories (SNL) conducted leak tests and limit state tests using a 1:4 scale model of a prestressed concrete containment vessel to study severe accident loads, failure mechanisms, and leakage rate [1]. The containment structure is highly complex, and due to the need for extremely large failure loads, limited experimental and analytical studies have been conducted. Thus, RG 1.216 defines the UPC of the containment structure based on SNL experimental results, using the strain of the free-field tendon, liner, and rebar [2]. However, due to the complexity of considering both the structure and fluids, there has been limited research or guidance on methods to calculate the actual leakage of radioactive materials. Thus, in this study, an ultimate pressure analysis of the APR1400 containment structure is performed using the Abaqus finite element analysis (FEA) program, and the leakage from the containment structure is calculated using a concrete damage index.

2. Methods

In this chapter, the 3D modeling of the APR1400 containment structure and the damage-based leakage estimation method are explained.

2.1 APR1400 3D modeling

APR1400 containment structure consists of a steel liner plate, rebar, prestressed tendons, and concrete (Fig. 1). In accordance with RG 1.216, six large penetrations, including two airlocks and one equipment hatch (E/H), were considered. The concrete element was modeled using a solid element (C3D8), and the concrete damage plasticity (CDP) material model in Abaqus was applied to simulate softening and gradual deterioration. The liner plate was modeled using a shell element (S4R), while the rebar and tendon were modeled using a truss element (T3D2). The stress-strain curve of the steel material was modeled as bi-linear. The liner plate and concrete inner wall elements were modeled to share nodes and be fully bonded, while the rebars and tendons were constrained to the concrete elements using the embedded feature.

Initially, gravity loads and prestressing forces from the tendons were applied. Then, the pressure load was uniformly applied to the inner walls and gradually increased. The analysis was terminated at 2.8 times the design internal pressure of the APR1400 (P_d = 60 psi), reaching 168 psi.

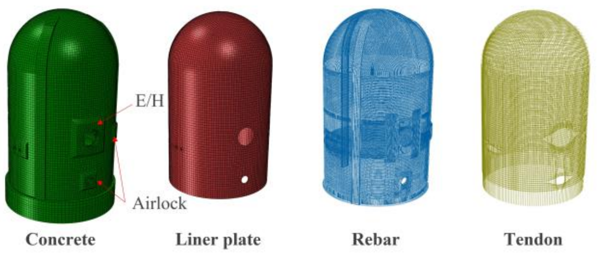

Fig. 1. Components of APR1400 3D modeling

2.2 Damage-based leakage

The permeability of concrete increases as it sustains damage due to external forces. Bary (1996) and Picandet et al. (2001) conducted tensile and compression tests on concrete, respectively, and measured permeability in relation to damage [3, 4]. Jason et al. (2007) compared previously proposed damage-permeability relationships with these experimental results [5]. Among them, the equation proposed by Souley et al. (2001), as shown in Eq. (1), exhibited the best agreement with the experimental data and was adopted in this study.

$$K = K_0 10^{C(D-D_0)} \quad (1)$$

where K_0 is the initial permeability of concrete (1.55×10^{-15} in^2 in this study) and D is damage index. C and D_0 are calibration parameters, with values of 8.67 and 0.035, respectively.

The damage of each finite element is calculated into permeability using Eq. (1). Then, the leakage rate can be computed using Darcy's law for compressible fluids as follows:

$$Q = \frac{KA}{\mu L}\left(\frac{P_i^2 - P_o^{\,2}}{2P_0}\right) \qquad (2)$$

where A and L are the cross-sectional area and length of the fluid path, respectively, and μ is the dynamic viscosity of air. P_i and P_o represent the internal and outer pressures, respectively, while P_0 is the pressure at which the volume flow rate is determined. The leakage rate of interconnected finite elements can be calculated by combining their permeability, length, and area coefficients in series or parallel.

The damage of the containment structure is closely related to the strain and progresses in the radial direction of the cylindrical structure. This indicates the direction of crack formation, and it is assumed that the leakage flows only in the radial direction. Additionally, the roof, concrete base, and buttress zones were not damaged, so leakage was neglected in these zones.

3. Results

3.1 Leakage rate

Figure 2 shows the leakage rate according to internal pressure and compares it with the SNL test results. Although the target containment structures in the Abaqus analysis (APR1400) and the SNL test (Ohi Unit 3) differ, the thickness and reinforcement ratio of their structural elements (concrete, liner plate, rebar, tendon) are very similar. Additionally, the SNL test was only study on leakage rate of prestressed concrete containment relative to internal pressure, making it the basis for comparison.

The total leakage rate is influenced by the initial permeability of the concrete, which varies depending on the type and condition of the concrete. The initial permeability of the concrete was adjusted so that the leakage rate of the APR1400 would be 0.1% volume/day at the design internal pressure (P_d). In SNL test, the containment structure maintained its structural integrity with almost no leakage up to 2P_d. However, at 2.5P_d, a leakage rate of 1.63% volume/day was observed, and it rapidly increased as cracks developed. The leakage rate of APR1400, calculated from ABAQUS results, showed a similar trend to SNL test. At 2.0P_d, the leakage rate was 0.3% volume/day, indicating minimal leakage. However, at 2.3P_d and 2.5P_d, the leakage increased rapidly to 0.5 and 54.23% volume/day, respectively. While there is no established criterion for evaluating leakage magnitude, the current APR1400 is calculated to maintain a leakage rate of 0.5% volume/day up to approximately 2.0 to 2.3P_d.

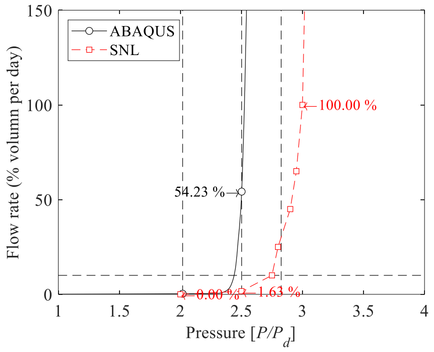

Fig. 2. Leakage rate according to internal pressure

3.2 Vulnerable area

The areas around the penetrations are more reinforced, with thicker concrete and a higher concentration of rebar and tendons. However, in the discontinuous zone adjacent to these reinforced areas, stress concentration occurs, leading to significant damage. Figure 3 shows the leakage rate at 2.3P_d, where leakage begins to increase, according to different locations. Significant damage and leakage are concentrated at the discontinuous zone. Particularly, significant leakage occurred at the upper and lower parts of the E/H, highlighting the importance of evaluating the structural integrity of this area.

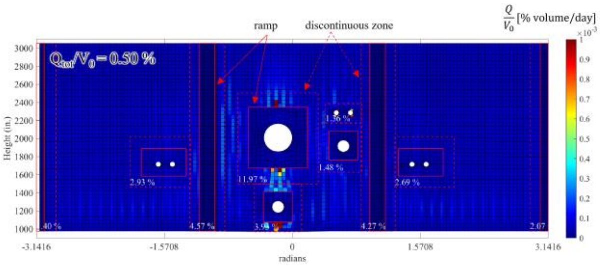

Fig. 3. Leakage rate at different locations at 2.3P_d

4. Conclusions

In this study, the finite element analysis of the containment structure under internal pressure was performed using the Abaqus CDP model, and the damage was calculated. Then, leakage rate was calculated using Darcy's law. The leakage results showed similar trend to the SNL test results. Particularly, there was minimal leakage up to 2.0P_d, with a significant increase after 2.3P_d. Leakage predominantly occurred at locations with stress concentrations, such as the E/H. These locations should be considered vulnerable areas for leakage and need to be accounted for in the design process.

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