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Estimation on Concrete Cracks of Containment Structures under Internal Pressure

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1. Introduction

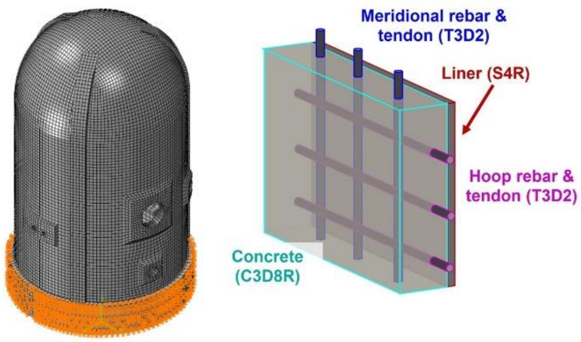
In tradition, assessment of internal pressure capacity is conducted considering the allowable strain limit [1], while the limit states of containment structures are defined considering the amount of leakage. To fill this gap, the amount of leakage should be estimated considering the damage status of the containment structures. This study focuses on estimation of concrete cracks, as a first step to estimate the amount of leakage in containment structures under internal pressure.

2. Finite element model

The target structure of this study is the APR-1400 nuclear power plant. The finite element (FE) model was developed using ABAQUS, as shown in Fig. 1 (a).

2.1. Element discretization

Fig. 1(b) depicts the composition and element types of the ABAQUS FE model. The concrete was modeled using an 8-node solid element (C3D8R). Rebars and tendons were modeled using 2-node truss elements (T3D2) and incorporated into concrete elements using an 'embedded element' option. Additionally, the liner plate was modeled using a surface element (S4R).

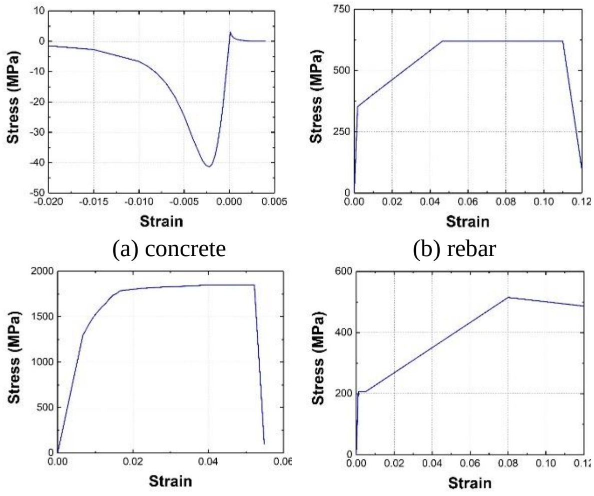


(a) Entire mesh (b) Element discretization

Fig. 1. Finite element model of APR-1400 containment structure

2.2. Material constitutive model

In this study, the concrete damaged plasticity model in ABAQUS was combined with Alfarah et al. (2017) [2] and was utilized to simulate the uniaxial behavior of concrete. The uniaxial behavior of rebars was defined considering Mansour and Hsu (2005) [3]. The uniaxial behaviors for prestressing tendons and liner plates were developed in accordance with Hahm et al. (2014) [4]. Fig. 2 shows the uniaxial stress-strain relation of these four materials.



(a) concrete (b) rebar

(c) tendon (d) Liner

Fig. 2. Uniaxial stress-strain relation of materials

3. Estimation of Concrete Cracks

3.1. Crack estimation equation

Crack estimation in this study is based on Rizkalla et al. (1984) [5]. According to Rizkalla et al. (1984) [5], the width of through-thickness cracks in prestressed concrete can be calculated based on stress distribution as follows:

(1) $w_{av} = \varepsilon_{s2} l_o + \varepsilon_m l_t$
(2) $\varepsilon_m = \varepsilon_{s2} \left| 1 - \left(\frac{f_{s2,cr}}{f_{s2}}\right)^2 \right|$
(3) $l_o = \frac{f_{s2,cr}}{6500\ psi} d_b$
(4) $l_t = s - l_o$

Where,
w_{av} is the average width of through-thickness cracks, ε_{s2} is the average strain of rebar or tendon in cracked section, ε_m is the average strain of rebar or tendon in spacing, l_o is the lost-bond length, l_t is the bond transfer length, f_{s2} is the stress of rebar or tendon in cracked section, and $f_{s2,cr}$ is the stress of rebar or tendon at crack initiation.

3.2. Pressure Analysis and investigation on rebar stress

In this study, static pressure analysis was conducted assigning pressure load to the inner side of the wall and dome. The containment structure fails at 0.964 MPa, when considering the allowable liner strain suggested in RG 1.216 (2010) [1]. Additionally, the stresses of steel elements are investigated considering the behavior of concrete elements nearby them, as shown in Table 1 and Fig. 3. In conclusion, the $f_{s2,cr}$ of median model is expected to be approximately 150 MPa.

Table 1. Average stress of steel in concrete group

Concrete group number	1st occurrence of plastic strain in concrete group	Average principal plastic strain of group = 0.0012
374	34.1 MPa	128.3 MPa
6	22.1 MPa	123.4 MPa
3721	30.1 MPa	137 MPa
836	29.6 MPa	150 MPa

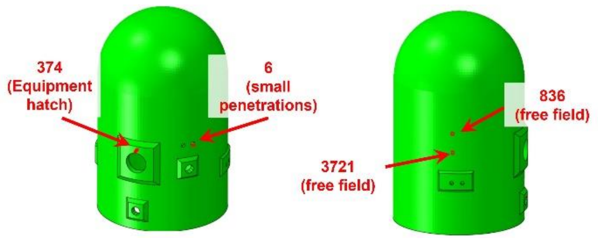


Fig. 3. Location of concrete group suggested in Table 1

3.3. Estimation on Crack Width

Based on the investigations described in section 3.2, crack widths of containment structures under internal pressure were estimated. Fig. 4. depicts concrete groups simplified into squares. The x-axis indicates angle, while the y-axis indicates height from the basemat. Red lines illustrate cracks in concrete groups. When the containment structure reaches ultimate pressure (0.964 MPa), the average crack width in cracked concrete groups is expected to be approximately 0.236 mm.

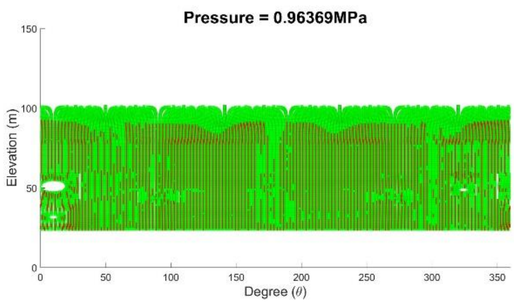


Fig. 4. Crack distribution of containment structure under ultimate pressure (0.964 MPa)

5. Conclusions

Based on the equations suggested by Rizkalla (1984) [5], the average crack width of containment structures under ultimate pressure (0.964 MPa) is estimated. When considering cracked sections only, the average crack width is expected to be 0.236 mm. Since Rizkalla (1984) [5] reported certain amounts of leakage after the average crack width exceeded 0.06 mm, this crack width is enough to induce leakage in containment structures. In future studies, detailed work will be conducted to estimate the sequence of crack propagation and amount of leakage.

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