Analysis of Prestressed Concrete Containment Vessel subjected to Internal Pressure

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1. Introduction

An accurate prediction on the crack initiation and overall failure mechanism of prestressed concrete containment vessel (PCCV) subjected to internal pressure has a very significant importance in nuclear industry since the PCCV is considered as the final safety barrier of nuclear power plant (NPP). Several experiments [1] related to this safety subject have been done in Korea and also a subsequent attempt [2-4] has been made to develop the simulation code NUCAS (Nuclear Containment Analysis System). Although some research results related to this subject has been provided in open literatures, we revisit this safety issue here to provide other views and remind all of us again of the importance of safety of the PCCV. Mainly, our work focuses on the cracking criteria and tension stiffening model for the analysis of the PCCV.

2. Material Models

In this section, material models used in the safety assessment of the PCCV are described. In particular, the cracking criteria and tension stiffening model are explained.

2.1 Cracking Criteria

The mechanical properties of concrete can abruptly change after cracking of concrete. To accomplish an accurate simulation of such a physical behavior, concrete failure envelopes are carefully prepared by two models: a standard plasticity model based on Drucker-Prager criterion [5] for concrete under tension-tension stress field and the Niwa expression [6] for tension-compression stress field.

For tension-tension stress field, the following Drucker-Prager criterion is used as

$$f(\sigma_1,\sigma_2)=\begin{bmatrix}\alpha(\sigma_1+\sigma_2)+\ \dots\\ \dots\ \beta\{(\sigma_1^2+\sigma_2^2)-(\sigma_1\sigma_2)\}\end{bmatrix}^{1/2}=\sigma_0 \quad (1)$$

In this study, two parameters $\alpha = 0.492\sigma_0$ and $\beta = 0.508$ is obtained from recent biaxial concrete panel test results [7] using the standard procedure [8].

For tension-compression stress field, Niwa model is adopted as

$$\left(\frac{\sigma_1}{f_t}\right)^{3/2}+\left(\frac{\sigma_2}{f_c'}\right)=1 \quad (2)$$

where f_c' and f_t are compressive and tensile strengths.

The original failure envelope proposed by Niwa is rather conservative which means that crack is supposed to occur in higher stress level than the result of biaxial panel test. So we modify the failure envelope with the different exponent value. Therefore, the overall failure envelop for concrete crack can be illustrated as in Fig. 1.

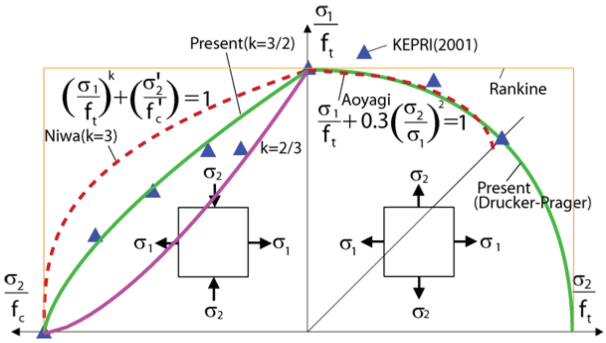

Fig. 1. Failure envelope under biaxial stress

2.2 Tension stiffening model

After the occurrence of crack in concrete, the crack will generally develop and propagate in the direction perpendicular to the major direction of the principal strain and then concrete is considered as anisotropic material. However, concrete is still partially capable of resisting tensile forces due to the bond between concrete and reinforcing steel, even after crack. From this point of view, we do not assume the zero strength for cracked concrete but there is some strength remained in cracked concrete as follows (see Fig. 2)

$$\sigma_t = f_t\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^c \quad (3)$$

where σ_t is tensile stress, ε_t is the current strain level, ε_{cr} is cracking strain, f_t is the tensile strength of concrete and c is the exponent value. Generally the values of the exponent c are $c = 0.2$, $c = 0.4$ and $c = 0.6$ for welded metal, deformed steel and round steel respectively [3].

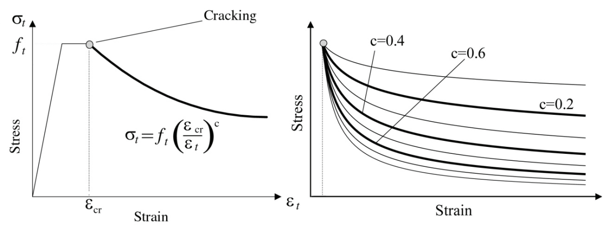

Fig. 2. Tension stiffening: (left) material model and (right) the effect of exponent c.

3. FE Technologies

A 8-node Reissenr-Mindlin shell element as shown in Fig. 3 is used to analyze the PCCV.

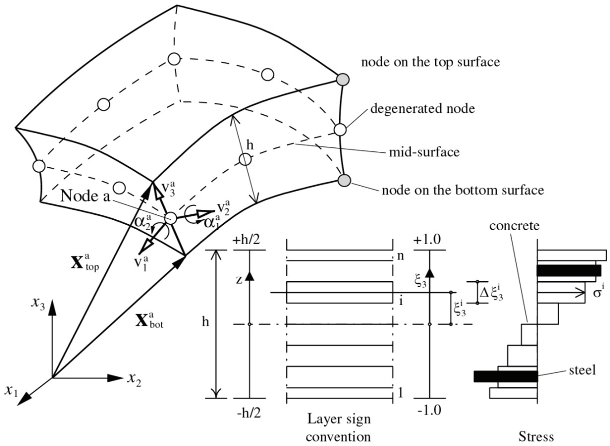

Fig. 3. 8-node degenerated shell element with layerwise concept

In this study, a layerwise concept [8] is introduced and so reinforcing steel can be placed in certain layer. Anisotropic material characteristic in the thickness direction is then considered by taking numerical integration through the thickness direction. The stress values of each layer are computed at the mid-layer and are assumed to be constant over the thickness of each layer. The stresses distribution of each layer can be illustrated as shown in Fig. 3.

4. FE Analysis of PCCV

The FE nonlinear analysis is carried out to provide the ultimate pressure capacity of the PCCV which is considered as shell structure if the foundation slab is treated as fixed boundary conditions. In addition, it can be also considered as axi-symmetric shell if we neglect three openings. The 240 8-node degenerated shell FEs are used to discretize the PCCV. A quarter of the PCCV is used in the FE analysis. The steel ratio $\rho_s = 0.02$ is used and self-weight is not considered here and the pre-stressing force is transformed into external uniform load ($q_e = 5.414 kgf/cm^2$) which is applied into the outer wall of the PCCV. See Table 1 for material properties.

Table 1. The properties of concrete and steel bar (kg/cm^2)

Steel bar		Concrete			
E_s	f_y	E_c	f_c'	f_t	υ_c
2039432	4218.1	316088	387.5	31.3	0.17

As shown in Fig. 4, the PCCV is deformed into a bell shape after the pre-stressing force is applied and then with subsequent internal pressure the shape of the PCCV returns to the initial shape at (b). With further increase of internal pressure inside of the PCCV, the shape of the PCCV is changed to the shape illustrated in Fig. 4(c). Overall numerical analysis result has a good agreement with reference solution [2]. Note that the initial crack occurs at (d) in Fig. 4 with the internal pressure values of $7.6 kgf/cm^2$.

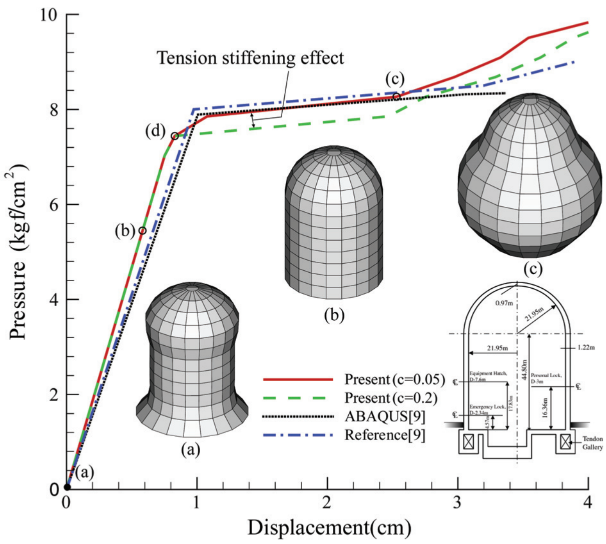

Fig. 4. Load-displacement path and deformed shapes of PCCV

5. Conclusions

The FE nonlinear analysis is carried out to provide the ultimate pressure capacity of the PCCV. The cracking criteria are prepared by using recent experiment results from plain concrete panel tests. It is then embedded in the simulation code ISADO-RC for the analysis. From numerical results, it is found to be that the present model is simple but can effectively predict overall failure mode of the PCCV. The present solution is provided as a benchmark test for FE analysis of the PCCV.

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