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Structural Integrity Evaluation of Kori-1 NPP Steel Containment for the Replacement of Steam Generator

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ABSTRACT

An analysis to determine the ultimate load of cylindrical steel shell with opening was performed. Stress concentration and second order deformation due to crane load was investigated through finite element analysis considering inelastic large deformation. It was verified that the current approximation analysis using combined elastic buckling criteria gives conservative results. The result of finite element analysis has shown that the structure follows elastic load-deflection behavior under the given crane load condition with safety factor of 10.3. The result of this study will give useful information for the replacement of the steam generator of a nuclear power plant.

1. Background and Objectives

In the field of electric power generation, an importance of nuclear power has been increased because of its large portion of electric facilities in Korea. Recently, extension of lifetime in the field of maintenance of the nuclear power plants has been main concern from economical point of view.

Replacement of steam generator is a main object determining the lifetime of containment vessel. The containment vessel consists of a 32m dia.×44.5m height cylindrical shell with thickness of 36.5mm and a spherical cap with thickness of 19mm. In order to upgrade the steam generator to be safer and more stable, KEPCO planned the Kori-1 SGR project. For accommodating the steam generator replacement, an about 7m×7m opening hole was made temporarily as shown in Fig. 1 and filled back after replacement. A built-in polar crane was be used for lifting and transporting the steam generators for the replacement.

The primary concern in the Kori-1 SGR(Steam Generator Replacement) project[1,3] was to investigate the stress distribution around the opening hole resulting from the crane operation during the period of replacement of steam generators.

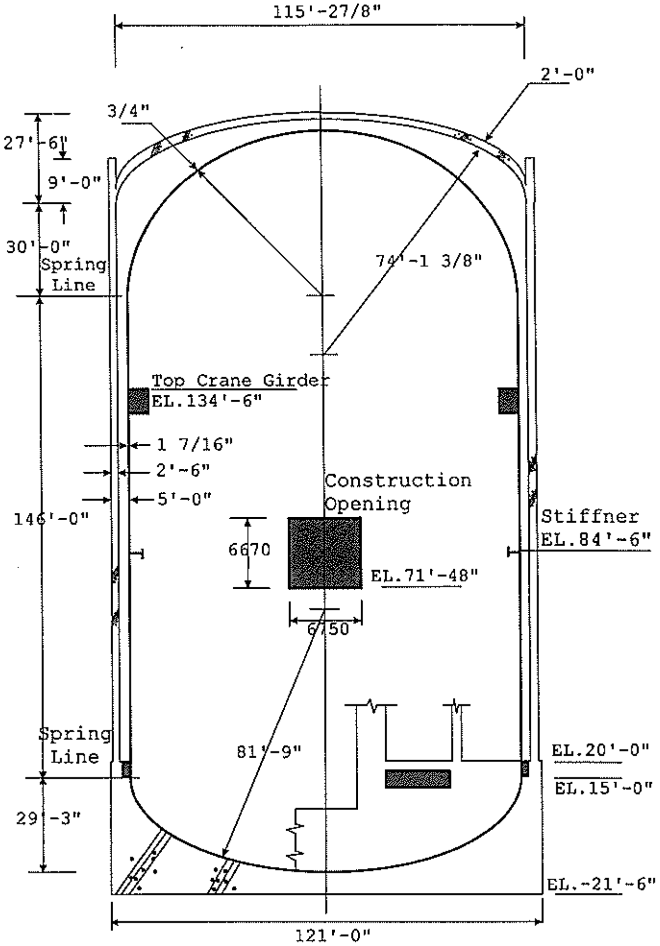


Fig. 1 Containment Vessel Cross Section for Kori-1 SGR Project

The stress resultants from the SAP90 finite element analysis were put into the "buckling criteria" prepared originally for the design of Kori-1 Nuclear Power Station.

In this study, it has been accomplished non-linear analysis of cylindrical containment vessel for structural stability estimation.

2. Buckling Stress Components for Cylindrical Containment Vessel

The basic loading components of buckling stresses for the cylindrical containment vessel under various loading, which were depicted in Fig. 2, are the axial compression only, the axial compression with internal pressure, the external pressure only and the torsion only.

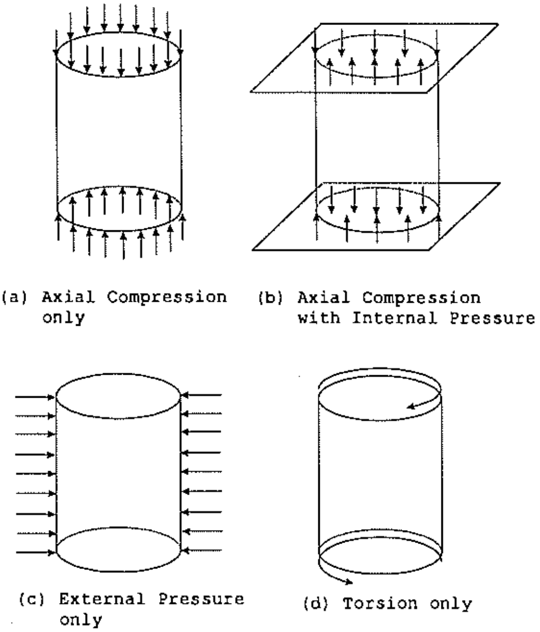


Fig. 2 Basic Loading Components of Buckling Stresses 7 for Cylindrical Containment Vessel

Equations for the basic components of buckling stresses were derived using the theory of mechanics and supplemented by experimental observations. In application of the basic buckling stress components to the cylindrical containment vessel subjected to the various types of loading, they were combined by two or three. For this purpose, a series of interaction equations were proposed. Those are as follows;

i) Axial compression and external pressure;
ii) Axial compression and pure bending;
iii) Axial compression and torsion;

iv) Axial compression, bending and torsion; and

v) Axial compression, external pressure and torsion.

More specifically, the buckling criteria in assessment of stress resultants from the finite element analysis of the cylindrical containment vessel were expressed as follows:

for $S_{11} < 0$, $S_{22} < 0$ and $S_{12} \neq 0$,

$$\frac{S_{11}}{f_{cr}(H)} + \frac{S_{22}}{f_{cr}(V)} + \left(\frac{S_{12}}{\tau_{cr}}\right)^2 < 1 \ . \tag{1}$$

for $S_{11} > 0$, $S_{22} < 0$ and $S_{12} \neq 0$,

$$\frac{S_{22}}{f_{cr}(V)} + \left(\frac{S_{12}}{\tau_{cr}}\right)^2 < 1 \ . \tag{2}$$

for $S_{11} < 0$, $S_{22} > 0$ and $S_{12} \neq 0$,

$$\frac{S_{11}}{f_{cr}(V)} + \left(\frac{S_{12}}{\tau_{cr}}\right)^2 < 1 \ . \tag{3}$$

for $S_{11} > 0$, $S_{22} > 0$ and $S_{12} \neq 0$,

$$\left(\frac{S_{12}}{\tau_{cr}}\right)^2 < 1 \ . \tag{4}$$

where S_{11} = hoop stress, S_{22} = meridional stress and S_{12} = shear stress resulting from the finite element analysis, and the positive sign convention is as shown in Fig. 3.

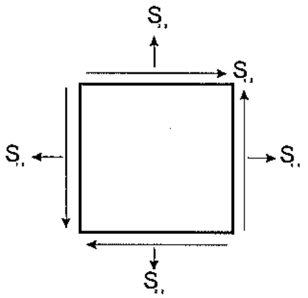


Fig. 3 Positive Sign Convention of Stress Components in a Finite Element.

3. Comments on Application of Buckling Criteria

3.1 Effect of Perpendicular Tensile Stress on Critical Buckling Stress

The loading case depicted in Fig. 2(b) is for the axial compression with internal pressure. The loading case was considered to derive the relationship between two normal stresses applied to a finite shell element, in which one is in compression and the other is in tension. Furthermore, the normal stress in compression is to be subjected to buckling. Then the corresponding total buckling stress is given by

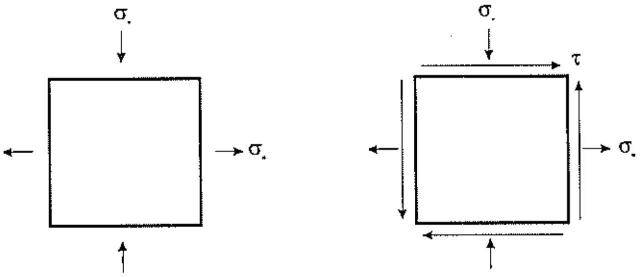
Equation (5).

$$\sigma_{cr} = \sigma_{cr}|_{P_i=0} + \Delta\sigma_{cr}\,. \tag{5}$$

Where $\Delta\sigma_{cr}$ is the increment of the critical buckling stress due to the internal pressure. In terms of buckling load, equation (5) becomes

$$P_{cr} = 2\pi\, R\, \sigma_{cr}\, t + \pi\, R^2\, P_i\,. \tag{6}$$

It is considered that equations (5) is dealing with the local stress level while equation (6) with the global one. It is also regarded that the relationship in equation (5) must have been derived from the relationship in equation (6), which means that the internal hydrostatic pressure causes the tensile hoop stress in the circular cylindrical shell and at the same time it may cause the additional upward resistance against the axially applied gravity load. From this reasoning, it is possible to imagine how such an argument, that the tensile hoop stresses in a shell element increase the critical buckling stress in the perpendicular axis, was derived. However, the total buckling load P_{cr} may not always increase due to the applied internal pressure. It must depends on the local buckling strength denoted by equation (5). In the local stress level under the considered loading condition, the stress resultants must be as shown in Fig. 4. Based on the engineering common sense, the tensile hoop stress σ_H must work adversely against the vertical buckling stress σ_v .



(a) A Shell Element under Axial Compression and Internal Pressure

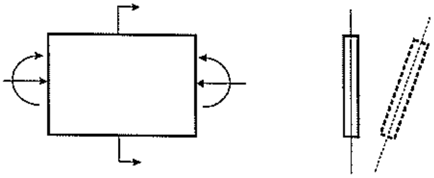
(b) A Shell Element under Axial Compression, Internal Pressure, and Shear

Fig. 4 Stress Resultants with Compressive and Tensile Normal Stresses

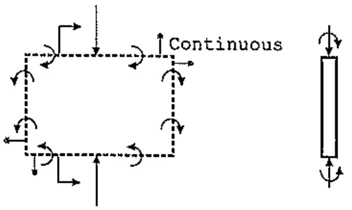
3.2 Flexural Buckling in Circular Cylindrical Shell

It is considered the flexural buckling of a plate to be an abrupt out-of-plane action for the external bending moment applied in-plane as depicted in Fig. 5.

Since shell elements in the cylindrical containment vessel are laterally restrained by neighboring shell elements, it is considered that the out-of-plane flexural buckling is not likely to occur. In order to validate the application of the buckling state of the cylindrical containment vessel subjected to the various loading including bending should be clearly defined.



(a) Flexural Buckling of a Plate



(b) A Shell Element Subjected to Axial Compression and Shear

Fig. 5 A Shell Element Subjected to Axial and Flexural Loading

3.3 Buckling of a Circular Cylindrical Shell with an Opening Hole

When a circular cylindrical containment vessel is under the various loading, shell elements around the opening hole, if exists, may be subjected to the severe stress concentration, compared to the other parts. Since the probable failure mode of the shell elements in such a condition has not been clearly defined, the buckling criteria may not be directly applicable to this case, in which an opening hole exists, as was to the containment vessel of Kori-1 Nuclear Power Station project, in which an opening hole is not existing. It should be noted that the buckling criteria were originally derived for the containment vessel in service in which there may be some internal pressure existing due to the operation of steam generators. However, in Kori-1 SGR project a temporary opening hole is existing in the containment vessel that means any internal pressure cannot be generated during the period of replacement. Accordingly, it should be recognized that the loading condition over the containment vessel with and without an opening hole is very much different. The element around the opening hole may be subjected to rather yielding than buckling.

4. Ultimate Stress Analysis of Cylindrical Containment Vessel

Because the element around the opening hole of a containment vessel may be subjected to rather yielding than buckling, nonlinear analysis considering plastic deformation was requested. So, it is performed ultimate stress analysis, considering geometric and material non-linearity, of cylindrical containment vessel using finite element program ABAQUS in order to estimate the stability of containment vessel with a 7m×7m opening subjected to crane loading at both edges of polar crane. To evaluate the effect of stiffener around the opening, we analyzed the cylindrical containment vessel with or without stiffener.

Fig. 6 shows 3-D analytical model for investigating the ultimate structural behavior of containment vessel.

We increased the load applied to finite element model and calculated the stress and displacement. Fig. 8 shows Von Mises stress distribution around the cylindrical containment vessel subjected to ultimate loading without stiffener and Fig. 9 shows Von Mises stress distribution around the cylindrical containment vessel subjected to ultimate loading with stiffener.

Fig. 7 depicts the relation of crane loading vs. displacement at node 2431 (which is located the polar crane in Fig. 6). X axis in Fig. 7 shows the displacement at node 2431 and Y axis is the magnification factor of crane loading.

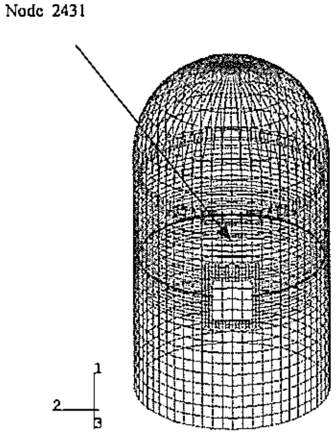


Fig. 6 3-D Finite Element Model

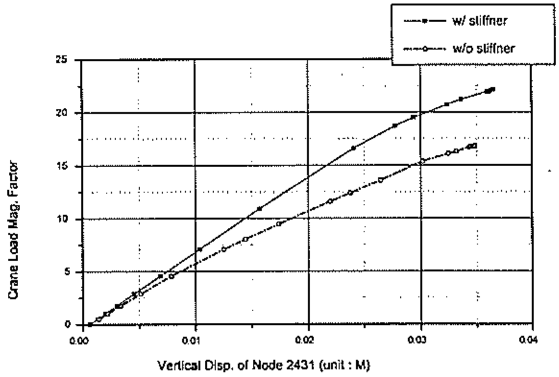


Fig. 7 The Relation of Crane Loading vs. Displacement at Node 2431

In the Fig. 8 and Fig. 9, it was shown that an installing stiffener around opening is effective to prevent deformation and stress concentration of the opening. In the Fig. 7, when the value of magnification factor of crane loading is within 1, cylindrical containment vessel behaves linear elastic. The maximum value of Von Mises stress is

2.47×10^3 t/m^2 at area around opening with stiffener and is 9% value of Von Mises's yield criteria 2.67×10^4 t/m^2.

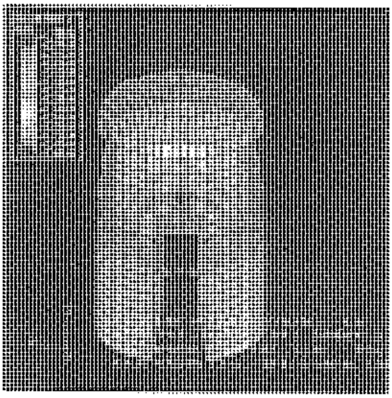


Fig. 8 Von Mises Stress Distribution subjected to Ultimate Loading without Stiffener

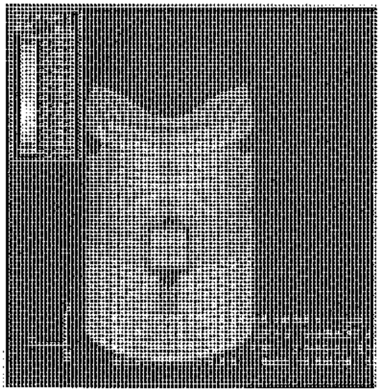


Fig. 9 Von Mises Stress Distribution subjected to Ultimate Loading with Stiffener

5. Conclusion

In this paper, it was found that the direct application of the buckling criteria, prepared by Lee[2] originally for the Kori-1 Nuclear Power Station project, seems to be inappropriate. Therefore, we performed ultimate stress analysis, considering geometric and material non-linearity of cylindrical containment vessel in order to estimate the ultimate capacity of containment vessel with an opening subjected to crane loading at both edges of polar crane. As a result, we found that when the cylindrical containment vessel is in service loading state, the vessel showed linear elastic behaviour and service load is about 9% of ultimate load capacity. Therefore, it is concluded that reinforcement due to opening is not needed.

Acknowledgements

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