ANALYTICAL STUDY ON DYNAMIC BUCKLING OF REACTOR CONTAINMENT VESSEL

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ABSTRACT

The objective of this study is to simulate the dynamic buckling of a reactor containment vessel under an earthquake load, using a nonlinear finite element method and to assess the safety margin of the conventional design. The nonlinear FEM is based on the MITC (Mixed Interpolated Tensorial Component) shell element proposed by Bathe, which has been modified by the authors to include the effect of large rotational increments. These MITC shell elements were used to model a typical steel PWR containment vessel and then a conventional static analysis and a dynamic analysis were performed. It was found that the buckling load estimated by the static analysis was smaller (about five-eighths) than the load estimated by the dynamic analysis.

1. INTRODUCTION

Large vertical storage tanks are widely used for many purposes, including storage of petroleum, LNG, and LPG. However, only a few examples of experimental research on dynamic buckling can be found. Yamaki^[1] investigated thin cylindrical shell buckling, Akiyama and Yuhara^[2] evaluated buckling load in a stiffened reactor containment vessel under a seismic excitation, using a large scale experimental model, and Fujita^{[3]~[5]} performed dynamic buckling tests of thin cylindrical shells.

Although the buckling phenomenon is dynamic and may have properties of multi degrees of freedom, many integrity studies on tank buckling have been based on linear analysis and have treated it as a static problem or modeled the dynamic effects as having only single degree of freedom.

This paper presents a nonlinear dynamic analysis, using the MITC shell element to simulate the buckling of a typical PWR steel containment vessel.

2. SUMMARY OF THE ANALYTICAL METHOD

2.1 DYNAMIC ANALYSIS

The basic equation for dynamic nonlinear problems is given by :

$$M\ddot{U}_i + C\dot{U}_i + Q_i = F_i \quad (1)$$

where F_i represents load, $\ddot{U}_i$ and Q_i are acceleration and internal force at the i -th load step respectively.

If adopting the Newmark- β time integration scheme, we have the following equations from (2) to (4), where $K = \partial Q_i / \partial U_i$ indicates the tangent stiffness matrix and the numerical iteration is performed until $\Delta U^{(k)}$, $\Delta \dot{U}^{(k)}$ and $\Delta \ddot{U}^{(k)}$ converge to sufficiently small values.

$$M\ddot{U}_i^{(k)} + C\dot{U}_i^{(k)} + K\Delta U_i^{(k)} = F_i - Q_i^{(k-1)} \quad (2)$$

$$\left(\frac{1}{\beta\Delta t^2}M + \frac{\gamma}{\beta\Delta t}C + K\right)\Delta U_i^{(k)} = F_i - Q_i^{(k-1)} - M\ddot{U}_i^{(k-1)} - C\dot{U}_i^{(k-1)} \quad (3)$$

where,

$$\begin{aligned} U_i^{(k)} &= U_i^{(k-1)} + \Delta U^{(k)} \\ \dot{U}_i^{(k)} &= \dot{U}_i^{(k-1)} + \Delta \dot{U}^{(k)} \\ \ddot{U}_i^{(k)} &= \ddot{U}_i^{(k-1)} + \Delta \ddot{U}^{(k)} \end{aligned} \quad (4)$$

2.2 SHELL ELEMENT

In this study the four-node shell element which includes the effect of large rotation increments is used. The formation of this element is based on the MITC shell element proposed by Bathe et al. [6], [7]. Fig. 1 shows the MITC element. A complete and symmetric tangent stiffness matrix was obtained by considering a Taylor expansion of a finite rotation tensor up to the quadratic term.

3. BUCKLING ANALYSIS

3.1 ANALYSIS MODEL

A symmetric(one half) finite element model of a typical PWR steel containment vessel using four-node MITC shell elements is shown in Fig.2. A polar crane and a ring girder have been modeled by beam element. The seismic response wave at the common base mat of a nuclear power plant is shown in Fig.3. For both the static and dynamic analyses, the response wave was normalized to correspond to an S_2 earthquake with a maximum acceleration of 500 Gal. A duration of two seconds was used which included the maximum acceleration value.

3.2 STATIC ANALYSIS

The static analysis was performed with the equivalent nodal forces, corresponding to the maximum load of the earthquake. The maximum load distribution shown in Fig.4 was obtained from the envelope of force and moment loads. This envelope was derived from the time history analysis of a beam type containment vessel model. The nodal forces were applied to the vessel model so as to be constant at a given elevation, but vary vertically to approximate the actual distribution. Then the force was taken as a proportional load and an incremental analysis by Ricks' method was made to find the buckling point. Figure 5 shows the relationship between the displacement at the top of the containment vessel and the load factor. It was found that buckling ($\det K = 0$) occurred at $\lambda = 5.21$. The deformation just after the buckling is shown in Fig.6.

3.3 DYNAMIC ANALYSIS

Three dynamic analyses were performed for S_2 design earthquake with the load factor λ of 3, 6, and 9. The damping was assumed to be of the Rayleigh type, i.e.

$$C = \alpha M + \beta K_0$$

where K_0 is the stiffness matrix of the undeformed structure, and the coefficients α and β are determined, such that the modal damping becomes about 1% at the two dominant modes in the linear analysis.

Figure 7 shows the displacement history at the top point of the containment vessel, and Fig. 8 shows the history of the maximum Von-Mises equivalent stress in the model. The dotted lines in each figure indicate the level at which static buckling occurs. Figure 9 shows the deformation of the model at 1.83 seconds, which corresponds to the maximum displacement response. The displacements in the figures are magnified by a factor of twenty. By comparing the deformation given by the dynamic analysis for $\lambda=9$ (Fig. 9) and that of the static analysis (Fig. 6), it can be seen that the shear buckling mode is similar, and that the circumferential wave number due to the ovalization is about eleven in both cases. However in the dynamic analysis, the amount of deformation is greater, and the ridges of the waves are nearly vertical.

In the experimental results [3] [5], it has been found that the displacement of the top of the vessel shows a discontinuous drop, and the overall stress suddenly increases, when buckling occurs. A similar trend can be observed in Figs. 7 and 8, especially for a load factor $\lambda=9$. The maximum stress history for $\lambda=9$ in Fig. 8 has two separate jumps at 0.7 and 1.5 seconds. A small increase can be seen for $\lambda=6$ at 1.0 seconds, however no change can be found for $\lambda=3$. As for the displacement histories shown in Fig. 7, the values for $\lambda=6$ and $\lambda=9$ are not significantly different after 1.5 seconds and the displacement for $\lambda=6$ is sometimes greater than that for $\lambda=9$.

A further indication of buckling is given when the determinant of the stiffness matrix reaches zero ($\det K=0$). In Figs. 7 and 8, the black and white circles show this condition for $\lambda=6$ and $\lambda=9$ respectively, but no buckling occurred for $\lambda=3$. The marks start at 0.93 seconds for $\lambda=6$ and 0.73 seconds for $\lambda=9$.

The relationship between the element stress nonlinearity and the rate of stress increase against λ was investigated in each element for each of the three dynamic analysis cases. The elements, where the rate exhibits strong nonlinearity, were localized and scattered in the case of $\lambda=6$ after 1.0 seconds. For $\lambda=9$, they were localized and scattered from 0.7 to 1.5 seconds, and widely spread from 1.5 to 2.0 seconds.

From these considerations, it was concluded that in the case of $\lambda=9$, "local buckling" occurred from 0.7 to 1.5 seconds, and then "shear buckling" took place from 1.5 to 2.0 seconds. In the case of $\lambda=6$, only the "local buckling" occurred after 1.0 seconds.

Further analysis was done for $\lambda=7$ and 8. Figure 10 shows a plot of the maximum top displacement and maximum stress versus the load factor. From these results, it was found that the lower limit of dynamic buckling was $\lambda=8$.

4. CONCLUSIONS

The nonlinear dynamic buckling phenomenon of a typical PWR steel containment vessel under an S_2 design earthquake (maximum acceleration of the base mat is 500 Gal) was simulated using a model with four node MITC shell elements. In the analysis, geometric nonlinearity was considered, but the material was assumed to be linear. The results were summarized as follows:

- (1) In the conventional static analysis, shear buckling occurred at the earthquake level which is about five times greater than the design earthquake.
- (2) In the dynamic analysis, local buckling occurred at the earthquake level which is six times greater than the design level, and global shear buckling occurred at over eight times of the design level.
- (3) The static analysis was found to give more conservative buckling threshold than the dynamic analysis.
- (4) It was concluded that the reactor containment vessel has an adequate safety margin to prevent buckling under the design earthquake.

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Fig. 1 4-node MITC Element

Fig. 3 Seismic Response Wave at the Common Base Mat

Fig. 2 FEM Model of a typical PWR Steel Containment Vessel

Fig. 4 Maximum Load Distribution

Fig. 5 Load-Displacement Relationship (Static Buckling)

Fig. 6 Deformation just after the Static Buckling
[Disp. $\times 40$]

FIG. 7 Displacement History at the Top of the Reactor Containment Vessel

Fig. 8 Maximum Von-Mises Stress

Fig.9 Deformation at $t=1.83$ sec [Disp. $\times 20$]

Fig.10 Maximum Top Displacement and Maximum Stress