Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division IX (include assigned division number from I to X)

FINITE ELEMENT RELIABILITY ANALYSIS OF AP1000 STEEL CONTAINMENT UNDER INTERNAL PRESSURES

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Keywords

Steel containment, internal pressure, yielding stress, FORM, FERM, sensitivity

ABSTRACT

AP1000 has been introduced to China since 2007, which is the third generation nuclear power plant developed by Westinghouse. The failure probability assessment of the containment building is an essential element of the level 2 PSA studies of nuclear power plant. In this paper, a 3D finite element model of the AP1000 steel containment vessel is built using the general-purpose nonlinear finite element analysis program ABAQUS. The software platforms of ABAQUS and MATLAB are combined to conduct reliability analysis of the steel containment vessel based on Finite Element Reliability Method (FERM). The reliability indices and sensitivity indices of the steel containment vessel under internal pressures are obtained. The results show that the yielding stress has largest effect on the containment among four parameters, and the head, which should be paid more attention to, is more important than the cylinder. The procedure based on FERM costs very little time, which shows that FERM is an efficient way to conduct the reliability analysis on the nuclear structure.

1 INTRODUCTION

The containment is the last safety barrier for limiting radioactive materials into the outside environment, so evaluating the integrity capacity of the containment under internal pressure is a critical part of risk assessment process. Many experiments and researches (Yamaura Y., etc., 1985; NUREG/CR-6706, 2001; OECD/NEA, 2005) have been conducted about many kinds of containments' integrity capacities under internal pressures from the deterministic view.

A procedure for the probabilistic failure assessment of a steel containment containing structural defects is presented (Sarmiento G.S., 1985), and in this reference "R-6 Failure Assessment Diagram" developed in the British Central Electricity Generating Board and advanced second moment are combined to calculate the reliability index of the steel containment containing defects. Some researchers (Tang H. T., etc., 1995) presented the extension of the deterministic leakage criteria developed in EPRI concrete containment research to probabilistic failure criteria and provided a process to deal with probabilistic risk assessments of nuclear concrete containment structures. A report of American Nuclear Regulatory Commission (NRC) gives the procedure, which combines the Latin Hypercube Sampling (LHS) techniques with finite element analysis method, to conduct fragility analysis of degraded containments (NUREG/CR-6920, 2006).

AP1000 steel containment vessel serves to limit releases in the event of an accident such as the loss of coolant accident (LOCA) (Westinghouse, 2011), so the reliability analysis of the steel containment vessel under internal pressure needs to be conducted.

In this paper, the software platforms of ABAQUS and MATLAB are combined to conduct the reliability analysis of the AP1000 steel containment vessel under internal pressures based on the FERM. This paper shows that the FERM based on FORM is an efficient way for conducting reliability analysis of the steel containment.

2 THE DETERMINISTIC MODEL OF AP1000 STEEL CONTAINMENT

2.1 Design characteristics and assumptions of AP1000 steel containment vessel

According to the reference (Westinghouse, 2011), some design characteristics of the steel containment vessel are list in table 1:

Table 1 Design characteristics of the steel containment vessel

Design characteristics	Values
Diameter	39.624 m
Height	65.634 m
Material	SA738, Grade B
Design Pressure	0.4065 Mpa
Cylinder Thickness	44.45 mm
Head Thickness	41.27 mm
Head Ellipsoidal Diameter	39.624 m
Head Ellipsoidal Height	11.468 m

There are three assumptions for modeling of AP1000 steel containment listed as follows:

1. The reference (Westinghouse, 2011) shows that the maximum pressure capabilities of equipment hatches and personnel airlocks are larger than the maximum pressure capabilities of ellipsoidal heads and the cylinder, so the equipment hatches and personnel airlocks are ignored in this paper, which makes the computation more efficient.

2. Do not consider the effect of two stiffeners and the crane girder, which make the steel containment safer under international pressures, on the steel containment.

3. As the bottom head is embedded in concrete, the part above the bottom head is assumed to be a free-standing structure.

These assumptions make the model of the containment vessel more conservative and safer.

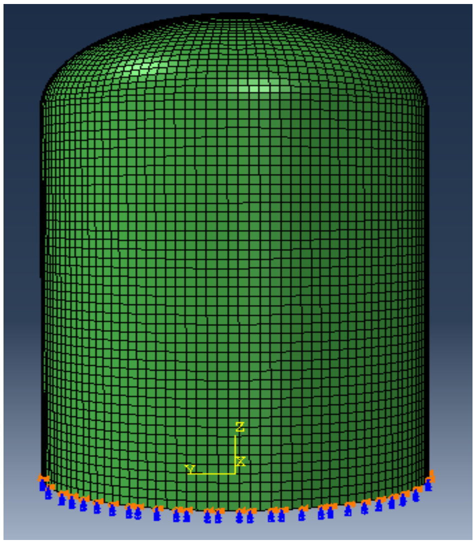

Fig.1 The finite element model

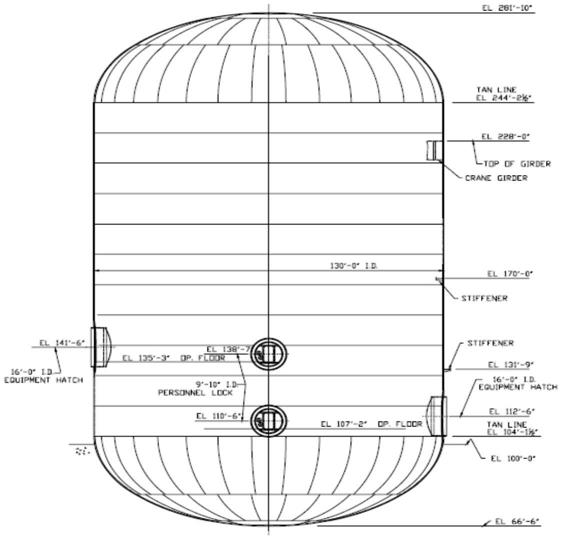

Fig. 2 The accurate model

2.2 Finite element modeling

The ideal elastic-plastic model is used as the constitutive model of steel material, as the failure criterion is that the containment reaches yielding stress in this paper. The material parameters of the steel containment vessel are list in table 2. As the thickness of the containment vessel is smaller than other dimensions, the shell element S4R is used in ABAQUS.

Table 2 Material parameters

Material parameters	Poisson ratio	Elastic module	Yielding stress	Density
Values	0.3	2.06×10^{11}(Pa)	4.14×10^{8} (Pa)	7830(Kg/m^3)

The stress contours of the containment under internal pressures are shown in figure 3.

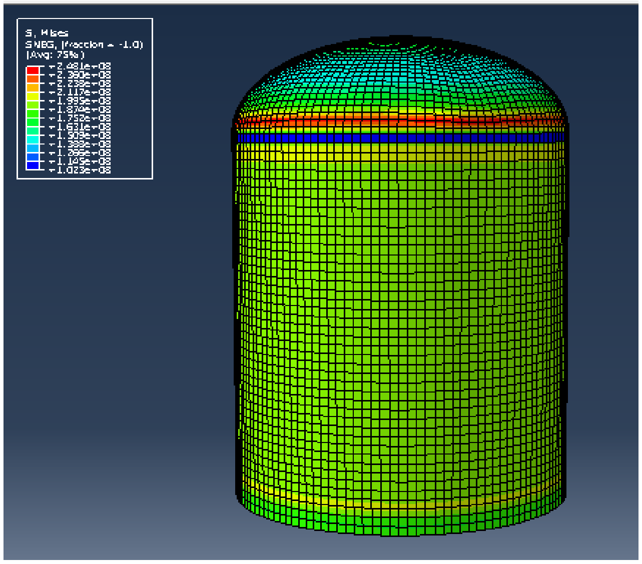

Fig. 3 The stress contours of the containment under internal pressures

The reference (Tang Z.R., 2011) gives the stress results of the middle part of the cylinder under internal pressure by means of the theoretical computation and finite element analysis. The results of this paper are compared to the reference (Tang Z.R., 2011) listed in table 3.

Table 3 The comparisons of results

Internal pressures (Mpa)	The reference (Tang Z.R., 2011)		This paper
	Mises stress (Mpa)		
	Theoretical values	ANSYS	ABAQUS
0.5	193.89	192.74	192.73
0.4	154.40	154.59	154.18
0.3	115.80	115.65	115.62
0.2	77.20	77.10	77.2

The comparions show that the results of the middle part of the containment vessel under internal pressures in this paper are accurate. Figure 3 shows that the stress of the knuckle part of the containment vessel is larger than other parts, which agree with the result of the reference (Westinghouse, 2011).

From two above comparions we could conclude that the model could give the accurate results of the containment vessel under internal pressures.

3 PROBABILITY MODELING FOR STEEL CONTAINMENT UNDER INTERNAL PRESSURES

3.1 Limit State Function (LSF) of steel containment under internal pressures

Structural LSF can be expressed as follows :

$$Z = g(R,S) = R - S \tag{1}$$

Where, R is the resistance of structures; S is the load effect on structures.

For different forms of loads on different structures, there are different kinds of LSF forms. R and S can represent stress, displacement, strain, load and etc. In this paper, Mises stress of the steel material is the resistance of containments, while the load effect on structures, S, is the stress of containment under internal pressures. Eq. (1) can be transformed to

$$Z = g(\mathbf{X}) = \sigma_S - \sigma(\mathbf{X}) \tag{2}$$

Where, **X** is basic random variable of structural parameters, which includes σ_S ; σ_S is the Mises stress of the steel material; $\sigma(\mathbf{X})$ is the stress of containment under internal pressures;

3.2 Uncertainties of variables

The capacities of structures under kinds of loads are influenced by the uncertainties of structural basic parameters, such as geometric sizes, material strength and etc. In this paper, four basic variables, which are respectively the head thickness of the containment (t1), the cylinder thickness of containment (t2), Poisson ratio of steel material (ν) and Mises stress (σ_s) of steel material, are selected for the integrity analysis of the containment under internal pressures. The statistical information of four variables is shown in table 4.

Table 4 Statistical information of basic RVs

RVs	Type of probability distribution	Coefficient of variation	Mean
t1	Normal	0.035	41.27 mm
t2	Normal	0.035	44.45 mm
ν	Lognormal	0.06	0.3
σ_s	Lognormal	0.09	414 Mpa

Notes: t1 is the thickness of the head; t2 is the thickness of the cylinder; ν is Poisson ratio of the steel material; σs is the yield stress of steel material.

4 FINITE ELEMENT RELIABILITY METHOD (FERM) BASED ON FORM

4.1 Basic Principles of FERM

Structural failure criterion can generally be expressed by load effects S, which includes stress, displacement and etc., while structural statistical information can be expressed by random variables V, such as material properties, load, geometry and so on. The relationship between S and V can expressed by Eq. (3), which is called “Mechanical Transformation”.

$$\mathbf{S} = \mathbf{S}(\mathbf{V}) \tag{3}$$

Structural limit state function (LSF) is defined as follows:

$$f = g[\mathbf{S}(\mathbf{V}), \mathbf{V}] \tag{4}$$

Structural failure probability can be given as:

$$p_f = \int_{g[\mathbf{s}(\mathbf{v}),\mathbf{v}] \le 0} f_{\mathrm{V}}(\mathbf{v}) d\mathbf{v} \tag{5}$$

The equation, $g[\mathbf{S}(\mathbf{V}), \mathbf{V}] \le 0$, is the structural failure domain.

The general non-normal random variable V can be transformed to the dependent normal variable Y through “Probability Transformation” as the following:

$$\mathbf{Y} = T(\mathbf{V}) \tag{6}$$

In standard normal space y, Eq. (5) can be transformed to:

$$p_f = \int_{G(\mathbf{y})\le 0} \varphi_n(\mathbf{y})d\mathbf{y} \tag{7}$$

$G(\mathbf{y})$ can be linearized at the design point y* as the following:

$$G(\mathbf{y}) \approx G(\mathbf{y}^*) + \nabla_{\mathbf{y}^*} G^T(\mathbf{y}-\mathbf{y}^*) = \nabla_{\mathbf{y}^*} G^T(\mathbf{y}-\mathbf{y}^*) \tag{8}$$

First order approximation of failure probability is:

$$p_f \approx p_{f1} = \int_{\beta-\boldsymbol{\alpha}^T\mathbf{y}\le 0} \varphi_n(\mathbf{y})d\mathbf{y} = \Phi(-\beta) \tag{9}$$

The design point y* can be obtained through the iterative formula:

$$\mathbf{y}_{i+1} = \left(\frac{G(\mathbf{y}_i)}{\left\|\nabla_{\mathbf{y}_i} G\right\|} + \boldsymbol{\alpha}_i{}^T \mathbf{y}_i \right) \boldsymbol{\alpha}_i \tag{10}$$

The gradient of $G(\mathbf{y})$ at design point is (Lu D.G. & Yang D. W., 2005):

$$\nabla_{\mathbf{y}} G = (\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T \cdot \nabla_{\mathbf{v}} g = (\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T \cdot [\nabla_{\mathbf{s}} g \cdot \mathbf{J}_{\mathbf{s},\mathbf{v}} + \nabla_{\mathbf{v}} g] \tag{11}$$

Where, $(\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T$ can be obtained through Probability Transformation;

In the FERM, $G(\mathbf{y}_i)$ can be obtained through deterministic FEM; As g is the explicit form of s and g, $\nabla_{\mathbf{s}} g$ and $\nabla_{\mathbf{v}} g$ can easily obtained; $(\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T$ is obtained through the Probability Transformation; As s is implicit form of v, $\mathbf{J}_{\mathbf{s},\mathbf{v}}$ is hard to calculate. In this paper, we calculate it by the central difference method.

4.2 Sensitivity analysis

Sensitivity analysis, which could result to the sensitivity index, is used to assess the importance of different basic parameters of structures. Actually, sensitivity index is co-production of FERM analysis. $G(\mathbf{u})$ is linearized at design point u* as follows:

$$G(\mathbf{u}) \approx \overline{G}(\mathbf{u}) = \nabla G^T\left(\mathbf{u} \text{-} \mathbf{u}^*\right) = \left\|\nabla G\right\|\left(\beta - \boldsymbol{\alpha}^T\mathbf{u}\right) \tag{12}$$

Variance of $\overline{G}(\mathbf{u})$ is :

$$\mathrm{Var}[\overline{G}] = \left\|\nabla G\right\|^2 (\alpha_1^2 + \alpha_2^2 + \cdots + \alpha_n^2) = \left\|\nabla G\right\|^2 \tag{13}$$

Where, α_i is variance of basic RVs, which is one part of variance of $G(\mathbf{u})$ and reflects the importances of corresponding RVs.

4.3 The procedure of FERM

In this paper, the software platforms of MATLAB and ABAQUS are combined to conduct the reliability analysis of the steel containment vessel under internal pressures. The basic steps of the procedure are summarized as follows:

1) LSF of the structure is determined.
2) The type of probability distribution of the basic random varibles and the corresponding statistical information are determined.
3) Conduct one time of finite element analysis by ABAQUS with the model parameters equaling to their mean values.
4) Conduct the reliability analysis by MATLAB based on FORM algorithm.
5) Replace the corresponding model parameters by the new design point.

6) Repeat step 3 ~ step 5 until the tolerance is smaller than the allowable tolerance error, which is usually 10^{-3}.
7) Compute the reliability index and the sensitivity index.

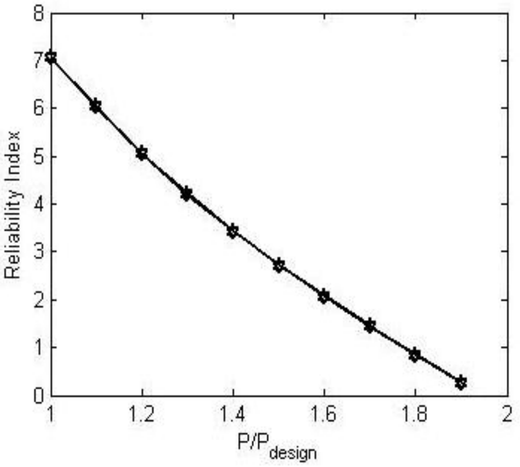

Fig. 4 The reliability indices

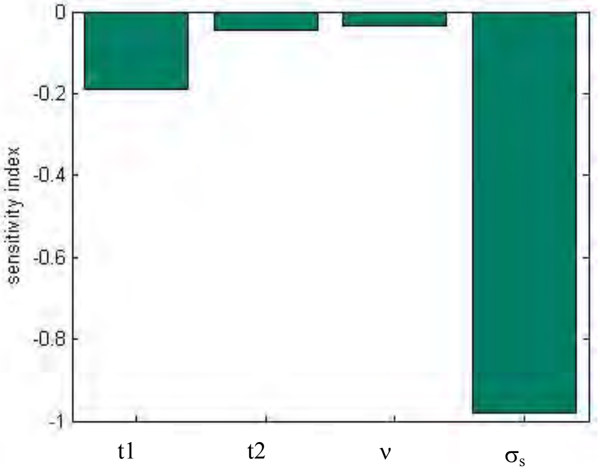

Fig. 5 The sensitivity indices

5 RESULTS OF FINITE ELEMENT RELIABILITY OF THE CONTAINMENT VESSEL UNDER INTERNAL PRESSURES

Reliability indices of the containment vessel under internal pressures are shown in figure 4. With the increase of internal pressures, the reliability index decreases. The sensitivity indices of four basic parameters are shown in figure 5. The yielding stress has the largest effect on the containment among four parameters. The thickness of head has the larger effect on the containment than the thickness of cylinder, so the head of the containment, which should be paid more attention to, is more important than the cylinder. The iteration of the procedure of FERM in this paper is usually less than ten times, which costs very little time.

6 CONCLUSIONS

In this paper the modeling of model based on three assumptions is conducted, which makes the computation more efficient and conservative. The statistical information of four basic parameters are determined. The software platforms of ABAQUS and MATLAB are combined to conduct reliability analysis of the steel containment vessel under internal pressures. The results show that the yielding stress of steel has the largest effect on the containment among four parameters. The thick of the head has larger effect than the cylinder, so we should pay more attention to the head. The iteration of the procedure in this paper is less than 10, and the procedure costs very little time, which show that the FERM based on FORM is an efficient way of dealing with the reliability of the steel containment.

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