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Paper:

Finite Element Reliability Analysis of Steel Containment Vessels with Corrosion Damage

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Containment vessels, which contain any radioactive materials that would be released from the primary system in an accident, are the last barrier between the environment and the nuclear steam supply system in nuclear power plants. Assessing the probability of failure for the containment building is essential to level 2 PSA studies of nuclear power plants. Degradation of containment vessels of some nuclear power plants has been observed in many countries, so it is important to study how the corrosion has adverse effects on the capacity of containment vessels. Conventionally, the reliability analysis of containment vessels can be conducted by using Monte Carlo Simulation (MCS) or Latin Hypercube Sampling (LHS) with the deterministic finite element analysis. In this paper, a 3D finite element model of an AP1000 steel containment vessel is constructed using the general-purpose nonlinear finite element analysis program ABAQUS. Then the finite element reliability method (FERM) based on the first order reliability method (FORM) is applied to analyze the reliability of the steel containment vessel, which is implemented by combining ABAQUS and MATLAB software platforms. The reliability and sensitivity indices of steel containment vessels under internal pressure with and without corrosion damage are obtained and compared. It is found that the FERM-based procedure is very efficient to analyze reliability and sensitivity of nuclear power plant structures.

Keywords: steel containment vessel, internal pressure, yield stress, finite element reliability method, first order reliability method, corrosion

1. Introduction

The containment vessel is the last safety barrier for limiting the escape of radioactive materials into the outside environment. This makes evaluating the integrity capacity of the containment vessel under internal pressure is a critical part of the risk assessment process. Many experiments and much research [1–3] on the integrity capacities of containment vessels under internal pressure have been conducted from the deterministic view.

Reference [4] presented a procedure for probabilistic failure assessment of a steel containment containing structural defects, in which the "R-6 Failure Assessment Diagram" developed by the British Central Electricity Generating Board and the advanced second moment are combined to calculate the reliability index of the steel containment containing defects [4]. Some researchers [5] extended the deterministic leakage criteria developed in the EPRI concrete containment vessel research to probabilistic failure criteria, and provided a process for dealing with probabilistic risk assessments of nuclear concrete containment structures.

The research on degradation in nuclear power plants has shown that the aging-related degradation on structures, systems and components (SSCs) in nuclear power plants should be considered [6]. In some nuclear power plants, degradation of containment vessels has been observed. Corrosion has been observed in many steel containment vessels, which could have an adverse effect on the ability of containment vessels to fulfill their intended functions. Many experts have studied the capacity of degraded containment vessels to resist leaks under internal pressurization. Fragility curves for a degraded steel containment vessel under internal pressurization were developed by Ellingwood and Cherry [7]. Cherry and Smith studied the effect of the corrosion of the steel shell under internal pressurization on the capacities of the steel containment [3]. A report by American Nuclear Regulatory Commission (NRC) details the procedure, which combines the Latin Hypercube Sampling (LHS) technique with finite element analysis, to conduct fragility analysis of degraded containment vessels [8].

The reliability index or fragility curves of containment vessels with or without corrosion under internal pressurization have been conventionally analyzed by using Monte Carlo simulation (MCS) or Latin Hypercube Sampling (LHS) with deterministic finite element analysis. However, both MCS and LHS are not efficient for reliability analysis of complex nuclear power plant structures when using the finite element analysis. In this pa-

Table 1. Steel containment vessel design characteristics.

Design characteristics	Values	Design characteristics	Values
Diameter	39.624 m	Cylinder thickness	44.45 mm
Height	65.634 m	Head thickness	41.27 mm
Material	SA738, Grade B	Head ellipsoidal diameter	39.624 m
Design pressure	0.4065 MPa	Head ellipsoidal height	11.468 m

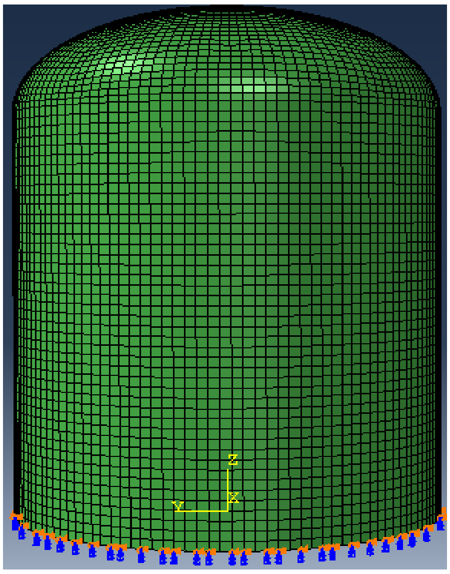

Fig. 1. The finite element model.

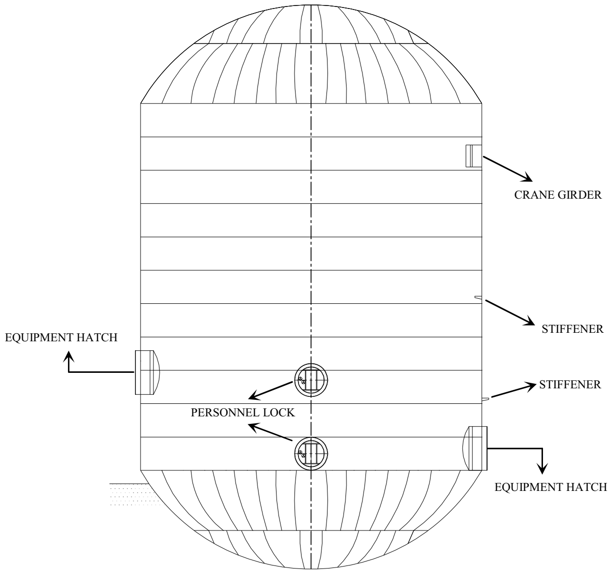

Fig. 2. The baseline model [14].

per, the finite element reliability method (FERM) based on the first order reliability method (FORM) is implemented since the FERM can greatly improve the computation efficiency for calculating the reliability index or fragility curves. As a stochastic finite element method, the FERM, which combines approximate analytical methods of structural reliability analysis with deterministic finite element methods of structural response analysis, can successfully overcome the difficulty in which structural responses are implicit functions of basic random variables. The FERM has thus been an effective tool for large-scale complex structural reliability analysis and risk assessment. In some engineering domains related to civil engineering, the FERM has been widely used. In structural engineering, Haldar et al [9] have made some studies on stochastic finite-element-based seismic risk of nonlinear structures. In bridge engineering, Frangopol and Imai [10, 11] conducted nonlinear finite element reliability analysis of a bridge. In hydraulic engineering, Liu et al [12, 13] made finite element reliability analysis of periodic thermal creep stresses in concrete and mass concrete structures. In nuclear engineering, however, the FERM has been seldom used for conducting the reliability or fragility analysis of structures, systems and components (SSCs) of nuclear power plants.

AP1000 steel containment vessels serve to limit releases in the event of an accident such as the loss of coolant accident (LOCA) [14], so reliability analysis of steel containment vessels under internal pressure needs to be conducted. What's more, the effects of corrosion damage on the reliability of steel containment vessels should be paid attention to. In this paper, the ABAQUS and MATLAB software platforms are combined to conduct reliability and sensitivity analysis of an AP1000 steel containment vessel under internal pressure based on the FERM. It is shown that the FERM is an efficient way for conducting reliability and sensitivity analysis of steel containment vessels.

2. Deterministic Modeling of the AP1000 Steel Containment Vessel

2.1. Design Characteristics and Modeling Assumptions of the Containment Vessel

According to Reference [14], the AP1000 steel containment vessel has the design characteristics listed in **Table 1**:

The following three assumptions are made in the deterministic modeling of the AP1000 steel containment:

(1) Reference [14] states 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.

Table 2. Material parameters.

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

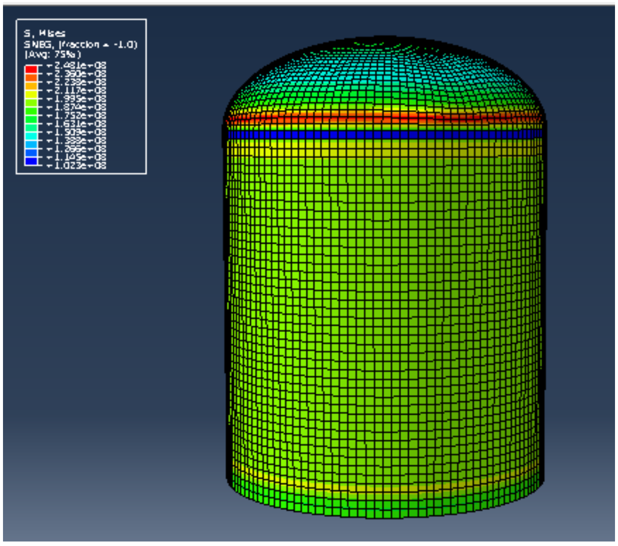

Fig. 3. Stress contours of containment vessels under internal pressure.

(2) The effect of two stiffeners and the crane girder, which make the steel containment safer under internal pressure, are not considered for the steel containment vessel.

(3) The bottom head is embedded in concrete, so the part above this head is assumed to be fixed to the ground.

The finite element model and the baseline model [14] of the AP1000 steel containment vessel are respectively shown in **Figs. 1** and **2**.

2.2. Finite Element Model of the Steel Containment Vessel

2.2.1. Finite Element Model of the Steel Containment Vessel with No Corrosion

The ideal elastic-plastic model is used as the constitutive model of steel material, because the failure criterion in this paper is that the containment vessel reaches yield stress. The material parameters of the containment vessel are listed in **Table 2**. As the thickness of the containment vessel is smaller than other dimensions, the shell element S4R, which is a four-node, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation, is used in ABAQUS [15]. The quadrilateral mesh elements are assigned to the S4R element type. The finite element model of the steel containment vessel with no corrosion has 8,769 nodes and 8,704 elements.

The stress contours of the containment vessel under internal pressure are shown in **Fig. 3**. It is found that the

Table 3. Comparison of results.

Internal pressures (MPa)	Reference [16]		This paper
	von 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	77.20

stress on the knuckle part of the containment vessel is the largest.

Reference [16] gives the stress results for the middle part of the cylinder under internal pressure by theoretical calculation and finite element analysis. **Table 3** compares the results given in this paper to those in Reference [16].

The comparison shows that the results for the middle part of the containment vessel under internal pressure are accurate. **Fig. 3** shows that the stress on the knuckle part of the containment vessel is larger than on other parts, which agrees with the results of Reference [14]. From the two comparisons above, it can be concluded that the finite element model of this paper gives accurate results for the containment vessel under internal pressure.

2.2.2. Finite Element Model of the Steel Containment Vessel with Corrosion Damage

Material parameters and geometric sizes other than the thickness for the containment with corrosion damage are the same with the containment model with no corrosion. Through reducing the thickness, the corrosion damage of the containment vessel could be considered. The shell thickness of the containment vessel is defined in the "Section" part of ABAQUS. In this paper, corrosion damage to the four locations on the containment vessel could be considered respectively, and there are further two assumptions: (1) the thickness in one region with corrosion is set to be smaller than the one in other regions with no corrosion; and (2) the thickness in each region is uniform. Each of four corrosion regions is five meters high. The finite element model of the containment vessel with corrosion damage is schematically shown in **Fig. 4**.

The discontinuities exist at the interface between shells of differing thickness, so in this paper, the use of shell elements introduces discontinuities. The thicker shell with no corrosion damage is gradually reduced in thickness over the length on the order of the shell thickness, and welded to the thinner shell of parts with corrosion damage [17]. In the models developed in this paper, a small region is included at the interface of shells of differing thickness to represent the transition region between thin-

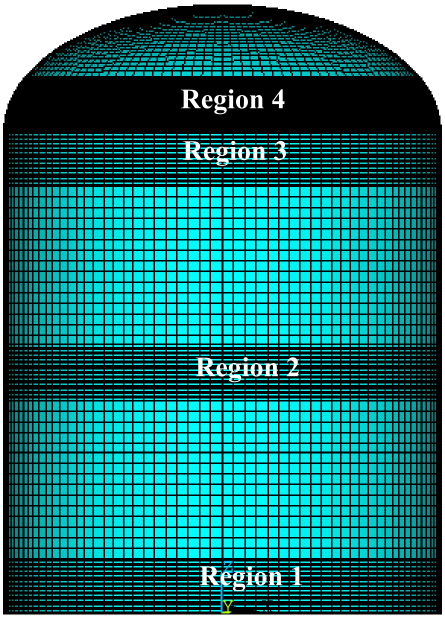

Fig. 4. Four regions with corrosion damage.

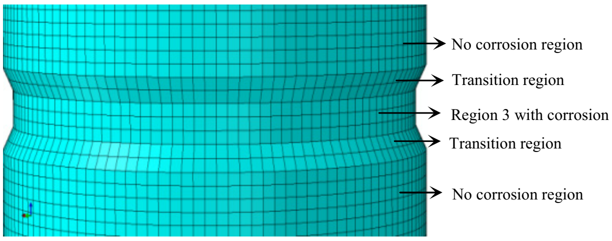

Fig. 5. Transition between regions differing in thickness.

ner parts with corrosion and parts with no corrosion. This transition region is set to a thickness equal to the average of the shells on either side [17]. The transition region is shown in **Fig. 5**.

3. Probability Modeling for the Steel Containment Vessel Under Internal Pressure

3.1. Limit State Function of the Steel Containment Vessel Under Internal Pressure

The limit state function (LSF) of a structure can be expressed as follows:

$$Z = g(R,S) = R - S \quad (1)$$

where, R is the resistance of the structure; S is the total load effect of the structure.

For different forms of loads on different structures, there could be different kinds of LSF forms. In Eq. (1), R and S can represent stress, displacement, strain, load, etc. Herein, the von Mises stress of the steel material is taken as the resistance of the containment vessel, while the load effect on the structure, S, is taken as the stress of the containment vessel under internal pressure. Eq. (1) is

Table 4. Statistical information of basic random variables.

Random variables	Type of probability distribution	Coefficient of variation	Mean
t_1	Normal	0.035	41.27 mm
t_2	Normal	0.035	44.45 mm
ν	Lognormal	0.06	0.3
σ_S	Lognormal	0.09	414 Mpa

Notes: t_1 is the thickness of the head; t_2 is the thickness of the cylinder; ν is Poisson ratio of the steel material; σ_S is the yield stress of steel material; E is the elastic modulus of steel material.

then transformed into

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

where, $\mathbf{X}$ is the basic random variables of structural parameters, which includes σ_S; σ_S is the von Mises stress of the steel material; and $\sigma(\mathbf{X})$ is the stress of the containment vessel under internal pressure.

3.2. Random Variables

The capacities of structures under loads are influenced by the uncertainties of basic parameters of structures, such as: geometric sizes, material strength, modeling uncertainty, etc. In this paper, four basic random variables are selected for reliability and sensitivity analysis of the containment vessel under internal pressure, i.e., the head thickness of the containment (t_1), the cylinder thickness of containment (t_2), Poisson ratio of steel material (ν), and the von Mises stress (σ_s) of steel material. The statistical information of the four basic random variables is shown in **Table 4** according to Reference [8].

Based on the above consideration, Eq. (2) can be expressed as

$$Z = g(\mathbf{X}) = \sigma_S - \sigma(\sigma_s, t_1, t_2, \nu) \quad (3)$$

From Eq. (3), it can be seen that the LSF is an implicit function of the basic random variables when the stresses are calculated by finite element analysis.

4. Finite Element Reliability Method Based on the First Order Reliability Method

4.1. Basic Principle of Finite Element Reliability Method

The failure criterion of structures can generally be expressed by load effects $\mathbf{S}$, which includes stress, strain, displacement, etc. While structural statistical information can be expressed by random variables $\mathbf{V}$, such as material properties, loads, geometric sizes, and so on. The relationship between $\mathbf{S}$ and $\mathbf{V}$ can be expressed by

$$\mathbf{S} = \mathbf{S}(\mathbf{V}) \quad (4)$$

This is a mechanical transformation.

The limit state function (LSF) of this structure is defined as

$$Z = g\left[\mathbf{S}(\mathbf{V}), \mathbf{V}\right] \quad (5)$$

Then the failure probability of structures can be calculated by

$$p_f = \int_{g[\mathbf{s}(\mathbf{v}),\mathbf{v}]\le 0} f_{\mathbf{V}}(\mathbf{v})d\mathbf{v} \quad (6)$$

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

The general dependent and non-normal random variable $\mathbf{V}$ should be transformed to the independent and standard normal variable $\mathbf{Y}$ through probability Transformation:

$$\mathbf{Y} = T(\mathbf{V}) \quad (7)$$

In the standard normal space $\mathbf{y}$, Eq. (6) can be transformed to

$$p_f = \int_{G(\mathbf{y})\le 0} \varphi_n(\mathbf{y})d\mathbf{y} \quad (8)$$

For the first order reliability method (FORM), $G(\mathbf{y})$should be linearized at the design point $\mathbf{y}^*$:

$$\begin{aligned} G(\mathbf{y}) &\approx G(\mathbf{y}^*) + \nabla_{\mathbf{y}^*} G^T(\mathbf{y}-\mathbf{y}^*) \\ &= \nabla_{\mathbf{y}^*} G^T(\mathbf{y}-\mathbf{y}^*) \end{aligned} \quad (9)$$

Then the first order approximation of the failure probability is

$$p_f \approx p_{f1} = \int_{\beta-\boldsymbol{\alpha}^T\mathbf{y}\le 0} \varphi_n(\mathbf{y})d\mathbf{y} = \Phi(-\beta) \quad (10)$$

The design point $\mathbf{y}^*$ can be obtained through the well-known HLRF iterative formula:

$$\mathbf{y}_{i+1} = \left(\frac{G(\mathbf{y}_i)}{\|\nabla_{\mathbf{y}_i} G\|} + \boldsymbol{\alpha}_i^T\mathbf{y}_i\right)\boldsymbol{\alpha}_i \quad (11)$$

where, $\boldsymbol{\alpha}_i = -\nabla G(\mathbf{y}_i)/||\nabla G(\mathbf{y}_i)||$ is the sensitivity vector in the i-th iteration.

The gradient of $G(\mathbf{y})$ at the design point [18] is:

$$\begin{aligned} \nabla_{\mathbf{y}} G &= (\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T \cdot \nabla_{\mathbf{v}} g \\ &= (\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T \cdot [\nabla_{\mathbf{s}} g \cdot \mathbf{J}_{\mathbf{s},\mathbf{v}} + \nabla_{\mathbf{v}} g] \end{aligned} \quad (12)$$

where, $(\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T$ can be directly 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 be easily obtained; $(\mathbf{J}_{\mathbf{y},\mathbf{v}}^{-1})^T$ is obtained through probability transformation; As $\mathbf{s}$ is implicit form of $\mathbf{v}$, $\mathbf{J}_{\mathbf{s},\mathbf{v}}$ is hard to calculate. In this paper, the central difference method is used to calculate the sensitivity:

$$\frac{\partial g}{\partial y} \approx \frac{g(y+\Delta y) - g(x-\Delta y)}{2\Delta y} \quad (13)$$

4.2. Sensitivity Analysis

Sensitivity analysis is used to assess the importance of different basic parameters of structures. Actually, the sensitivity index is a by-product of FERM analysis [19]. The sensitivity vector at the design point $\mathbf{y}^*$ is:

$$\boldsymbol{\alpha} = -\frac{\nabla G(\mathbf{y}^*)}{\|\nabla G(\mathbf{y}^*)\|} = \nabla_{\mathbf{y}}\beta(\mathbf{y}^*) \quad (14)$$

Since $G(\mathbf{y})$ is linearized at design point $\mathbf{y}^*$:

$$\begin{aligned} G(\mathbf{y}) &\approx \bar{G}(\mathbf{y}) \\ &= \nabla G^T(\mathbf{y}-\mathbf{y}^*) = \|\nabla G\|\left(\beta - \boldsymbol{\alpha}^T\mathbf{y}\right) \end{aligned} \quad (15)$$

Then it is easily verified that the variance of $\bar{G}(\mathbf{u})$ is

$$\begin{aligned} \mathrm{Var}[\bar{G}] &= \|\nabla G\|^2 (\alpha_1^2 + \alpha_2^2 + \cdots + \alpha_n^2) \\ &= \|\nabla G\|^2 \end{aligned} \quad (16)$$

From Eq. (16), it can be seen that α_i^2 is proportional to the contribution of random variable y_i to the total variance of the linearized limit state function. Clearly, the larger this contribution is, the more important random variable y_i is. Hence, the elements of the sensitivity vector α provide relative measures of importance of the basic random variables in the standard normal space. So in this paper, the sensitivity vector α is selected as a tool for analyzing the relative importance of the basic random variables.

4.3. Procedure of Finite Element Reliability Method

In this paper, the software platforms MATLAB (MATLAB 7.11 version) [20] and ABAQUS (ABAQUS/CAE 6.10-1 version) [15] are combined to conduct reliability and sensitivity analysis of the steel containment vessel under internal pressure. The basic steps of the procedure are summarized as follows:

1) Determine the LSF of the considered structure;
2) Determine the type of probability distributions of the basic random variables and the corresponding statistical information;
3) Conduct one time of finite element analysis by ABAQUS with the model parameters equaling to their mean values;
4) Conduct reliability analysis by MATLAB based on FORM algorithm;
5) Replace the corresponding model parameters by the new design point according to the HLRF algorithm;
6) Repeat step 3 $\sim$ step 5 until the tolerance is smaller than the allowable tolerance error, which is usually 10^{-3};
7) Calculate the reliability index and the sensitivity index.

5. Results of Finite Element Reliability Analysis of AP1000 Steel Containment Vessels Under Internal Pressure

5.1. Steel Containment Vessels with No Corrosion

Reliability indices of the containment vessel with no corrosion under internal pressure are shown in **Fig. 6**.

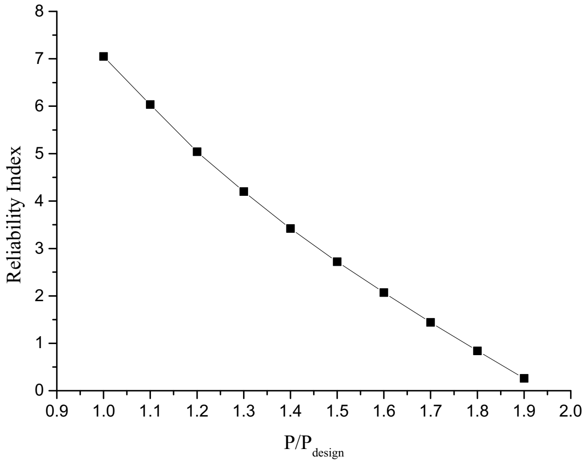

Fig. 6. Reliability indices of the containment vessel with no corrosion.

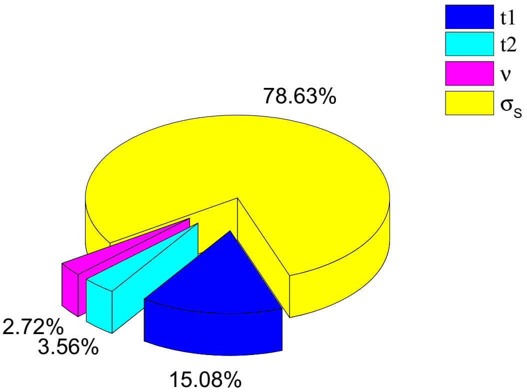

Fig. 7. Sensitivity indices of the containment vessel with no corrosion.

With the increase of internal pressure, the reliability index decreased. The sensitivity indices of four basic parameters are shown in **Fig. 7**. It can be seen that the yield stress has the largest effect on the containment among four parameters. The thickness of the head has a larger effect on the containment vessel than the thickness of cylinder, so the head of the containment vessel, which should be paid more attention to, is more important than the cylinder.

5.2. Steel Containment Vessels with Corrosion

Four regions with corrosion damage of the steel containment vessels are considered for 25% and 50% corrosion damage. The sensitivity indices for the degraded containment vessels are shown in **Figs. 8–15**. With the changing of the corrosion region, the sensitivity indices are different. For containment vessels in regions 1–3 with corrosion, the sensitivity index of the thickness of the cylinder is larger than the thickness of the head. In contrast, for the containment in region 4 with corrosion, the sensitivity index of the thickness of the cylinder is smaller than the thickness of the head.

The reliability indices of steel containment vessels in different regions with corrosion under design internal pressure are shown in **Table 5**. It is found that when

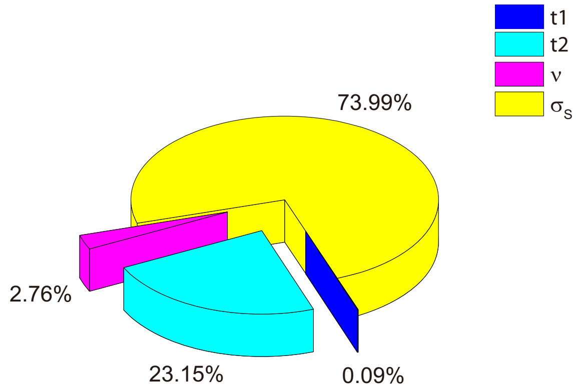

Fig. 8. Sensitivity indices of the model with 25% corrosion damage in Region 1.

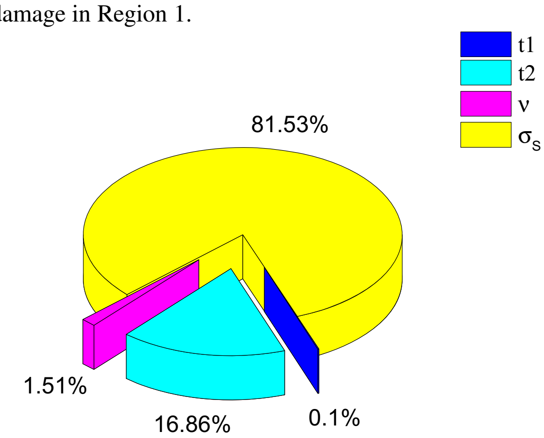

Fig. 9. Sensitivity indices of the model with 50% corrosion damage in Region 1.

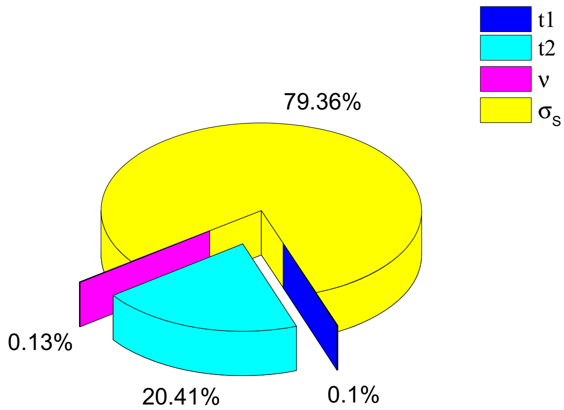

Fig. 10. Sensitivity indices of the model with 25% corrosion damage in Region 2.

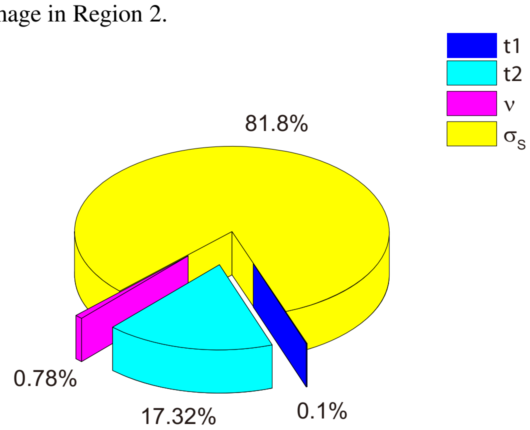

Fig. 11. Sensitivity indices of the model with 50% corrosion damage in Region 2.

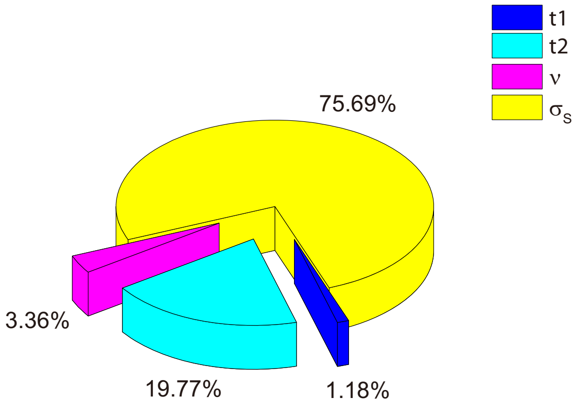

Fig. 12. Sensitivity indices of the model with 25% corrosion damage in Region 3.

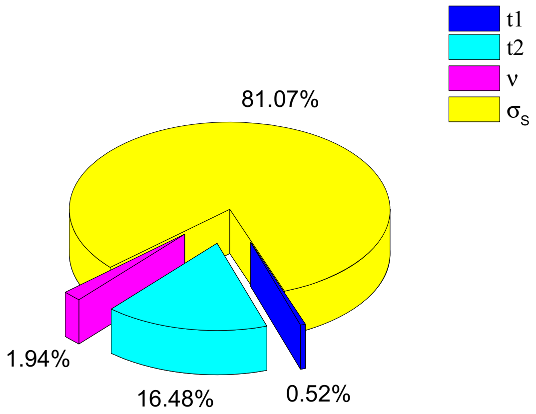

Fig. 13. Sensitivity indices of the model with 50% corrosion damage in Region 3.

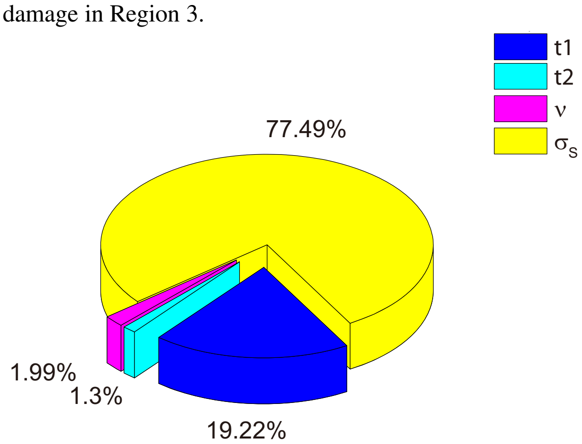

Fig. 14. Sensitivity indices of the model with 25% corrosion damage in Region 4.

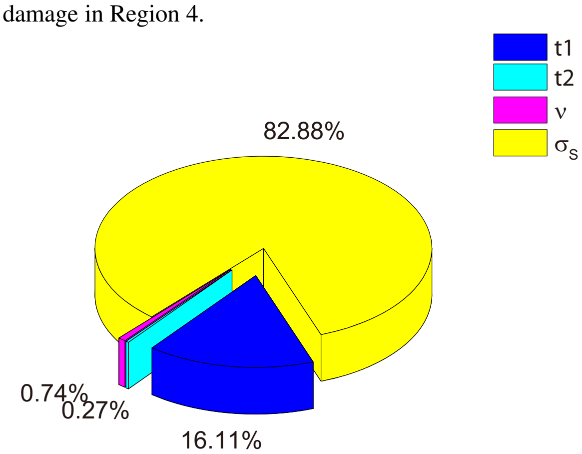

Fig. 15. Sensitivity indices of the model with 50% corrosion damage in Region 4.

Table 5. Comparison results of reliability indices of steel containment vessels in different regions with corrosion under design internal pressure.

Corrosion ratio	Region 1	Region 2	Region 3	Region 4
25%	5.178	6.790	5.487	4.182
50%	0.829	2.295	1.385	0.033

Table 6. Comparison results of the FERM and MCS.

Corrosion ratio	β		CPU time/h		Iteration times	
	FERM	MCS	FERM	MCS	FERM	MCS
0%	7.051	6.998	0.96	21.24	6	2.0×10^3
25% in Zion 1	5.178	5.021	1.27	103.8	8	10^4

Note: CPU type: i5-2410M 2.30 GHz; P = P_{design}

the head had some corrosion damage, the reliability indices are the lowest; and when some corrosion existed on the cylinder, the reliability index of the containment in region 1 is the lowest and the reliability index of the containment in region 2 is the largest. So we could find that the head should be paid more attention to, and the region 1 and region 3 are weaker than the middle part of the cylinder.

6. Verification by Monte Carlo Simulation

To verify the accuracy and efficiency of the algorithms and programs based on FERM, Monte Carlo simulation (MCS) is utilized to calculate the reliability indices of the AP1000 steel containment vessel under internal pressure, and some results are listed in **Table 6**. The comparison results of FERM and MCS show that the FERM based on MATLAB and finite element software ABAQUS is of good accuracy and efficiency.

7. Conclusions

The finite element models of an AP1000 containment vessel with and without corrosion are respectively set up using ABAQUS. The statistical information for four basic parameters is determined. Then the ABAQUS and MATLAB software platforms are combined to conduct reliability and sensitivity analysis of the steel containment vessel under internal pressure. The results show that the yield stress of steel has the largest effect on the containment among four parameters. The thickness of the head has a larger effect than the cylinder, so we should pay more attention to the head. As the changing of the corrosion region, the sensitivity indices are different. The middle part of the cylinder is stronger than other parts of the cylinder. The iteration of the procedure in this paper is less than 10, and the procedure takes very little time, which shows that the FERM based on FORM is an efficient way of dealing with the reliability of steel containment vessels.

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