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FRAGILITY ANALYSIS OF PRESTRESSED CONCRETE CONTAINMENT SUBJECTED TO SEVERE ACCIDENT CONDITIONS

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Abstract: *Containment is the most important structure in nuclear power plants, the main function of which is to prevent the leakage of radioactive materials into environment during the accident conditions, therefore it is very important to gain profound insight into the performance of the containment under severe accident conditions. This paper presents fragility analysis of prestressed concrete containment vessels under severe accidents. Firstly, detailed three-dimensional finite element model of the containment is established with consideration of the material nonlinearity and non-uniform effective prestressing distribution along the prestressed tendon. Secondly, a custom developed Matlab program combined with python script was developed to update the material parameters in ABAQUS input files to generate 30 samples with Latin Hypercube Sampling technique. Subsequently nonlinear FE analysis of the 30 samples is running automatically with batch programs. Fragility curves for five critical locations and different confidence levels with consideration of aleatory randomness and epistemic uncertainty had been investigated. Therefore, the weakness of the containment and the performance of containment subjected to severe accident conditions can be understood in depth. Finally, sensitivity analysis is conducted to show the relative importance of individual random variable. Results indicated that: structural failure of containment is dominated by the equipment hatch location; Sensitivity analysis for the input random variables reveals that modulus of elasticity of prestressed tendon contributes most to the pressure capacity of containment.*

Key words: Containment, Fragility analysis, Sensitivity analysis

1. Introduction

Nuclear power as one of most clean energies ensures national energy security, reduces greenhouse gases and improves the ecological environment. The key issue for nuclear energy industry is how to ensure the nuclear safety. Containment as the most important shielding structure in nuclear power plants plays an important role in ensuring nuclear safety in NPPs. The main function of the containment is to prevent the release of radioactive materials to the environment. Following the Great East Japan earthquake in 2011, a loss of cooling at the Fukushima Daiichi plant led to the overheating of several reactors and the release of radioactive material, which have highlighted the need for a robust design of concrete containment. The structural integrity of nuclear containment under internal pressurization from the design-basis accident and beyond design-basis accident can be quantified by the ultimate pressure capacity. Extensive research including experimental and numerical analysis has been performed in the over 30 years, experimental studies such as the 1:4 scale PCCV test model at Sandia National Laboratory in USA [1], focus on the ultimate capacity pressure of the containment. Regarding numerical analysis of nuclear containment ultimate pressure capacity under accident conditions, the development of nonlinear finite element solution techniques is rapid. The commercial finite element analysis software and the numerical simulation approach had been widely used in nuclear industry. Hu et.al conducted an analytical study using ABAQUS finite element program to predict the ultimate pressure capacity of the PWR prestressed concrete containment at Maanshan nuclear power plant [2]. The effect of the structural behavior and integrity of nuclear

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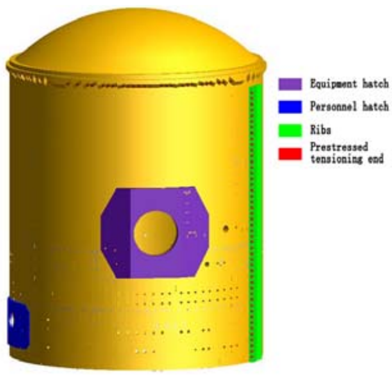
containment had been extensively studied [3]. Recently, Zhou et.al [4] used Monte Carlo method to conduct structural fragility analysis and compare the structural fragility curve calculated with NPP design codes with consideration of material uncertainty. The United States Nuclear Regulatory Commission (NRC) has released a policy statement encouraging the use of probabilistic risk assessment method in all areas of regulatory decision-making and probabilistic risk assessment approach had been used in deciding plant specific changes to the licensing basis [5]. Probabilistic finite element investigation in conjunction with finite element analysis gives a new way to account for uncertainties associated with the calculation of ultimate pressure for the real scale concrete containment structures[6].So it is imperative to investigate the performance of the containment under accident scenario, meanwhile, the above mentioned studies mostly are deterministic studies of the containment structures, but such deterministic numerical and experimental studies do not give any insight into the reliability of the containment under beyond design basis events. What's more, due to the heavy computational work for complex structures like containment structures and low efficiency of Monte Carlo Sampling approach, the prestressed tendons are usually modeled with smeared reinforcement or a shell layer, the non-uniform force losses are not considered [7]. Last but not least, fragility of the containment structures with consideration different types of uncertainty and fragility curves for different locations of the containment is not thoroughly investigated. See the drawbacks and limitations as previously mentioned. This paper presents fragility analysis of containment structures from innovative perspective. The originality and significance of this paper are addressed in the following aspects:

- Detailed FE model of containment is established and the state-of-art sampling technique-Latin Hypercube Sampling approach with consideration the non-uniform effective prestressing distribution of the length of the tendons is included.
- Fragility in different locations and different confidence levels with consideration aleatory randomness and epistemic uncertainty had been thoroughly investigated to get profound insight into the pressure capacity and safety margin of the containment.
- Sensitivity analysis for input random variables had been conducted to provide better understanding of the significance of the various factors that contribute to the risk.

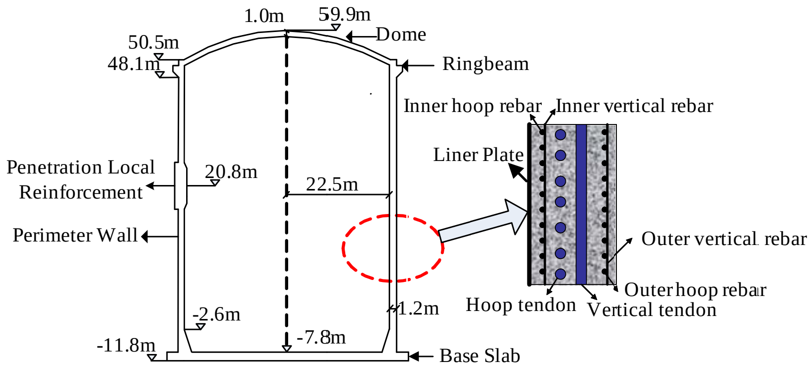
2. Modelling of the Containment

2.1 Containment geometry

The containment is a typical prestressed concrete pressure vessel with an internal metal liner, this PCCV model is composed of a circular base slab, an upright cylinder and a hemispherical dome. In addition, there are penetrations in the containment including equipment hatch, two Personnel airlocks, major pipe penetrations. Two buttresses are designed vertically and are projected to the outside surface of the cylindrical wall. Two layers of reinforced steel bars are embedded along the vertical and hoop direction in the concrete wall, the interior surface of the containment is lined with steel liner to provide leak-tightness. Prestressed tendons are placed in two orthogonal directions in the containment wall. Sketch of the PCCV model is shown in Fig. 1.



(a) 3D schematic diagram of containment



(b)Sectional view of containment

Figure 1.Schematic diagram of containment

All the dome tendons are tensioned from both ends and anchored at the vertical exterior side of the ring beam. Horizontal tendons are anchored between alternate buttresses. The vertical tendons are anchored at the bottom of the base slab in the tendon gallery and on top of the ring beam. The effective stress in prestressed tendons considers the short-term (right after transfer of prestressing) and the long-term losses (at the end of plant life) with respect to Eurocode [8].

To reflect the behavior of containment under accident scenarios with desired accuracy, all penetrations such as equipment hatch, two personnel airlocks, main stream lines penetrations and local stiffening of the cylindrical wall are modeled. To perform fragility analysis, the probability distribution of each random variable has been selected based on relevant literatures [9]. Due to coupling relation between the compressive and the tensile strength and elasticity modulus of concrete, the number of random variables can be reduced. For the sake of simplicity, the variation of material density and poisson's ratio is neglected and all the random variables are assumed to follow normal distribution. The materials used in containment and their stochastic mechanical properties are listed in Table1.

Material Name	**Grade**	**Random variable[MPa]**	**Random variable notation**	**Distribution**	**Mean[MPa]**	**COV**
Concrete	C60	f_c	x_1	Normal	58	0.14
Reinforced steel bars	HRB500	f_y	x_2	Normal	543	0.05
		E_y	x_3	Normal	200000	0.03
Prestressed tendons	54T15	f_p	x_4	Normal	1878	0.07
		E_p	x_5	Normal	200000	0.03
Steel liner	P265GH	f_s	x_6	Normal	325	0.07
		E_s	x_7	Normal	200000	0.03
Electrical penetration assemblies	P265GH	f_a	x_8	Normal	325	0.07
		E_a	x_9	Normal	200000	0.03

Table1 Statistics characteristic of random variables

Note: f_c is compressive strength of concrete; f_y is yield strength of reinforced steel bar; E_y is modulus of elasticity of reinforced steel bar; f_p is yield strength of prestressed tendons; E_p is modulus of elasticity of prestressed tendons; f_s is the yield strength of steel liner; E_s is modulus of elasticity of steel liner; f_r is yield strength of electrical penetration assemblies; E_r is the modulus of elasticity of electrical penetration assemblies.

2.2 Constitutive models

2.2.1 Concrete

In this paper, the uniaxial stress-strain curve of concrete is determined according to the Chinese code for design of concrete structures [10]. The constitutive relationship of concrete is shown in Fig. 2.

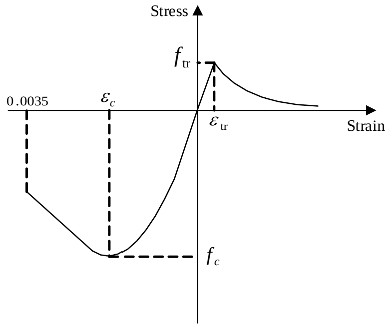


Figure 2. Uniaxial stress-strain curve of concrete

2.2.2 Steel liner and reinforced steel bar

Reinforced steel bar used in the containment is HRB500. In this paper, the elastic modulus is assumed as 200000MPa and the poisson's ratio assumed as 0.3. The steel liner is made up from P265GH and its elastic modulus and poisson's ratio are the same as reinforced steel bar. The reinforced steel bar and steel liner material constitution is illustrated in Fig. 3. Both the reinforced steel bar and steel liner is assumed to be elastic-perfectly plastic.

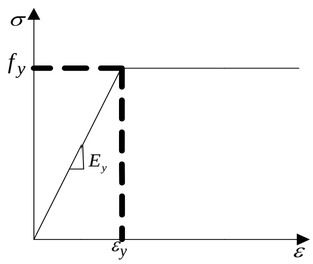


Figure 3. Constitution for reinforced steel bar and steel liner

2.2.3 Prestressed tendons

Bilinear elasto-plastic behavior is used for the stress-strain curve of prestressed tendons, at the same time, kinematic hardening model with Von-Mises failure criterion is used for prestressed tendons. Constitution of prestressed tendons is indicated in Fig.4. Where ε_p , ε_u , f_u and E'_p denote the yield strain, strain at the ultimate strength, ultimate strength and hardening modulus for prestressed tendons, respectively. These values are calculated with respect to the relevant code [8].

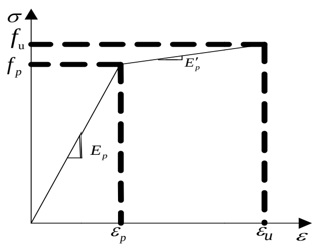
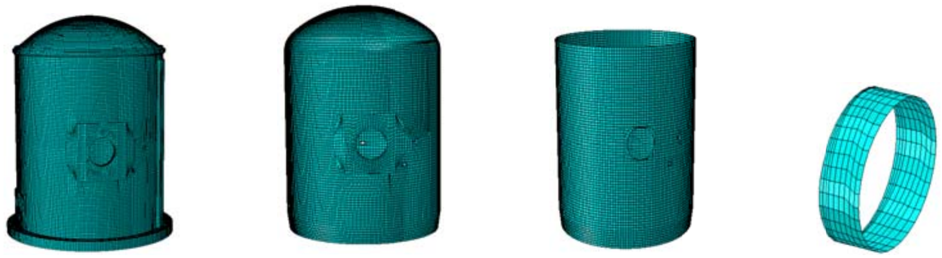


Figure 4. Stress–strain curve for prestressed tendon

2.3 Finite Element mesh and constraints

The concrete structure was meshed using reduced integrated 8-noded brick element (C3D8R in ABAQUS). Moreover, there have been some wedge elements of type C3D6 element at penetrations. The steel liner and electrical penetration assemblies were modelled by fully integrated 4-noded general shell elements and some reduced integrated 4-noded general shell elements (S4R) and some reduced integrated 3-noded general shell elements(S3) at discontinuity zones. Prestressed tendons were meshed by fully integrated 2-noded truss elements (T3D2 element). The surface elements (SFM3D4) are used to represent each layer of reinforcing steel rebar. The steel liner and electrical penetration assemblies at penetrations were defined as the skin of the concrete solid elements, which share the same node with concrete solid element. All prestressed tendons and reinfored steel bars were embedded into concrete solid element with embedded technique and the sliding effect is ignored [11]. The finite element models of the containment structures are shown in Fig.5.



(a)Concrete (b)Steel liner (c)Reinforced steel bar layer (d)Electrical penetration assemblies

Figure 5.Mesh of containment FE model

2.4 Loading procedure and boundary conditions

All degrees of freedom at the bottom of the containment model were constrained (as shown in Fig. 6).The analysis process is divided into two steps. For the first analysis step, the gravity load and the prestressing are applied to containment structure. In next step, the linearly increasing internal pressure is applied uniformly on the internal surface of the containment.

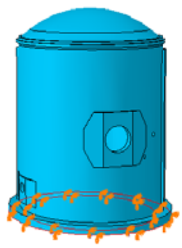


Figure 6. Boundary conditions of the containment

2.5. Mesh sensitivity analysis

Choosing appropriate mesh density is of great significance for finite element analysis, the mesh size can neither be too large nor too small. If the mesh size is too large, the accuracy of the results is low, if the mesh size is too small, the computational work is heavy but accuracy is not obviously improved. What's more, for concrete materials, the calculation results are sensitive to the mesh size because of its cracking characteristics [12].So mesh sensitivity is conducted to determine the appropriate mesh size. The maximum strain of steel liner versus internal pressure for different mesh size is plotted in Fig.7. It can be seen that, except for mesh size 1.2m condition, the predicted results are close to each other. It indicates that the calculated results are sensitive to mesh density when the mesh size is higher than 1.0m. So the mesh size of 1.0m is adopted in this paper.

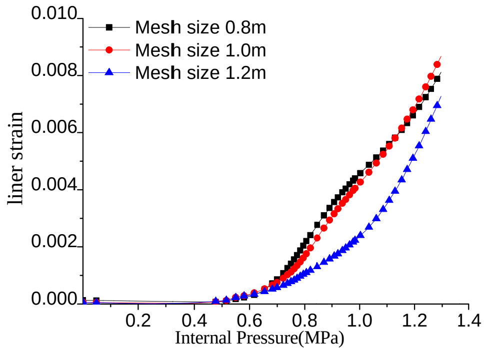


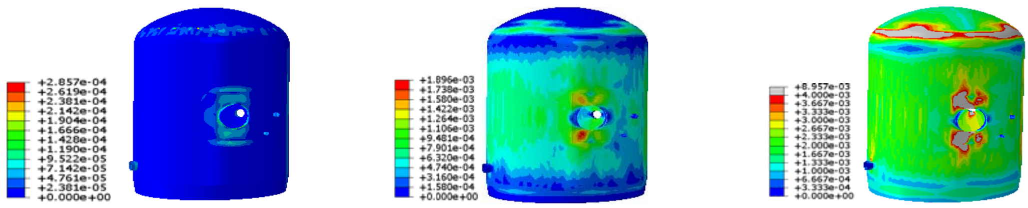
Figure 7. Maximum liner strain versus internal pressure

2.6. Failure Criteria

There are two different types of containment failures (i.e. functional failure and structural failure [13]). The functional failure denotes that the containment loss its function, i.e. a leak rate exceeds the maximum requirement. The structural failure is mainly measured by stress or strain of structures such as prestressed tendons and reinforced steel bars. The functional failure is measured by leakage rate, and mainly depended on the integrity of the steel liner. The functional failure is in general assumed to be the most probable failure type. So in this paper, the failure criteria is based on functional failure which is defined here as the critical loading in the response where the principal strain in the liner at a location reaches a value of 0.004 [14].

3. Nonlinear response of the containment under different pressure level

For steel liner, the strain is relative small at lower pressure condition, the maximum strain is occurred near the equipment hatch due to the strain concentration effects. When the internal pressure reaches 0.84MPa, the steel liner in the cylinder wall location is increasing rapidly. The maximum strain near the equipment hatch is about 0.2% .When the internal pressure goes up to 3 times of the design pressure, the strain near the equipment hatch and geometry discontinuity zones of dome became tremendous high. The strain in these locations is beyond 0.4% which means that the liner in those locations begins to loss their functions as mentioned previously.The strain distribution of the steel liner is depicted in Fig. 8.



(a) *(b)* *(c)*

Figure 8. Maximum principal strain distribution of steel liner under different pressure level (a)0.42MPa, (b)0.84MPa and (c)1.26MPa

4. Fragility analysis of the containment

4.1 Latin Hypercube Sampling Method

Latin hypercube sampling (LHS) is widely used random sampling method for Monte Carlo-based uncertainty quantification and reliability analysis in computational science, engineering and mathematics [15].This method was first developed by McKay et.al [16].The main ingredients for LHS sampling approach can be summarized as following:

1) Dividing cumulative distribution of each variable into N intervals. Each input random variable x_i, $i=1,2,...,K$ is described with known statistical probability parameters (such as the cumulative distribution function $F(x_i)$ and mean value and standard deviation of random variable x_i), The cumulative distribution function $F(x_i)$ is divided into N intervals with equal probability of $1/N$.

2) Coupling of input variables with tables of random permutations of rank numbers to obtain a $N \times K$ design matrix. Each row of the design matrix is used for computer simulation to obtain the correspond output Y_i. N Simulations can get an output $Y = [Y_1, Y_2, ..., Y_N]^T$, after that statistical characteristic can be evaluated.

4.2 Fragility analysis process

Firstly, the refined three-dimensional FE model of prestressed concrete containment vessel was built by the commercial program ABAQUS. Secondly, Latin hypercube sampling Matlab [17]code had been developed to generate stochastic FE samples which consider material uncertainties, thirdly, the customed-based computing program is used to generate material data files. Since ABAQUS is a deterministic FEA software, python development environment is used for developing the deterministic FE model and then for updating the uncertain input parameters for each FE simulation[18]. Fragility analysis process for the containment in this paper is shown in Fig. 9.

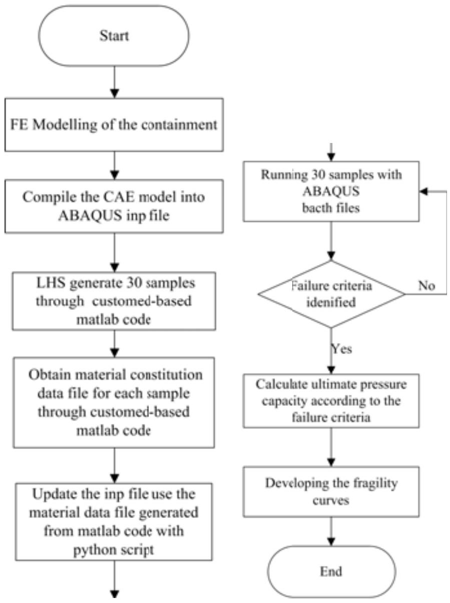


Figure 9. Flowchart for containment fragility analysis

4.3 Fragility results analysis

Based on the analysis of the 30 samples of the FE model of containment, the failure results of 30 samples correspond to the above mentioned criterion had been obtained. Fig. 10 presents the distribution of failure internal pressure for 5 critical locations in the containment.

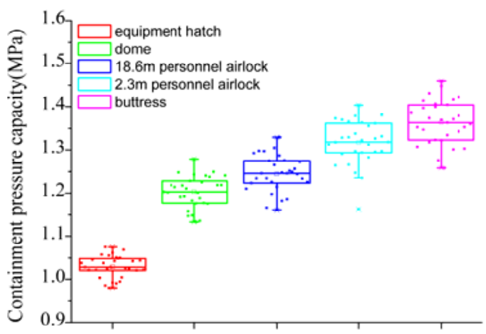


Figure 10. Distribution of pressure capacity for five critical failure location results

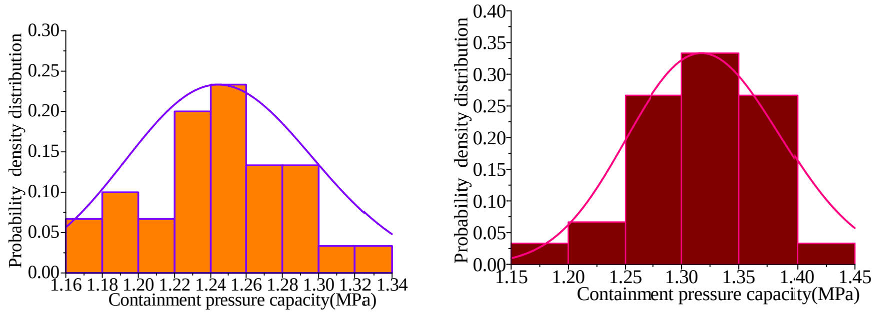
The pressure capacity of the containment generally follows lognormal distribution [19]. However it is only given from engineering experiences, thus it needs theoretical proving. In this paper chi-square goodness-of-fit test [20] is conducted to check whether the lognormal distribution is plausible, test results show the pressure capacity of the containment following the lognormal distribution is acceptable. Table2 provides a summary of Chi-square goodness fit tests (take the failure location at equipment hatch results as an example).

Pressure interval	**Observed frequencies** n_i	**Theoretical frequencies** e_i	$v=(n_i-e_i)^2/e_i$
0.96-0.98	1	0.2509	2.2369
0.98-1.00	4	1.5039	4.1432
1.00-1.02	2	4.9636	1.7695
1.02-1.04	11	8.6865	0.6162
1.04-1.06	9	8.3378	0.0526
1.06-1.08	3	4.5258	0.5144
Summation	30	30	9.3328

Table2 Chi-square goodness-of fitting test results

Note: Critical value of Chi-square distribution for 5% significance level is 11.07.

The histogram and distribution fitting for five critical locations in the containment are shown in Fig. 11. (Only two airlocks are selected to be illustrated here)



(a) *(b)*

Figure 11. Histogram for (a)18.6m Personnel airlock,(b)2.3m Personnel airlock

The uncertainties of the containment include both aleatory randomness and epistemic uncertainty, so the fragility obtained above needs to be modified for engineering practical use. There are three types of uncertainties, i.e. geometric uncertainty, structural analysis uncertainty β_1 (which is considered as epistemic uncertainty), material properties uncertainty β_2 (which is considered as aleatory randomness).The overall uncertainty in the containment capacity is generally insensitive to variations in geometric properties [21], so the geometric uncertainty is negelcted in this paper.The median capacity and coefficient of variation with consideration material uncertainty are dertermined from the results of the 30 samples using the following formula:

$$p_m = \exp\left(\frac{1}{30}\sum_{i=1}^{30}\ln p_i\right) \tag{1}$$

$$\beta_2 = \sqrt{\frac{1}{29}\sum_{i=1}^{30}(\ln p_i - \ln p_m)^2} \tag{2}$$

Table3 lists the mean p_m and the corresponding variation parameter β_2 for the above mentioned five critical locations.

Critical failure locations	p_m	β_2
Buttress	1.364	0.037
Equipment hatch	1.029	0.025
18.6mPersonnel airlock	1.244	0.034
2.3m Personnel airlock	1.316	0.039
Dome	1.203	0.030

Table3 Parameters of fragility curves

To obtain fragility curves with consideration of two types of uncertainties so that it can be more applicable for engineering use. In this paper, the fragility curves for containment with consideration of material uncertainties had been modified.The composite standard deviation by uncertainty analysis was also obtained by SRSS combination rules [22]:

$$\beta = \sqrt{\beta_1^2 + \beta_2^2} \quad (3)$$

Reference [23] suggests a value of 0.12 for structural analysis uncertainty. the composite fragility curves consider two types of uncertainty can expressed as:

$$p_f(p) = \Phi\left(\frac{\ln(p/p_m)}{\beta}\right) = \int_{-\infty}^{p} \frac{1}{\sqrt{2\pi}\cdot\beta\cdot p} \exp\left\{-\frac{\ln(p/p_m)}{2\beta^2}\right\} dp \quad (4)$$

Where p is the internal pressure.

It is clear from Fig.12 that the failure location of equipment hatch is the controlling failure location for the five critical failure locations. Except for the failure location of buttress case, the other four cases show small difference in fragility curves.

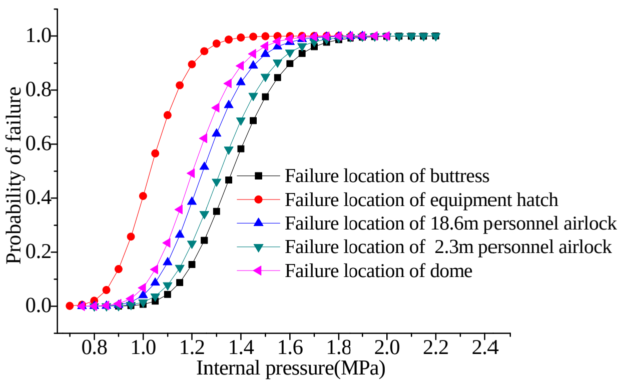


Figure 12. Composite fragility curves for five critical failure locations

4.3 Sensitivity analysis

The sensitivity analysis is very useful in engineering field, through sensitivity analysis, the dominant uncertainty parameter which contributes most to the analysis results can be identified and then it can allow us better make the decision on how to allocate resources. In general, these can be divided into local and global sensitivity analysis [24]. The local sensitivity measures determine the influence of parameters by varying one parameter at a time and keeping the other parameters constant. Global sensitivity analysis considers uncertainties of all parameters simultaneously and evaluates their joint contribution to the analysis results. The problem arising with different variables being measured in different units can be eliminated by standardizing all variables [25]:

$$x_i^* = (x_i - \bar{x}_i)/\sigma_{x_i} \quad (5)$$

Where x_i is random variable, $\bar{x}_i$ and σ_{x_i} are the mean value and standard deviation, respectively.

So the construction of regression models which approximate the response surface is calculated as:

$$Y^* = \lambda_0 + \sum_{i=1}^{n} \lambda_i \cdot x_i^* \tag{6}$$

Where λ_0 and λ_i are multiple linear regression constant and regression coefficients, respectively.

The larger the absolute value of a_i^*, the more influence of the random variable x_i.The normalized sensitivity factor s_i for input random parameter can be rewritten as follow:

$$s_i = \frac{\lambda_i}{\delta_i} \tag{7}$$

Where δ_i is the coefficient of variation for input random variable x_i.

The sensitivity factor for input stochastic variables for five critical failure locations based on multiple linear regression are listed in Table5. It should be noted that the larger the absolute value of s_i the more influence of the parameter x_i.The random input parameter x_5 (material modulus factor) demonstrates the greatest impact on pressure capacity for the five critical locations .While the other parameters do not show the consistent tendency on pressure capacity for the five critical locations.

sensitivity factor	**Critical failure locations**				
	Equipment hatch	**Dome**	**18.6m Personnel airlock**	**2.3m Personnel airlock**	**Buttress**
S_1	0.067	0.049	-0.020	-0.152	-0.072
S_2	0.024	0.066	0.138	-0.130	0.452
S_3	0.230	0.038	0.142	-0.014	0.142
S_4	0.016	-0.010	0.020	-0.110	0.039
S_5	0.320	0.618	0.730	0.522	0.644
S_6	0.199	0.163	0.093	0.176	0.123
S_7	0.012	0.024	-0.044	0.112	0.058
S_8	-0.017	0.004	0.069	0.436	0.016
S_9	-0.006	-0.040	-0.016	-0.656	-0.112

Table5 Normalized sensitivity factor for five critical locations

5. Conclusion

Fragility analysis of prestressed concrete containment vessel had been conducted with state of the art sampling techniques LHS method based on detailed three-dimensional FE model with consideration non-uniform pre-stressing distribution, nonlinear behavior of materials, fragility curves for five critical locations under different confidence levels with the consideration of different types of uncertainties had been investigated. Sensitivity analysis is conducted for the input random variables to gain insight into the contribution of different random variables. The following conclusions can be made:

(1) The equipment hatch is most vulnerable location for the five critical locations. The functional failure of the containment is dominated by the equipment hatch.

(2) Elastic modulus of prestressed tendon is the most dominant factors with regard to input uncertainties.

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