Probabilistic Assessment of the Ultimate Pressure Capacity of the Prestressed Concrete Containment Buildings

Hyung Kui PARK[1], Daegi HAHM[2], Min Kyu KIM[3]

[1] *Korea Atomic Energy Research Institute: 989-111 Daedeik-daero, Yuseong-gu, Daejeon, 305-353, hyungkui@kaeri.re.kr*
[2] *Korea Atomic Energy Research Institute: 989-111 Daedeik-daero, Yuseong-gu, Daejeon, 305-353, dhahm@kaeri.re.kr*
[3] *Korea Atomic Energy Research Institute: 989-111 Daedeik-daero, Yuseong-gu, Daejeon, 305-353, minkyu@kaeri.re.kr*

In this study, the probabilistic internal pressure fragility analysis was performed by using the non-linear finite element analysis method. The target structure is one of the containment buildings of the Korean standard nuclear power plant. The 3-dimensional finite element model of the containment building was developed with considering the large equipment hatches. To consider uncertainties in the material properties and structural capacities, we performed the sensitivity analysis of the ultimate pressure capacity with respect to the variation of four important uncertain parameters. The results of the sensitivity analysis were used to the selection of the probabilistic variables and the determination of their probabilistic parameters. To reflect the present condition of the tendon pre-stressing force, the data of the pre-stressing force acquired from the in-service inspections of tendon forces were used for the determination of the median value. Two failure modes (leak, rupture) were considered and their limit states were defined to assess the internal pressure fragility of target containment building. The results of the sensitivity analysis were used to the selection of the probabilistic variables and the determination of their probabilistic parameters. To reflect the present condition of the tendon pre-stressing force, the data of the pre-stressing force acquired from the in-service inspections of tendon forces were used for the determination of the median value. Two failure modes (leak, rupture) were considered and their limit states were defined to assess the internal pressure fragility of target containment building. The internal pressure fragilities for each failure mode were evaluated in terms of median internal pressure capacity, high confidence low probability of failure (HCLPF) capacity, and fragility curves with respect to the confidence levels. The HCLPF capacity was 115.9 psig for leak failure mode, and 125.0 psig for rupture failure mode.

I. Introduction

As can be seen from the Fukushima nuclear power plant accident, the containment building is the final protecting shield to prevent radiation leakage. Thus, a structural soundness evaluation for the containment pressure loads owing to a severe accident is very important. Recently, a probabilistic safety assessment has been commonly used to take into account the possible factors of uncertainty in a structural system. An assessment of the internal pressure fragility of the CANDU type containment buildings considering the correlation of structural material variables [1], and an assessment of the internal pressure fragility of the CANDU type containment buildings using a nonlinear finite element analysis, were also performed [2]. However, for PWR type containment buildings, a fragility assessment has not been performed yet using a nonlinear finite element model (FEM) analysis

In this study, the probabilistic internal pressure fragility analysis was performed by using the non-linear finite element analysis method. The target structure is one of the containment buildings of the Korean standard nuclear power plant. The 3-dimensional finite element model of the containment building was developed with considering the large equipment hatches. To consider uncertainties in the material properties and structural capacities, we performed the sensitivity analysis of the ultimate pressure capacity with respect to the variation of four important uncertain parameters. The results of the sensitivity analysis were used to the selection of the probabilistic variables and the determination of their probabilistic parameters. To reflect the present condition of the tendon pre-stressing force, the data of the pre-stressing force acquired from the in-service inspections of tendon forces were used for the determination of the median value. Two failure modes (leak, rupture) were considered and their limit states were defined to assess the internal pressure fragility of target containment building.

II. Finite Element Model of Containment Building

The PWR containment building is composed of a foundation slab, cylindrical wall, and an upper dome. It is a pre-stressed concrete structure. The vertical and horizontal tendons were placed in a cylindrical wall and the upper dome. Three buttresses are located in a cylindrical wall for the horizontal tendons to settle. Figure 1 shows the whole finite element modeling of the containment building. Figure 2 shows the tendon arrangement of the containment building. Figure 3 shows the rebar arrangement of the containment building.

The material properties of the containment building are organized in Tables 1. The material properties of the tendon are organized in Tables 2. The concrete damaged plasticity model [3], [4] was used for the concrete material model. The variables for configuring the model of material are organized in Tables 3. The steels in the tendon, rebar, and liner were modeled using the piecewise-linear stress-strain curves.

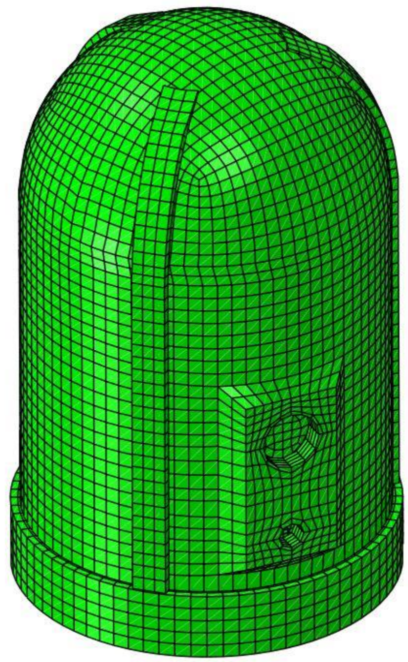
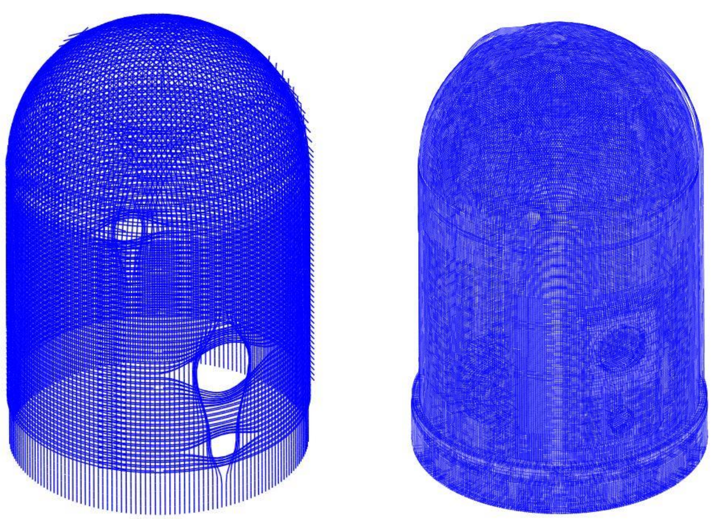


Fig. 1. The finite element model of the prestressed containment building.



(a) Tendon (b) Rebar

Fig. 2. The shape of finite element model of rebar and tendon

Table 1. The material Properties of the containment building (psi)

Category	Foundation slab	Wall, dome
Compressive strength	4000	5500
Tensile strength	474	556
Modulus of elasticity	4230000	
Density(lb/in³)	0.00022	
Poisson ratio(%)	0.17	

Table 2.The material Properties of the tendon (psi)

Ultimate tensile strength	1861.6MPa	
Section of tendon	54.3cm2	
Number of tendon	Vertical direction	Reverse U 96EA
	Circumferential direction of wall	135EA
	Circumferential direction of dome	30EA
Tensile force	43.4MPa	

Table 3. The variables for configuring the model of material

Variables	Value
Dilation angle (Dilation angle in the p–q plane)	36.0
Flow potential eccentricity, ε	0.10
fb0/fc0 (The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress)	1.16
KC (The ratio of the second stress invariant on the tensile meridian)	0.667
Viscosity Parameter, μ	0.00

III. Sensitivity Analysis and Fragility Assessment

I.A. The Selection of the Probabilistic Variables

To consider uncertainties in the material properties and structural capacities, we performed the sensitivity analysis of the ultimate pressure capacity with respect to the variation of four important uncertain parameters. To evaluate the influence of variables, we developed four case of analysis model. The variables for four cases of analysis model are organized in Tables 4.

Table 4. The assumptions of factors affecting the sensitivity

	Items	Range of volatility(%)
Case1	Tensile strength of concrete	±30
Case2	Tensile force	±10
Case3	Thickness of steel liner	
Case4	Strength of steels	

I.B. The Results of the Sensitivity Analysis

The results of the sensitivity analysis were used to the selection of the probabilistic variables and the determination of their probabilistic parameters.

Figure 3 shows the result of the sensitivity analysis about strain of liner. Figure 4 shows the result of the sensitivity analysis about strain of tendon. The results at the point of maximum response were analyzed. Figure 5 shows the result of the sensitivity analysis.

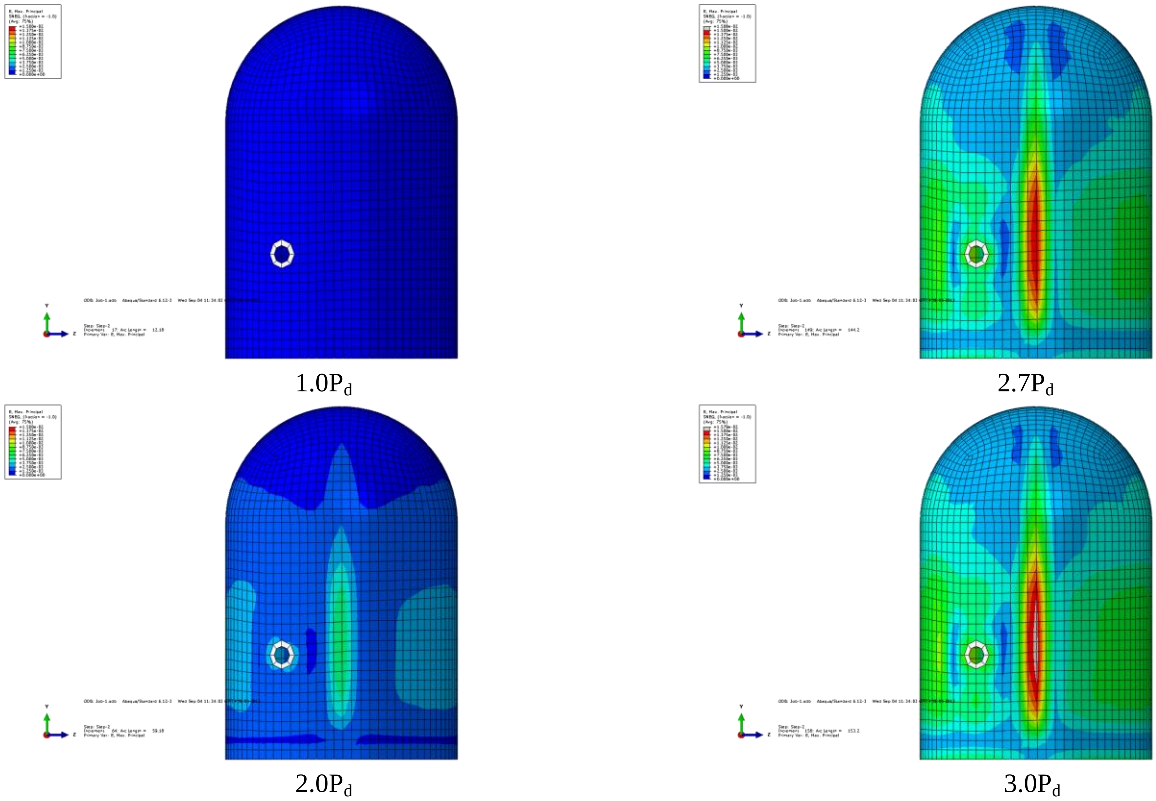


Fig. 3. The result of the sensitivity analysis about strain of liner

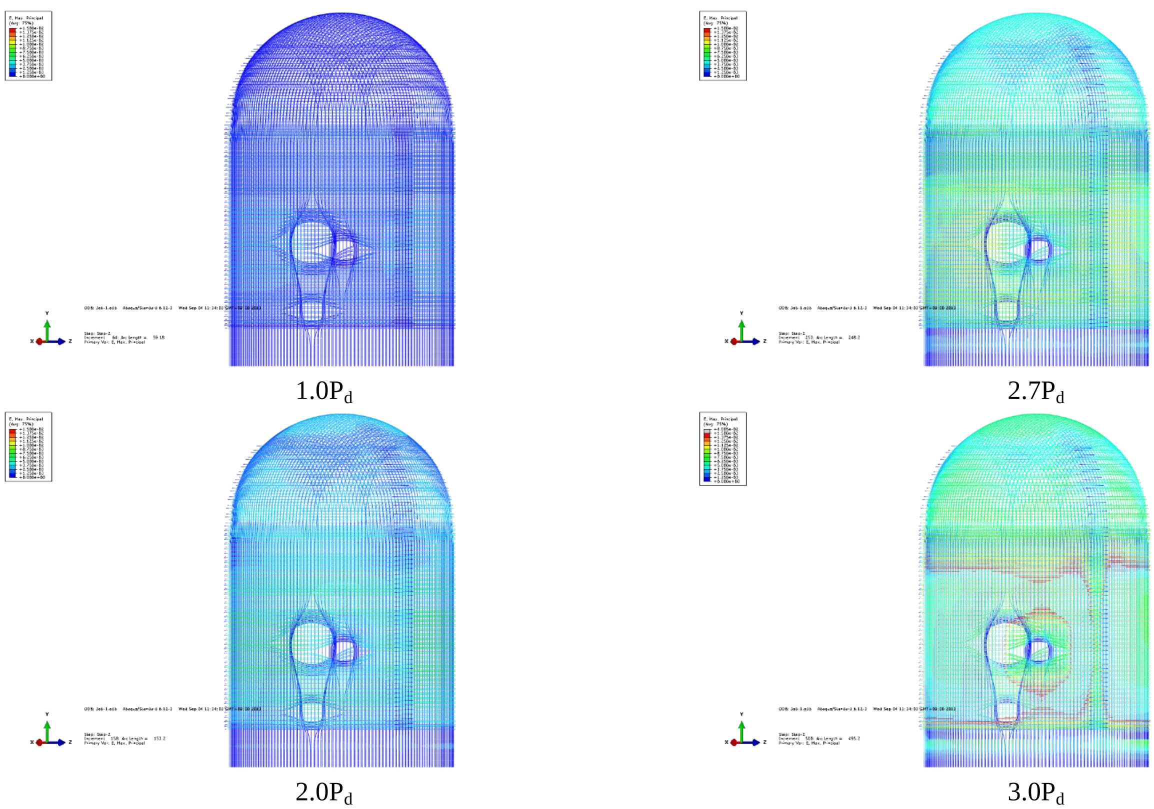
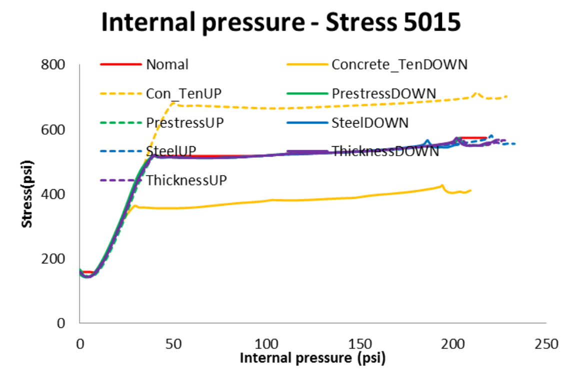
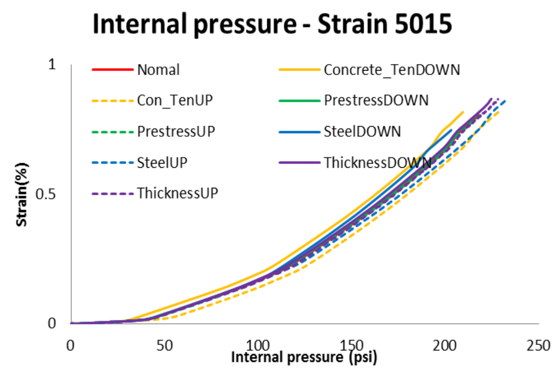


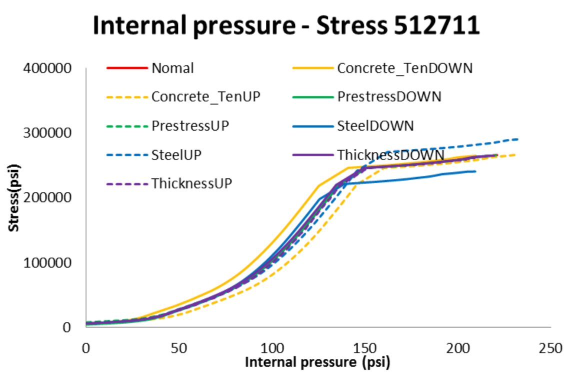
Fig. 4. The result of the sensitivity analysis about strain of tendon



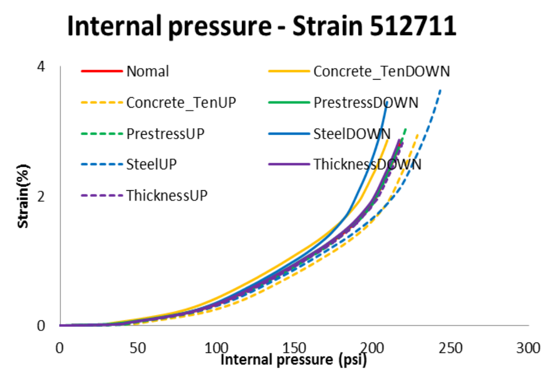
(a) Inner pressure-Stress of concrete



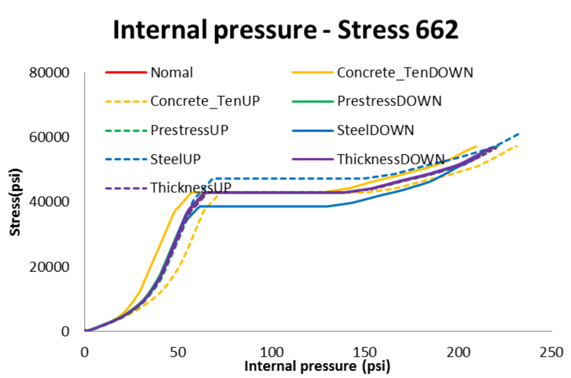
(b) Inner pressure-Strain of concrete



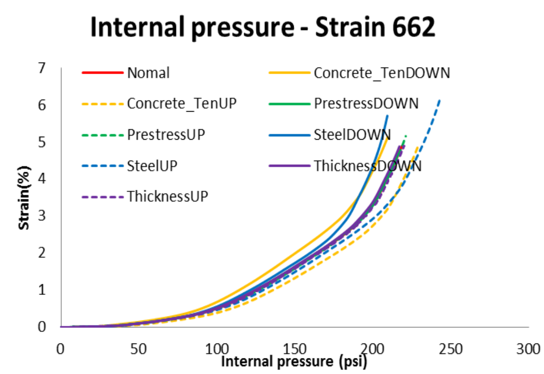
(c) Inner pressure-Stress of tendon



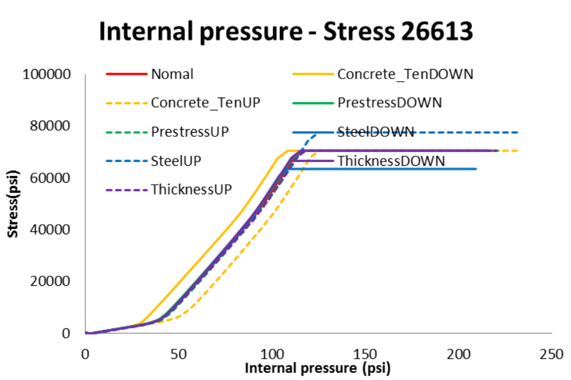
(d) Inner pressure-Strain of tendon



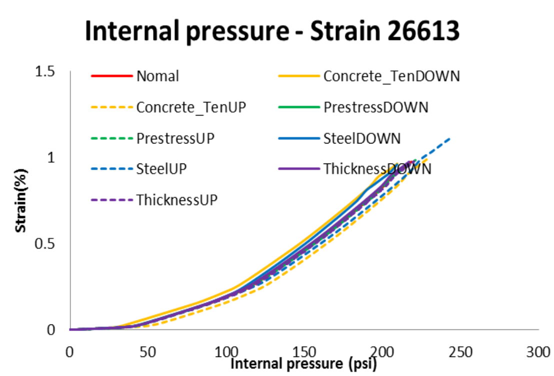
(e) Inner pressure-Stress of liner



(f) Inner pressure-Strain of liner



(g) Inner pressure-Stress of rebar



(h) Inner pressure-Strain of rebar

Fig. 5. The result of the sensitivity analysis

Figure 5 (b) shows the changes in the compressive strength of concrete based on the results of a sensitivity analysis. Based on 3Pd(171 psi), a ±10.2% difference in response occurred.

Figure 5 (d) shows the changes in the steel strength based on the results of the sensitivity analysis. Based on 3Pd(171 psi), a ±6.7% difference in response occurred. The changes in the pressure response were considered to have occurred owing to changes in the material strength. The Comparing analysis results of factors affecting the sensitivity are organized in Tables 5.

Table 5. The Comparing analysis results of factors affecting

Items		Concrete	Rebar	Steel liner	Tendon
Strength of concrete	+	12.6	6.3	7.6	4.0
	-	12.5	6.3	7.0	4.0
Strength of steel	+	0.0	1.7	2.5	1.5
	-	0.0	1.1	1.3	7.0
Thickness of steel liner	+	1.1	1.1	1.9	0.5
	-	0.9	1.1	0.6	0.5
Tensile force	+	0.4	0.0	0.6	0.0
	-	2.6	0.0	0.0	0.0

I.C. The Results of the Fragility Assessment

For the internal pressure fragility assessment, 30 sets of an FE model considering the material uncertainty of concrete and steel were established. With this input FE model, we performed an UPC analysis, and assessed the internal pressure fragility capacity. For the target containment building, the median capacity of the liner leakage is estimated as 116 psi. The median capacity of the rebar and tendon rupture is about 196 psi and 141 psi, respectively.

Figure 6 shows the fragility curves of the leak. Figure 7 shows the fragility curves of the rupture.

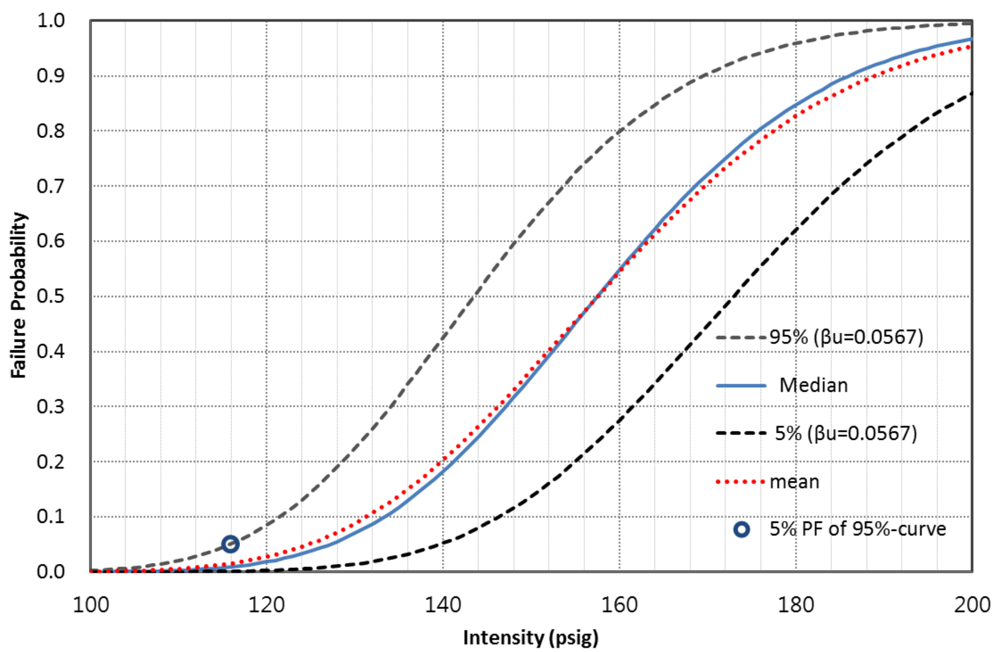


Fig. 6. The fragility curves of the leak

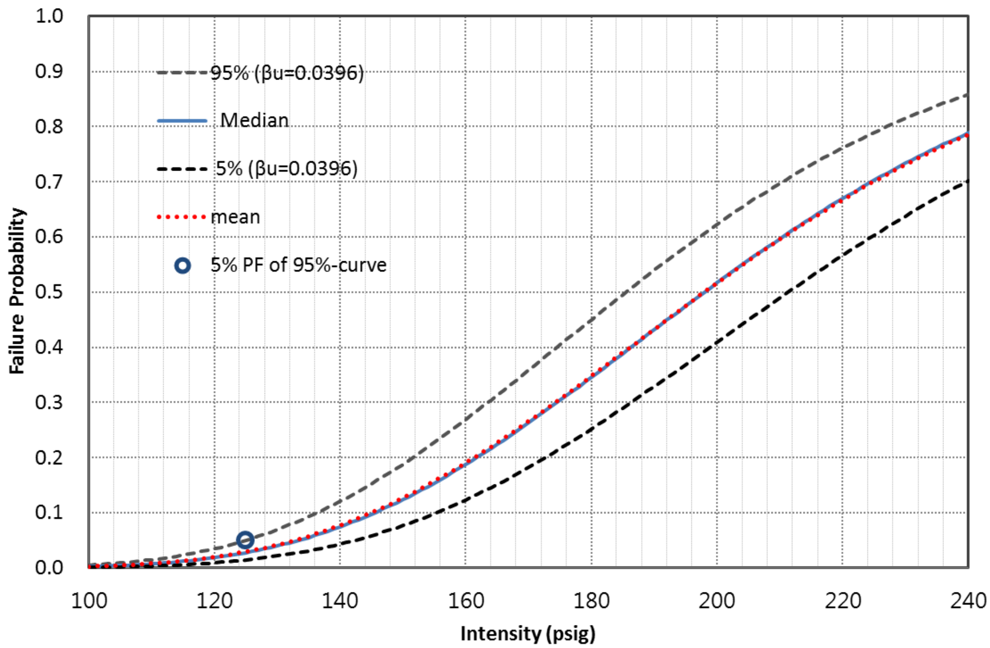


Fig. 7. The fragility curves of the rupture

IV. Conclusions

A nonlinear finite element analysis of the PWR containment building was performed for a material sensitivity analysis and internal pressure fragility assessment. The sensitivity of the concrete strength is relatively higher compared to that of the steel strength. According to changes in the structure of the material, about 6-10% ultimate internal pressure differences occurred. Thirty sets of an FE model considering the material uncertainty of concrete and steel were composed for the internal pressure fragility assessment.

The internal pressure fragilities for each failure mode were evaluated in terms of median internal pressure capacity, high confidence low probability of failure (HCLPF) capacity, and fragility curves with respect to the confidence levels. The HCLPF capacity was 115.9 psig for leak failure mode, and 125.0 psig for rupture failure mode.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No.2012M2A8A4025985)

REFERENCES

1. Hahm Daegi, Kim Jung Han, Choi In-Kil, Lee, Hong-Pyo, Assessment of Internal Pressure Fragility of Containment Buildings Considering the Correlation of Structural Material Variables, Computational Structureal Engineering Institute of Korea, Conference Paper 2011, p.396-399, 2011.
2. Hahm Daegi, Choi In-Kil, Lee, Hong-Pyo, Assessment of the Internal Pressure Fragility of the CANDU Type Containment Buildings using Nonlinear Finite Element Analysis, Computational Structureal Engineering Institute of Korea, Vol.23-4, p.445-451, 2010.8.
3. Lubliner, J., Oliver, J., Oller, S. and Onate, E. (1989), "A plastic-damage model for concrete," International Journal of Solid and Structures, 25:299-329.
4. Lee, J. and Fenves, G.L. (1998), "Plastic damage model for cyclic loading of concrete structures," Journal of Engineering Mechanics, 124(8):892-900.