Evaluation of the Ultimate Pressure Capacity of PCCV Considering Aging

Sang-Kuen Lee[1)], Sang-Kyun Woo[1)], Young-Chul Song[1)]

1) Korea Electric Power Research Institute, Korea

ABATRACT

This paper is described the evaluation of the ultimate pressure capacity of a prestressed concrete containment vessel (PCCV) considering short-term(5 years) aging of structural materials in service on Yonggwang Nuclear Power Plant Unit 3 (YGN #3) in Korea which was started operation in 1994. The numerical analyses are carried out by using the ABAQUS finite element program on a design criteria condition and aging condition considering material properties changed of time-dependant materials respectively. From the results, it is verified that the structural capacity of the prestressed concrete containment structure of YGN #3 on the present short-term aging condition retains still integrity. In addition, the sensitivity for the reduction of the ultimate pressure capacity of containment according to the degradation levels of the main structural materials is assessed. The results of the sensitivity analysis show that, when the degradations of each materials are considered as individual or combinational forms, the sensitivity for the structural capacity reduction by degradations appears largely in the order of tendon, reinforcing-bar and concrete degradation for the former, and tendon and reinforcing-bar, tendon and concrete, and reinforcing-bar and concrete combinational degradation for the latter respectively.

INTRODUCTION

From a safety standpoint, the containment is one of the most important components of a nuclear power plant (NPP) because it serves as the final barrier to the release of fission products to the outside environment under postulated accident conditions. Ensuring that the structural capacity and leak-tight integrity of the containment has not deteriorated unacceptably due either to aging or environmental stressor effects is essential to reliable continued service evaluations and informed aging management decisions. A major focus of operating plants, therefore, is benchmarking of existing design criteria and assessment of containment performance under severe accident conditions.

Safety-related nuclear power plant structures are designed to withstand loadings from a number of low-probability external and internal events, such as earthquakes, tornadoes, and loss-of-coolant accidents. Loadings incurred during normal plant operation, therefore, generally are not significant enough to cause appreciable degradation. However, these structures are susceptible to aging by various processes depending on the operating environment and service conditions. The effects of these processes may accumulate within these structures over time to cause failure under design conditions, or lead to repair. As an example, time-related aging can affect the ability of a NPP containment to perform satisfactorily in the unlikely event of a severe accident by reducing its structural capacity or jeopardizing its leak-tight integrity. Aging is considered to be any phenomenon that decreases the load-carrying capacity of a containment or reduces the service life[1)].

In this paper, the reduction of structural capacity of a concrete containment by short-term aging is assessed by ultimate internal pressure analysis for YGN #3 in Korea which is started operation in 1994. We, first, surveyed and reported all short-term aging occurred with increasing of service time, and then with considering material properties changed of time-dependant materials the ultimate pressure capacities of concrete containment of YGN #3 under design or short-term aging condition are assessed and compared. Fig. 1 provides a flow diagram which show an approach process adopted here for the structural capacity evaluation of NPP concrete containments in service. In addition, to assess as numerical quantity the structural capacity reduction due to a individual or combinational degradation among main structural materials: concrete, tendon and reinforcing bar (rebar), the sensitivity analysis for the reduction of the ultimate pressure capacity of a concrete containment according to the degradation levels of them is followed.

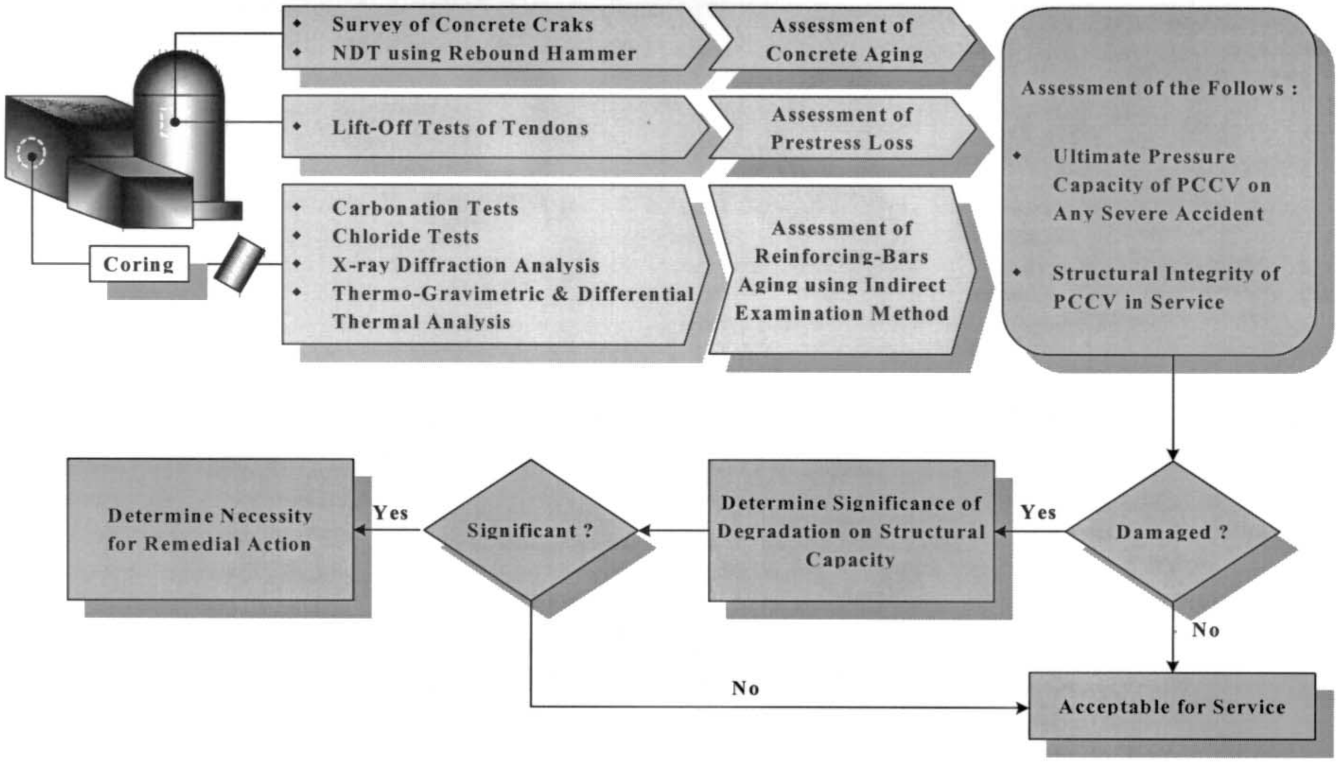

Fig. 1. Structural integrity evaluation process for containment in service

Description of the Structure

The prestressed concrete containment building which hosts the reactor core and its cooling system consists of a massive foundation slab and a vertical cylindrical wall closed on the upper part by a hemispherical dome. The structure has an additional prestressing system for the wall and the dome consisting of non-adherent tendons, and its interior is protected with a steel liner having a sealing role. Fig. 2 shows vertical and horizontal cross-sections of the structure, including the main geometrical parameters for YGN #3 containment what the design pressure is 54 psi. The most important dimensions of the structure are: interior diameter of the wall 144 ft, interior total height 219 ft, interior height of the cylinder 47 ft, thickness of the foundation slab 12 ft, thickness of the cylindrical wall 4 ft, thickness of the dome at its highest point 3 ft 6 inch average liner thickness 1/4 inch.

There are three vertical buttresses on the outer side of the cylindrical wall spaced at 1208, which serve as support for the horizontal prestressing system. The penetrations in the cylindrical wall are: the personnel airlock, the equipment hatch, the emergency airlock, the main steam penetration, the fuel transfer penetration and the purge line penetration.

The prestressing system is shown in Fig. 2. There are 135 horizontal wall tendons and 30 dome tendons, with 2408 each, anchored in the three buttresses and 96 vertical tendons in two families (N-S, E-W) anchored in a perimetrical gallery located in the lower part of the foundation slab.

INVESTIGATION OF AGING PHENOMENA

To detect short-term aging phenomena on YGN #3 containment, a visual survey and some precision examinations are conducted. In results of the visual survey, there are not detected any large faults (surface cracks, spallings, and water leakage) that can affect to the structural capacity of containment. And, as a means of precision examinations the nondestructive strength evaluation of concrete using the rebound hammer on the wall surface of the containment and the prestress loss evaluation of tendon using the lift-off tests on the post-tensioning system are applied. For the other examination items (carbonation depth, chloride testing, X-ray diffraction analysis, thermo-gravimetric and differential-thermal analysis) which essentially are required coring for the structure body, here are indirectly performed them on some safety-related NPP structures located around the containment. The reason is to avoid any structural injury in side of safety and protection for the containment. From these results there is defined the present short-term aging condition of YGN #3 containment as follows.

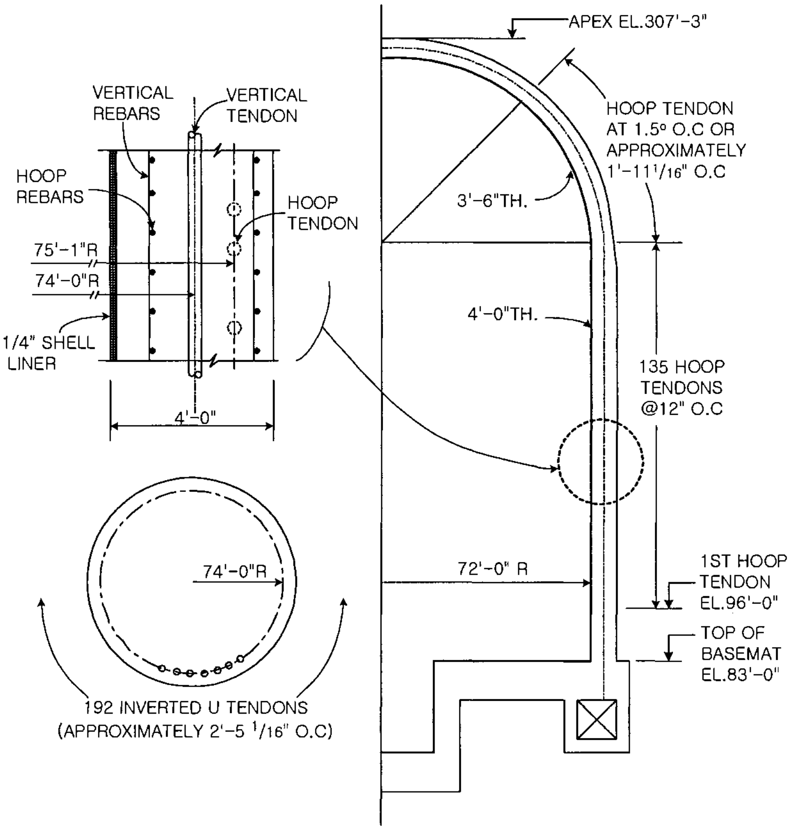

Fig. 2 Axisymmetry Geometry of YGN #3 Containment

Concrete

From a visual survey, there were not quite detected any serious cracks which are able to affect to the structural capacity of YGN #3 containment. A few cracks detected in visual survey only are micro material cracks by initial hydration heat and shrinkage, which may be almost occurred in initial construction condition. In assessing a ultimate pressure capacity of YGN #3 containment in this investigation, therefore, the concrete cracks could be excluded in considering items because these micro cracks cannot affect to structural capacity of the containment.

The design criteria strength of the wall and dome concrete for YGN #3 containment is 5500psi (385kgf/cm^2) in concrete age 91 days. In the present time, when the age of YGN #3 is 5 years, but, the nondestructive concrete strength evaluated using a rebound hammer was assessed as a 40% lager strength, 7600psi (535kgf/cm^2), than the design criteria. In addition, the young modulus could be calculated by the equation provided in ACI-349[2)] using the present nondestructive concrete strength. Here concrete strength and young modulus will be used as the inputs in nonlinear FE analysis of YGN #3 containment considering short-term aging condition.

Steel Reinforcing Bars

Numerous reinforcing bars are arranged as double reinforcement form with a grid net in the wall, dome and base of a concrete containment. Because, it is impossible that the corrosion of the reinforcing bars is assessed to a numerical quantity on considering the latest technical level for a nondestructive corrosion measurement for embed reinforcing bars. In this paper, therefore, an indirect estimation method is used to find whether the corrosion is occurred in surface of reinforcing bars. The method is one using the safety-related structures that are exposed to the same environment with containment. There are first taken the concrete cores as the required number from the safety-related structures that are auxiliary control building, fuel storage facility, component cooling water heat exchanger building, diesel generator building and essential service water intake structure on YGN #3. The some precision examinations and chemical component experiments for them are next conducted. From the results, the aging of the concrete is diagnosed, and then the possibility of corrosion occurrence for embed reinforcing bars is indirectly decided on the analogy of whether the surroundings of the bars are standing under the corrosion environment. Because there were not found the primary factors of corrosion occurrence in the concrete cores, finally, the steel reinforcing bars within YGN #3 containment could be considered to maintain their integrity. In FE analysis of YGN #3 containment considering short-term aging condition, therefore, the inputs for the steel reinforcing bars are applied to the same values with the design criteria condition.

Tendons

The major concern in aging of prestressed tendons is a loss of load carrying capacity of the containment structure. Due to the tendons carrying high steady-state tensile stress, a small reduction in the load bearing area can ultimately lead to reduced structural capacity. Relaxation of the prestressed tendons, along with creep and shrinkage of the concrete, produces a reduced level of compressive stress in the containment concrete. Loss of prestress could have important consequences during an accident, when pressures inside a containment may cause the concrete shell and steel liner to enter a state of tension. This could result in concrete cracking, and any cracks forming in the steel liner could permit radioactive gases to leak to the outside environment. However, a little loss of prestress should not affect the containment's structural performance due to the integrity of the prestressed concrete containment being based on a highly redundant system of numerous tendons.

Due to the prestressing system of the YGN #3 containment structure to be consisted of unbonded type, the corrosion of the tendons can exclude due to the grease is fully filled within the duct which is wrapped round the tendons. This consequently implies to be not loss of prestress by the tendon's corrosion. To assess loss of prestress for YGN #3 containment on the short-term condition when the YGN #3 containment's age is 5 years, this investigation used lift-off test results in the in-service inspection. In results of the lift-off tests, it provides that the average loss of the effective prestressing force is about 7.77% for 11 tendons selected of existing vertical and horizontal tendons. This conjectural reduced-percentage will be commonly applied for all tendons on assessing the YGN #3 containment's structural capacity considering short-term aging condition.

ULTIMATE PRESSURE CAPACITY EVALUATION

Finite Element Analysis

The computer program ABAQUS[3)] is used to evaluate each ultimate pressure capacity considering the design criteria and short-term aging condition of the structural materials. The short-term aging condition includes the values changed of concrete's physical properties as Table 1 and the conjectural average reduced-percentage (7.77%) of the effective prestressing force for YGN #3 prestressing system.

Fig. 3 shows a finite element model of YGN #3 containment. The finite element model is an axisymmetry and consists of 2000 nodes and 1987 elements. The steel liner is modeled with two-noded axisymmetric composite shell elements. The concrete shell, dome and base mat are modeled with four-noded axisymmetric solid elements. All rebar and tendons in the containment structure are modeled using isotropic rebar sub-elements. Liner anchors are modeled as beam elements similar to the actual conditions. Slippage of the tendon within the tendon sheaths is not considered. Some constitutive equations for structural materials are used to analysis. In case of concrete, Saenz model[4)] is applied to represent concrete's nonlinear behavior subjected to uniaxial compression and a biaxial failure criteria by Kupfer and Gerstle(1973)[5)] is applied to define failure surface on the membrane behavior. In case of reinforcing steel, bilinear stress-strain diagram by Hsu[6)], which is provided from embed bar within concrete and Von-Mises yielding criteria is adopted. In case of tendon, Ramberg-Osgood model[7)] is used to represent tendon's nonlinear behavior.

The criteria for ultimate pressure capacity of prestressed concrete containment is defined as 1% strain in the post-tensioned steel tendons anywhere in the containment shell and dome. The load combination considered to analysis in this investigation is as follow without some load items (e.g. water pressure, equipment load and temperature load) which provide relatively small effect to the structural capacity.

$$1.0D + 1.0F + 1.0Pa \quad (1)$$

Where, D is the self-weight of the structure, F is the prestressing load, and Pa is the internal pressure under severe accident.

Table 1. Material Properties

	Condition	
	Design criteria	Short-term (5 years)
Concrete (wall & dome)		
Compressive strength, F_c' (psi)	5,500	7,600
Young's modulus, E_c (ksi)	4,700E3	4,970E3
Poisson's ratio, ν_c	0.17	0.17
Reinforcement bar (rebar)		
Yield stress, f_y (ksi)	60	
Young's modulus, E_s (ksi)	29,000	
Poisson's ratio, ν_s	0.3	
Tendon		
Ultimate strength, f_{pu} (ksi)	270	
Young's modulus, E_s (ksi)	28,000	
Poisson's ratio, ν_t	0.3	
Liner plate		
Yield stress, f_y (ksi)	32	
Young's modulus, E_s (ksi)	29,000	
Poisson's ratio, ν_s	0.3	

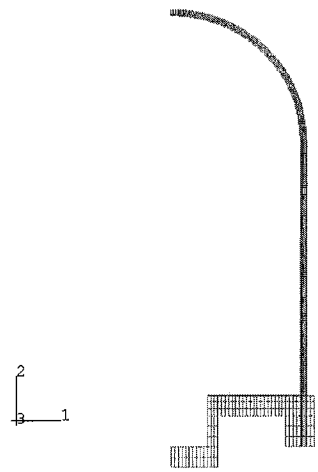

Fig. 3 Axisymmetric finite element model

Analysis Results

Table 2 shows the summery of nonlinear finite element analysis results on the design criteria and short-term aging condition of the structural materials for YGN #3 subjected to internal pressure in severe accident. In comparison of the pressure values in tendon yielding point of mid-hight wall, we can find that the internal pressure in 1% tendon strain for short-term aging condition is smaller only 1psi (0.6%) than design criteria. The major reason is due to the average 7.77% loss of the effective prestressing force. The internal pressure in time appearing concrete through-cracks, but, is larger 8 psi (7.6%) than design criteria condition because the strength of concrete has been increased during time of more than 5 years. The structural capacity of the YGN #3 containment which the age is 5 years therefore, is still carried on very good condition.

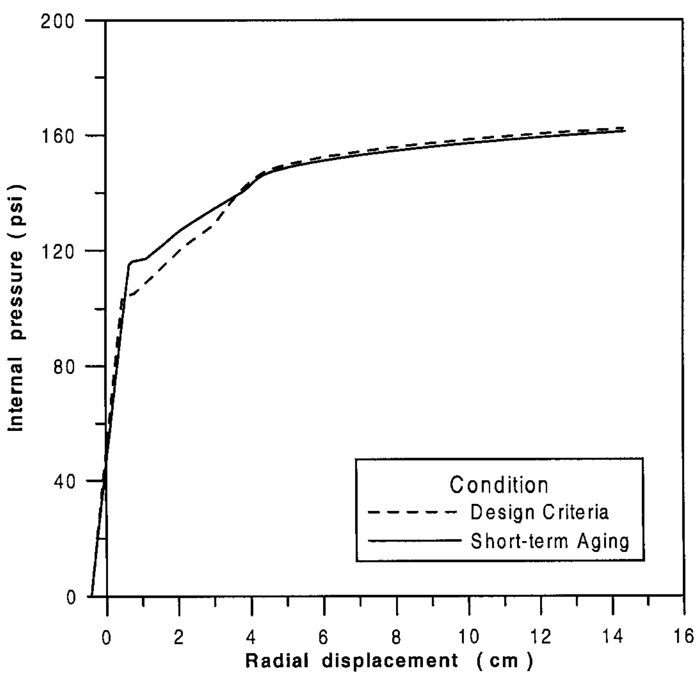

Fig.4 Relationships between Internal Pressure and Radial Displacement at Mid-hight Wall

Table 2. Summery of FE Analysis Results under Internal Pressure
(D: Design Criteria, A: Short-term Aging Condition)

Materials	Wall-Basemat Junction		Mid-Height Wall		Dome	
	D	A	D.	A.	D	A
Concrete Through Cracks	110.2	130.4	104.2	112.2	119.2	138.4
Liner Yielding	162.1	163.4	120.2	126.4	Elastic	Elastic
Outer-Reinforcing Bar Yielding	Elastic	Elastic	147.2	146.2	〃	〃
Inner-Reinforcing Bar Yielding	〃	〃	146.2	145.2	〃	〃
Tendon Yielding (1% strain)	〃	〃	159.2	158.2	〃	〃

(unit : psi)

SENSITIVITY ANALYSIS ACCORDING TO DEGRADATIONS OF STRUCTURAL MATERIALS

The main structural materials of containment, concrete, reinforcing steel bars and tendons, are the representative materials that their degradation can lead to large reduction of structural capacity relatively. Therefore, to assess the effect due to the individual or combinational degradations of them is very important in sides of the maintenance management and safety upgrade of a prestressed concrete containment. In this investigation, the sensitivity for the reduction of ultimate pressure capacity considering the assumed individual and combinational degradation levels as Table 3 is evaluated by FE analysis and then a principal component affecting structural capacity reduction of the containment is determined.

The Effect of Individual Degradations

To identify the effect by individual degradations that are represented as shadow items in Table 3, ultimate internal pressure capacities of the containment considering any single degradation of them are sequentially assessed for each case. Assumed-degradation levels for materials are considered 0, 5 and 10% respectively. Here degradation is simply considered by reducing the material stiffness. The materials other than one object in an individual degradation keep the design criteria condition. Fig. 5 ~ 7 show the relationships of material yielding-points and radial maximum displacements at mid-height wall, which are provided from the results of nonlinear analysis for containment considering assumed individual-degradation under ultimate internal pressure. The figures, finally, imply that the most sensitive material affecting the structural capacity reduction of containment among the three main materials is tendon, the second is reinforcing bar, and the third is concrete. In the viewpoint of individual degradation, therefore, the aging of a prestressed concrete containment has to be preferentially managed by this order.

The Effect of Combinational Degradations

In general the aging phenomenon of materials are mainly represented by not individual but combinational forms of material degradations. To identify the effect by combinational degradations that are represented as no shadow items in Table 3, ultimate internal pressure capacities of the containment considering any combinational degradation for them are sequentially assessed for each case. Assumed degradation levels for materials are the same as over individual degradation. Fig. 8 ~ 10 show the relationships of material yielding points and radial maximum displacements at mid-height wall, which are provided from the results of nonlinear analysis of containment considering assumed combinational degradation under ultimate internal pressure. The figures, finally, imply that the most sensitive combinational form, affecting the structural capacity reduction of containment among the three combination ranges, is a combination of the tendon and reinforcing bar degradations, the second is a combination of tendon and concrete degradations, and the third is a combination of reinforcing bar and concrete degradations. In the viewpoint of combinational degradation, therefore, the aging of a prestressed concrete containment has to be preferentially managed by this order.

Table 3. Assumed Degradation Combinations for Main Structural Materials

Materials	Notations	Assumed Degradation level (%)		
		Concrete (C)	Reinforcing bar (S)	Tendon (T)
Concrete & Reinforcing bar	C0S0T0*	0	0	0
	C0S5T0		5	
	C0S10T0		10	
	C5S0T0	5	0	0
	C5S5T0		5	
	C5S10T0		10	
	C10S0T0	10	0	0
	C10S5T0		5	
	C10S10T0		10	
Concrete & Tendon	C0S0T5	0	0	5
	C0S0T10			10
	C5S0T0	5	0	0
	C5S0T5			5
	C5S0T10			10
	C10S0T0	10	0	0
	C10S0T5			5
	C10S0T10			10
Reinforcing bar & Tendon	C0S0T5	0	0	5
	C0S0T10			10
	C0S5T0	0	5	0
	C0S5T5			5
	C0S5T10			10
	C0S10T0	0	10	0
	C0S10T5			5
	C0S10T10			10

* Design criteria condition

CONCLUDING REMARKS

The following remarks are made from the results of the ultimate pressure capacity evaluation considering design criteria and short-term aging condition for YGN #3 in service, and of sensitivity analysis for structural capacity reduction according to assumed individual or combinational degradations of main structural materials in a PCCV.

1. The structural capacity of YGN #3 in service is judged to be still retained very good condition because the nonlinear behavior in short-term aging condition almost consist with that in initial design criteria.
2. In case assuming the individual degradations, the most sensitive material affecting the structural capacity reduction of containment due to its degradation was tendon, and in case assuming the combinational degradations, the most sensitive combinatinational form was the tendon and reinforcing bar combination. In the aging management of PCCVs, the manager should impose the weight in the order of tendon, reinforcing bar and concrete
3. On the future in-service inspection of PCCVs, the evaluation of ultimate pressure capacity considering aging of materials should be added to existing inspection items for more secure maintenance management.

REFERENCES

1. Norris, W. E., Naus, D. J. and Graves III, H. L., “Inspection of Nuclear Power Plant Containment Structures”, Nuclear Engineering and Design 192, pp. 303 ~ 329, 1999.
2. ACI, "Code Requitements for Nuclear Safety Related Concrete Structures (ACI-97)", PART 4, Chap. 8.5, 1997.
3. Hibbit, H. D. et al., " ABAQUS User's Manual ", HKS, Inc., 1998.
4. Kabaila, A. and Saenz, L. P., " Equation for the Stress-Strain Curve of Concrete", *ACI Journal, Proceeding* Vol. 61 No.3, pp. 1227 ~ 1239, 1964.
5. Kufer, H. B. and Gerstle, K. H., "Behavior of Concrete under Biaxial Stresses", Journal of Engineering Mechanics Division, ASCE, Vol. 99, pp. 853, 1973.
6. Hsu, T. T. C., " Unified Theory of Reinforced Concrete" CRC Press, 1993.

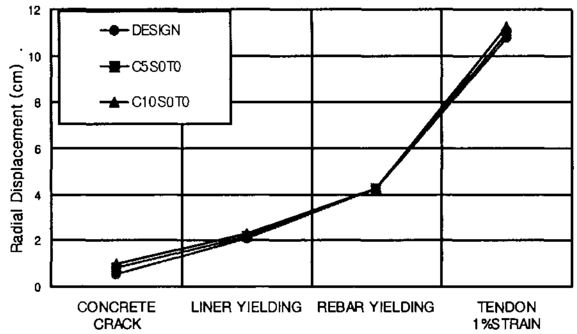

Fig. 5 Radial displacement by concrete degradation

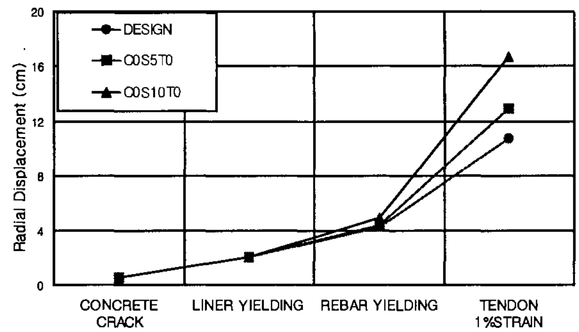

Fig. 6 Radial displacement by rebar degradation

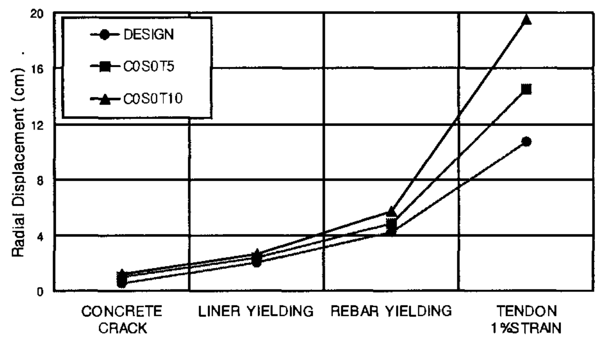

Fig. 7 Radial displacement by tendon degradation

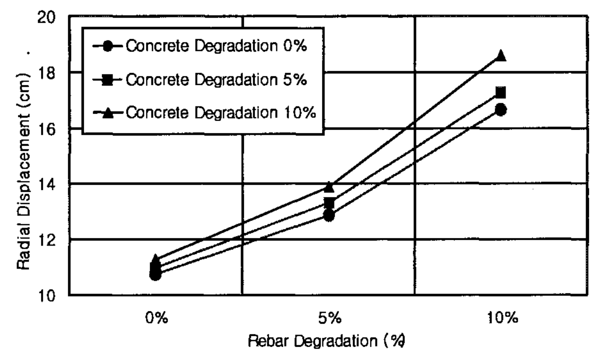

Fig. 8 Combination of concrete and rebar degradation

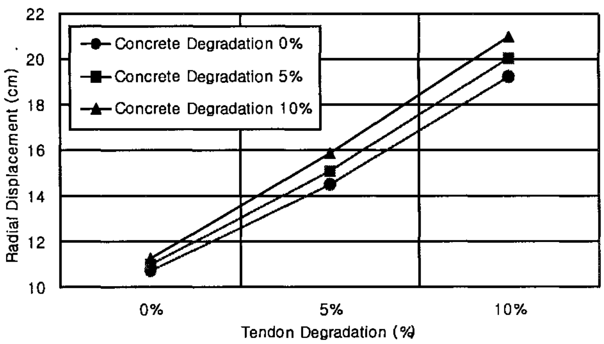

Fig. 9 Combination of concrete and tendon degradation

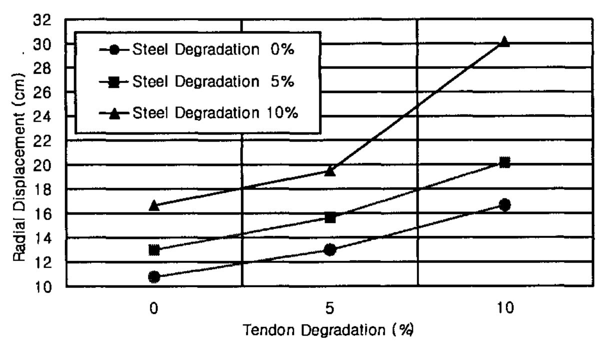

Fig. 10 Combination of rebar and tendon degradation