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Prediction of Prestressing Losses by Concrete Creep and Shrinkage

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ABSTRACT

This study is to predict prestressing losses of containment structures of nuclear power plants induced by concrete creep and shrinkage. In this study, reflecting the prestressing losses due to influence that occurred after prestressing of each tendon and the results of concrete long-term test, a personal-computer program which could predict prestressing losses of containment structures was developed.

As a case study, this program was applied to containment structures of Youngkwang 3 & 4 NPP's and analytical results were compared with test results of Inservice Inspection of containment structures. From this comparison, it was proved that this program could well predict prestressing losses by concrete creep and shrinkage.

1. INTRODUCTION

Reactor containments are made by prestressed concrete to withstand internal pressure when LOCA(Loss of Coolant Accident) occurs. As containment structures have some deformations by concrete creep and shrinkage and the prestressing losses of tendons occur, it is necessary to predict the prestressing losses of tendons and apply it to the design and construction and evaluate the structural integrity of containment structures. Therefore it is very important to develop and continuously apply the program which can well predict the prestressing losses of containment structures.

In this study, a personal-computer program was developed to predict prestressing losses of containment structures of nuclear power plants induced by concrete creep and shrinkage. As this program was designed to represent prestressing losses and allowable prestressing forces of each tendon by means of GUI(Graphic User Interface) system, it can be easily and effectively used for Inservice Inspection of containment structures in nuclear power plants.

2. DETERMINATION OF PRESTRESSING LOSSES

The following procedures apply to the prestressed concrete containment structures typically used for light-water reactors. For containments that operate at sustained high temperatures, the time-dependent characteristics need to be evaluated at correspondingly high temperatures.

2.1 Initial Losses

The initial seating force(F_0) should be modified to allow for the following influences : a known amount of slip at anchorage, a loss caused by elastic shortening of the structure, influence of wire breakage during construction.

Loss from slip at anchorage should be determined based on prior experience and the testing history of the prestressing system to be used. The influence of slip at anchorage should be allowed for in the computation of initial prestressing forces.

Coefficients for determining the losses from friction should be determined before the start of the installation and should be verified and modified during the construction. In comparing the liftoff forces for ungrouted tendons, friction loss need be considered only for the fixed ends of tendons that have been tensioned from one end. For the purposes of inspecting ungrouted tendons, consideration of this loss can be avoided by comparing forces at tensioned ends.

If all tendons in a specific direction(hoop, vertical, etc.) are prestressed simultaneously, the loss of prestressing force from elastic shortening(F_{LES}) can be given by (Eq. 1).

$$F_{LES} = \frac{F_0}{A_{cn}E_c + A_sE_s + A_pE_p + A_lE_l + A_dE_d} \times E_pA_p \qquad \text{(Eq. 1)}$$

where, F_0 is the initial seating force

A_{cn} is the net concrete area

A_s, A_p, A_l, A_d are the areas of reinforcing steel, prestressing steel, liner, and duct, respectively

E_c, E_s, E_p, E_l, E_d are the moduli of elasticity of concrete, reinforcing steel, prestressing steel, liner, and duct, respectively

However, the number of tendons to be prestressed is large, and the prestressing operation is performed in a systematic sequence so that the structure is more or less symmetrically prestressed during the process. Thus, the first tendons that are tensioned undergo a full loss from the subsequent elastic shortening of the structure, while the tendons that are tensioned last undergo almost no loss from elastic shortening. For all practical purposes, the loss of prestressing force from elastic shortening can be estimated and accounted for by using the following linear relationship(Eq. 2)

$$F_{LES}^{n} = \frac{n_r}{N} F_{LES} \qquad \text{(Eq. 2)}$$

Where, N represents the total number of tendons in a particular direction

n represents the sequential number of a randomly selected tendon to be tensioned in that direction

n_r represents the number of tendons to be tensioned after the n^{th} tendon

If the sequence of tensioning tendons in different directions are intermingled, the stresses produced in one direction by the tendons tensioned in the other directions must be considered.

Thus it is essential that the complete history of tensioning a tendon be recorded, including its seating force(F_0), the number of tendons tensioned before and after it, and any provision to account for the slip at anchorage. The modified initial prestressing force F_i at the tensioned end can be calculated and recorded as (Eq. 3)

$$F_i^n = F_o^n - F_{LES}^n - F_{LSA} \qquad \text{(Eq. 3)}$$

Where, F_{LSA} is the loss of prestressing force due to slip at anchorage.

2.2 Time-Dependent Losses

Limits on expected time-dependent losses at the end of the service life of the structure(generally 40 years), as well as those at one year after prestressing, should be established considering the variations in the following factors : effect of concrete creep, shrinkage and relaxation of prestressing tendons.

2.2.1 Effect of Concrete Creep

One of the most significant and variable factors in the computation of time-dependent losses in prestressed concrete containment structures is the influence of concrete creep. Creep is thought to consist of two components : drying creep and basic creep. Drying creep is thought to be due to the exchange of moisture between the structure and its environment. Its characteristics are considered to be similar to those of shrinkage, except that they represent an additional moisture movement resulting from the stressed condition of a structure. The amount of drying creep depends mainly on the volume-to-surface ratio of the structure and the mean relative humidity of the environment. For prestressed concrete containment structures having a volume-to-surface ratio in excess of 60 cm, the relative influence of drying creep is negligible compared to basic creep.

The significant parameters that influence the magnitude of basic creep can be summarized as follows : concrete mix type, age at loading, the magnitude of the average sustained stress and temperature. Table 1 represents concrete mix type of containment structures in Ulchin #3 & 4 NPP's.

Table 1. Concrete Mix Type of Containment Structures in Ulchin #3 & 4 NPP's.

Strength (psi)	W/C (%)	S/A (%)	Water (lb)	Cement (lb)	Sand (lb)	Gravel (lb)	WRA (oz)	AEA (oz)
5,500	44.5	38.0	288	647	1097	1791	41.41	0.62

As an acceptable method of determining basic creep for Table 1 as a function of age at loading, Eq. 4 derived by Hansen was used.

$$\frac{\varepsilon_c}{f_c} = A[1 - e^{-\frac{1}{30}(t-t_0)}] + B\log_{10}\frac{t}{t_0} \qquad \text{(Eq. 4)}$$

where, t = time when creep value is desired, in days

t_0 = time of loading after average time of concrete placement, in days

f_c = average sustained concrete stress

ε_c = creep strain at time t when the age of concrete at loading is t_0
A, B = are constants to be determined from tests

To determine the value of constants A and B, the concrete long-term test was performed(Table 2).

Table 2. The Results of Long-Term Creep Test

Items	Aslope	Amin	B
Test Results	-0.02203	0.2656×10^6	0.1555×10^6

Creep strain applied to each tendon can be described as Eq. 5.

$$\varepsilon_{creep} = \frac{\varepsilon_c}{f_c} \times f_{cr} \times \frac{E_{ps}}{f_{ps}} (\%) \qquad \text{(Eq. 5)}$$

where, f_{cr} = average modified seating force / A_{cn}
E_{ps} = the modulus of elasticity of prestressing steel
$f_{ps} = f_o^n / A_p$

2.2.2 Effect of Shrinkage of Concrete

Table 3 provides typical shrinkage values that could be used for computation of prestressing losses caused by shrinkage.

Table 3. Variation of shrinkage strain with relative humidity

Mean daily relative humidity (annual %)	40 year shrinkage strain $\varepsilon_{s,40}(\times10^{-6})$
Under 40 %	130
40 to 80 %	100
above 80 %	50

Shrinkage strain applied to each tendon can be described as Eq. 6.

$$\varepsilon_{sh} = \varepsilon_s \times \frac{E_{ps}}{f_{ps}} \times 100 \, (\%) \qquad \text{(Eq. 6)}$$

2.2.3 Effect of Relaxation of Prestressing Steel

The stress relaxation properties of prestressing steel vary with its chemical composition and thermal/mechanical treatment. Manufacturers should be able to provide data on the long-term loss in prestressing steel stress from pure relaxation. In this study, the stress relaxation value of prestressing steel was used by 2.8% which was suggested by manufacturer.

2.3 Construction of Tolerance Bands

Tolerance bands for groups and subgroups of tendons should be constructed and should be used for comparison of measured prestressing forces with the forces predicted for the time of inspection. It is recognized that each of the factors affecting the time-dependent characteristics of tendon forces are subject to variations. To account for these variations in prescribing the tolerance band, the following method was used(Ref. 2).

2.3.1 Determine Creep

The creep strains at any time after prestressing can be determined by the Hansen's Model. The high and low creep strains can be determined by increasing the extrapolated creep values by 25% and decreasing them by 15%, respectively.

2.3.2 Determine Shrinkage

To allow for the associated uncertainty in the assumed values, strain should be varied by $\pm 20\%$. The shrinkage strains at any time between the time of prestressing (consider zero shrinkage at $t = 10$ days) and 40 years can be estimated by considering shrinkage strain to vary linearly with the logarithm of time.

2.3.3 Determine Relaxation of Prestressing Steel

A $\pm 15\%$ variation in relaxation values obtained by extrapolation of 1000-hour tests is to be provided.

The upper and lower bounds for prestressing forces at 1 year and 40 years after prestressing can be found by adding up the low and high losses and subtracting them from F_i. For the purpose of constructing tolerance bands for various groups of tendons, it is sufficiently accurate to consider prestressing force to vary linearly with the logarithm of time.

3. Prediction Program & Results of Prestressing Losses

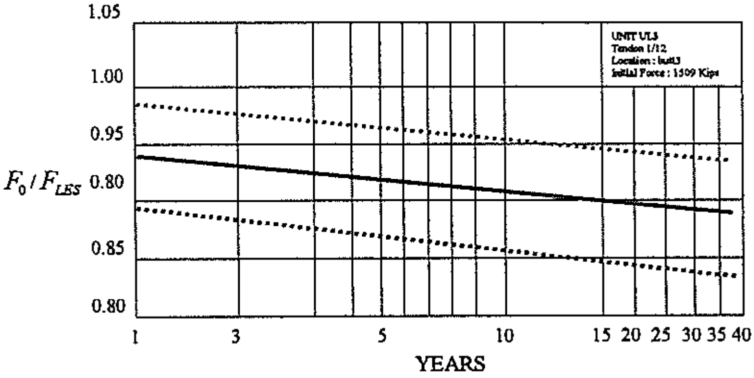
In this study, a personal-computer program was developed to predict prestressing losses of containment structures of nuclear power plants induced by concrete creep and shrinkage, reflecting the above procedures. This program is composed of three major parts in which are the pre-processor, calculation module and post-processor. Input data for this program are : material properties of concrete, rebar, linerplate and duct, test results of concrete creep and shrinkage, relative humidity, dimension of containment structures, and the number of prestressing tendon related containment structures. To obtain better results, this program was designed to reflect the prestressing losses due to influence that occurred after prestressing of each tendon, thus it can predict prestressing losses and allowable prestressing forces of each tendon.

Using this program, prestressing losses of containment structures of Ulchin #3 & 4 NPP's were predicted and an example of them was presented in Table 4. Analytical results were compared with test results of Inservice Inspection of containment structures. From this comparison, it was proved that this program could well predict prestressing losses by concrete creep and shrinkage.

Table 4. The Prediction Results of Prestressing Losses of Ulchin #3 NPP's

<Ul3> Normalized Remaining Prestressing Force in Horizontal Direction												
No.	Fo (kips)		1	3	5	10	15	20	25	30	35	40
1/12 B2	1467.01	Max.	0.970	0.960	0.955	0.949	0.945	0.943	0.941	0.939	0.937	0.936
		Mean	0.930	0.918	0.912	0.904	0.900	0.896	0.894	0.892	0.890	0.889
		Min	0.864	0.848	0.841	0.831	0.825	0.821	0.818	0.815	0.813	0.811
1/12 B3	1508.80	Max	0.970	0.960	0.956	0.949	0.946	0.943	0.941	0.940	0.938	0.937
		Mean	0.931	0.919	0.914	0.906	0.901	0.898	0.896	0.894	0.892	0.891
		Min	0.867	0.851	0.844	0.834	0.829	0.825	0.822	0.819	0.817	0.815

Figure 1 represents the tolerance band of acceptable prestress of containment structure of Ulchin #3 NPP's. In Figure 1, vertical axis represents that initial seating force(F_0) is divided by prestressing force estimated in Inservice Inspection of containment structure(F_{LES}) and horizontal axis time after prestressing, years.



<Fig. 1> Tolerance Band of Acceptable Prestress

4. CONCLUSIONS

The summaries of this study are herein.

(1) A personal-computer program was developed to predict prestressing losses of containment structures of nuclear power plants induced by concrete creep and shrinkage.
(2) As this program was designed to represent prestressing losses and allowable prestressing forces of each tendon by means of GUI(Graphic User Interface) system, it can be easily and effectively used for Inservice Inspection of containment structures in nuclear power plants.
(3) As a case study, this program was applied to containment structures of Youngkwang 3 & 4 NPP's and analytical results were compared with test results of Inservice Inspection of containment structures. From this comparison, it was proved that this program could well predict prestressing losses by concrete creep and shrinkage.

REFERENCES

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