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Effective Prestress Force Considering Instantaneous Loss in Reactor Containment Building

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Abstract: Reactor Containment Building (RCB) is the most important structure in a nuclear power plant since it is the last barrier against contaminated materials. Since RCB should not be cracked under design internal pressure, post-tension is typically applied along wall and dome in RCB. However, it is not simple to precisely evaluate effective prestress force along prestress tendons since many parameters such as frictions and anchorage slip should be taken into the account. In this paper, effective prestress force has been rationally evaluated through numerical iteration algorithm to consider prestress loss due to wobble and curvature frictions and anchorage slip together. Predictions through the numerical algorithm showed that effective prestress force could be significantly affected by the friction coefficients, and the minimum effective prestress force was found at the mid-point between the anchorages. In addition, concrete compressive stress attained by the effective prestress force was compared with concrete tensile stress induced by design internal pressure. The comparison results indicated that RCB was not cracked under the design internal pressure although the friction coefficients showed a wide range on their values.
Keywords: prestress, post-tension, friction, anchorage slip, instantaneous loss, reactor containment building

I. INTRODUCTION

Reactor Containment Building (RCB) in a nuclear power plant is the most important structure as an aspect of the last barrier against contaminated materials which are generated from the fission reaction. Especially in a severe situation which could be caused by Loss of Coolant Accident (LOCA), internal pressure of RCB may go up to 0.41 MPa and it may reach even higher impact pressures in the case of hydrogen explosions [1-2]. Therefore, the RCB is designated to have capacity to keep radioactive materials in itself under any accidents.

In order to attain the capability with RCB, prestressed concrete concept is typically employed for prevention of containment failure. Through prestressing, concrete in RCB can be subjected to compression in advance so that cracks in RCB can be prevented even under design load or pressure which induces tensile stress in concrete. Among prestressing methods, post-tensioning is applied on RCB since RCB has cylindrical and spherical shape for wall and dome, respectively. When concrete structure as like RCB is subjected to post-tensioning, one of the most important things on design is to evaluate effective prestress force. However, it is not simple to evaluate effective prestress force because prestress force can be significantly affected by lots of parameters, such as anchorage slip, frictions between prestress tendons and sheath, time dependent behaviour of concrete, tendon relaxation, and so on [3]. In addition, friction coefficients generally show a wide range of differences even through code provisions [4-7].

In this paper, effective prestress force in RCB will be rationally evaluated with consideration of main parameters which affects effective prestress force variations along prestress tendons. In addition, in order to consider a wide range of friction coefficients, several friction coefficients will be taken into the account of effective prestress force evaluation. To investigate structural safety in RCB, results of post-tensioning will be compared with the design internal pressure.

II. LOSS OF PRESTRESS FORCE IN POST-TENIONED MEMBERS

When post-tension is applied to concrete structures, effective prestress force is affected by many parameters such as 1) concrete elastic shortening due to compression by prestress, 2) friction between tendons and sheaths, 3) anchorage slip, 4) creep and shrinkage of concrete, and 5) tendon relaxation. Due to the parameters 1), 2), and 3), jacking force at the anchorage significantly decreases to initial effective prestress force after completion of anchorage slip, which is called instantaneous loss. Then, the initial effective prestress force has time-history on its value due to the parameters 4) and 5). On design of post-tensioned concrete structures such as reactor containment building, loss of prestress force due to frictions and anchorage slip is one of the most important key issues since the effect of the other parameters is not as considerable as the effect of friction and anchorage slip. In this chapter, therefore, mechanism regarding the instantaneous loss of prestress force is described with consideration of frictions and anchorage slip. In addition, evaluation algorithm is presented to evaluate effective prestress force considering the main parameters on loss of prestress together.

A. Loss of Prestress Force due to Frictions and Anchorage Slip

When prestress is applied along tendons, friction loss due to curvature and wobble should be taken into the account of effective prestress force (see **Fig.1**). Curvature friction loss is due to intended angle change along tendons while wobble friction loss is due to imperfect alignment of tendons. Therefore, loss of prestress due to the wobble friction is proportional with length of tendons while one due to the curvature friction is proportional with angle change of tendon profile. Consequently, loss of prestress due to the frictions (Δf_{fr}) at a distance x from the anchorage, can be calculated as following [3];

$$\Delta f_{fr} = f_j \left(1 - e^{-(Kx+\mu\alpha)}\right) \quad (1)$$

where f_j is jacking stress along tendon at the anchorage, K and μ are wobble and curvature friction coefficients, respectively, and α is accumulated angle change along the tendon profile from the anchorage.

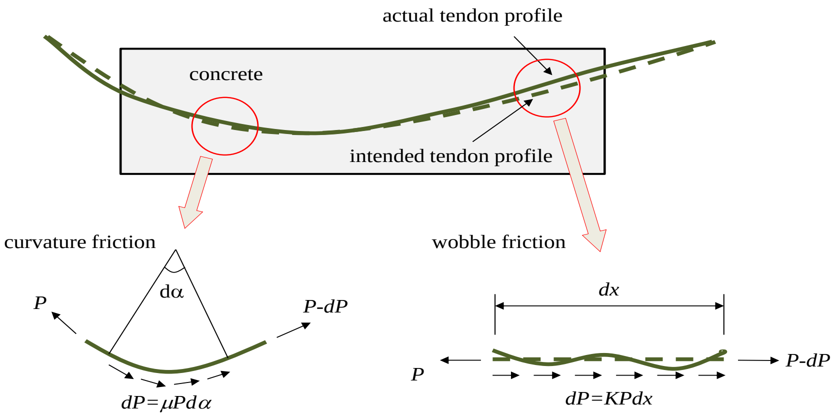


Fig.1: Curvature and wobble friction along tendons

In addition to the wobble and curvature friction, effect of anchorage slip should be considered since elongation of tendons is reduced by anchorage slip as illustrated in **Fig.2**. Based on assumption that prestresses before and after the release of tendons exhibit symmetry along the tendon profile, the instantaneous loss of prestress can be evaluated as illustrated in **Fig.3**, where **Fig.3(a)** shows a case that entire length of the tendons is affected by the anchorage slip while **Fig.3(b)** shows the other case. It is noted that prestress in the reactor containment building is represented by **Fig.3(b)** since length of tendons is long enough to cover the transfer length in which prestress of tendons is affected by the anchorage slip. After release, therefore, loss of prestress due to the anchorage slip (Δf_A) can be calculated for tendon stress profile within the distance of transfer length from the anchorage, as following [8];

$$\Delta f_A = 2 f_j \left(e^{-(Kx+\mu\alpha)} - e^{-(Kl+\mu\alpha)}\right) \quad (2)$$

where l is transfer length due to the anchorage slip.

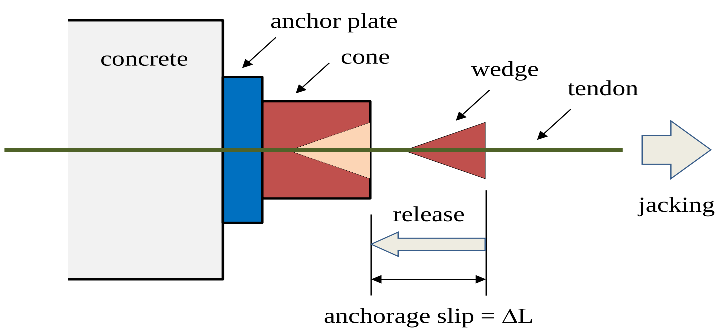
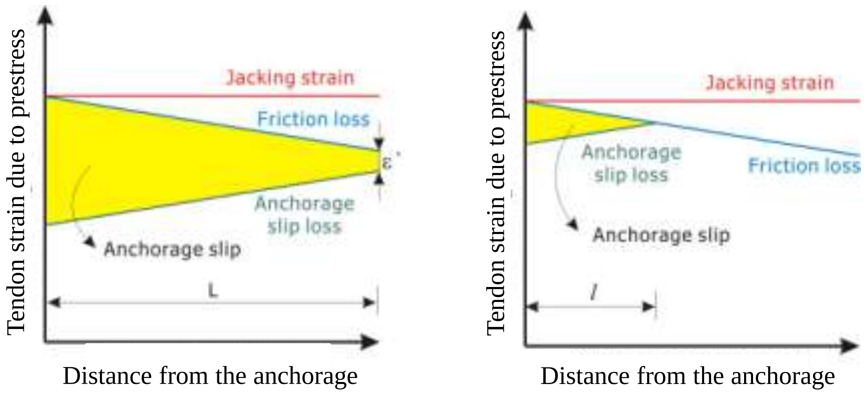


Fig.2: Effect of anchorage slip on tendon elongation



(a) When tendon length is short (b) When tendon length is long

Fig.3: Prestress force along tendons under jacking and after instantaneous loss [8]

B. Numerical Algorithm for Evaluation of Effective Prestress Force

Although simple methods are presented as a lump-sum method, numerical analysis algorithm has been developed in this paper to more rationally evaluate effective prestress force considering anchorage slip and frictions together. Since direct simple calculation is not available, iteration procedure has been developed as presented in **Fig.4**. As can be seen in the figure, initial assumption is made on transfer length representing the distance from the anchorage where anchorage slip has effect on effective prestress. Then, the area between tendon strains under jacking and after instantaneous loss is calculated, and it is compared with anchorage slip provided by manufacturer for the anchorage system. If the area is larger than the designated anchorage slip, the transfer length should be reduced, otherwise it should be increased. Through this iteration, the transfer length meeting the designated anchorage slip can be found, and then effective prestress force after the instantaneous loss can be evaluated.

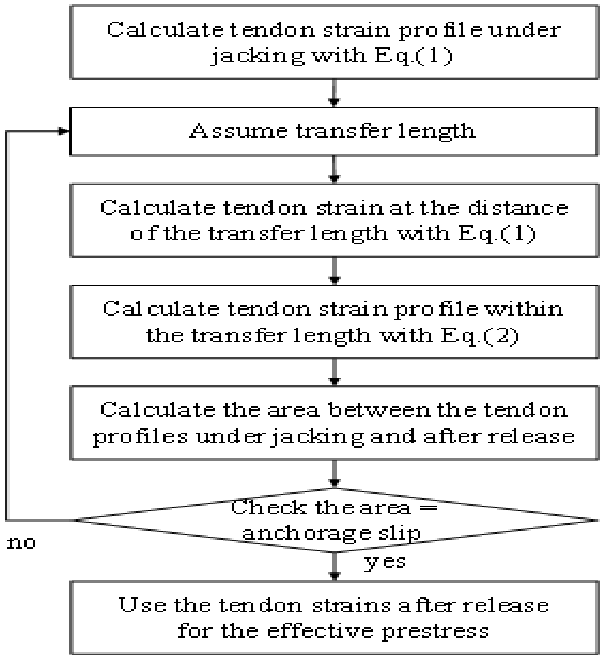
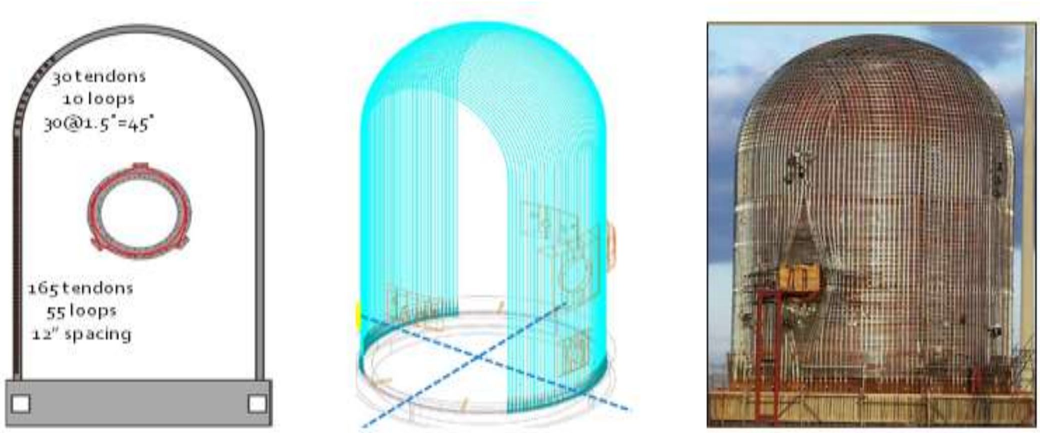


Fig.4: Numerical algorithm to evaluate effective prestress force

III. POST-TENSION IN REACTOR CONTAINMENT BUILDING

In order to attain the capability with the RCB, RCB is typically post-tensioned with lots of prestressing strands. In general, RCB has cylindrical shape along wall while it has spherical shape along dome. Considering the shape of the RCB, post-tensioning is conducted for horizontal and vertical directions separately. In the case of APR1400, for the horizontal prestressing, each strand covers 240° of the wall on a plan view, so each concrete section along the wall has two tendon lines as illustrated in **Fig.5(a)**. Distance between horizontal tendon lines is about 300 mm, so total 165 and 30 tendon lines are arranged in the wall and dome of the RCB, respectively. For vertical tendons, on the other hand, total 100 tendon lines are arranged along the wall and dome in the RCB as illustrated in **Fig.5(b)**. Distance between vertical tendon lines is about 750 mm. It is noted that each tendon line consists of 42 seven-wire strands of which nominal diameter is 15.2 mm; consequently, the cross-section area of each tendon line is 5,825 mm^2. Example for the alignment of tendon lines is presented in **Fig.5(c)**.



(a) Horizontal tendon alignment (b) Vertical tendon alignment (c) Examples for tendon alignment **[9]**

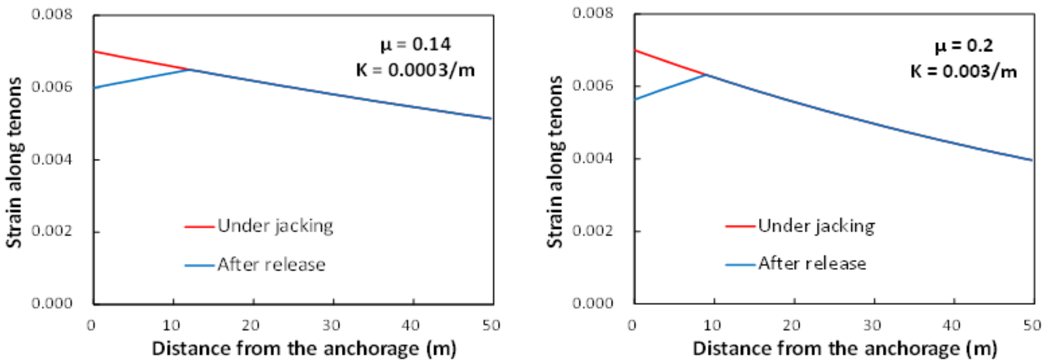
Fig.5: Prestressing tendon alignment in reactor containment building

IV. EFFECTIVE PRESTRESS FORCE IN REACTOR CONTAINMENT BUILDING

A. Effective Prestress Force along Horizontal Tendons

Fig.6 shows tendon strains along horizontal tendons evaluated with consideration of anchorage slip and frictions together. It is noted that tendon strains represent effective prestress force since effective prestress force can be directly calculated from product of tendon strains and elastic modulus. As can be seen in the figure, tendon strain was affected by anchorage slip only within the transfer length from the anchorage. The maximum prestress force was located at the distance of transfer length from the anchorage. Since the entire length of tendons was large, the minimum effective prestress force was evaluated at the mid-point between the anchorages as post-tensioning was conducted at the both ends of the tendons. Consequently, it can be inferred that the effective prestress force at the mid-point between the anchorages should be considered on the design for reactor containment building.

In addition, the effect of the friction coefficients was investigated since range of the friction coefficients was broad through several design provisions [4-7]. **Fig.6(a)** shows tendon strain profiles evaluated with the friction coefficients generally adopted on design of reactor containment building in APR1400 [10] while **Fig.6(b)** shows tendon strain profiles evaluated with the average friction coefficients in ACI 318-08 [4] and KCI 2012 [6]. As compared in the figure, effective tendon strains decreased as the friction coefficients increased. Therefore, it can be inferred that the friction coefficients are better to be thoroughly investigated in practical construction site.

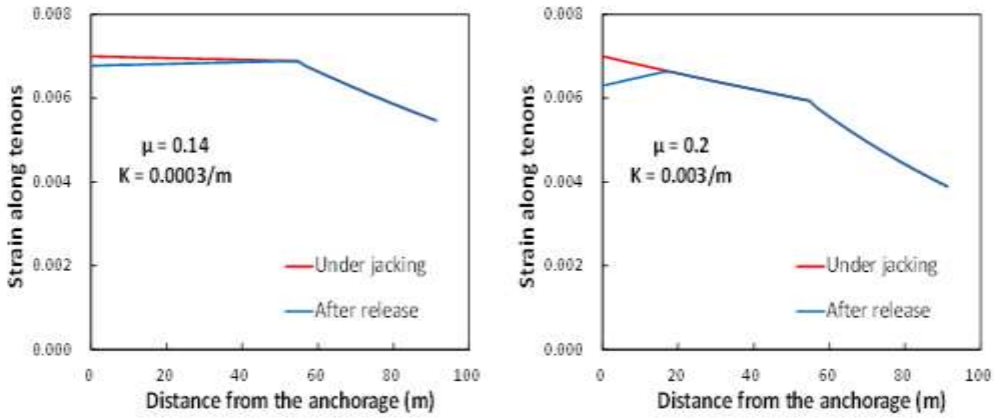


(a) $\mu = 0.2$ and $K = 0.003$ (b) $\mu = 0.14$ and $K = 0.0003$

Fig.6: Effective prestress force along horizontal tendons

B. Effective Prestress Force along Vertical Tendons

As the same manner with the horizontal tendons, effective prestress force was evaluated along vertical tendons as presented in **Fig.7**. As can be seen in the figure, similar tendency can be found on the effective prestress force along the vertical tendons; effective prestress force decreased as the friction coefficients increased. In addition, the maximum and minimum effective prestress forces are located at the distance of transfer length from the anchorage and at the mid-point between the anchorages, respectively. However, the transfer length was more significantly affected by the friction coefficients in the vertical tendons than the horizontal tendons since there was no curvature through reactor containment building wall.



(a) $\mu = 0.2$ and $K = 0.003$ (b) $\mu = 0.14$ and $K = 0.0003$

Fig.7: Effective prestress force along vertical tendons

C. Effect of Prestress Force against Design Internal Pressure

RCB should not be cracked under the design internal pressure, 0.41 MPa, which may be caused by undesirable accident. This indicates that concrete compressive stress attained by post-tensioning in the RCB should be larger than concrete tensile stress induced by the design internal pressure.

The maximum concrete tensile stress induced by the design internal pressure can be evaluated for the wall and dome in RCB, separately, with fundamental assumption that the design internal pressure is uniformly distributed in the RCB. In RCB wall, the maximum concrete tensile stress (σ_w) induced by internal pressure (p) can be calculated through application of plane stress theory in cylindrical pressure vessels [11], as following;

$$\sigma_w = pr/t_w \tag{3}$$

where r is radius of the RCB on a plan view, and t_w is thickness of the RCB wall.

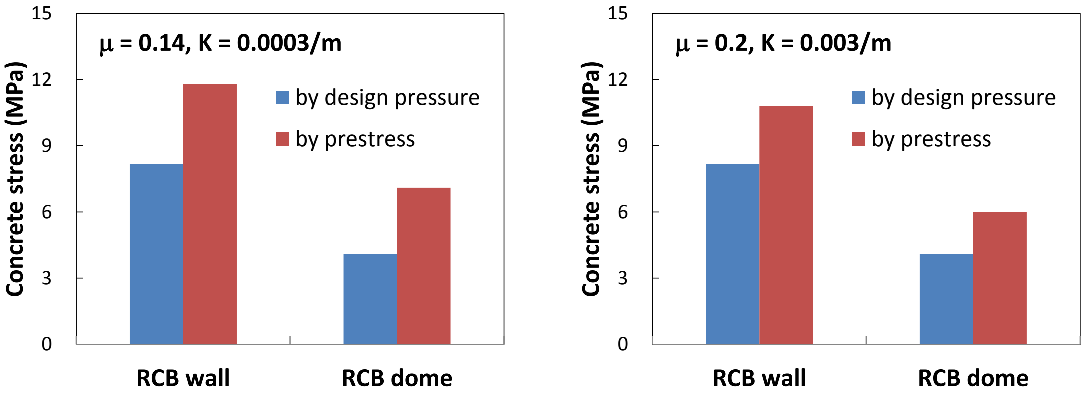
In RCB dome, as similar to the RCB wall, the maximum concrete tensile stress (σ_d) induced by internal pressure (p) can be calculated through application of plane stress theory in spherical pressure vessels [11], as following;

$$\sigma_d = pr/(2t_d) \tag{4}$$

where t_d is thickness of the RCB wall.

Concrete compressive stress attained by post-tensioning can be simply calculated by dividing prestress force with effective concrete area. It is noted that the minimum effective prestress force should be taken into the account of concrete compressive stress due to prestress since the weakest section should be considered for structural safety.

In **Fig.8**, the maximum concrete tensile stress evaluated for the design internal pressure is compared with the minimum concrete compressive stress calculated with the effective prestress force presented in **Fig.6 and 7**. As compared in the figures, the concrete compressive stress attained by post-tensioning is larger than the concrete tensile stress induced by the design internal pressure. Although concrete compressive stress attained by post-tensioning is affected by the friction coefficients, it can be concluded that the current design for the prestress tendons satisfies the requirement that RCB should not be cracked under the design internal pressure.



(a) $\mu = 0.2$ and $K = 0.003$ (b) $\mu = 0.14$ and $K = 0.0003$

Fig.8: Concrete stress due to design inner pressure and prestress

V. CONCLUSIONS

In this paper, effective prestress force in RCB was evaluated. When the effective prestress force was evaluated, instantaneous loss due to anchorage slip, wobble friction, and curvature friction were rationally considered together. From the evaluated effective prestress force, concrete compressive stress attained by post-tensioning was compared with concrete tensile stress induced by the design internal pressure. Conclusions found in this paper can be summarized as followings;

1) In order to consider effects of anchorage slip, wobble friction, and curvature friction on effective prestress force, a numerical algorithm was developed.

2) The results through the numerical algorithm indicated that the maximum effective prestress was found at the distance of transfer length from the anchorage while minimum was found at the mid-point between the anchorages.

3) As wobble and curvature friction coefficients increased, effective prestress force decreased in general.

4) Concrete compressive stress attained by the effective prestress force was larger than concrete tensile stress induced by the design internal pressure, so it can be concluded that concrete in RCB is not cracked under the design internal pressure.

5) This paper will be useful for more rational design on post-tensioning system in RCB.

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