論文

EFFECT OF GROUTING VOID ON ULTIMATE TENDON STRESS IN POST-TENSIONED CONCRETE MEMBER

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ABSTRACT: Extensive investigation shows that deterioration due to insufficient grouting is a serious problem in post-tensioned concrete bridges which may have a detrimental effect on the load carrying capacity and durability of such structures. This paper presents an analytical method to evaluate ultimate tendon stress in the post-tensioned member with grouting void. Parametric analysis is carried out to study the effects of the void-span ratio on strain reduction coefficient, ultimate tendon stress and bending moment with various tendon profiles, load geometry patterns and partial prestressing ratios.
KEYWORDS: post-tensioned concrete member, grouting void, void-span ratio, strain reduction coefficient, ultimate tendon stress

1. INTRODUCTION

Investigations on the post-tensioned PC bridges with internally grouted tendons indicate varieties of defects due to imperfect grout condition ranging from minor voids to complete loss of grout. It poses a serious durability problem in such structures **[1]**. So far, most of the research works on the deteriorating post-tensioned bridges are mainly focused on the improvement of non-destructive testing methods for examining the degree of grouting and for maintenance measures of PC tendons with insufficient grouting **[2]**. Seldom literatures are available on methods for evaluating the behaviors of PC members with various levels of grouting void. Due to the lack of knowledge on the effects of deterioration on the residual behaviors of the existing structures, some of them may be repaired, strengthened or replaced unnecessarily or at great cost.

In order to evaluate the effect of grouting void on the PC tendon stress in post-tensioned PC member, a nonlinear analytical method is devised considering the concept of member's strain compatibility in the region of un-grouted tendon for the calculation of the tendon stress in the ultimate state. In addition, elastic analytical methods for those in un-cracked and cracked states are also discussed. The parameters investigated include void-span ratio, load application type, PC tendon profile and partial prestressing ratio ($PPR=f_{py}A_{ps}/(f_{py}A_{ps}+f_yA_s)$). Based on the grouting mechanism **[3]**, the analysis is conducted on simply supported member by gradually increasing the total void's length from mid-span to supports symmetrically.

Results of parametric analysis indicate that the strain reduction coefficient of PC tendon is very sensitive to the void-span ratio while the loss of ultimate stress and moment capacity are not if failure mode is controlled by the crush of concrete. These phenomena imply that repair or strengthening is not necessary even if the voids are existed in members on condition that a reliable corrosion protection is provided for PC tendons and consequently no risk of tendon rupture will happen.

Before describing the nonlinear analytical method for the ultimate state and presenting the results of this investigation, strain reduction coefficient of PC tendon in elastic cracked or un-cracked state is introduced next.

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2. ELASTIC ANALYSIS IN UN-CRACKED AND CRACKED STATES

A simplified method to predict the stress in prestressing unbonded tendons for both elastic un-cracked section and elastic cracked section was proposed by Naaman **[4]**. The key point is to introduce strain reduction coefficient Ω or Ω_{cr} to simplify the analysis of beams prestressed with unbonded tendons to that of beams prestressed with bonded tendons. Ω or Ω_{cr} is defined as the ratio of strain increase $(\Delta\varepsilon_{psu})_m$ in the unbonded tendons to the strain increase $(\Delta\varepsilon_{psb})_m$ in the equivalent bonded tendon. $(\Delta\varepsilon_{psu})_m$ is assumed to be the same in any section along the span and equals to the average strain increment $(\Delta\varepsilon_{psu})_{av}$ in concrete at the tendon level along the span. Both $(\Delta\varepsilon_{psu})_m$ and $(\Delta\varepsilon_{psb})_m$ are strain increases beyond the effective prestress and calculated in the section of maximum moment. Note that Ω=1 represents the case where tendon is fully bonded along its entire length.

For simply supported beams with constant cross section, symmetrical loading and tendon profile, and symmetrical distribution of grouting voids, Ω_v or $\Omega_{cr,v}$, corresponding to un-cracked and cracked states separately, can be calculated in the following equations by using l_v instead of l of Eqs(8-9) in Ref.[5] .

$$\Omega_v = \frac{2}{M_{max} e_{max} l_v} \int_0^{l_v/2} M(x) e(x) dx \qquad \text{...... (1)}$$

$$\Omega_{cr,v} = \Omega_v \frac{I_{cr}}{I_g} + \frac{2}{l_v}(1 - \frac{I_{cr}}{I_g}) \int_0^{l_{cr}/2} \frac{M(x)e(x)}{M_{max} e_{max}} dx \qquad \text{......(2)}$$

where M_{max} and M(x) are the maximum bending moments at the critical section (mid-span here) and any section x along the span, respectively, and e_{max} and e(x) are the corresponding eccentricities of the tendons at these sections. l_v is the total length of grouting void, which in this study is assumed to vary from zero to span L corresponding to various void-span ratio(l_v/L) between zero and one. For the analysis of the elastic cracked state, only one crack is assumed to occur at the section with the maximum moment, and the beam is divided into two parts, one cracked portion with inertia moment I_{cr} and length l_{cr}, one un-cracked portion with I_g and (L- l_{cr}).

Ω_v and $\Omega_{cr,v}$ are calculated for most common types of loads and tendon profiles with different void-span ratios in each case. Since $\Omega_{cr,v}$ is greatly influenced by ratio I_{cr}/I_g, not so sensitive to the value of l_{cr}/L for small l_{cr} **[5]**, the second part of Eq.(2) is neglected. Meanwhile I_{cr}/I_g is set to be 0.8 in the process of calculation.

After the determination of strain reduction ratio Ω_v or $\Omega_{cr,v}$, the general approaches developed for beams prestressed or partially prestressed with bonded tendons can be used provided that strain increment in tendon is modified by appropriate Ω_v or $\Omega_{cr,v}$.

3. NONLINEAR ANALYSIS METHOD

3.1 ASSUMPTIONS

The followings are the main assumptions adopted in the nonlinear analysis:

(1) The constitutive relationships of concrete, PC tendon and reinforcing steel are taken from current JSCE standard code.
(2) The strain of concrete and bonded reinforcement is linearly distributed across the depth of the section.
(3) Perfect bond is assumed in fully grouted sections and totally unbonded in un-grouted sections along the void length l_v which means the frictional force between the tendon and surrounding material is neglected.

3.2 NONLINEAR ANALYSIS PROCEDURE

The theory for unbonded beam, similar to that explained in the elastic analysis above, is used in the ultimate state for the sections where voids are presented. Because of the slip of the PC tendon relative to the surrounding concrete inside the region of grouting void, the tendon stress $f_{ps,v}$ cannot be evaluated solely on force equilibrium and sectional strain compatibility. Instead, $f_{ps,v}$ depends on the total elongation of the tendon between the two ends of the grouting void under the given level of externally applied load.

$$\Delta l_{ps,v} = \sum_{n=1}^{N}(\Delta\varepsilon + \varepsilon_{ce})l_n ......(3) \qquad \Delta\varepsilon_{ps,v} = \Delta l_{ps,v} / L ......(4)$$

$$\varepsilon_{ps,v} = \varepsilon_{pe} + \Delta\varepsilon_{ps,v} ......(5) \qquad f_{ps,v} = F(\varepsilon_{ps,v}) ......(6)$$

where,

$$\Delta\varepsilon = (\frac{d_p - c}{c})\varepsilon_c ......(7)$$

$$\varepsilon_{ce} = \frac{A_{ps} f_{pe}}{A_c E_c}(1 + \frac{e^2}{r^2}) ......(8)$$

$$\varepsilon_{pe} = f_{pe} / E_{ps} ......(9)$$

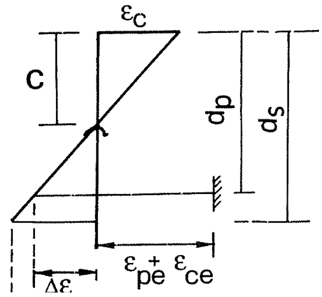

Fig.1 Strain distribution along the depth of the cross-section

A computer code is established to calculate $\Omega_{u,v}$, $f_{ps,v}$ and $M_{u,v}$ of PC member with grouting void in the ultimate state. The beam is divided into N segments and the cross-section is divided into a number of layers. It means that the curvature is assumed to be uniform over each segment and the concrete stress is assumed as uniform over each layer. The total elongation $\Delta l_{ps,v}$ of PC tendon above effective prestress, the average PC tendon strain $\Delta\varepsilon_{ps,v}$ and corresponding stress $f_{ps,v}$ can be calculated as followings (**Fig.1**):
l_n is the length of beam segment n, ε_{pe} is the effective prestrain, r is the radius of gyration of section, e is the eccentricity of PC tendon. As far as the number N, the segment length less than equivalent plastic spread length L_p (**Fig.2**) **[6]** is recommended since the total elongation of the unbonded PC tendon is mainly produced in the plastic regions of the beam. Theoretically, voids inside the plastic region will induce larger change in the values of $\Omega_{u,v}$ than that outside the plastic region. L_p is measured outside the constant moment region while the total equivalent plastic region length l_p can be expressed by **[6]**:

$$L_p = 0.5d_p + 0.05Z ......(10) \qquad l_p = L_0 + 2L_p ......(11)$$

The maximum moment capacity is determined by the governing situation according to the following two criteria: (1) the concrete strain ε_{cu} in the uppermost layer of the critical section reaches 0.0035; (2) the tendon stress $f_{ps,v}$ is $0.93f_{pud}$, where f_{pud} is the ultimate design strength of PC tendon.

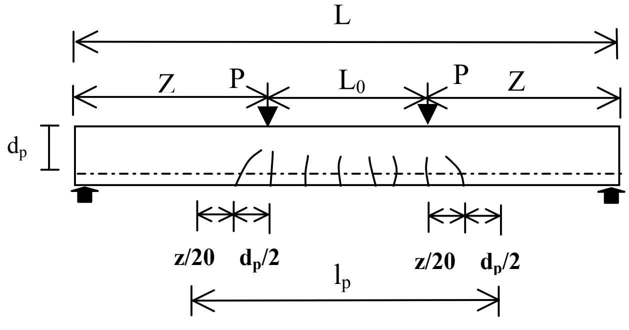

Fig2. Schematic diagram of equivalent plastic hinge region

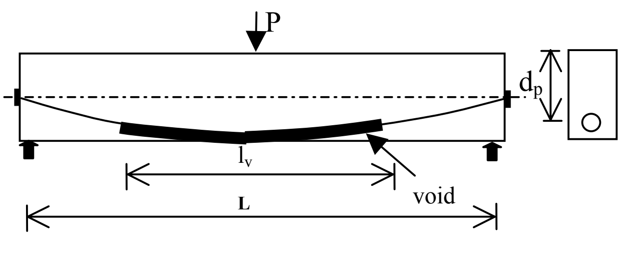

Fig.3 Beam model for numerical analysis

4. EFFECT OF VOID-SPAN RATIO ON TENDON STRESS

In order to investigate the effect of void-span ratio on tendon stress in the post-tensioned concrete member, parametric analysis is conducted using the program developed above. The parameters investigated include: (1) void-span ratio l_v/L (0, 0.1, 0.2,…, 0.9,1.0); (2) three types of applied loads and two types of tendon profiles: concentrated load (straight and parabolic tendon), uniformly distributed load (straight and parabolic tendon) and two 1/3-point concentrated load (straight tendon profile); (3) two types of PPR: 0 and 0.6. The model for numerical analysis is based on a simply supported beam with symmetrical load and tendon profile (**Fig.3**). The distribution of grouting void is also idealized to expand from the mid-span to two supports symmetrically. Analytical results of the effects of void-span ratio on $\Omega_{u,v}$, $f_{ps,v}$ and $M_{u,v}$ are shown in **Fig.4~9** (where, p: parabolic tendon; s: straight tendon; u: uniformly distributed load; c: concentrated load; t: two 1/3-points load).

4.1 EFFECTS OF VOID-SPAN RATIO ON Ω_v, $\Omega_{cr,v}$ AND $\Omega_{u,v}$

It is clear from **Figs.4~9** that Ω_v, $\Omega_{cr,v}$ and $\Omega_{u,v}$ are located between 1 and Ω, Ω_{cr} or Ω_u with the increase of void-span ratio from 0 to 1, respectively, which correspond to the boundary situations of the fully bonded and fully unbonded PC tendons.

$\Omega_{u,v}$ decreases more sharply than Ω_v and $\Omega_{cr,v}$ at the area near the mid-span where void-span ratio is very small (**Fig.4**). It means that the reduction of tendon strain is mainly concentrated in this region especially in the ultimate state. Thus, voids existed in this area will cause larger unfavorable effect than those in other places. This phenomenon also indicates that the voids located in the plastic region will induce more significant decrease of $\Omega_{u,v}$. This can be improved by adjusting PPR appropriately (**Fig.5**). It is known that ordinary bonded reinforcement may help scatter the cracks and reduce the width of the crack, which implies that the plastic hinge range is enlarged consequently.

An important result of this analysis is that load geometry style shows strong effect on strain reduction ratios of tendon, but not the tendon profiles (**Fig.6, and 7**). This is because the plastic hinge length L_p is largely dependent on the position of applied load. Beams loaded under concentrated loads encounter the largest reduction in $\Omega_{u,v}$ with the increase of the void-span ratio because of the shortest L_p. Note that no reduction of $\Omega_{u,v}$ in the cross-sections between the two 1/3-point loading positions because of the same external moment and the same tendon eccentricity in this region. This has also been verified by the experimental results in reference **[7]**.

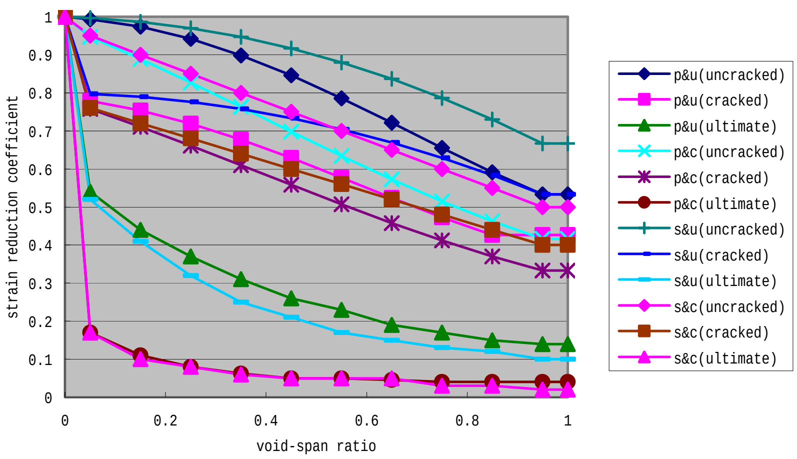

Fig.4 Variations of Ω_v, $\Omega_{cr,v}$ and $\Omega_{u,v}$ with the change of void-span ratio

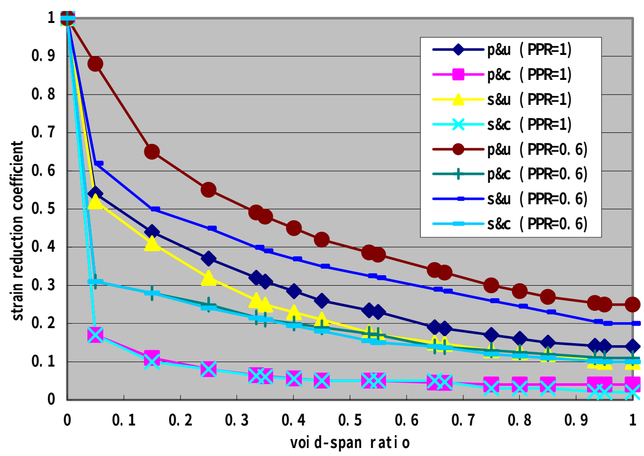

Fig.5 Effect of PPR on $\Omega_{u,v}$

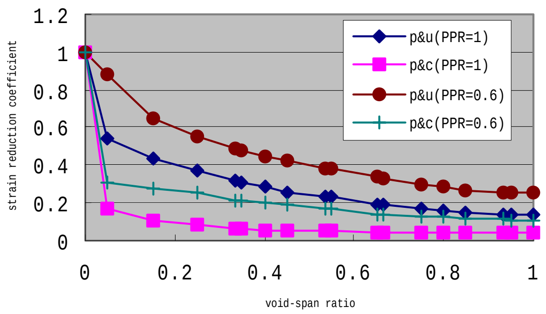

Fig.6 Effect of load geometry style on $\Omega_{u,v}$ (parabolic tendon profile)

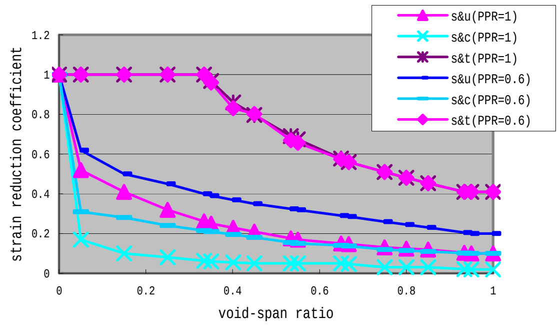

Fig.7 Effect of load geometry style on $\Omega_{u,v}$ (straight tendon profile)

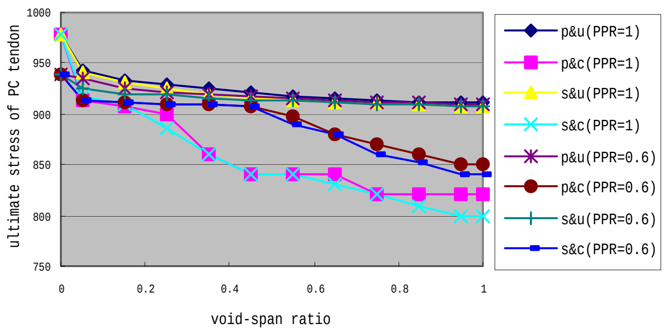

Fig. 8a Variation of $f_{ps,v}$ with the change of void-span ratio

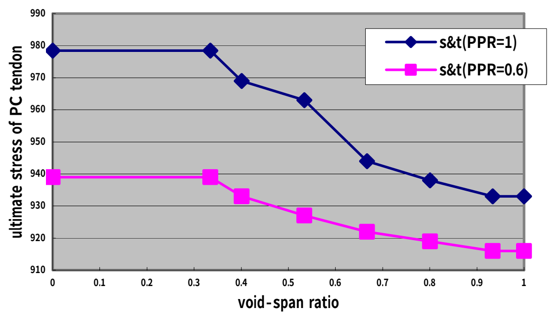

Fig.8b Variation of $f_{ps,v}$ with the change of void-span ratio

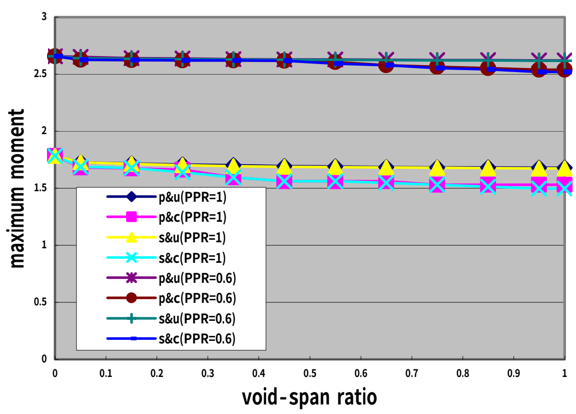

Fig. 9a Variation of $M_{u,v}$ with the change of void-span ratio

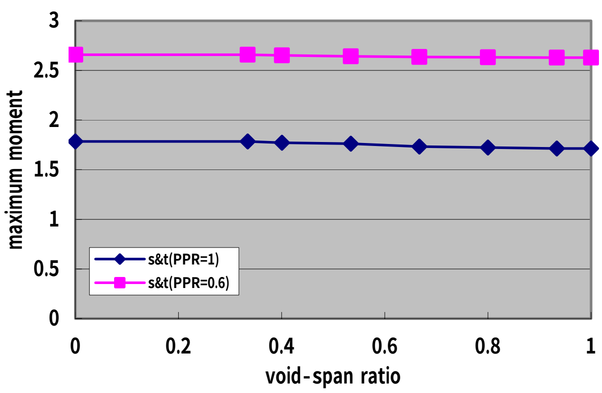

Fig.9b Variation of $M_{u,v}$ with the change of void-span ratio

4.2 EFFECTS OF VOID-SPAN RATIO ON $f_{ps,v}$ AND $M_{u,v}$

It is observed in **Fig. 8a** that the magnitude of f_{ps} does not vary with the increase of void-span ratio as rapidly as that in $\Omega_{u,v}$, since $f_{ps,v}$ depends on not only $\Omega_{u,v}$ but also the depth of neutral axis (Eq.10 in **Ref.[4]**). The largest reduction of $f_{ps,v}$ is in the case of concentrated load with straight tendon. PPR value has strong effect on $f_{ps,v}$ because of the reasons explained before. In the case of two 1/3-point load (**Fig.8b**), no effect occurs if the voids are inside the area of the constant external moment with the same tendon eccentricity.

Effects of void-span ratio on $M_{u,v}$ are shown in **Fig.9a** and **9b**. Much less reduction of the moment capacity is found with the increase of the void-span ratio than that for $f_{ps,v}$, especially for those beams with PPR value of 0.6.

5. CONCLUSION

For the purpose of investigating the effect of grouting void on the ultimate tendon stress in the post-tensioned concrete members, an analytical method is proposed based on the member's strain compatibility along the grouting void, force equilibrium in the cross section and the nonlinear relationship of constitutive materials. Relationship of void-span ratio versus the tendon's strain reduction coefficients (namely, Ω_v, $\Omega_{cr,v}$ and $\Omega_{u,v}$), ultimate tendon stress $f_{ps,v}$ and maximum moment $M_{u,v}$ are obtained by parametric study.

It is concluded that the effect of void-span ratio on $\Omega_{u,v}$ is most significant for beams with concentrated load and PPR value of 1.0. Larger decrease of $\Omega_{u,v}$ occurs near the mid-span when voids exist in this area. This can be diminished to some extent by increasing the length of plastic region expected to develop in the member through changing the load geometry style or PPR values. Effects of void-span ratio on f_{ps} and M_u are not as apparent as that on $\Omega_{u,v}$ because they are not only $\Omega_{u,v}$ but also neutral axis dependent.

Thus, grouting voids have no serious effect on the ultimate stress and moment capacity of PC members provided that they are not located under the concentrated loads and the beams are suitably designed with additional ordinary reinforcement. It should be noted that concrete crush is the only failure mode in this study without considering the tendon failure induced by corrosion. And, failure of a tendon in voids will cause a loss of prestress over the total length of the tendon in this range and may significantly reduce load capacity.

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