DESIGN METHOD OF POST-TENSIONED PC STRUCTURE CONSIDERING SECONDARY INTERNAL FORCES

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ABSTRACT

The post-tensioned concrete structures with complex redundant restraints are encountered very often in China, such as the super long structures, the large-scale industrial plant structures, etc. The redundant restraints in statically indeterminate structure result in secondary internal force especially secondary axial force which affects structural reinforcement design. This paper studies the influence of effective prestressing force distribution and tendon profile on secondary axial force. The necessity of considering secondary axial force, as well as secondary moment and secondary shear force in PC structure design is confirmed, and the structure design formula are provided. A numerical example shows that for a bonded PC structure, the tendon area calculated by the design code in force is 20% less than that calculated by the method proposed in this paper, which causes redundant normal reinforcement usage but unsatisfying serviceability; while considering secondary axial force as prestressing loss will result in excessive usage of prestressed tendon in design.

Keywords: *Prestressed Concrete Structure, Lateral Restraint, Restraint Effect, Secondary Internal Forces, Secondary Axial Force, Effective Prestressing Distribution, Prestressing Loss, Tendon Geometry, Reinforcement Design*

INTRODUCTION

In statically indeterminate prestressed concrete structure, vertical members could affect the deformation of horizontal members and then affect the prestress transfer or establishment in horizontal members, which is called restraint effect. When the restraint becomes greater, the calculated ultimate bearing capacity of PC beam will exceed the real capacity, and the calculated crack width and deflection will be less than the real ones. It is reported that restraint effect is relevant to the column-beam stiffness ratio, structure type as well as construction procedures[1, 2].

The samller the column-beam stiffness ratio, the larger the restraint effect, and the higher reduction of prestress on mid-span beams. Xiong[3] studied a 2-sroty framed structure and did anaysis on one story. When stiffness ratio increases from 0.25 to 4, the axial force decreases from 0.63% to 5.33% in side-span beam, and decreases from 0.98% to 9.08% in mid-span beam. Zheng & Wang[4] calculated the prestressing effect in the one-story one-span PC framed structure, 60% of the prestressing force is lost because of the lateral restraint.

As for one-story multiple-bay frame, the constraint effect augments with the increase of span and bay number, and the ends of each bay are affected most. Zhang & Lv[5] proposed the criteria for considering the lateral restraint effects: span $L \geq 20$ m, bay number $n > 3$; or $L \geq 30$ m, $n \geq 2$; or $L \geq 39$ m. Wang & Meng[6] presented the similar conclusion.

When the column stiffness is high for single-span multi-story structure, large secondary axial force may occur in beams of the bottom and top levels which affects serviceability and bearing capacity of the structure. It is very simlimar for multi-span multi-story structure to single-span multi-story structure, when the continuous beam is long, the lateral deformation of side-beam is large. That means the axial deformation affects more on the side beams. The loss of the axial pre-compression is more when it is near the intermediate span; and the effect becomes even bigger with the increase of column-beam stiffness ratio. In a five-story PC frame, when the bay number changes from 2 to 6, the loss in axial pre-compression force increases from 1.47% to 8.50%.

High-rise framed tube structure is comprised of tube (or shear walls) and exterior columns, and the tube stiffness is high enough to be regarded as fix-end restraint to beams. In addition, it should pay special attention to prestressing effectiveness of the top and bottom levels of high-rise structures whose columns with large section dimension and stiffness undertake very huge vertial loads. A tube-in-tube structure in Chongqing adopted bonded prestressed flat beam system to reduce the story height. If the measure of reducing secondary axial force is not taken into consideration, the loss of pre-comporession could have reached 47.7% only for single-floor loading condition[7].

The Songjiang Swimming Fitness Centre in Shanghai is designed as a large span PC grillage beam multiple-story framed structure, whose loss of prestressing caused by lateral constraints could reach 15% -30%[3].

When prestressing the trussed girder of the changeover floor, it not only affects this level itself, the beams and slabs of the adjacent levels also absorb a large amount of pre-compression force, and big secondary bending moments in the adjacent columns are resulted at the column ends. Xiong *et al.* [8-10] stated from a project the effective prestressing established in the trussed girder of changeover floor only reached 62.9% of the actual load.

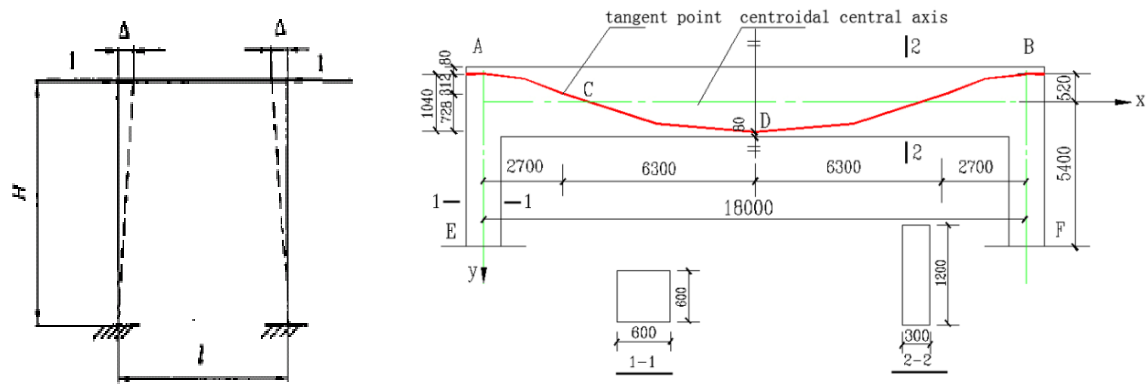
The constraint from the framed column causes the decrease of prestressing along the beam axis and its effect also depends on the construction sequences. The research work by Jian & Wu[11] proves that when using "prestressing each level just after casting" or "casting the whole structure, then prestressing" method, the top level is significantly affected by lateral restraint, the bottom level is affected relatively less, and the effects on other levels could be neglected. While combining these two construction methods, the bottom level is most affected by lateral constraint, then the following first level of concreting in lifts.

This paper studies the influence of effective prestressing force distribution and tendon profiles on secondary internal forces as well as their effects on reinforcement design. After considering all influence factors of constraints, the authors propose that the current design code based only on span and bay number is not reasonable since the considerable restraint effect is not taken into account. And the essence of restraint is the secondary internal forces resulted in the structure. The structural design formula should include the overall effect of secondary axial force, secondary moment and secondary shear force. From the detailed anlysis of examples, the reinforcement design method covered here is more accurate and reliable than the in-force national design code, no matter it is for bonded presressed structure or non-bonded prestressed structure.

THE INFLUENCE OF EFFECTIVE PRESTRESSING FORCE ON RESTRAINT EFFECT

Prestressing effectiveness in statically indeterminate structure is related to the restraint effect. In practice, effective prestressing force varies along the length of the structural member; especially when the tendon geometry is complicated, effective prestressing force distribution changes more remarkably. Thus, an unreasonable design may be resulted by overlooking the changes in effective prestressing force distribution.

An single-span prestressed concrete symmetric frame is studied as an example (Fig. 1). It is assumed that there is no rotation at both ends of beam and columns.



(a) Calculation Diagram (b) Structural Member and Tendon Profile

Fig. 1 Restraint Effect in One-Story One-Span PC Frame

NEGLECTING EFFECTIVE PRESTRESSING FORCE DISTRIBUTION

The equilibrium equation in displacement is established based on the principle of structural mechanics:

$$\begin{cases} \dfrac{\Delta P H^3}{12 E_c I_c} = \dfrac{X\, l/2}{E_b A_b} \\ \Delta P + X = 1 \end{cases} \tag{1}$$

Where:

E_b, E_c —— elastic modulus of concrete(beam and column);

A_b —— beam section area;

I_c —— column section moment of inertia;

l —— framed beam span;

H —— column height;

△P —— shear force on column;

X —— axial force in beam when unit prestressing force is loaded on structure.

Then, the influence coefficient of lateral restraint neglecting effective prestressing force distribution is:

$$\eta_1 = \frac{X}{1} = \frac{1}{1 + \dfrac{6 E_c I_c l}{E_b A_b H^3}} = \frac{E_b A_b H^3}{E_b A_b H^3 + 6 E_c I_c l} \tag{2}$$

CONSIDERING EFFECTIVE PRESTRESSING FORCE DISTRIBUTION

Denoting unit prestressing loss as function f(x), axis x coincides with the beam axis, and the origin point is located at the beam end. Considering prestressing loss and the real distribution of effective prestressing, the beam compressive displacement is calculated as follows:

$$\begin{cases} \dfrac{\Delta PH^3}{12E_cI_c} = \dfrac{\dfrac{Xl}{2} - \int_0^{\frac{l}{2}} f(x)\,dx}{E_bA_b} \\ \Delta P + X = 1 \end{cases} \tag{3}$$

The influence coefficient of lateral restraint considering effective prestressing distribution is:

$$\eta_2 = X = \frac{E_bA_bH^3 + 12E_cI_c\int_0^{\frac{l}{2}} f(x)\,dx}{E_bA_bH^3 + 6E_cI_cl} \tag{4}$$

The difference of the influence coefficient of lateral restraint is:

$$\Delta\eta = \eta_2 - \eta_1 = \frac{12E_cI_c\int_0^{\frac{l}{2}} f(x)\,dx}{E_bA_bH^3 + 6E_cI_cl} \tag{5}$$

Results are shown in Table 1 when considering different column-beam stiffness ratios (i_c/i_b). The restraint coefficient is smaller if considering a uniform effective prestressing force distribution, which underestimates the lateral constraint and increases the usage of prestressed reinforcement in design. The restraint coefficient reducess when the beam-column stiffness ratio decreases and the actual prestressing in beam is also decreased. The difference of the influence coefficient of lateral restraint increases when the beam-column stiffness ratio decreases and the lateral stiffness of vertical members increases.

Table 1 Influence of Beam-Column Stiffness Ratio on Restraint Coefficients

Section（mm×mm）		i_c/i_b	η_1	η_2	$k=(\eta_2-\eta_1)/\eta_2$
Beam	**Column**				
300×1200	600×600	0.83	0.9798	0.9824	0.26%
	800×800	2.63	0.9389	0.9466	0.81%
	800×1000	5.14	0.8873	0.9014	1.57%
	1000×1200	11.11	0.7847	0.8117	3.32%
	1000×1400	17.64	0.6965	0.7346	5.18%
	1200×1600	31.60	0.5617	0.6166	8.91%
	1400×1800	52.50	0.4355	0.5062	13.97%
	1500×2000	77.16	0.3442	0.4264	19.27%

For a beam section of 300mm×1200mm, column section of 600mm×600mm, considering different friction coefficients in the example, the corresponding results are shown in Table 2.

Table 2 Friction Effect on Restraint Coefficients

	K	μ	η_1	η_2	K
Unbonded	0.0035	0.10	0.3442	0.3915	12.09%
Bonded	0.0015	0.25	0.3442	0.4129	16.63%
	0.0010	0.30	0.3442	0.4205	18.14%
	0.0014	0.55	0.3442	0.4670	26.30%

If the effective prestressing force distribution is treated as uniform, the restraint coefficients are the same when friction coefficient varies greatly, which does not match the reality. Taking into account the real distribution of effective prestressing force could reflect the restraint effect better. The restraint coefficient increases along with the increasement of friction loss. The greater the friction loss, the greater the variation of effective prestressing force distribution, the difference in restraint coefficients between two methods is also greater. Therefore, the real distribuation of effective prestressing force should be applied when considering restraint effect.

THE INFLUENCE OF TENDON PROFILE

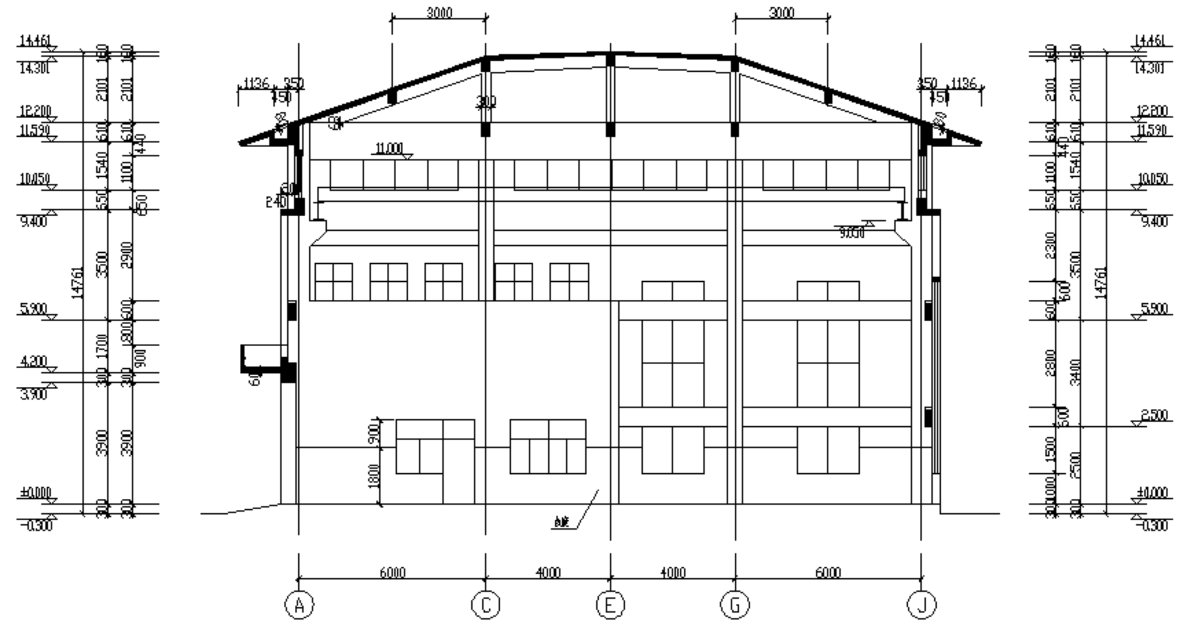
The influence of tendon geometry on constraint effect is discussed for a prestressed beam of a machinery room (Fig. 2).

COMPARING DIFFERENT CALCULATION MODELS

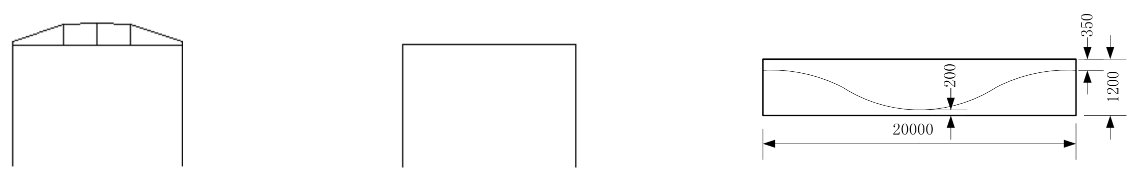
Two different models are described as follows:

1）Consider the restraint effect of roof; and the loads are carried by both roof truss and PC beams. Choose the sixth framework for reinforcement design using tension-bending model, as shown in Fig. 2 (b);

2）Neglect the restraint effect and load-bearing capacity of roof;, all loads are carried by PC beams. Choose the sixth framework for reinforcement design using design model for bending member, as shown in Fig. 2 (c). The tendon geometry is also shown in Fig. 2(d).



(a)



(b) Tension-Bending (c) Bending (d) Tendon Geometry

Fig. 2 Structure Diagram

The secondary axial forces caused by the primary axial force and the primary moment are calculated respectively and the results are colleced in the following table.

Table 3 Secondary Axial Force Summation

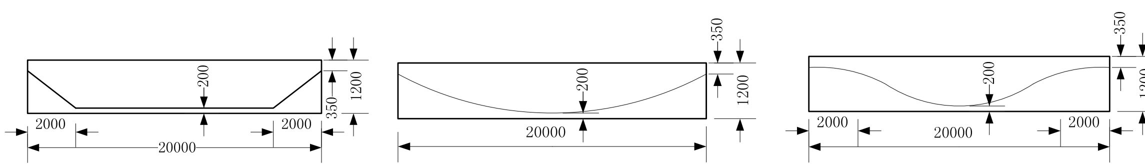
Model	Model 1 - Fig. 2(b)	Model 2 - Fig. 2(c)
Equivalent Axial Force（KN）	-1498.2	-1498.2
Secondary Axial Force caused by Primary Axial Force（KN）	78.99	1.37
Secondary Axial Force caused by Primary Moment（KN）	-171.35	10.22
Net Secondary Axial Force（KN）	-92.36	11.59
(Net/Equivalent) x100%	6.17%	0.77%

In Model 1, the secondary axial force caused by the primary moment is large compressive force which makes the net secondary axial force compressive. While in Model 2, where the primary moment is ignored, the secondary axial force is in tension which does not match the actual situation. This is mainly because in this structure, the roof truss and beam formed an arch-type mechanism; the beam undertakes the load mainly from the counterforce of roof truss and very little moment is allocated on beam. In the meantime, the column supporting the roof truss does not carry thrust from it, thus the secondary axial force plays a leading role in beam with very small moment. As a result, the design should consider a tension-bending model, as shown in Fig. 2(b). The simplified pure bending model in Fig. 2(c) is not reasonable.

COMPARING DIFFERENT TENDON GEOMETRIES

With two calculation models shown in Fig. 2 (b) and (c), four different tenson profiles are studied, which include tendons with straight line, polygonal line, two parabolic curve, four parabolic curve geometry, as shown in Fig. 3. Only the results of secondary axial forces considering the influence of tendon geometries are shown in Table 4.

（a）Straight Line Type 1 （b）Straight Line Type 2



（c）Polygonal Line （d）Two Parabolas （e）Four Parabolas

Fig. 3 Tendon Profiles

When using the tension-bending model of Fig. 2 (b), the percentage of secondary axial force over equivalent axial force is more than 5%, the influence of constraints can not be overlooked; if using the pure bending model of Fig. 2 (c), the restraint effect is little. Clearly, if this structure is simplified as a general framework in analysis, the secondary axial force will inevitably be neglected and hidden dangers are resulted. On the other hand, when beams have tendon laid in the form of straight and polygonal line, the secondary axial force is in tension; and when beams have tendon laid with the form of parabolic curves, the secondary axial force is in compression. Due to the variation of tendon profiles, the secondary axial forces of structure could change from tension to compression possibly in large magnitude. It will certainly lead to differences in structural reinforcement design.

Table 4 Secondary Axial Force Caused by Different Tendon Geometries

	Model	Straight Type 1	Straight Type 2	Poly-gonal	Two Parabolas	Four Parabolas
Equivalent Axial Force （KN）	Fig. 2 (b)	-1000	-1000	-1000	-1000	-1000
	Fig. 2 (c)	-1000	-1000	-1000	-1000	-1000
Secondary Axial Force（KN）	Fig. 2 (b)	86.07	84.36	16.87	-119.53	-114.93
	Fig. 2 (c)	-11.41	35.01	15.79	8.69	6.79
Secondary Axial Force in Percentage	Fig. 2 (b)	8.61%	8.44%	1.69%	11.95%	11.49%
	Fig. 2(c)	1.14%	3.50%	1.58%	0.87%	0.68%

For normal framed structure, the secondary axial force is usually in tension which reduces the effectiveness of prestressing. In this sample structure, the constraint effect of roof truss as arch is very obvious. If the continuous parabolic curve is chosen as the tendon profile other than the straight line, the primary moment (from the eccentricity of tendon) could result in compressive secondary axial force and the structural behavior is fundamentally changed. Thus, the secondary axial force also depends on the tendon geometry.

THE DESIGN METHOD CONSIDERING SECONDARY INTERNAL FORCES, ESPECIALLY SECONDARY AXIAL FORCE

A COMPARISON OF DESIGN FORMULA FOR TWO VIEWPOINTS

At present, there are two main viewpoints about restraint effects in PC structure, one is prestressing loss, another is secondary internal forces, especially secondary axial force[12-17]. Prestressing loss in prestressed tendon or bar which is the reduction of the actual prestressing force loaded, is caused by friction, anchorage, etc. And the secondary internal forces in PC member are resulted from the redundant restraints in statically indeterminate PC structure under prestressing forces. It represents different meanings and results when these two effects occur in different locations.

It will lead to errors in structural design if restraint effects are considered as prestressing loss. Here is an example of a rectangular frame beam shown in Fig. 4.

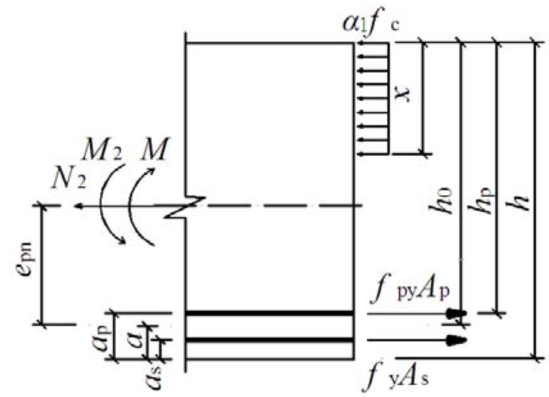


Fig. 4 PC Beam Section under Ultimate Bending State

Point of Application for Secondary Axial Force

Secondary axial force is originated from restraint effect and its point of application is located at the gravity center of beam section. While the application point for prestressing loss coincides with the location of prestressed bars, which is different from the prior one. If restraint effect is treated as prestressing loss, the resulted secondary axial force is applied at the location of prestressing tendon, other than at the gravity center of beam section.

Normal Stress of Concrete by Prestressing σ_{pc}

When secondary axial force is neglected:

$$\sigma_{pc} = \frac{N_p}{A_n} \pm \frac{N_p e_{pn}}{I_n} \pm \frac{M_2}{I_n} y_n \tag{6}$$

If secondary axial force acting at the gravity center is included, then:

$$\sigma_{pc} = \frac{N_p - N_2}{A_n} \pm \frac{N_p e_{pn}}{I_n} \pm \frac{M_2}{I_n} y_n \tag{7}$$

Where:
σ_{pc} —— normal stress of concrete
N_p —— prestressing force
N_2 —— secondary axial force.

When restraint effect is treated as prestressing loss, the resultant force of prestressing force and secondary axial force is:

$N'_p = N_p - N_2$ (8)

Then,

$$\sigma_{pc} = \frac{N_p - N_2}{A_n} \pm \frac{(N_p - N_2)e'_{pn}}{I_n} \pm \frac{M_2}{I_n} y_n \tag{9}$$

In which,

$$e'_{pn} = \frac{\sigma_{pe} A_p y_{pn} - \sigma_{l5} A_s y_{sn}}{\sigma_{pe} A_p - \sigma_{l5} A_s} \tag{10}$$

$\sigma_{pe} = \sigma_{con} - \sigma_l - \sigma_2$ (11)

$\sigma_2 = N_2/A_y$ (12)

Obviously, the formula for normal stress of concrete (9) is not correct, i.e., regarding restraint effect as prestressing loss is not proper for structural design.

Ultimate Limit State Equation of PC Beam Section

As mentioned above, secondary axial force is acting at the gravity center of the section. Then, the ultimate bearing capacity of rectangular beam could be calculated as below:

$$\begin{cases} M \le f_y A_s (h_0 - \frac{x}{2}) + f_{py} A_p (h_p - \frac{x}{2}) - N_2 (\frac{h}{2} - \frac{x}{2}) + M_2 \\ \alpha_1 f_c b x = f_y A_s + f_{py} A_p - N_2 \end{cases} \tag{13}$$

From Eq.(13), when secondary axial force is tensile, it is unfavourable for member bending resistance; overlooking secondary axial force will result in unsafe design.

When restraint effect is treated as prestressing loss, the ultimate bending resistance of rectangular section under bonded prestressing is calculated by Eq.(14), where ultimate stress of bonded tendon is expressed as f_{py}:

$$\begin{cases} M \le f_{py} A_p (h_p - \frac{x}{2}) + f_y A_s (h_0 - \frac{x}{2}) + M_2 \\ \alpha_1 f_c b x = f_y A_s + f_{py} A_p \end{cases} \tag{14}$$

From Eq.(14), it is concluded that when treating restraint effect as prestressing loss, the ultimate bending resistance of the bonded PC member is same as that when secondary axial force is not included in design.

When restraint effect is regarded as prestressing loss, the design stress level of unbonded tendon is $\sigma_{pu} = \sigma_{pe} + \Delta\sigma_p$, where $\sigma_{pe} = \sigma_{con} - \sigma_l - \sigma_2$, the ultimate bending resistance of that beam section is:

$$\begin{cases} M \le \sigma_{pu} A_p (h_p - \frac{x}{2}) + f_y A_s (h_0 - \frac{x}{2}) + M_2 \\ \alpha_1 f_c bx = f_y A_s + \sigma_{pu} A_p \end{cases} \quad (15)$$

Where,

$$\begin{aligned} \alpha_1 f_c bx &= f_y A_s + \sigma_{pu} A_p \\ &= f_y A_s + (\sigma_{con} - \sigma_l + \Delta\sigma) A_p - \sigma_2 A_p \\ &= f_y A_s + \sigma'_{pu} A_p - \sigma_2 A_p \end{aligned} \quad (16)$$

σ'_{pu} is the ultimate stress of unbonded tendon when not considering restraint effect or secondary axial force.

For PC structure with unbonded prestressing tendon, the calculated bending capacity from Eqs. (15) and (16) is smaller when including secondary axial force at the ultimate state.

Therefore, regarding restraint effect as prestressing loss, a PC structure can not be designed properly for bonded or unbonded prestressing. It will be unsafe for the bonded prestressed structure and conservative for the unbonded prestressed structure.

NUMERIAL EXAMPLE

The effect of restraint is demonstrated by the secondary axial force and secondary bending moment resulted. Three different circumstances are studied for the same structure in the aspect of reinforcement design, including: 1) Conventional design method - no restraint effect; 2) Considering restraint effect as prestressing loss; and 3) Actually reflecting restraint effect as secondary axial force.

The detailed information of the structure could be described as: A PC frame structure has a story height of 4.6m, a span of 30-meter long, and a column spacing of 8.4m. And the frame cloumn section is b×h=1500mm×2500mm, beam section b×h=350mm×1600mm, with 200mm thick cast-in-situ slab. The dead load is 79.1kN/m, live load 12.6kN/m, live load quasi-permanent value φ_q=0.4. Same concrete with strength of C40 is used for beam, column and slab. The steel strands of 1860MPa level φ^j15.2 are used for prestressing tendon, HRB335 deformed rebar for non-prestressed reinforcement.

Conventional Design Method - No Restraint Effect

Estimate prestressing tendon area A_p by Eq.(6), then calculate non-prestressed reinforcement A_s by Eq.(14).

Considering Restraint Effect as Prestressing Loss

Estimate prestressing reinforcement A_p by Eq.(9), then use Eq.(14) to calculate A_s in bonded PC structure, or use Eq.(15) for A_s in unbonded PC structure. In which, $\sigma_{pe} = \sigma_{con} - \sigma_l$.

Actually Reflecting Restraint Effect as Secondary Axial Force

Estimate A_p by Eq.(7), then calculate A_s by Eq.(13).

The comparison results are shown in Table 5.

Table 5 Comparison of Reinforcement Area (in mm^2)

			Conventional Design Method	Restraint Effect as Prestressing Loss	Restraint Effect as Secondary Axial Force
Bonded	A_p		2780	7228	3475
	A_s	Midspan	1473	1473	1473
		Support	5892	1473	2946
Unbonded	A_p		2780	7089	3336
	A_s	Midspan	1473	1473	2455
		Support	7365	1473	5401

For bonded PC structure, prestressed reinforcement area is underestimated by 20% and non-prestressed reinforcement area is overestimated significantly when neglecting restraint effect, and the cracking resistance or serviceability may not be satisified. Considering restraint effect as prestressing loss will lead to excessive usage of prestressing reinforcement in addition to higher ratio of prestressing strength which may reduce structural ductility.

The similar results are observed for unbonded PC structure. Because of a higher effective prestressing force in unbonded prestressed tendon, the prestressing reinforcement area is smaller and non-prestressing tendon area is larger than those of bonded PC structure.

CONCLUSIONS

（1）For PC structure, the influence of effective prestressing force distribution on restraint effect can not be ignored. Restraint coefficients reduce with the decrease of beam-column stiffness ratio and increase of friction. Ignoring the distribution of effective prestressing will deviate restraint effect from the actual state. The deviation is augmented when the beam-column stiffness ratio decreases and the friction loss increases.

（2）Restraint effect in PC structure is associated with tendon geometry. In certain structures with large restraints, structural behavior or deformation could have fundamental changes when secondary axial force varies from compression to tension.

（3）The essence of the restraint effect of PC structure is the resulted secondary internal forces when the deformation of members is restrained upon being prestressed. The magnitude of the secondary internal forces is related to the stiffness ratio of structural members, the distribution of effective prestressing, structural type and construction sequences, etc. The in force structural design code only considers the secondary moment and the secondary shear force; the code is not reasonable in judging restraint effect only based on span and bay number. By comparing this proposed design method with other two methods, conclusions could be drawn as: neglecting restraint effect, the calculated section bending-load bearing capacity is larger than the actual one. Restraint effect could not be regarded as prestressing loss; otherwise, the bending-load bearing capacity for either bonded or unbonded PC members can not be correctly calculated. In this aspect, the proposed design approach is more accurate and reliable than the existing national design code.

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