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ON THE REDUCTION OF PRESTRESSING FORCE NEAR SUPPORTS IN PARTIALLY PRESTRESSED CONCRETE FLEXURAL MEMBERS

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Straight tendons in pretensioned members can cause high-tensile stresses in the concrete extreme fibers at end sections because of the absence of the bending stresses due to self-weight and superimposed loads and the dominance of the moment due to prestressing force alone. Accordingly, the concrete tensile stresses at the ends of a member prestressed with straight tendons may limit the service load capacity of the member. It is therefore important to establish limiting zone in the concrete section within which the prestressing force can be applied without causing tension in the extreme concrete fibers. Two practical methods are available to reduce the stresses at the end sections due to the prestressing force. The first method based on changing the eccentricity of some tendons by raising them towards the end zone. The second method is based on bond prevention by encasing some of the tendons in plastic sheathing, effectively moving the point of application of prestressing force inward toward midspan for part of tendons. The present study focuses on a proposed third method to reduce the effect of the prestressing force near end supports by using straight strands with limited initial prestressing value in compression zone. New equations were suggested for the cracking moment and the prestressing force which consider the prestressed tendons in compression zone.

Keywords: Pretension, Strands, Stress, Top fibers, Compression zone, Cracking.

1 INTRODUCTION

It should be recognized that almost prestressed concrete members implicit significant amount of nonprestressed bonded reinforcement in addition to the prestressed steel. The nonprestressed reinforcement may be included in the flexural member to facilitate its fabrication, or due to strength and serviceability consideration. Such concrete members, which reinforced with combination of prestressed and nonprestressed reinforcement, are called partially prestressed concrete members. They occupy the whole spectrum of reinforcing range between fully reinforced and fully prestressed concrete members (Libby 1990), (Lin and Burns 1982), (Tadros *et al.* 1985).

Prestressing can be used to best advantage by varying the position of the prestressing force. Tendons whether bars, wires, strands, or made up cables may be used either straight or curved. Straight steel tendons are still the most commonly used tendons in pretensioned concrete members. Continuously curved tendons are used primarily in posttensioning applications. Cast-in ducts are positioned in the concrete unit to a continuous curve chosen to suit the varying bending moment distribution along the members.

From the theoretical viewpoint, it should be recognized that the profile of the prestressed steel, in accordance with (Figure 1. a, b, c, d) is considered to be the most appropriate placement of the longitudinal steel in the flexural structural member because of this distribution is compatible with the principal tensile stresses trajectory. At the same time it is considered as the most complicated and costly from the practical viewpoint (Libby 1990), (Lin and Burns 1982).

Two practical methods are available to reduce the stresses at the end sections due to the applied prestressing force. These common methods are: (1) Changing the eccentricity of some tendons by raising them towards the support zone (see Figure 1. a, b, c, d). This leads to reduce the moment value due to prestressing force. In sequence, the stresses at the ends can be reduced, and the service load capacity of the member can be increased, and (2) Sheathing portion of the tendons by plastic tube or a heavy paper or cloth tape having a waterproof adhesive at the immediate ends of the member. This eliminates the prestress transfer of part of the tendons at some distance from the support section. Here portion of the tendons prevented from bonding to the concrete at the immediate ends of the member, and, in so doing, preventing the unbounded tendons from prestressing the concrete at the ends.

If the path of the tendons is to be other than straight, vertical forces must be applied to the tendons to change their path. The devices used to apply the vertical forces and deflect the tendons from the straight path are called tendon deflectors or tendon-deflecting mechanisms. These mechanisms consist of devices that support the tendons in high position and devices that hold the tendons in the lower position. These devices are referred to as hold-up devices and hold-down devices, respectively (Libby 1990).

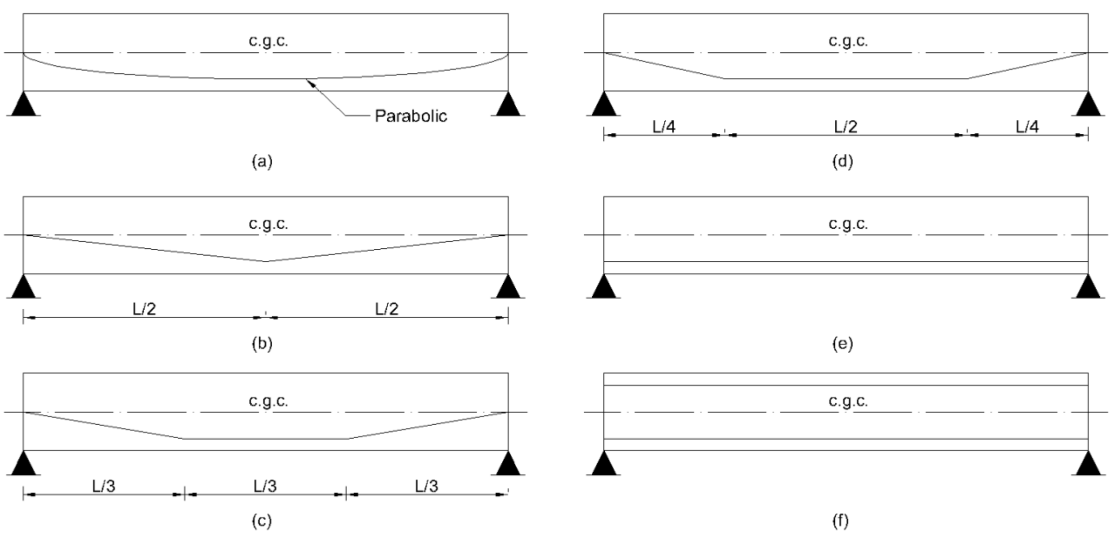

Figure 1. Profile of prestressed steel in flexural concrete members.

Significant disadvantages of the use of deflected tendons include the large capital investment in the stressing bed, the cost of the deflecting mechanisms, the friction losses that occur along the deflected tendons, the secondary stresses in the tendons where they pass over small-diameter pins and rollers, and the extra labor required to deflect the tendons (Libby 1990).

It is believed also that bond prevention can be used to advantage with complete safety if the tendons that will remain unbounded. The main disadvantage of this method is that AASHTO Standards (AASHTO 2014) restricted the number of partially debonded tendons which should not be exceeding 25% of the total number of tendons. Also, the number of debonded tendons in any horizontal row shall not exceed 40% of the number of tendons in that row. Additionally, if the bond is prevented at the end of a strand tendon, and the design allows tension in the pre-compressed tensile zone, the length required for flexural bond stresses to develop the strength of the tendon, (ℓ_d), is taken to be twice as great as that for a tendon that is bonded to the end of the member, see section 25.4.8.1 in ACI building code (ACI 318 2014).

These restrictions are considered to be the main disadvantages of the sheathing method because of the following: (1) Many practical cases may be encountered in which it is required to debond number of tendons more than the mentioned above percentages, and (2) Members that are of such a nature that high moments may occur near their ends, such as short simple spans and short cantilevers, require special consideration with respect to transfer and development lengths.

2 REDUCTION OF PRESTRESSING FORCE NEAR SUPPORT SECTIONS

It is obvious that the use of the straight profile (Figure 1.e) for the longitudinal prestressing steel in tension zone will be more economic than using other profiles if an approach is used to achieve a particular control for limiting or eliminating the tensile stresses which produced at the pretensioned compression zone of the section due to the effective prestressing force.

The proposed approach in this study is based on limiting or eliminating the tensile stresses at the extreme pretensioned compression zone fibers of the section by using straight longitudinal prestressing steel in compression zone with cross sectional area, A'_{ps}, not more than 15% of the area of the prestressing steel in tension zone, A_{ps} (Figure 1.f). Additionally, the value of the prestress introduced in the prestressing steel of the compression zone, f'_{pe}, shall be determined in such a manner that: (1) at the moment of transfer of the prestressing force, the tensile stress at the extreme concrete fibers shall not exceed 75% of the concrete modulus of rupture, f_r, and (2) at the moment of the flexural failure of the member these tensile stresses, f'_{pe}, must be nullified or progressed as compressive stresses. The reason for this is attributed to that "the prestressed steel in compression zone adversely affects the moment capacity of the structural member in the case if the generated prestress value not depleted entirely".

3 MODIFIED PRESTRESSING FORCE

ACI building code (ACI 318 2014), AASHTO Standards (AASHTO 2014) and PCI Design Handbook (2010) determine the effective prestressing force, P_e, according to the following equation:

$$P_e = A_{ps}\, f_{pe} \tag{1}$$

In partially prestressed concrete members and due to the existing bond between the nonprestressed steel and the surrounding concrete, compressive stresses are generated in nonprestressed steel. These stresses are created due to the shrinkage and creep of concrete after the exposure of the concrete member to the compressive prestressing force (Tadros *et al.* 1985). Accordingly, Eq. (1) becomes invalid to assess the effective prestressing force.

The proposed in the present study equation for determining the effective prestressing force, which considers the above mentioned factors, takes the following form:

$$P_e = A_{ps}\, f_{pe} + A'_{ps}\, f'_{pe} - A_s\, f_s - A'_s\, f'_s - \int f_c\, dA \tag{2}$$

where A_{ps} - cross-sectional area of the longitudinal prestressing steel in tension zone, mm^2; f_{pe} - effective prestress, after all losses, in the longitudinal prestressing steel in tension zone, N; A'_{ps} - cross-sectional area of the longitudinal prestressed steel in compression zone, mm^2; f'_{pe} - effective prestress, after all losses, in the longitudinal prestressed steel in compression zone, MPa; A_s – cross-sectional area of the longitudinal nonprestressed steel in tension zone, mm^2; f_s - compressive stress in the longitudinal nonprestressed steel in tension zone due to shrinkage and creep of concrete, MPa; A'_s - cross-sectional area of the longitudinal nonprestressed steel in compression zone, mm^2; f'_s - compressive stress in the longitudinal nonprestressed steel in compression zone due to shrinkage and creep of concrete, MPa; f_c – stress in concrete discrete parts, MPa; and dA – cross-sectional area of the concrete discrete part, mm^2.

The eccentricity of the effective prestressing force relative to the center gravity of the concrete section can be determined by equality the moment from the prestressing force and the moment from its components.

$$e_{ce}=\frac{A_{ps}\ f_{pe}\ y_{ps}-A'_{ps}\ f'_{pe}\ y'_{ps}-A_s\ f_s\ y_s+A'_s\ f'_s\ y'_s\mp\int f_c\ y_c\ dA}{P_e} \tag{3}$$

where y_{ps}, y'_{ps} - distance from the center gravity of the concrete section and the point of existence of the resultant of prestressing forces in tension and compression zones, respectively, mm; y_s, y'_s - distance from the center gravity of the concrete section and the point of existence of the resultant forces of the nonprestressed steel in tension and compression zones, respectively, mm; and y_c - distance between the center gravity of the concrete section and the center of the concrete discrete part under consideration, mm.

4 CRACKING MOMENT AT SERVICEABILITY STAGE

It is worth to mention out that if the point of application of the resultant prestressing force in a structural concrete member is restricted to a field that does not exceed r_c^2/c_b above the centroidal axis and r_c^2/c_t below the centroidal axis, tensile stresses will not occur in the concrete fibers of the section. This field in which the prestressing force can be applied without tensile stresses is called the elastic kern zone.

It is generally recommended to evaluate the magnitude of the cracking moment M_{cr} of the fully or partially prestressed concrete members in order to determine the reserve strength and overload limits that the designed section has. As already noted, for flexural prestressed concrete members is of great importance to consider the nonlinear strains of concrete in compression zone. Adoption of a triangular stress block in the compression concrete often leads to significant inaccuracies in the calculation. This is clearly shown by experimental works with concrete and reinforced concrete compression members subjected to bending moment. When the longitudinal compression force located on the boundary of elastic kern of the section and even within it, but near the boundary, it is indicated that the longitudinal compression force causes cracks on the extreme concrete fibers of the section, which according to the formulas of the strength of materials must have had either zero or compressive stresses (Zalesov *et al.* 1988).

At serviceability stage, the moment producing first cracks at bottom fibers in partially prestressed concrete girders is usually calculated by the elastic theory, assuming that cracking starts when the tensile stress in the extreme concrete fibers reach their modulus of rupture f_r. Most available test data seem to indicate that the elastic theory is sufficiently accurate up to the point of cracking, and the method is currently used. The ACI 318 code value for modulus of rupture, f_r, is $0.62\sqrt{f'_c}$ where both f_r and f'_c are in MPa.

It should be pointed out that the concrete modulus of rupture, f_r, is only a measure of the beginning of opening hair cracks which are often invisible to the naked eye. A tensile stresses which are greater than f_r required to produce visible cracks (Lin and Burns 1982).

To produce zero stress at the bottom concrete fibers, the center of the pressure (C-line) must be raised from the prestressing steel level to the upper kern point.

The distance from the center gravity of the section to the upper elastic kern point, k_t, can determined by the following equation

$$k_t = \frac{I_c}{A_c\ c_b} = \frac{r_c^2}{c_b} \tag{4}$$

Hence the elastic moment, M_{s1}, which required to move the compressive resultant from the level of the steel centroid to the upper kern point can be evaluated by multiplying the prestressing force by its lever arm, thus

$$M_{s1} = P_e\ (e_{ce} + k_t) = P_e \left(e_{ce} + \frac{I_c}{A_c\ c_b} \right) = P_e\ (e_{ce} + \frac{r_c^2}{c_b}) \tag{5}$$

Consequently, the additional moment, M_{s2}, required to develop the first flexural crack at the extreme tension fibers due to overload, such as the bottom fibers at mid-span of a simply supported beam, is

$$M_{s2} = \frac{f_r\ I_c}{c_b} = \frac{0.62\sqrt{f_c'}\ I_c}{c_b} \tag{6}$$

Accordingly, the total moment at cracking of the extreme bottom fibers at serviceability stage, M_{crs}, is given by

$$M_{crs} = M_{s2} + M_{s1} = \frac{0.62\sqrt{f_c'}\ I_c}{c_b} + P_e \left(e_{ce} + \frac{I_c}{A_c\ c_b} \right) \tag{7}$$

where A_c - gross cross-sectional area, mm^2; I_c - moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, mm^4; c_b - distance from centroidal axis of the gross section, neglecting reinforcement, to the extreme fiber in tension, mm; e_{ce} - eccentricity of the effective prestressing force relative to center gravity of the concrete section (c.g.c), mm; r_c – radius of gyration of cross-section of a flexural member, mm; and f_c' - specified 28-days compressive strength of concrete, MPa.

5 CRACKING MOMENT AT TRANSFER STAGE

Following the elastic theory, the moment producing first cracks at top fibers in partially prestressed concrete members can be determined at transfer stage. To produce zero stress at the top concrete fibers of the simply supported beam, the center of the pressure (C-line) must be shifted down from the level of the steel centroid to the lower kern point.

The distance from the center gravity of the section to the lower elastic kern point, k_b, calculated from the following equation:

$$k_b = \frac{I_c}{A_c\ c_t} = \frac{r_c^2}{c_t} \tag{8}$$

The elastic moment, M_{t1}, which is required to shift the C-line to the lower kern point is determined as follows

$$M_{t1} = P_i \, (k_b - e_{ci}) = P_i \left(\frac{I_c}{A_c \, c_t} - e_{ci} \right) = P_i \, (\frac{r_c^2}{c_t} - e_{ci}) \tag{9}$$

The additional moment, M_{t2}, required to develop the first flexural crack at the extreme tension fibers such as the top fibers at mid-span of a simply supported beam, is

$$M_{t2} = \frac{f_r \, I_c}{c_t} = \frac{0.62 \sqrt{f'_{ci}} \, I_c}{c_t} \tag{10}$$

where c_t - distance from centroidal axis of the gross section, neglecting reinforcement, to the extreme fiber in compression, mm; e_{ci} - eccentricity of the initial prestressing force relative to center gravity of the concrete section, (c.g.c), mm; P_i – initial prestressing force, N; and f'_{ci} - specified compressive strength of concrete at the time of initial prestress, MPa.

Accordingly, the total moment at cracking of the extreme top fibers at transfer stage, M_{crt}, is

$$M_{crt} = M_{t2} + M_{t1} = \frac{0.62 \sqrt{f'_{ci}} \, I_c}{c_t} - P_i \left(e_{ci} - \frac{I_c}{A_c \, c_t} \right) \tag{11}$$

6 CONCLUSION

An approach is proposed that based on limiting or eliminating the tensile stresses at the extreme pretensioned compression zone fibers of the section. That can be achieved by using straight longitudinal prestressing steel in compression zone with cross-sectional area not more than 15% of the area of the prestressing steel in tension zone and limited value of initial prestress.

Two equations were proposed to determine the cracking moment in flexural prestressed concrete members at transfer stage of prestressing force and at serviceability stage. These equations are considering the presence of prestressing steel in compression zone of the section.

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