Cracking Analysis of Partially Prestressed Concrete Tie Under the Effect of Primary and Secondary Cracks

Maurizio Taliano

Abstract A mathematical model for the cracking analysis of a concrete tie reinforced by ordinary and prestressing steels, subjected to a statically applied axial force, is proposed. The two types of steels do not have only different diameters, but also different bond properties, since in general the prestressing steel presents a lower bond quality with respect to the ordinary steel. The model is based on the assumptions of linear elastic σ-ε laws for both types of steels, as well as for the concrete, and on the bond law proposed in *fib* Model Code 2010. Both the crack formation stage and the stabilized cracking stage are analyzed. In particular, in the stabilized cracking stage, under the assumption that the crack spacing is maximum and equal to twice the transmission length, the effect of primary and secondary cracks is taken into account. This leads to distinguish, in the stabilized cracking stage, an initial transitional phase where the transfer length of ordinary steel is smaller than the transfer length of prestressing steel, followed by a fully developed phase, where the two transfer lengths are equal to each other. Finally, the theoretical results of the crack spacing and the crack width, obtained with this refined model are compared to the experimental data available in the literature.

Keywords Partially prestressed concrete · Cracking · Maximum crack spacing · Maximum crack width

1 Introduction

Partially prestressed concrete, in which ordinary steel is present with the prestressing steel, is a suitable alternative to reinforced or fully prestressed concrete. Among the various advantages of simultaneously adopting ordinary and prestressing steels, partially p.c. beams present an improved structural serviceability with reduced crack widths in comparison to fully prestressed concrete beams, thanks to the better bond

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of ordinary steel to the concrete. In effects, for partially prestressed beams international standards (fib Model Code 2010 [1], Eurocode 2 [2]) permit the formation of cracks under the frequent load combination, with crack width limits dependent on the environmental exposure class.

The study of the cracking behavior of a concrete tie reinforced with ordinary and prestressing steels is here developed with a mathematical model, named general model. This model is based on a previous work performed by Taliano [3] where the cracking analysis of a concrete tie reinforced with ordinary bars of different diameters is performed taking into account the effect of secondary cracks or Goto cracks. But, here, a further extension of this refined crack prediction model is developed, where the two types of steel do not have only different diameters, but also different bond properties. According to *fib* Model Code 2010 both the crack formation phase and the stabilized cracking phase are considered. In particular, in the stabilized cracking stage it is assumed that the crack spacing is maximum and equal to twice the transmission length of the prestressing steel.

2 Refined Model for the Cracking Analysis

A partially prestressed concrete tie subjected to a statically applied axial force is considered. Both ordinary and prestressing steels and concrete have linear elastic behaviour. For the sake of simplicity, the concrete section is reinforced by one prestressing tendon ($n_p = 1$) located at the centre of the section and four reinforcing bars ($n_s = 4$) located at the four corners (Fig. 1a). As the static conditions of the concrete vary, passing from compression to tension before and after decompression, the considerations made hereafter concern the behavior that occurs beyond the decompression of the concrete section. In other words, forces, deformations, stresses and strains are intended, in the following, as forces, deformations, stresses and strains beyond the decompression.

The formation of a crack determines the redistributions of stresses, strains and deformations around the crack that can be studied under two main situations: crack formation stage (Fig. 1b–d) and stabilized cracking stage (Fig. 2b–d). In both stages, around the crack the assumption of plane section is lost and, therefore, the elongations of ordinary and prestressing steels differ from the deformation of the concrete. It means that slips, s_s and s_p, occur between concrete and ordinary and prestressing steels:

$$s_s = u_s - u_{c,s} \tag{1}$$

$$s_p = u_p - u_{c,p} \tag{2}$$

where u_s and u_p, and $u_{c,s}$ and $u_{c,p}$ are the elongations of the ordinary bars, prestressing steel and concrete, respectively, from the relevant zero slip sections of the ordinary

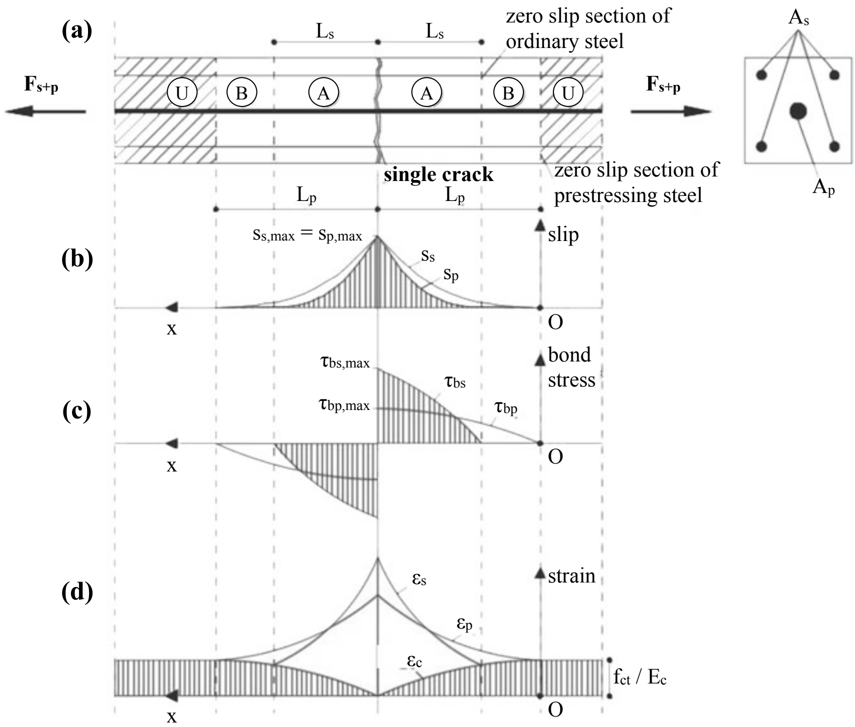

Fig. 1 Crack formation stage: **a** concrete tie reinforced with ordinary and prestressing steels; **b** distribution of the slips; **c** bond stresses; **d** longitudinal strains of ordinary and prestressing steels and concrete

and prestressing steels till the considered section. In particular, $u_{c,s}$ represents the elongation of the concrete determined from the zero slip section of the ordinary bars, while $u_{c,p}$ represents an analogous concrete elongation but referred to the prestressing steel. As a consequence, in general on the same section these two deformations differ because the starting points for their calculation, that means the zero slip sections for ordinary and prestressing steels, do not coincide.

The equations used to solve the mathematical problem are formally identical to that ones introduced by Taliano [3] in case of concrete tie reinforced with ordinary bars of different diameters. But, when the prestressing steel assumes the form of single strands or strand bundles, some modifications are needed in these equations. In effects, while the area of the transversal section, A_p, is associated to the nominal diameter ϕ_p, the external surface U_p, in contact to the concrete, is determined from the equivalent diameter, $\phi_{p,eq}$. And according to *fib* Model Code 2010 the equivalent diameter can be determined as follows: $\phi_{p,eq} = 1.75 \cdot \phi_{wire}$ for single 7-wire strands, $\phi_{p,eq} = 1.20 \cdot \phi_{wire}$ for single 3-wire strands and $\phi_{p,eq} = 1.6 \cdot \sqrt{A_p}$ for strand bundles, being ϕ_{wire} the wire diameter. This is a theoretical aspect that characterizes the

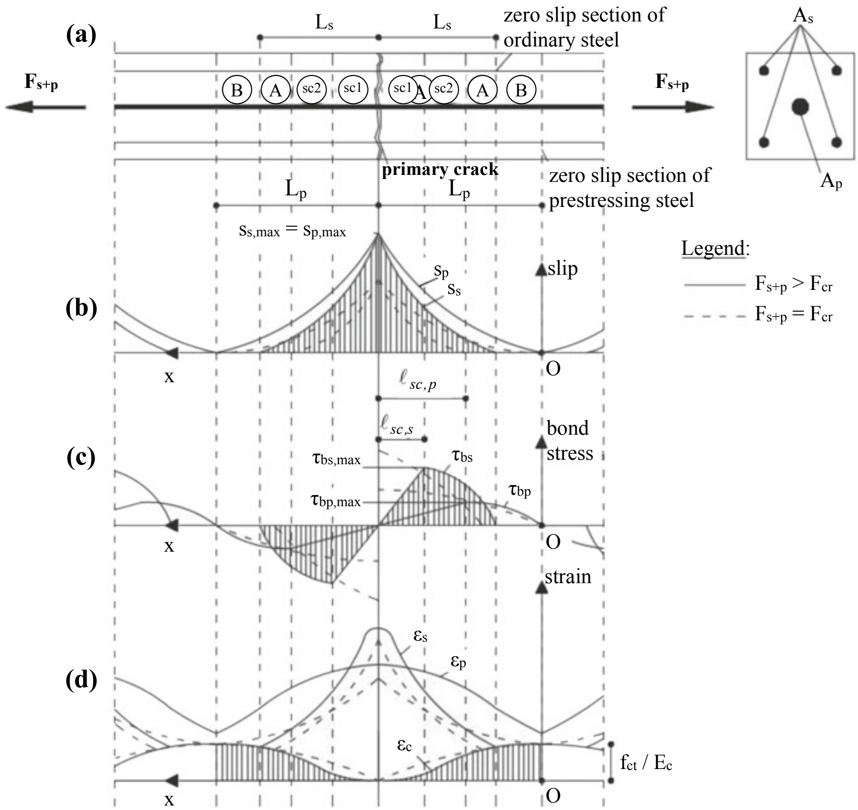

Fig. 2 Stabilized cracking stage when $L_s < L_p$: **a** concrete tie reinforced with ordinary and prestressing steels; **b** distribution of slips; **c** bond stresses; **d** longitudinal strains of ordinary and prestressing steels and concrete

cracking analysis of partially prestressed concrete tie that brings to do not simplify the nominal and equivalent diameters to each other in the differential equations that describe the mathematical model.

2.1 Bond Laws for Ordinary and Prestressing Steels

As far as the ordinary steel, the bond stress, τ_{bs}, can be expressed, in accordance with *fib* Model Code 2010, as a function of the slip, s_s, that occurs between steel and concrete, setting that the conditions for pull-out failure are met:

$$\tau_{bs} = \tau_{\max} \cdot \left(\frac{s_s}{s_1}\right)^{\alpha} = K_s \cdot s_s^{\alpha} \quad 0 \leq s_s \leq s_1 \tag{3}$$

being τ_{max} the bond resistance ($\tau_{max} = 2.5 \cdot \sqrt{f_{cm}}$ for good bond conditions); s_1 the value of slip corresponding to the attainment of τ_{max} ($s_1 = 1$ mm); α a numerical coefficient that can vary from 0 to 1. It has been shown in Debernardi et al. [4, 5] that a good value of the exponent α is equal to 0.25 in case of RC ties.

Actually, *fib* bond law for ordinary reinforcement is formed by various branches. But, as the maximum slip does not overcome 0.2 mm, a value that is obtained by dividing by two the maximum allowable crack width given by standards, for cracking analyses *fib* bond law can be limited to the first branch expressed by Eq. (3).

Prestressing steel presents reduced bond properties when compared to ordinary steel [6]. The effect of the different bond behavior of prestressing and ordinary steels was studied experimentally and theoretically by Rudlof and Hegger [7, 8] in case of post-tensioned ties. These Authors show that the bond strength of prestressing steel can be assumed as directly proportional to that one of the ordinary steel, through a bond factor, ξ, dependent on the type of prestressing steel (Table 1). Eurocode 2 as well as *fib* Model Code 2010 also provide values of the ξ factor, as shown in Tables 2 and 3. The values of ξ-factor proposed by Eurocode 2 refer to many cases, both for pre-tensioned and post-tensioned bonded steels with normal and high strength concretes: they are in agreement with the experimental values obtained in [7] in case of post-tensioned steels with normal strength concretes under short-term loading as well as the values proposed by *fib* Model Code 2010 in case of pre tensioned steels. In case of post-tensioned steels with high strength concretes Eurocode 2 also gives values that are in agreement with those obtained experimentally by Rudlof [7] under

Table 1 Bond factors ξ provided by Rudlof [7]

Type of prestressing steel	Pre-tensioned	Post-tensioned (bonded)	
		NSC	HSC
Smooth bars and wires	n.a.	0.30 (0.23)	0.18 (0.17)
Bundle of strands	n.a.	0.55 (0.41)	0.56 (0.29)
Indented wires	n.a.	n.a.	n.a.
Ribbed bars	n.a.	0.70 (0.56)	0.19 (0.13)

Table 2 Bond factors ξ provided by Eurocode 2

Type of prestressing steel	Pre-tensioned	Post-tensioned (bonded)	
		NSC	HSC
Smooth bars and wires	n.a.	0.30	0.15
Bundle of strands	0.60	0.50	0.25
Indented wires	0.70	0.60	0.30
Ribbed bars	0.80	0.70	0.35

Table 3 Bond factors ξ provided by *fib* Model Code 2010

Type of prestressing steel	Pre-tensioned	Post-tensioned (bonded)
Smooth bars and wires	n.a.	0.2
Bundle of strands	0.6	0.4
Indented wires	n.a.	n.a.
Ribbed bars	0.8	1.0

long-term loading, unless for ribbed bars where the bond factor is overestimated. As far as *fib* Model Code 2010, it does not distinguish between normal and high strength concretes, however it provides values that are, on average, in agreement with the values of Eurocode 2, except for ribbed bars for which the bond factor is assumed equal to 1.0 and so largely overestimated. In the following the bond factors proposed by *fib* Model Code 2010 (Table 3) are taken as reference in the calculations. Therefore, the adopted bond law for prestressing steel has a form that is analogous to that of ordinary steel, as a function of the slip, s_p, with a bond strength reduced by the ξ factors given in Table 3 (NB: ξ < 1):

$$\tau_{bp} = \xi \cdot \left[\tau_{\max} \cdot \left(\frac{s_p}{s_1} \right)^{\alpha} \right] = K_p \cdot s_p^{\alpha} \quad 0 \leq s_p \leq s_1 \tag{4}$$

2.2 Crack Formation Stage

A crack occurs in a section of the concrete tie when the concrete stress due to the applied axial load overcomes its tensile strength. The cracking force after decompression is:

$$F_{cr} = f_{ct} \cdot A_c \cdot \left(1 + \alpha_e \cdot \rho_s + \alpha_p \cdot \rho_p\right) \tag{5}$$

where in case of rectangular section $A_c = B \cdot H - A_s - A_p$.

The compatibility condition of the displacements requires that, at the crack, the distance between the two faces of the crack remains constant over the section, with the two sides of the crack parallel to each other and normal to the member axis. Therefore, at the crack the relative deformations (slips) of ordinary or prestressing steels and the concrete are the same (Fig. 1b), assuming the maximum value equal to the half of the crack width:

$$s_{s,max} = s_{p,max} = w/2 \tag{6}$$

As the assumption of plane section is lost, at the cracked section strains and stresses of ordinary and prestressing steels are unknown as well as the distances, L_p

and L_s, from the crack, where the condition of perfect bond (null slips) is restored for prestressing and ordinary steels (Fig. 1d).

Three different zones can be observed around a single crack, each with different behaviour (Fig. 1a):

- zone A, adjacent to the crack and extending for a distance equal to Ls from the crack, where all the steels are in slipping contact with the concrete ($s_p \geq s_s > 0$);
- zone B, extending from a distance L_s to a distance L_p from the crack, where the ordinary bars are perfectly bonded to the concrete ($s_s = 0$ and $\varepsilon_s = \varepsilon_c$), although the perfect bond condition is not observed for the prestressing steel ($s_p > 0$ and $\varepsilon_p > \varepsilon_c$);
- zone U (undisturbed), where both bars are perfectly bonded to the concrete ($s_s = s_p = 0$ and $\varepsilon_s = \varepsilon_p = \varepsilon_c$).

The two unknowns of the problem, that is, the transmission lengths of ordinary and prestressing steels, L_s and L_p, are determined through an iterative procedure. Convergence is reached when the concrete stress at the crack is equal to zero, and the ordinary and prestressing steels have the same maximum slip.

The following equations are used, with reference to an x-axis with origin at the zero slip section of the prestressing steel:

- in zone U, where perfect bond conditions can be applied, strains, stresses and deformations of materials are known;
- in zone B, only the ordinary bars are in perfect bond conditions with the concrete, while for prestressing steel it is possible to determine the distribution of slip of the prestressing steel, sp, in a closed form:

$$s_p(x) = \left[\frac{(1-\alpha)^2}{2 \cdot (1+\alpha)} \cdot \frac{\tau_{\max}}{s_1^\alpha} \cdot \frac{U_p}{E_p \cdot A_p} \cdot \frac{1 + \alpha_e \cdot \rho_s + \alpha_p \cdot \rho_p}{1 + \alpha_e \cdot \rho_s} \cdot x^2 \right]^{\frac{1}{1-\alpha}} \quad (7)$$

  from which the strains, stresses and deformations of the concrete and steels can be obtained.
- in zone A, the following two second-order differential equations can be derived to study the slipping contact between the ordinary and prestressing steels and the concrete

$$\begin{cases} \ddot{s}_s(x) = \frac{4 \cdot K_s \cdot (1+\alpha_e \cdot \rho_s)}{E_s \cdot \varphi_s} \cdot s_s^\alpha + \frac{(\xi \cdot K_s) \cdot U_p \cdot \alpha_p \cdot \rho_p}{E_p \cdot A_p} \cdot s_p^\alpha \\ \ddot{s}_p(x) = \frac{4 \cdot K_s \cdot \alpha_e \cdot \rho_s}{E_s \cdot \varphi_s} \cdot s_s^\alpha + \frac{(\xi \cdot K_s) \cdot U_p \cdot (1+\alpha_p \cdot \rho_p)}{E_p \cdot A_p} \cdot s_p^\alpha \end{cases} \quad (8)$$

2.3 Stabilized Cracking Stage with Maximum Crack Spacing

The crack spacing is here assumed as maximum and equal to twice the transmission length of the prestressing steel, L_p, determined at the crack formation stage. For compatibility of the deformations, ordinary and prestressing steels present the same maximum slip at the crack (see Eq. (6)).

At the beginning of this stage, the transmission length of the ordinary bars, L_s, is smaller than that of the prestressing steel, L_p, so that continuity with the previous stage is maintained. However, the increase in the length L_s goes on until the situation in which the transmission length of the ordinary bars, L_s, equals the transmission length of the prestressing steel, L_p. Therefore, when the axial load increases, two different phases form the stabilized cracking stage. An initial transitional phase, during which the transfer length of ordinary steel is smaller than the transfer length of prestressing steel, but it increases as the axial load increases. This phase is followed by a fully developed phase, in which the transfer length of ordinary steel remains unchanged and equal to the transfer length of prestressing steel.

In both these two phases, as in case of an RC tie in the stabilized cracking stage under the assumption that the crack spacing is maximum [4, 5], the equilibrium condition requires to modify the distributions of bond stresses close to the primary crack. Linear distributions of bond stresses on ordinary and prestressing steels are adopted which, on the physical point of view, represent the effect of secondary cracks that occur around the primary crack. The lengths, over which bond stresses are reduced, are named as lengths of reduced bond of ordinary and prestressing steels, $\ell_{sc,p}$ and $\ell_{sc,s}$. These length tend to increase when the axial load increases.

Initial transitional phase ($L_s < L_p$). Two new zones occur around each primary crack, because of the presence of secondary cracks. Starting from a primary crack, four different zones can be observed (Fig. 2):

- zone SC1, adjacent to the crack, where all the steels are in slipping contact with the concrete, and secondary cracks are observed on both ordinary and prestressing steels ($s_p \geq s_s > 0$). The extent of this zone is equal to the length, $\ell_{sc,s}$, of the internal cracking of ordinary steels;
- zone SC2, which extends over a part of the length $\ell_{sc,p}$, beyond the length $\ell_{sc,s}$, and is equal to $\ell_{sc,p} - \ell_{sc,s}$. Ordinary and prestressing steels are in slipping contact with the concrete ($s_p \geq s_s > 0$), but secondary cracks are only observed on the prestressing steel;
- zone A, over the length $\ell_{sc,p}$, delimited on the other side by the zero slip section of the ordinary bars, whose extent is $L_s - \ell_{sc,p}$. Ordinary and prestressing steels are in slipping contact with the concrete ($s_p \geq s_s > 0$), but no secondary cracks form;
- zone B, which falls between the two zero slip sections of the ordinary and prestressing steels, whose extent is $L_p - L_s$. The ordinary bars are perfectly bonded to the concrete ($s_s = 0$), while the prestressing steel is in slipping contact with the concrete ($s_p > 0$).

The unknowns of the problem are the transmission length of the ordinary bars, L_s, and the lengths of the internal cracking, $\ell_{sc,s}$ and $\ell_{sc,p}$. They can be determined through an iterative procedure, verifying that, at the cracked section, the concrete stress is equal to zero and the ordinary and prestressing steels have the same maximum slip, and that the ratio between the maximum bond stresses of the prestressing and ordinary steels that occur in two different sections, at distances $\ell_{sc,s}$ and $\ell_{sc,p}$ from the primary crack, respectively, is constant and equal to the ξ-factor, that means:

$$t_{bp,max} = \xi \cdot \tau_{bs,max} \tag{9}$$

The calculation method is based on the following differential equations:

- for zone SC1 ($L_s - \ell_{sc,s} \leq x \leq L_p$), because of the presence of internal secondary cracks it is assumed that bond stresses τ_{bs} and τ_{bp} reduce linearly close to a primary crack, according to the model proposed by Debernardi et al. [4, 5]:

$$\begin{cases} \ddot{s}_s(x) = \frac{4\cdot(1+\alpha_e\cdot\rho_s)}{E_s\cdot\varphi_s} \cdot \frac{\tau_{bs,\max}}{\ell_{sc,s}} \cdot \left(L_p - x\right) + \frac{U_p\cdot\alpha_p\cdot\rho_p}{E_p\cdot A_p} \cdot \frac{\tau_{bp,\max}}{\ell_{sc,p}} \cdot \left(L_p - x\right) \\ \ddot{s}_p(x) = \frac{4\cdot\alpha_e\cdot\rho_s}{E_s\cdot\varphi_s} \cdot \frac{\tau_{bs,\max}}{\ell_{sc,s}} \cdot \left(L_p - x\right) + \frac{U_p\cdot\left(1+\alpha_p\cdot\rho_p\right)}{E_p\cdot A_p} \cdot \frac{\tau_{bp,\max}}{\ell_{sc,p}} \cdot \left(L_p - x\right) \end{cases} \tag{10}$$

  where $\tau_{bs,max}$ and $\tau_{bp,max}$ are the maximum bond stresses of the ordinary and prestressing steels that occur at the abscissas $x = L_p - \ell_{sc,s}$ and $x = L_p - \ell_{sc,p}$, respectively;
- for zone SC2 ($L_p - \ell_{sc,p} \leq x \leq L_p - \ell_{sc,s}$):

$$\begin{cases} \ddot{s}_s(x) = \frac{4\cdot K_s\cdot(1+\alpha_e\cdot\rho_s)}{E_s\cdot\varphi_s} \cdot s_s^\alpha + \frac{U_p\cdot\alpha_p\cdot\rho_p}{E_p\cdot A_p} \cdot \frac{\tau_{bp,\max}}{\ell_{sc,p}} \cdot \left(L_p - x\right) \\ \ddot{s}_p(x) = \frac{4\cdot K_s\cdot\alpha_e\cdot\rho_s}{E_s\cdot\varphi_s} \cdot s_s^\alpha + \frac{U_p\cdot\left(1+\alpha_p\cdot\rho_p\right)}{E_p\cdot A_p} \cdot \frac{\tau_{bp,\max}}{\ell_{sc,p}} \cdot \left(L_p - x\right) \end{cases} \tag{11}$$

- for zone A ($L_{s2} - L_{s1} \leq x \leq L_{s2} - \ell_{sc,p}$):

$$\begin{cases} \ddot{s}_s(x) = \frac{4\cdot K_s\cdot(1+\alpha_e\cdot\rho_s)}{E_s\cdot\varphi_s} \cdot s_s^\alpha + \frac{(\xi\cdot K_s)\cdot U_p\cdot\alpha_p\cdot\rho_p}{E_p\cdot A_p} \cdot s_p^\alpha \\ \ddot{s}_p(x) = \frac{4\cdot K_s\cdot\alpha_e\cdot\rho_s}{E_s\cdot\varphi_s} \cdot s_s^\alpha + \frac{(\xi\cdot K_s)\cdot U_p\cdot\left(1+\alpha_p\cdot\rho_p\right)}{E_p\cdot A_p} \cdot s_p^\alpha \end{cases} \tag{12}$$

- for zone B ($0 \leq x \leq L_p - L_s$), no equation is needed for ordinary bars that are perfectly bonded to the concrete, while the differential equation for the prestressing steel is:

$$\ddot{s}_p(x) = \frac{(\xi \cdot K_s) \cdot U_p}{E_p \cdot A_p} \cdot \left(\frac{1 + \alpha_e \cdot \rho_s + \alpha_p \cdot \rho_p}{1 + \alpha_e \cdot \rho_s}\right) \cdot s_p^\alpha \tag{13}$$

Fully developed phase ($L_s = L_p$). Both steels are in slipping contact with the concrete from the zero slip section to the cracked section. Three different zones can be distinguished around a primary crack (Fig. 3):

- zones SC1 and SC2, which are under the same conditions as the SC1- and SC2-zones described above for the initial phase;
- zones A ($0 \leq x \leq L_p - \ell_{sc,p}$), where non-linear distributions of bond stresses are observed on both ordinary and prestressing steels.

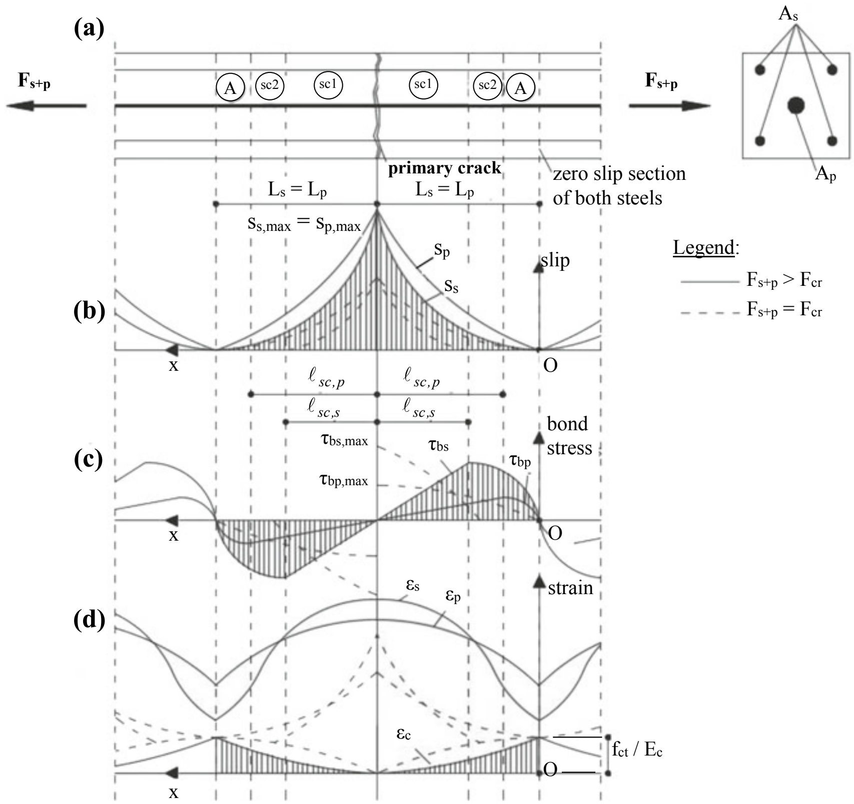

Fig. 3 Stabilized cracking stage when $L_s = L_p$: **a** concrete tie reinforced with ordinary and prestressing steels; **b** distribution of slips; **c** bond stresses; **d** longitudinal strains of ordinary and prestressing steels and concrete

The mathematical problem presents three unknowns, that means the lengths of the internal cracking, $\ell_{sc,s}$ and $\ell_{sc,p}$, and the stress, σ_{pE}, of the prestressing steel at the zero slip section. They are determined through iterative calculations considering, as boundary conditions, a null concrete stress at the crack, a maximum slips for ordinary and prestressing steels at the crack and a constant ratio between the maximum values of the bond stresses of ordinary and prestressing steels equal to the ξ-factor (see Eq. (9)). The last boundary condition is consistent with the initial transitional phase, where the maximum bond stresses of ordinary and prestressing steels are proportional to each other through the ξ-factor. On the other hand, a previous analysis concerning the cracking behaviour of a concrete tie reinforced with small and large ordinary bars has shown that this assumption is acceptable [3].

3 Comparison Between Experimental and Theoretical Data

The theoretical results obtained with the refined model are compared to the experimental data obtained by Rudlof [7]. These data refer to tests on concrete ties reinforced with four ordinary bars and post-tensioned with different types of prestressing steels all located in the centre of the section, without stirrups, with lengths of 1800 mm and square sections of 220 mm width. A groove at the mid-length of the ties marked the location of the first crack. In this section, in order to determine the forces that act on the ordinary and prestressing steels, strain gauges were glued on each ordinary bar, being applied after removing locally the ribs for their application. The measurements of crack width were performed by a mechanical extensometer (Staeger) with gauge length of 100 mm whose measuring points (3×18) form a grid on the two faces of the specimens. From these measurements it was possible to determine the axial mean deformations of ties on a measuring base of 1700 mm.

Here, the sample named K7 is considered, reinforced by four bars of 10 mm diameter and one central tendon composed by 3 strands, each of 0.6″ nominal diameter ($A_p = 420\ \text{mm}^2$). Concrete has a medium compressive strength ($f_c = 51.6$ MPa) as well as the grout ($f_{c,mortar} = 47.3$ MPa) and a splitting tensile strength of 2.46 MPa. The theoretical calculations are performed assuming $\xi = 0.5$. The comparison is made as a function of the applied axial force, in terms of stresses of ordinary and prestressing steels at the cracked section (Fig. 4a), mean strain of ordinary steel (Fig. 4b), twice of the transmission lengths of ordinary and prestressing steels (Fig. 5a) and crack opening (Fig. 5b). From the comparison of the experimental and theoretical values of the mean strain of ordinary steel (Fig. 4b) it results a quite good agreement between experimental and theoretical data. From Fig. 5a it appears that the mean value of the experimental crack spacing, which is equal to 180 mm, is included between the

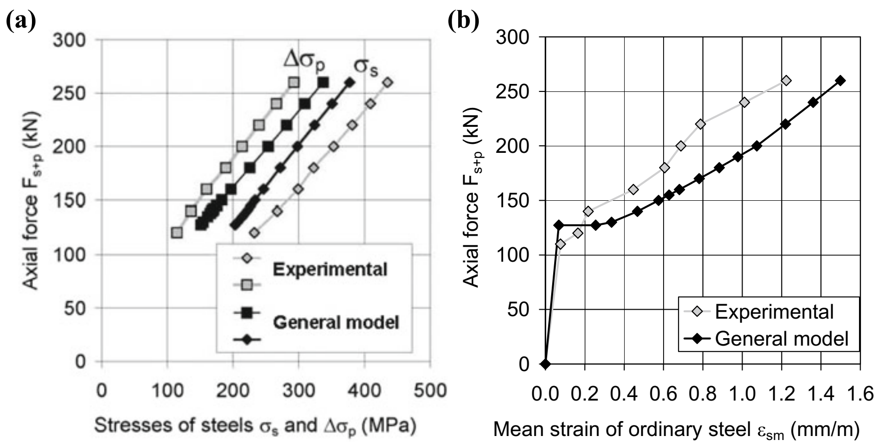

Fig. 4 Comparison between experimental and theoretical results (specimen K7): **a** stresses of ordinary and prestressing steels; **b** mean strain of ordinary bars

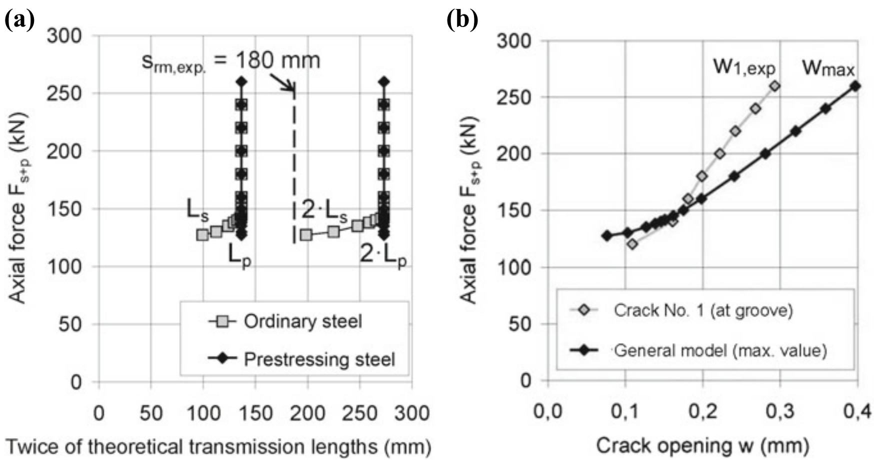

Fig. 5 Specimen K7: **a** twice of the transmission lengths of ordinary and prestressing steels; **b** local values (experimental) and maximum values (theoretical) of crack opening

maximum and minimum values of the theoretical crack spacing. This leads to a safe overestimation of the maximum theoretical crack opening (Fig. 5b).

4 Conclusions

A refined model for the cracking analysis of a concrete tie reinforced with ordinary and prestressing steel, subjected to a statically applied axial force, is proposed. The theoretical results obtained with the general model are compared to the experimental data available in the literature allowing the stress redistributions between prestressing and reinforcing steels and the strains and the deformations to be determined. This leads to a safe overestimation of the maximum theoretical crack opening.

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