Martí Vargas, JR. (2013). Predicting Strand Transfer Length in Pretensioned Concrete: Eurocode versus North American Practice. Journal of Bridge Engineering. 18(12):1270-1280. doi:10.1061/(ASCE)BE.1943-5592.0000456.

PREDICTING STRAND TRANSFER LENGTH IN PRETENSIONED CONCRETE: EUROCODE VERSUS NORTH AMERICAN PRACTICE

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Abstract

Prestressing strands are commonly used in pretensioned prestressed concrete bridges construction. Transfer length is an important parameter for structural design. This paper presents a comparative study on strand transfer length provisions from Eurocode-2 and North American practice, and identifies similarities and differences between both models. A database of measured transfer lengths according to several authors has been compiled and compared with predictions according to code provisions. The intervals of predictions are smaller than those corresponding to the experimental results, and they are smaller when code provisions are more simplified: the interval from Eurocode-2 is greater than that from ACI-318 which, in turn, is greater than the interval from AASHTO. The number of underestimated cases is lower for Eurocode-2 because of the higher predicted values, but situations in which a short transfer length is unfavorable are neglected by all models because they are not good predictions of shorter measured transfer lengths. When a transfer length estimation criterion is based on an allowable free end slip, more cases are excluded from the ACI-318 provisions.

CE Database subject headings: Bridge; Prestressed concrete; Bonding; Effective stress

Author keywords: Bridge; Concrete; Strand; Bond; Prestress; Transfer length; Transmission length

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Introduction

The use of prestressing strands is commonplace in the construction of pretensioned concrete structures and bridges. There are two procedures for prestressing a concrete member through strands: post-tensioning and pre-tensioning. The manufacturing process for pretensioned concrete members by pre-tensioning includes: tensioning the prestressing strands between abutments using provisional end anchorages; casting concrete around the prestressing strands; releasing the strand tension once the concrete achieves sufficient strength thereby transferring the prestress force to the member. The prestressing force in the strands is transferred to the concrete by bond in the end regions of the member. In each end region, the stress in the prestressing strand varies from zero at the end of the member to a constant maximum value (effective stress), which is achieved at a certain distance from the member end. Fig. 1 offers an idealization of the prestressing strand stress profile in a pretensioned prestressed member after prestress transfer.

According to ACI-318 –ACI: American Concrete Institute– (ACI 2011), the distance over which the strand should be bonded to the concrete to develop the effective prestress in the prestressing strand is defined as transfer length. Eurocode-2 calls this length transmission length (CEN 2004 –CEN: Committee European of Normalization–).

Transfer length is an important parameter for pretensioned concrete structural design (Russell and Burns 1996; Barnes et al. 2003). In the precast prestressed concrete industry, obtaining a good product within a short period of time is essential. Therefore, it is necessary to achieve the required concrete compressive strength as soon as possible so that the member can accept the transfer of the prestressing force at detensioning, and the member can be removed from the bed. The accuracy of any attempt to check the actual material stresses in the end region of pretensioned members depends upon the transfer length estimation. In addition, transfer length represents the first portion of the development length (in ACI-318; anchorage length in

Eurocode-2) over which the prestressing strand should be bonded so that a stress in the prestressing strand at nominal strength of the member, f_{ps}, may develop.

Consequently, it is necessary to contemplate some implications for bridge designs according to strand transfer length:

a) A short transfer length increases stresses and the risk of cracking (by concrete splitting, bursting or spalling) in the end regions. This may result in complete bond loss, especially if there is no confining reinforcement (den Uijl 1995). In these cases, it is possible to redevelop effective prestressing force by bond at a distance from the damaged location (Kasan and Harries 2011).

b) A long transfer length reduces the available member length to resist bending moment and shear, and therefore increases member cost.

Moreover, design strength provided by a pretensioned member shall be taken as the nominal strength multiplied by the strength reduction factors in sections within the transfer length (also within the development length). If a critical section occurs within these regions -where the strand is not fully developed- failure may occur by bond slip (ACI 2011). Thus, web shear cracks, which extend into the transfer length, can cause a bond-slip failure of the prestressing strands (Reed and Peterman 2004).

Strand transfer length depends on the properties of both the prestressing strand and the surrounding concrete, and also on several design and manufacture parameters (FIB 2000 –FIB: International Federation for Structural Concrete–; PCI 2011 –PCI: Precast/Prestressed Concrete Institute–). Some of the most important properties and parameters are: concrete strength at the time of detensioning, level of prestress force at detensioning, concrete cover, strand spacing, size of the cross-section, type of strand, strand diameter, strand surface condition (clean, oiled, rusted, epoxy-coated), detensioning method (sudden, gradual), confining reinforcement around the strand, concrete consolidation around strands, time-dependent effects, and vertical strand location in the concrete section.

There is also no consensus as to the main parameters to be considered in the models and equations predicting transfer length (Martí-Vargas et al. 2007a, 2012b). A perfect example of this is the case of the North American practice [ACI-318 (ACI 2011); AASHTO LRFD BDS –American Association of State Highway and Transportation Officials, Load and Resistance Factor Design, Bridge Design Specifications– (AASHTO 2012)] and Eurocode-2 (CEN 2004): provisions for transfer length are not a function of concrete strength in ACI-318 and AASHTO LRFD BDS, while Eurocode-2 provisions include concrete properties.

This paper presents the findings of a research project that examined the differences in predicted transfer length when using the Eurocode-2 and codes typically used in North America. A carefully selected database spanning a variety of experimental transfer length results has been compiled. Based on the data collected, strand transfer length predictions based on different provisions have been examined.

Background: transfer bond model and strand stress changes

For prestressing strands, there are three bond mechanisms (FIB 2000): adhesion, friction and mechanical action. A very small slip destroys adhesion. Then activation of the friction mechanism and mechanical action takes place, while radial compressive stresses around the prestressing strand causes bond stresses due to the prestress transfer. These radial compressive stresses are the response of the surrounding concrete to both the strand diameter increase and the displacement of the prestressing strand when a slip occurs. Mechanical action in prestressing strands notably differs from that in wires because their helical shape allows for increased bond stress when a greater slip occurs. As consequence, the longitudinal contraction of the prestressing strand results in a radial expansion of the tendon which is known as the Hoyer Effect (FIB 2000; Barnes et al. 2003).

Janney (1954) was one of the pioneers to research bond characterization and its relation with the transfer length of prestressing strands. The results obtained by Janney (1954) showed an inelastic response of the surrounding concrete with radial microcracking along almost the entire transfer length. On the other hand, according to Guyon (1953), the hypothesis of uniform bond stress distribution is an unattainable limit since there will always be a zone exhibiting elastic behavior along the transfer length. An analytical transfer bond model that considers both a longer plastic zone and a smaller elastic zone located at the end of the transfer length was proposed by Cousins et al. (1990). However, several authors have reported a plastic response along almost the entire strand transfer length (Janney 1954; Barnes et al. 2003; Martí-Vargas et al. 2007a). Consequently, authors and codes such as Eurocode-2 and ACI-318 generally assume bond models by considering uniform bond stress distribution (linear variation of the prestressing stress; see Fig. 1) along the transfer length.

In order for equilibrium to occur, the prestressing strand force must be equal to the force developed in the prestressing strand over the transfer length by assuming the uniform bond stress according to Eq. (1):

$$f_s A_p = L_t P_p U_t \tag{1}$$

where f_s is the effective stress (strand stress after transfer), A_p is the cross-sectional area of the prestressing strand, L_t is transfer length, P_p is the perimeter of the prestressing strand, and U_t is the average bond stress along the transfer length.

Based on Eq. (1), researchers have proposed several equations to predict transfer length based on experimental results and theoretical studies. Normally, regression analyses and statistical models provide descriptions of the effects of the aforementioned properties and parameters on transfer length (Martí-Vargas et al. 2006b; García-Taengua et al. 2011). The majority of these equations predicting transfer length take a parametric form in accordance with the structure of Eq. (2) (Martí-Vargas et al. 2007a):

$$L_t = \left[\left(\frac{f_{sx}^{n} A_p}{(k_1 \pi d) U_t} + k_2 \right) \cdot \chi \right] \cdot \lambda \tag{2}$$

where (only an additional notation) f_{sx} is the prestressing strand stress, n is an exponent, k_1 is the perimeter factor (k_1 = 4/3 for a seven-wire strand, k_1 = 1 for a circular cross-section), d is the nominal diameter of the prestressing strand, k_2 is an adjustment constant, χ is a factor to account for the type of release, and λ is a factor to obtain bound values for transfer length. Wan et al. (2002a) proposed the application of a top bar effect factor, and Martí-Vargas et al. (2012a) reported the effects of concrete composition on bond stress. An additional factor, ξ , for transfer length models has been proposed to account for time-dependent increases in transfer length (Caro et al. 2012) based on strand stress changes relating to the manufacturing process of pretensioned prestressed concrete members, as follows: a) strands are tensioned in a casting bed from zero to $f_{s,jack}$ –strand stress at jacking–, which decreases to $f_{s,bed}$ –strand stress at anchoring– by seating at provisional strands anchoring; b) the concrete member is cast around the strands, and $f_{s,bed}$ diminishes to f_{s0} –strand stress just before prestress transfer– because of strand relaxation losses; c) at release, strands shorten and the surrounding concrete shortens with them: prestress losses due to concrete elastic shortening range from f_{s0} to f_{si} –initial effective stress, just after prestress transfer– occur in the central zone of the member (see Fig. 1); and d) several time-dependent prestress losses gradually occur by concrete creep and shrinkage and strand relaxation and, consequently, effective stress changes from f_{si} to a final value f_{se} –effective stress after allowing for all prestress losses–.

Code provisions for transfer length

Eurocode-2

According to Eurocode-2 (Section 8.10.2, CEN 2004), the prestress may be assumed to be transferred to the concrete by a constant bond stress f_{bpt}, as follows:

$$f_{bpt} = \eta_{p1}\eta_1 f_{ctd}(t) \tag{3}$$

where η_{p1} is a coefficient that takes into account the type of tendon and the bond situation at release (3.2 for 3- and 7-wire strands), η_1 accounts for the tendon position during casting (1.0 for good bond conditions, and 0.7 otherwise), and $f_{ctd}(t)$ is the design value of strength at time of release.

The basic transmission (transfer) length (l_{pt}) value is given by:

$$l_{pt} = \alpha_1\alpha_2\phi\sigma_{pm0} / f_{bpt} \tag{4}$$

where α_1 accounts for the release procedure (1.00 for gradual release, 1.25 for sudden release), α_2 is a tendon area factor (0.25 for tendons with circular cross-sections, 0.19 for 3- and for 7-wire strands), ϕ is the nominal tendon diameter, and σ_{pm0} is the tendon stress just after release.

The transfer length should be taken as the less favorable of two values (l_{pt1}, l_{pt2}), depending on the design situation:

$$l_{pt1} = 0.8 l_{pt} \tag{5}$$

$$l_{pt2} = 1.2 l_{pt} \tag{6}$$

Normally, the lower value is used to verify local stresses at prestress transfer, whereas the higher value is for ultimate limit states.

The upper design value of transfer length is within the anchorage length. Fig. 2 illustrates the strand stresses according to the Eurocode-2 transfer length model.

This model coincides with Model Code 2010 –MC-2010- (FIB 2010) which also provides two values for transfer length. However, both models differ in relation to the obtained bound values, as follows:

- in the Eurocode-2 model, Eq. (4) initially computes a mean transfer length value, and Eq. (5) and Eq. (6) produces the lower bound and upper bound values, respectively; the upper/lower ratio is 1.2/0.8 = 1.5.
- in the MC-2010 transfer length model, the action effect that needs verifying in the design is considered by a factor α_{p2} (α_{p2} = 1 to calculate anchorage length when considering moment and shear capacity; α_{p2} = 0.5 to verify the transverse stress in anchorage zone); the upper/lower ratio is 1/0.5 = 2. With a non-specified value of α_{p2} = 0.75 (by averaging the established values α_{p2} = 1 and α_{p2} = 0.5), corresponding to a mean transfer length value, the calculation of the transfer lengths from MC-2010 and Eurocode-2 coincides.

ACI-318

Current ACI-318 provisions on transfer length first appeared in ACI Code 318–63 (ACI 1963) and derive from Eq. (1) using (Tabatabai and Dickson 1993): $f_s = f_{se}$; $A_p = 0.725\pi d^2/4$; $P_p = 4\pi d/3$; and U_t = 400 psi (2.76 MPa), resulting in (ACI-318, Section 12.9, the first part of Eq. 12-4):

$$L_t = \frac{f_{se} d_b}{3000} \ (f_{se} \text{ in psi}) \tag{7a}$$

$$L_t = \frac{f_{se} d_b}{20.7} \ (f_{se} \text{ in MPa}) \tag{7b}$$

where f_{se} is the effective stress in the prestressing strand after allowing for all prestress losses, and d_b is the nominal diameter of the prestressing strand.

According to the ACI Code 318-63 (ACI 1963) Commentary, it is worth noting that this relationship estimates average transfer length. This equation remains to date in ACI Code 318-11 (ACI 2011) in spite of a considerable number of proposed modifications (Floyd et al. 2011). In addition, several authors consider that the use of the term f_{si} in Eq. (7a-7b) rather than f_{se} for design purposes is more rational as transfer length is established at the release of prestress (Shahawy et al. 1992; Deatherage et al. 1994).

As a reasonable limit for the higher transfer length values, Russell and Burns (1996) recommended Eq. (8a-8b) for design applications:

$$L_t = \frac{f_{se} d_b}{2000} \quad (f_{se} \text{ in psi}) \tag{8a}$$

$$L_t = \frac{f_{se} d_b}{13.8} \quad (f_{se} \text{ in MPa}) \tag{8b}$$

Fig. 3 shows the relationship between strand stress and the distance over which the strand is bonded to the concrete, as represented by Eq. (7a-7b). Fig. 3 includes the effects of considering f_{si} rather than f_{se}, and of predicting transfer length by Eq. (8a-8b), which implies $U_t = 267$ psi (1.84 MPa).

On the other hand, the transfer length requirement mentioned in the ACI-318 shear provisions (Section 11.3.4) is 50 strand diameters, while the transfer length may be taken as 60 strand diameters according to AASHTO LRFD BDS (AASHTO 2012) provisions for prestressing strand development (Section 5.11.4.1).

Allowable free end strand slip

Variation in strand stress along the transfer length at prestress transfer involves slips between the strand and the surrounding concrete. It is possible to use these slips as an indirect method to estimate transfer length (Martí-Vargas et al. 2007b). Anderson and Anderson (1976) used this method as a simple non-destructive assurance procedure to monitor bond quality within precasting plants. Guyon (1953) proposed the following equation for uniform bond stress distribution:

$$L_t = 2\frac{\delta E_p}{f_{s0}} \tag{9}$$

where δ is the strand end slip, E_p is the strand modulus of elasticity, and f_{s0} is the strand stress immediately before prestress transfer.

Several authors (Anderson and Anderson 1976; Petrou et al. 2000; Wan et al. 2002b) have established an allowable free end slip ($\delta_{allowable}$), which results in a transfer length equal to that computed by the ACI-318 provisions for transfer length. By setting Eq. (9) to be equal to Eq. (7a-7b), the implied allowable end slip value by Eq. (10a-10b) is:

$$\delta_{allowable} = \frac{1}{6000}\frac{f_{s0}}{E_p} f_{se} d_b \text{ (Customary units)} \tag{10a}$$

$$\delta_{allowable} = \frac{1}{41.4}\frac{f_{s0}}{E_p} f_{se} d_b \text{ (SI units)} \tag{10b}$$

It is possible to extend Eq. (9) by setting it to equal Eq. (4) by considering the Eurocode-2 provisions, as follows:

$$\delta_{allowable} = \frac{1}{2}\frac{f_{s0}}{E_p} \alpha_1 \alpha_2 \phi \sigma_{pm0} / f_{bpt} \text{ (SI units)} \tag{11}$$

Eurocode-2 versus North American practice

There are similarities between the Eurocode-2 (CEN 2004) and ACI-318 (ACI 2011) provisions for transfer length: a) both models consider uniform bond stress; b) transfer length depends directly on the nominal strand diameter -also in AASHTO LRFD BDS (AASHTO 2012)-; and c) the effective stress after allowing for all prestress losses (f_{se} in ACI-318, $\sigma_{p\infty}$ in Eurocode-2) is the maximum strand stress considered along the transfer length to calculate development length. Table 1 summarizes the differences between both models.

Influence of concrete strength

Fig. 4 presents the predicted transfer length values of several prestressing strand nominal diameters. Eq. (4), Eq. (7a-7b) and the AASHTO LRFD BDS (AASHTO 2012) provisions provide these lengths. In order to calculate transfer length, the following relationships have been used: $f_{s0} = 0.75f_{pu}$ [f_{pu}: nominal strand strength; f_{pu} = 1860 MPa (270 ksi)], $f_{si} = 0.9f_{s0}$, and $f_{se} = 0.8f_{s0}$. Since the Eurocode-2 includes the effects of concrete strength, specified concrete compressive strengths of 50 MPa (7.25 ksi) and 100 MPa (14.50 ksi) at 28 days of age were used for comparison.

As seen in Fig. 4, transfer length decreases when concrete strength increases for the lengths predicted from Eurocode-2. The simplified model from AASHTO LRFD BDS provides higher transfer length values than the ACI-318 provisions. Similar transfer length values were obtained from the ACI-318 and Eurocode-2 when using a specified concrete compressive strength at 28 days equal to 100 MPa (14.50 ksi).

Data provided from tests

The transfer length may be determined experimentally, and over the years, there have been several experimental research programs examining the bond of prestressing strands (by way of example, see references included in Table 2). There are several experimental methods frequently used to determine transfer length: the longitudinal concrete surface strain profile (Rusell and Burns 1997), the prestressing strand end slip (Guyon 1953), the bond strength determination by push-pullout test (Hegger et al. 2007), and the prestressing strand force at several cross-sections (Martí-Vargas et al. 2006a, 2012c).

A data set of measured transfer lengths was compiled from an extensive review of the literature. All transfer lengths were measured using one of the three previously mentioned techniques. The data set includes measured transfer lengths and establishes several requirements for materials and manufacture parameters: nominal strand strength of 1860 MPa (270 ksi), strand diameter of 12.5 mm (0.49”) to 13 mm (0.51”), and initial strand stress level of 70-80% of nominal strand strength.

A total of 12 different sources reporting all the aforementioned input variables and spanning a variety of practical transfer length prediction situations were selected for the study which resulted in 202 transfer length samples. Table 2 summarizes this data, and Fig. 5 shows the measured transfer length versus the concrete compressive strength at the time of prestress transfer for this data.

In this data set, concrete strength at prestress transfer (f'_{ci}) covers a wide range (from 20 to 55 MPa [2.9 to 8 ksi]). In general, transfer length decreases when f'_{ci} increases. Fig. 5 includes trend lines of the test results for some sources showing this relationship. The range of measured transfer lengths for a single concrete compressive strength is ample. Furthermore, the range of concrete compressive strength values varies considerably for a single transfer length. The high transfer length results obtained by Cousins et al. (1990) -which may have been caused by additional unreported factors such as strand surface condition- are an anomaly in relation to the other test results.

Predicting strand transfer length from measured parameters

The experimental results provided above have been compared with the theoretical predictions obtained from the Eurocode-2 and ACI-318 provisions (Eq. (4) and Eq. (7a-7b), respectively. Fig. 6 shows the transfer lengths predicted from Eurocode-2 provisions, and Fig. 7 provides those from ACI-318 and it also offers the AASHTO LRFD BDS prediction ($60 \cdot 12.7 = 762$ mm [30”]) as a reference. As observed, the predicted transfer lengths from Eurocode-2 vary between 650-1300 mm (25.6”-51.2”) (Fig. 6), whereas ACI-318 gives predictions within a

600-800 mm (23.6”-31.5”) interval (Fig. 7). This small interval is because ACI-318 does not consider concrete properties; indeed, only slight variations based on strand stress and diameter affect transfer length predictions for this model. The AASHTO reference appears as a top value (Fig. 7).

With the Eurocode-2 predictions (Fig. 6), it can be again observed the higher measured values by Cousins et al. (1990). However, the Eurocode-2 predicted transfer lengths using Cousins et al. data that are within a typical range of values.

Figs. 8, 9 and 10 show the transfer length ratios (calculated/measured) obtained from Eurocode-2, ACI-318, and AASHTO, respectively, versus the measured transfer lengths. These figures also depict the average value and the standard deviation of these ratios. For all cases, the ratios decrease as measured transfer lengths increase. The obtained ratios are grouped closer together when the transfer length models are simplified. The results are grouped closest together when the AASHTO equation is used followed by the ACI-318 and then the Eurocode-2 equations. The 80% of the results are within the corresponding average ± standard deviation range for all three models, although practically all the measured transfer lengths by Cousins et al. (1990) are excluded of these ranges for being greater, and some results obtained by den Uijl (1995) and by Rose and Russell (1997) are excluded because they are smaller.

The higher ratios correspond to Eurocode-2, followed by AASHTO and ACI-318. Consequently, the number of underestimated transfer lengths (ratio < 1) is smaller for Eurocode-2: practically the only underestimated lengths are the measured transfer lengths by Cousins et al. (1990). However, AASHTO and ACI-318 also underestimate the measured transfer lengths obtained by other authors.

Based on the transfer length predicted from the measured parameters, Fig. 11 depicts the average value ± standard deviation for the three models, and also includes the experimental values. The predicted values are greater than the experimental value in all cases. Once again, it can be observed that the higher value corresponds to Eurocode-2, followed by AASHTO which, in turn, comes before ACI-318. The intervals average value ± standard deviation are smaller than those corresponding to the experimental results, and they are smaller when code provisions are more simplified: the interval from Eurocode-2 is greater than the interval from ACI-318 which, in turn, is greater than that from AASHTO.

Fig. 11 offers the lower and the upper bound values of predicted transfer lengths, when available: lower and upper bound values from Eurocode-2 according to Eq. (5) and Eq. (6), respectively, and the upper bound value from the North American practice according to Eq. (8) proposed by Russell and Burns (1996). As observed, the lower and upper bound values from Eurocode-2 range the interval average value ± standard deviation of the Eurocode-2 predictions. On the other hand, the lower bound value from Eurocode-2 coincides with the average value from AASHTO.

Fig. 11 also shows that both the upper values are greater than those of the greater measured transfer lengths (average value + standard deviation). However, no model offers good predictions of the shorter measured transfer lengths (average value – standard deviation): the North American practice does not offer this prediction and the lower bound value from Eurocode-2 is much greater than the shorter measured transfer lengths (this lower bound value is also greater that the average measured transfer lengths). Therefore, situations in which a short transfer length is unfavorable are neglected, as are the verifications of local stresses at prestress transfer.

Predicting allowable free end strand slip

Based on the compiled experimental data set, the sources reporting measured values of transfer length and free end strand slip for comparison purposes have been selected. Figs. 12

and 13 depict the measured transfer lengths versus the corresponding free end slip recorded in beams by several authors. The allowable free end slip according to Eq. (11) and the average transfer length value predicted from measured parameters according to Eurocode-2 have been plotted in Fig. 12. Analogously the allowable free end slip according to Eq. (10a-10b) and the average transfer length value predicted from measured parameters according to ACI-318 have been plotted in Fig. 13.

Both figures show the percentages of the results included in each sector. As observed in the figures, there is a wide range of end slips that correspond to the same transfer length. Moreover, there is wide range of transfer length values for a given end slip.

Figs. 12 and 13 also depict that when the measured transfer length is shorter than the predicted transfer length, the allowable free end strand slip limit is exceeded in 0.6% of the cases (by applying the Eurocode-2 provisions) and in 2.8% of the cases (by applying the ACI-318 provisions). On the other hand, for the measured free end slips that are less than the allowable free end strand slip, measured transfer lengths are longer than the predicted transfer length in some cases: 0.6% of the cases (by applying the Eurocode-2 provisions) and 4.6% of the cases (by applying the ACI-318 provisions). Consequently, the use of an assurance procedure for bond quality based on a limit value for the allowable free end slip is not completely reliable, and these criteria exclude more cases when applying the ACI-318 provisions.

Conclusions

This research offers a comparative study on transfer length provisions from Eurocode-2 and North American practice. Both models consider a uniform bond stress, strand diameter, and the effective stress after allowing for all prestress losses is used for calculating development length. The differences between the models include strand stress (just after release in

Eurocode-2, and after all the prestress losses in ACI-318), type of transfer length value (bound values in Eurocode-2, and average values in ACI-318), and concrete strength at release, tendon type, tendon position and release procedure (parameters only included in the Eurocode-2).

The experimental data used in the study was composed of measured transfer lengths determined by several authors. These results were compared with the theoretical predictions from Eurocode-2 and North American practice. The predicted transfer lengths from ACI-318 were very similar (600-800 mm [23.6”-31.5”]) which was expected since this model considers only the strand parameters. The predicted values from the Eurocode-2 vary vastly (between 650-1300 mm [25.6”-51.2”]) due to the fact that the model considers concrete properties. On average, the predicted values are greater than the experimental values in all the transfer length models. Higher values correspond to Eurocode-2 (it would be a good estimation of the longer measured transfer lengths), followed by AASHTO, and then ACI-318 (the best prediction of the average experimental values).

Predicted transfer length values result in smaller ranges than those corresponding to the measured transfer lengths, and these ranges are smaller when code provisions are more simplified: the range from Eurocode-2 is greater than the range from ACI-318 which, in turn, is greater than that from AASHTO.

The Eurocode-2 bound values practically range the interval average value ± standard deviation of the Eurocode-2 predictions. The lower bound value from Eurocode-2 is similar to the average AASHTO value. However, situations in which a short transfer length is unfavorable are neglected because no model offers good predictions of shorter measured transfer lengths: the North American practice does not offer this prediction and the lower bound value from Eurocode-2 is greater than the measured transfer lengths.

The transfer length ratio (calculated/measured) according to Eurocode-2 and North American practice shows a tendency in which these ratios decrease when the measured transfer lengths increase. The number of underestimated cases is smaller for Eurocode-2 because of the higher resulting ratios.

Finally, the use of a transfer length criterion based on the allowable free end slip excludes more cases when applying the ACI-318 provisions.

Acknowledgment

Financial support has been provided by the Spanish Ministry of Education and Science, Ministry of Science and Innovation, and European Regional Development Found (Project BIA2006-05521 and Project BIA2009-12722).

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