Formulation of New Development Length Equation for 0.6 in. Prestressing Strand

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The use of 0.6 in. (15 mm) diameter prestressing strand was prohibited by the FHWA in October 1988 due to a lack of data supporting the behavior of pretensioned concrete beams with this new size strand. (Note that the FHWA restriction on 0.6 in. strand was removed in May 1996.) In its memorandum, the FHWA imposed a 1.6 multiplier for the then-current transfer and development length equations and prohibited the use of 0.6 in. (15 mm) diameter prestressing strand. The proposed multipliers were based on the results of tests on small rectangular beams and are not fully applicable to full-scale members. As a part of a larger research project with The University of Texas at Austin, research was conducted at Texas Tech University to provide additional test data and to formulate a new development length equation. In this study, the transfer and development length results from various studies were collected in addition to the results obtained from the tests performed in regional laboratories. Proposed equations for transfer and development length are compared with current equations in ACI, AASHTO, and other codes. Comparisons show that the proposed equations give better estimates than other equations for 0.5 and 0.6 in. (13 and 15 mm) diameter prestressing strand.

Currently, there are several proposed equations to replace the existing ACI development length equation[1] for 0.6 in. (15 mm) diameter prestressing strand. Some proposed equations from various studies[2-4] were based on the results of experiments on small rectangular beams. However, Russell and Burns[5] showed that the size of the section has an effect on the transfer length, which is a part of the development length.

Therefore, equations based on the tests using small sections are not fully applicable to full-scale members used in actual construction. Also, the use of 0.6 in. (15 mm) diameter prestressing strand was prohibited by an FHWA memorandum[6] in October 1988 due to a lack of data supporting the behavior of pretensioned concrete beams caused by the interaction of this new size strand with concrete.

Because of these uncertainties, there has been a need to produce an equation that is based on the results from research with full-scale members. The purpose of the research conducted at Texas Tech University (TTU), as part of a larger research project with The University of Texas at Austin, was to provide additional test data for addressing the FHWA moratorium and to formulate a new development length equation for 0.6 in. (15 mm) diameter prestressing strand.

It should be emphasized that prohibition of the use of 0.6 in. (15 mm) diameter prestressing strand at a 2 in. (51 mm) center-to-center spacing in pretensioned concrete beams was lifted by another FHWA memorandum[7] in May 1996 as a result of numerous experimental studies that had been conducted using 0.6 in. (15 mm) strand.

In this study, the transfer and development length results from various studies have been collected in addition to the results obtained from tests performed in TTU's Structural Laboratory. The new formula for the transfer and development lengths of 0.5 and 0.6 in. (13 and 15 mm) diameter strand was compared with ACI,[1] AASHTO Standard,[8] and AASHTO-LRFD[9] equations, as well as equations proposed by Buckner[10] and Lane.[11]

DATA COLLECTION

To ensure that data collected from various research studies had common properties, several requirements were established, focusing on the materials and the type of measurements made in the studies. If a study met these requirements, its data were used in the formulation of the transfer and development length equations. The types of members and the number of data points from each study used in the formulation of the transfer and development length equations are listed in Table 1.

The only restriction applied to the concrete was that it had to be normal weight concrete. The prestressing strands were limited to uncoated, 0.5 or 0.6 in. (13 or 15 mm) diameter, Grade 270 low-relaxation strand due to their common usage. Only full-size AASHTO standard I-girders, state-specific I-girders, rectangular beams, and T-beams were included in this study. These full-size beams were considered with and without the deck slab. Flame-cut release of the prestressing strand was used with all collected data.

Transfer length criteria were limited to measured strain profiles that were used to determine the transfer lengths of the specimens. The selected method to determine the transfer length was the 95 percent Average Maximum Strain (AMS) method.[5] In this method, the AMS for the specimen was determined by computing the numerical average of all the compressive strains contained within the plateau region of the strain profile at the end of the beam. A line corresponding to 95 percent of the AMS was drawn.

For fully bonded strand, the transfer length was selected as the distance from the end of the beam to the intersection of the 95 percent AMS line and the beam's strain profile. For partially debonded strand, the transfer length was selected as the distance from the debonding point of that strand to the intersection of the 95 percent AMS line and the beam's strain profile.

When the 100 percent AMS method was used to determine the transfer length and the actual strain data were not available, the transfer lengths from these studies were multiplied by 0.90 to approximate their 95 percent AMS value. The criteria for the development length tests were that end slip measurements had been taken during the tests and that the tests had been classified as a flexural failure, hybrid failure, or bond failure. Development length tests conducted using

Table 1. Research studies included in the formulation of the proposed equations.

Organization	Beam type	Strand diameter (in.)	Concrete strength (psi)	Transfer length data points used	Development length data points used
Texas Tech University[12]	AASHTO Type I	0.6	5050 to 7440	60	12
FHWA Phase II[11]	AASHTO Type II	0.5 0.6	6130 to 10,860	18 4	19 4
FHWA/INDOT[13]	AASHTO Type I	0.5	5600 to 6800	0	4
Florida A&M University and Florida State University[14]	AASHTO Type II	0.5 0.6	5110 to 7440	12 7	0 0
Auburn University[15]	T-beams	0.5	6310 to 11,620	14	10
University of Texas at Austin[16]	Texas 22 in. I-beam	0.5 0.6	5110 to 5640	4 12	0 10
University of Texas at Austin[17-19]	Rectangular	0.6	13,090 to 13,220	3	4
University of Texas at Austin[20] and University of Tennessee at Knoxville[21]	AASHTO Type I	0.6	6040 to 14,060	179	36
			Total	313	95

Note: 1 in. = 25.4 mm; 1 psi = 0.006895 MPa.

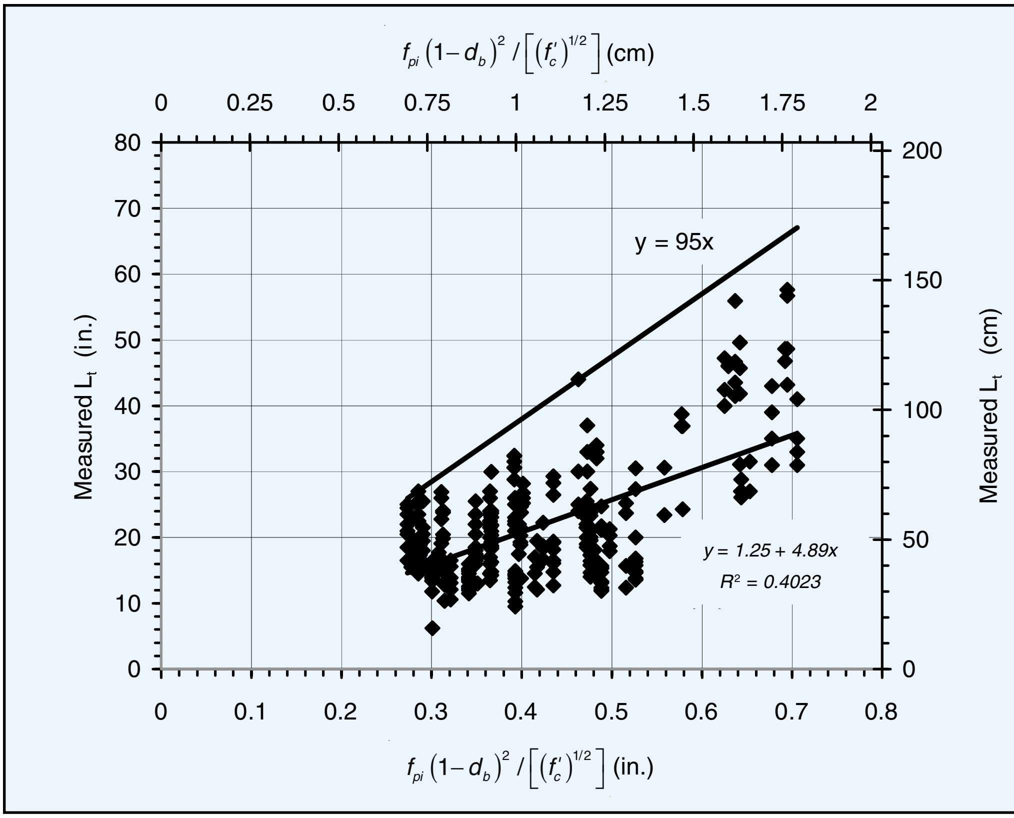

Fig. 1. Measured transfer lengths versus $f_{pi}(1-d_b)^2/\left[(f'_c)^{1/2}\right]$.

one or two load points were accepted. In the formulation of the new development length equation, development length data were accepted from studies that included both transfer length and development length tests.

NEW TRANSFER LENGTH FORMULATION

In both the ACI and AASHTO codes, as well as in other development length equation proposals, the first component of the equation predicts the transfer length. Having a separate expression for the transfer length is important because of the shear provisions in ACI and AASHTO. In these codes, the transfer length affects the vertical shear component of the prestressing force in the transfer region in the case of the draped strands, affecting the shear capacity of the member. A number of parameters were investigated for use in the proposed transfer length equation. These parameters were:

- Stress in the prestressing strands after short-term losses, f_{si} (ksi)
- Stress in the prestressing strands after long-term losses, f_{se} (ksi)
- Stress in the prestressing strands prior to release, f_{pi} (ksi)
- Square root of concrete compressive strength at the time of the short-term transfer length measurements, $\sqrt{f'_{ci}(\text{psi})}$
- Square root of 28-day concrete compressive strength for the long-term transfer length measurements, $\sqrt{f'_c(\text{psi})}$
- Diameter of the prestressing strands, d_b (in.)

These parameters were investigated using different statistical models[22] to maximize their correlation and to provide for ease of use by practicing engineers.

Linear Regression Model

To develop this model, various combinations of the above parameters were placed into a single variable that was used to predict the transfer length. From the collected transfer length data, the following general trends were observed:

1. For the 0.5 and 0.6 in. (13 and 15 mm) diameter strand data, an increase in the diameter of the prestressing strand decreased the transfer length. The strand diameter increase led to an increase in the strand force for the same percentage of prestress. At the same time, the strand perimeter, which affects the transfer bond stresses, especially mechanical interlock and Hoyer's effect, also increased. This increase in transfer bond forces could be larger than the corresponding strand force increase for the same percentage of prestress, thus shortening the transfer length.
2. An increase in the concrete strength decreased the transfer length. Other studies[2-5] have also shown that an increase in the concrete strength decreases the transfer length.
3. An increase in the effective prestress force increased the transfer length. Other studies[2-5] have also shown that an increase in the prestress force increases the transfer length.

Based on these observations, different combinations of the variables were used in several trial simple-regression models. From these trials, where L_t denotes transfer length:

$$L_t = 1.25 + 48.9\,\frac{f_{se}(1-d_b)^2}{\sqrt{f'_c}} \text{ (in.)} \qquad (1)$$

Eq. (1) was selected having the best correlation coefficient (R^2 = 0.3444) of the trial models. Later, the form of

$f_{se}\left(1-d_b\right)^2/\sqrt{f_c'}$ was modified by changing the effective prestress, f_{se}, to the initial prestress, f_{pi}, to make the proposed transfer length equation simpler to use in practice by eliminating the need to calculate prestress losses. Also, this substitution led to an increased correlation coefficient of $R^2 = 0.4023$. The fit of the modified Eq. (1) is shown in Fig. 1.

This regression model provides the mean estimate of the transfer length for Grade 270 low-relaxation strand with strand diameters ranging from 0.5 to 0.6 in. (13 to 15 mm) and with the concrete strengths ranging from 4000 to 14,000 psi (26.2 to 96.5 MPa). Since the regression model is a best-fit model and does not provide conservative results, the ordinate intercept and slope of modified Eq. (1) were adjusted to produce conservative results. After adjusting the slope and the ordinate intercept as shown in Fig. 1, the modified, adjusted model is no longer a best-fit model but does exceed the 95 percent confidence interval for the data.

Following the above-described modification and adjustment, the proposed equation to predict the transfer length of the strand becomes:

$$L_t = 95\,\frac{f_{pi}\left(1-d_b\right)^2}{\sqrt{f_c'}}\ \text{(in.)} \qquad (2)$$

The values of this transfer length term from Eq. (2) will range from 76 to 26 in. (1930 to 660 mm) when the strand diameter, d_b, ranges from 0.5 to 0.6 in. (13 to 15 mm) and the concrete strength, f_c', ranges from 4000 to 14,000 psi (27.6 to 96.5 MPa). The f_{pi} value is 202.5 ksi (1396 MPa).

PROPOSED FLEXURAL BOND LENGTH FORMULATION FOR FULLY BONDED STRANDS

In both the ACI and AASHTO codes, as well as in other development length equation proposals, the second component of the equation is the flexural bond length. The flexural bond length of each beam series was determined by taking the shortest strand embedment length that resulted in a flexural bond failure as the development length for the series and subtracting from it the average transfer length of that beam series.

After the flexural bond length was calculated for each beam series, a number of parameters were selected for possible use in a new flexural bond length equation. These parameters were:

- Ultimate tensile strength of the prestressing strand, f_{pu} (ksi)
- Average stress in the prestressing strands at ultimate load, f_{ps} (ksi)
- Stress in the prestressing strands after all losses, f_{se} (ksi)
- Stress in the prestressing strands prior to release, f_{pi} (ksi)
- Square root of concrete compressive strength at 28 days, $\sqrt{f_c'\,(\text{psi})}$
- Diameter of the prestressing strand, d_b (in.)

These parameters were investigated in different simple linear regression models to maximize their correlation and to provide for ease of use by practicing engineers.

Linear Regression Model

To develop this model, various combinations of the above parameters were used to predict the flexural bond lengths of the strand. From the collected flexural bond length data, the following general trends were observed.

1. For the 0.5 and 0.6 in. (13 and 15 mm) diameter strand data considered in this study, an increase in the diameter of the prestressing strand decreased the flexural bond length. The strand diameter increase led to an increase in the strand force for the same percentage of prestress. At the same time, the strand perimeter, which affects the flexural bond forces, especially mechanical interlock and Hoyer's effect, also increased. This increase in flexural bond force could be larger than the corresponding strand force increase for the same percentage of prestressing, thus shortening the flexural bond length.

2. An increase in concrete strength did not have any significant effect on the flexural bond length. However, some studies have shown that an increase in the concrete strength decreases the flexural bond length.

3. An increase in ($f_{ps} - f_{se}$) led to a slight decrease in the flexural bond length. However, it is theoretically known that the flexural bond length is directly proportional to ($f_{ps} - f_{se}$).

Based on these observations, different combinations of the variables were used in several trial simple regression models. From these trials, where L_{fb} denotes flexural bond length:

$$L_{fb} = 1.7 + 328.6\,\frac{\left(f_{ps}-f_{se}\right)\left(1-d_b\right)^2}{\sqrt{f_c'}}\ \text{(in.)} \qquad (3)$$

Eq. (3) was selected as having the best correlation coefficient ($R^2 = 0.473$) of the trial models. Later, the form of $\left(f_{ps}-f_{se}\right)\left(1-d_b\right)^2/\sqrt{f_c'}$ was modified by substituting f_{pu} for f_{ps} and f_{pi} for f_{se} to make the flexural bond length equation simpler to use in practice. These two substitutions eliminated the need to calculate the stress in the strand at ultimate loading, f_{ps}, and the need to estimate the prestress losses to determine f_{se}. Also, these two substitutions led to an increased correlation coefficient of $R^2 = 0.6858$. The fit of the modified Eq. (3) is shown in Fig. 2.

This regression model provided the mean estimate of the flexural bond length for Grade 270 low-relaxation strands with strand diameters ranging from 0.5 to 0.6 in. (13 to 15 mm) and with concrete strengths ranging from 4000 to 14,000 psi (27.6 to 96.5 MPa). Since the regression model is a best-fit model and does not provide conservative results, the ordinate intercept and slope of modified Eq. (3) were adjusted to provide conservative results.

After adjusting the slope and the intercept as shown in Fig. 2, the modified adjusted equation is no longer a best-fit model but does exceed the 95 percent confidence interval for the data. Following the described modification and adjustment, the proposed equation to predict the flexural bond length, L_{fb}, becomes:

$$L_{fb} = 8 + 400\,\frac{\left(f_{pu}-f_{pi}\right)\left(1-d_b\right)^2}{\sqrt{f_c'}}\quad \text{(in.)} \qquad (4)$$

The values of this flexural bond length term from Eq. (4) will

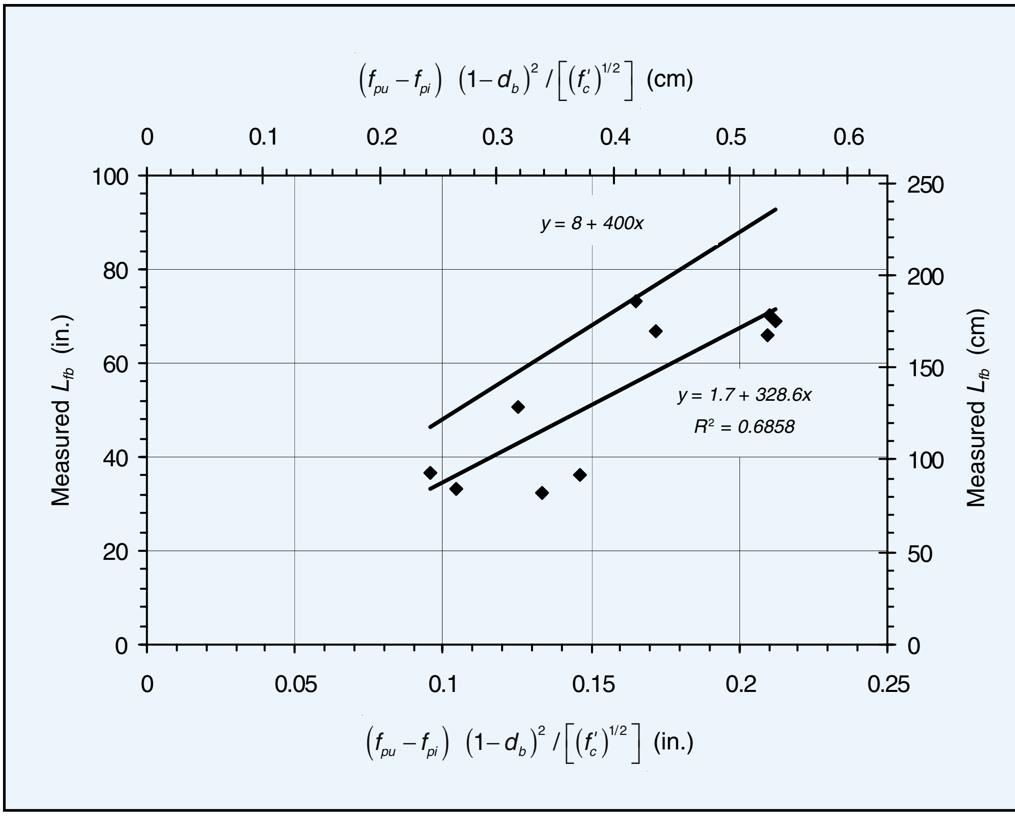

Fig. 2. Measured flexural bond lengths versus $(f_{pu}-f_{pi})(1-d_b)^2/[(f'_c)^{1/2}]$.

range from 115 to 45 in. (2921 to 1143 mm) when the strand diameter, d_b, ranges from 0.5 to 0.6 in. (13 to 15 mm) and the concrete strength, f'_c, ranges from 4000 to 14,000 psi (27.6 to 96.5 MPa). Values of f_{pu} and f_{pi} are 270 and 202.5 ksi (1860 and 1396 MPa), respectively.

PROPOSED DEVELOPMENT LENGTH EQUATION

Fully Bonded Strands

Since the development length is the summation of the transfer and the flexural bond lengths, the proposed development length equation is the sum of Eqs. (2) and (4). Thus, the new proposed development length equation is:

$$L_d=\left[95\frac{f_{pi}(1-d_b)^2}{\sqrt{f'_c}}\right]+\left[8+400\frac{(f_{pu}-f_{pi})(1-d_b)^2}{\sqrt{f'_c}}\right]\ \text{(in.)} \qquad (5)$$

with the first and second terms of Eq. (5) being equal to the transfer length and flexural bond length, respectively.

This development length equation can be used for Grade 270 low-relaxation strands with strand diameters ranging from 0.5 to 0.6 in. (13 to 15 mm) and with the concrete strengths ranging from 4000 to 14,000 psi (27.6 to 96.5 MPa), with development lengths ranging from 191 to 71 in. (4850 to 1803 mm). Values of f_{pu} and f_{pi} are 270 and 202.5 ksi (1860 and 1396 MPa), respectively.

Partially Debonded Strands

Since a limited number of data points were available for the partially debonded strands, statistical analyses were not applied to development length results from beams with partially debonded strands. The test results obtained from the joint projects at Texas Tech University and The University of Texas at Austin are shown in Table 2.

These test results show that partially debonded strands have longer development lengths than fully bonded strands because of higher load stresses at the location where the transfer begins. Also, an increase in the percent of debonding leads to an increase in the development length of the partially debonded strands.

In addition, the current ACI and AASHTO code requirements for partially debonded strands are that development length of the partially debonded strands should be twice the development length value required for fully bonded strands. Based on observations of the experimental data in this study and current code requirements, a general recommendation is made that Eq. (5) should be multiplied by two when applied to beams with partially debonded strands.

COMPARISION OF PROPOSED EQUATIONS WITH CURRENT CODES AND OTHER EQUATIONS

Measured transfer and development length values are compared with predicted values from ACI 318,[1] AASHTO Standard,[8] AASHTO-LRFD,[9] Lane,[11] Buckner,[10] and the equations proposed in this paper. All of these equations are provided in Table 3.

Transfer Length Comparison

Comparisons of the collected transfer length data with ACI 318/AASHTO Standard and AASHTO-LRFD are shown in Figs. 3 and 4, respectively. As seen in

Table 3, both ACI 318/AASHTO Standard and AASHTO-LRFD provide constant transfer length estimates for a given strand diameter because transfer length expressions are a function of only the diameter of the prestressing strand. Neglecting the strength of the concrete and the level of prestress results in unconservative results for the majority of the transfer length data of the 0.5 in. (13 mm) diameter strand and some of the 0.6 in. (15 mm) diameter strand. A 45-degree line is drawn in Figs. 3 to 11 to clearly show this unconservatism.

Any data point above the line shows that the measured transfer length value is greater than the predicted value. All three code equations are very unconservative for 0.5 in. (13 mm) diameter prestressing strand and slightly unconservative for 0.6 in. (15 mm) diameter prestressing strand.

Table 2. Effect of debonding on development length.

Organization	Beam series	Percent debonding	Experimental L_d, in.
Texas Tech University	L0RX	0	54
	L4RX	50	96
	L6RX	75	114
University of Texas at Austin	L0BX	0	54
	L4BX	50	96
	L6BX	75	114
	M0BX	0	54
	M4BX	50	>60
	M9BX	75	114
	H0BX	0	54
	H4BX	50	>62
	H9BX	75	114

Note: 1 in. = 25.4 mm.

Measured transfer length values are compared with values predicted by the Buckner[10] equation in Fig. 5. As seen in that figure, the Buckner equation is unconservative for a large amount of the 0.5 in. (13 mm) strand data, but is unconservative for only one data point for the 0.6 in. (15 mm) diameter strand. The Buckner equation predicts transfer lengths that are 10 to 20 percent longer than those predicted by the current code equations.

Measured transfer length values are compared with values predicted by the Lane[11] equation in Fig. 6. The Lane transfer length expression gives conservative results for all the measured transfer length values, as seen in Fig. 6. However, the Lane equation is overly conservative for the predicted values around 100 in. (2540 mm), which are from lower strength concretes; this could result in uneconomical designs.

Measured transfer length values are compared to values predicted by the equation proposed in this paper in Fig. 7. The proposed transfer length equation predicts conservative values for all the measured values. In addition, the overly conservative values predicted by the Lane equation have been

Table 3. Equations used to compare with measured data.

Author	Transfer length	Development length
ACI 318[1] and AASHTO Standard[8]	$L_t = \frac{f_{se}}{3} d_b$ $L_t \approx 50 d_b$	$L_d = L_t + \left(f_{ps} - f_{se}\right) d_b$ $L_d = \left(f_{ps} - \frac{2}{3} f_{se}\right) d_b$
AASHTO-LRFD[9]	$L_t = 60 d_b$	$L_d = \left(f_{ps} - \frac{2}{3} f_{se}\right) d_b$
Buckner[10]	$L_t = \frac{1250 f_{si}}{E_c} d_b$ $L_t \approx \frac{f_{si}}{3} d_b$	$L_d = L_t + \lambda\left(f_{ps} - f_{se}\right) d_b \quad 1.0 \le \lambda \le 2.0$ $\lambda = \left(0.6 + 40\varepsilon_{ps}\right)$ or $\left(0.72 + 0.102 \frac{\beta_1}{\omega_p}\right)$
Lane[11]	$L_t = \frac{4 f_{pt}}{f'_c} d_b - 5$	$L_d = L_t + \frac{6.4\left(f_{ps} - f_{se}\right) d_b}{f'_c} + 15$
Proposed Eqs. (2) and (5)	$L_t = 95 \frac{f_{pi}\left(1 - d_b\right)^2}{\sqrt{f'_c}}$	$L_d = L_t + 8 + 400 \frac{\left(f_{pu} - f_{pi}\right)\left(1 - d_b\right)^2}{\sqrt{f'_c}}$

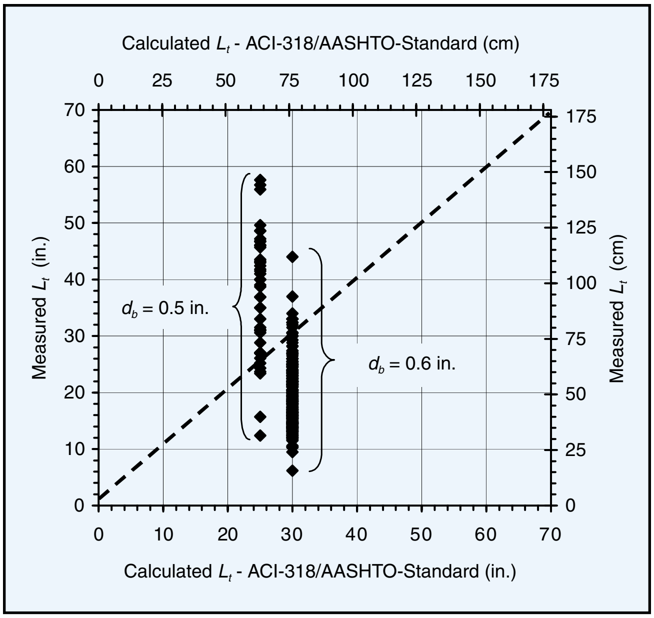

Fig. 3. Comparison of measured transfer lengths with ACI 318/AASHTO Standard.

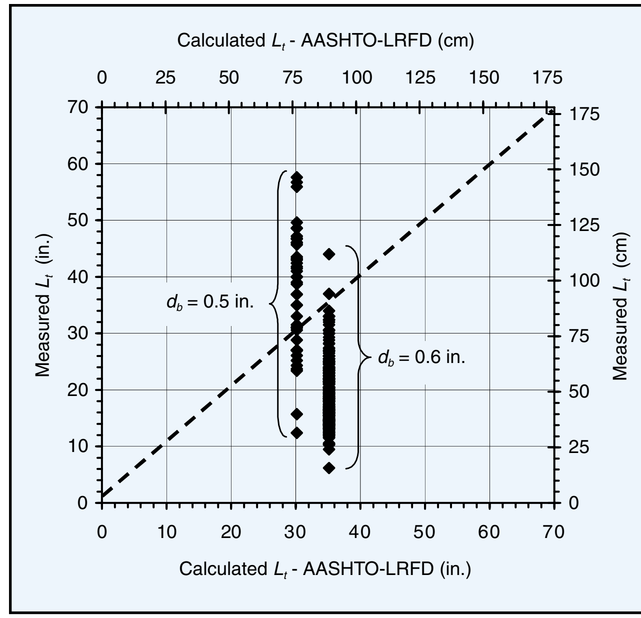

Fig. 4. Comparison of measured transfer lengths with AASHTO-LRFD Specification.

eliminated. All the data points are below the 45-degree line. In the proposed transfer length equation, the 28-day concrete strength is used as it is in the Lane transfer length equation.

Development Length Comparison

Although any failure is undesirable, engineers prefer a visible warning before a complete failure occurs so that loss of life can be avoided. Ductile flexural failure modes are desirable because they provide structural distress warnings such as large cracks and excessive deflections. Brittle strand slip/shear and bond failures can occur without any apparent warnings and such failure modes must be prevented. A hybrid failure is a failure wherein flexural failure and strand end slip occur simultaneously, indicating that the embedment length tested was borderline.

In the following comparisons of the experimentally determined development lengths with values predicted by code and proposed equations, a 45-degree line is drawn again; all slip/shear and bond failures should fall below this line, and this trend would indicate that the predicted development length is greater than the embedment length that would cause a slip/shear or bond failure to occur. Flexural failures can fall above or below the 45-degree line because they are the desired type of failure. Ideally, all the hybrid failures should be on the 45-degree line because they are the boundary between the flexural and bond failure modes.

A comparison of the experimentally determined development length results with code values is shown in Fig. 8. ACI

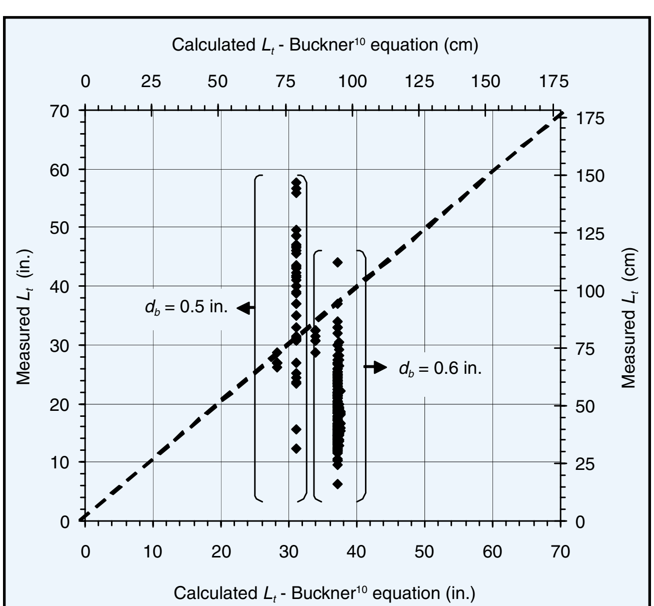

Fig. 5. Comparison of measured transfer lengths with the Buckner[10] equation.

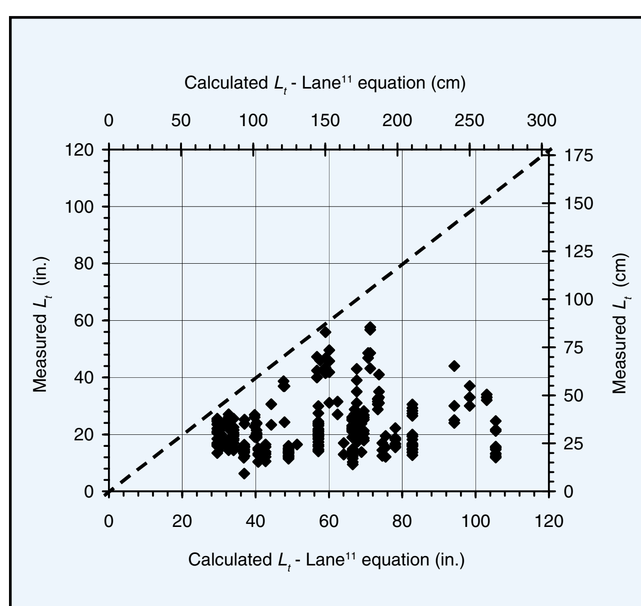

Fig. 6. Comparison of measured transfer lengths with the Lane[11] equation.

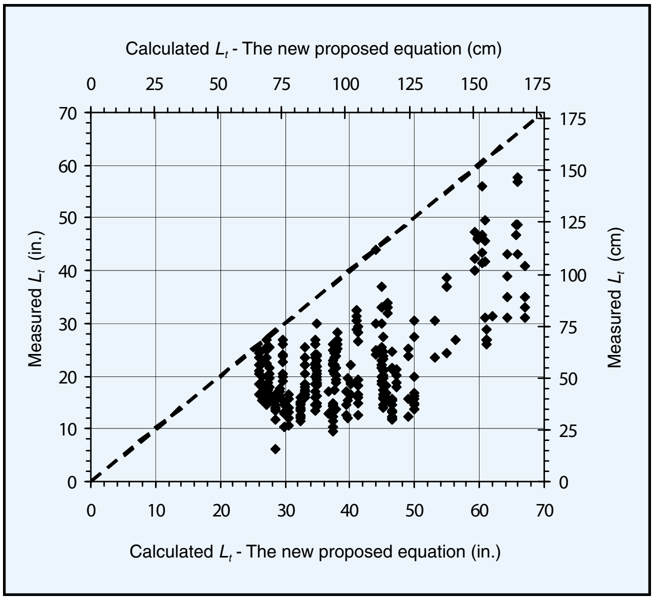

Fig. 7. Comparison of measured transfer lengths with the new proposed equation.

318 and both AASHTO codes use identical expressions to predict the development length of the strand. The code expression gives unconservative predictions for most of the slip/shear and bond failures, as seen in Fig. 8 by the locations of the data points above the 45-degree line. All the hybrid failures are also above the 45-degree line, which also indicates that they are unconservative. Only a small number of the flexural failures are located below the 45-degree line.

A comparison of the experimentally determined development length results with the Buckner[10] equation values is shown in Fig. 9. Here, all of the embedment length values that resulted in bond and slip/shear failures are below the 45-degree line, indicating conservative predictions. The majority of the embedment length values that resulted in flexural failure are below the 45-degree line. This indicates overly conservative values for embedment lengths that resulted in flexural failure. The embedment length values that resulted in hybrid failures are below and above the 45-degree line, indicating conservative and unconservative values, respectively.

A comparison of the experimentally determined embedment length results with the Lane[11] equation is shown in Fig. 10. The Lane equation predicts conservative values for the embedment lengths that resulted in bond failures, as seen by these data points falling below the 45-degree line. However, it gives unconservative predictions for most of the embedment length values that resulted in slip/shear failures, as seen by these values being located above the 45-degree line. The embedment length values that resulted in hybrid failures are above the 45-degree line, indicating conservative results. A similar trend for hybrid failures was seen with the Buckner equation.

A comparison of the experimentally determined embedment length results with the proposed development length equation is shown in Fig. 11. The proposed development length equation gives conservative predictions for the majority of slip/shear and all of bond failures. Only two slip/shear failures occur above the 45-degree line while all the bond and the rest of the slip/shear failures are below the 45-degree line.

The embedment lengths that resulted in a flexural failure mode are equally distributed above and below the 45-degree line, with those values below the line falling reasonably close to the line, indicating that the proposed development equation is conservative but not overly conservative. Also, the hybrid failure values are very close to the 45-degree line, indicating that the proposed equation is a valid estimate of the boundary between the flexural and bond failure.

CONCLUSIONS

Based on this study, the following observations can be made relative to the transfer and development lengths, and the formulation of the new development length equation:

1. Study transfer length values were compared to the requirements of ACI 318,[1] AASHTO Standard,[8] and AASHTO-LRFD.[9] These values are $50d_b$, $50d_b$, and $60d_b$, respectively. All three code equations are very unconservative for 0.5 in. (13 mm) diameter prestressing strand and slightly unconservative for 0.6 in. (15 mm) diameter prestressing strand.

2. Study transfer length values were compared to the transfer length values predicted by the Buckner[10] equation. It was found that the Buckner equation was also unconservative for 0.5 in. (13 mm) diameter prestressing strand but was only slightly unconservative for 0.6 in. (15 mm) diameter prestressing strand. The Buckner equation predicts transfer length values that are 10 to 20 percent longer than those predicted by the current code equations.

3. Study transfer length values were compared to the same values predicted by the Lane[11] equation. Although the Lane equation was conservative for all the transfer length values, it predicted overly conservative values for structural members with low concrete strengths.

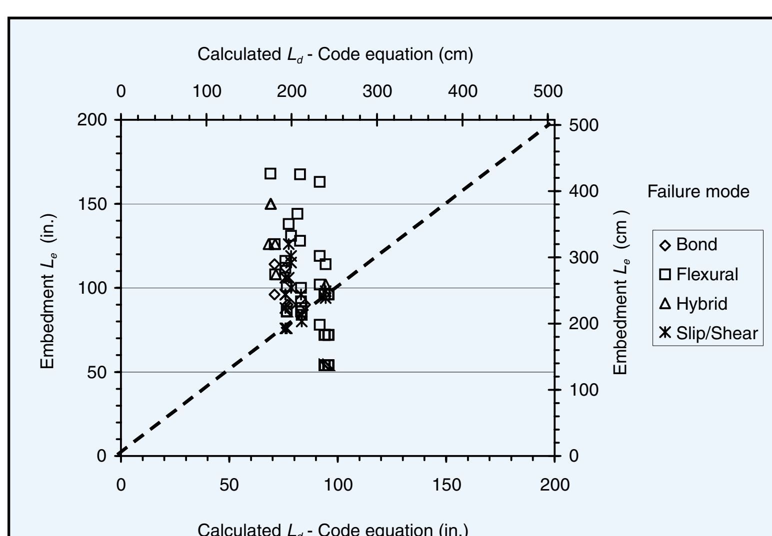

Fig. 8. Comparison of development length results with code equation.

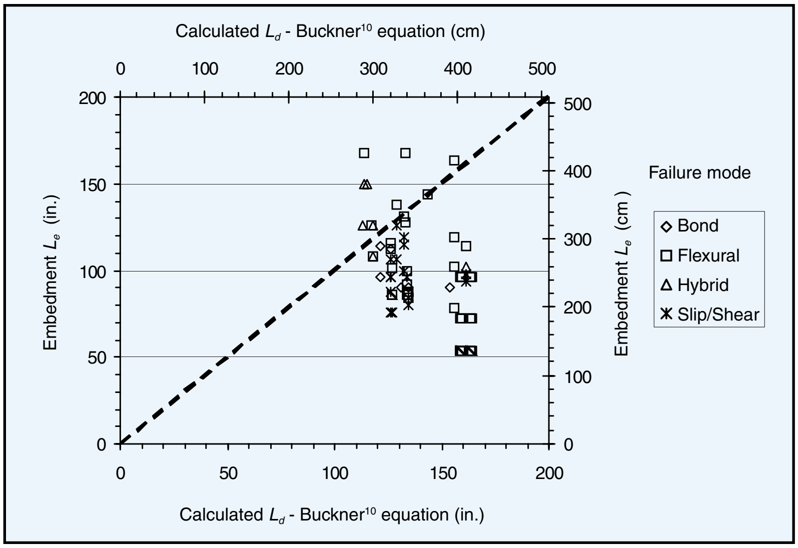

Fig. 9. Comparison of development length results with the Buckner[10] equation.

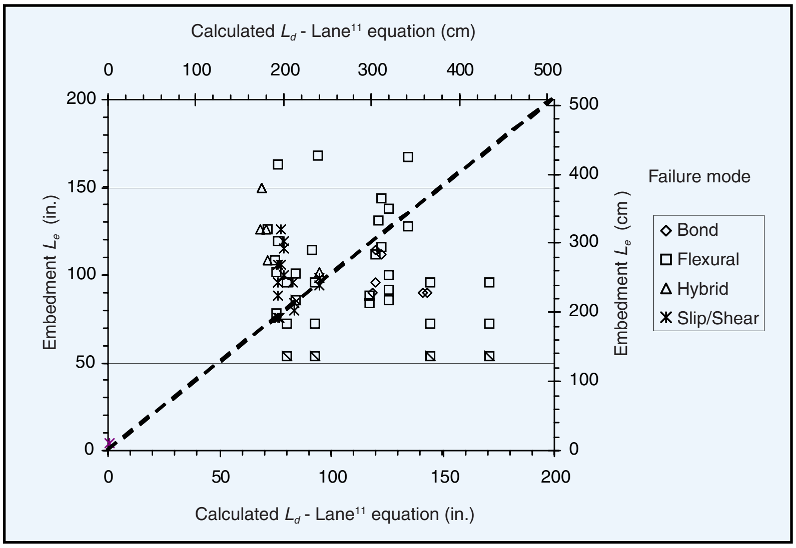

Fig. 10. Comparison of development length results with the Lane[11] equation.

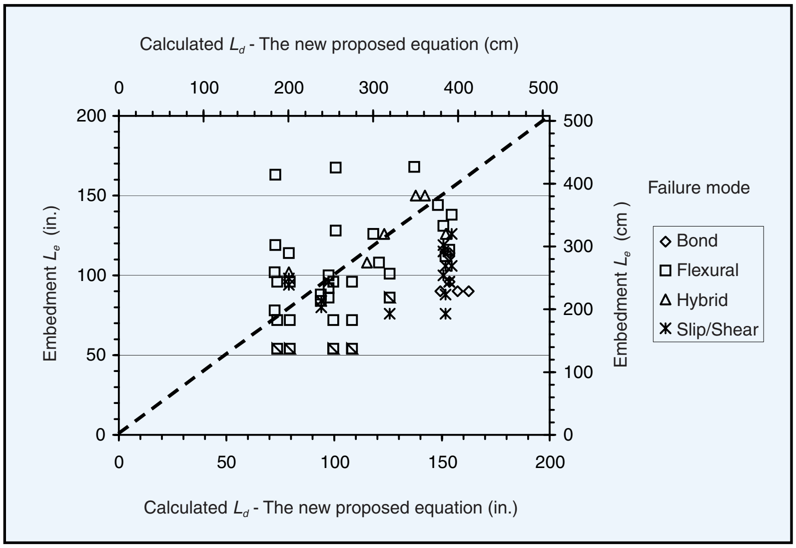

Fig. 11. Comparison of development length results with the proposed equation.

4. Study transfer length values were compared to values predicted by the proposed transfer length equation. The proposed transfer length equation was conservative for all the transfer length values, but not overly conservative for low-strength concrete members as was the Lane[11] equation.

5. Results for development length values were compared to the requirements of ACI 318,[1] AASHTO Standard,[8] and AASHTO-LRFD.[9] All three codes have the same development length requirements. The code expressions gave unconservative predictions for development length values that resulted in the slip/shear, bond, and hybrid failures.

6. Resulting development length values were compared to the values predicted by the Buckner[10] equation. The Buckner equation gave conservative predictions for development length values that resulted in the slip/shear and bond failures. However, for some of the development length values that resulted in flexural failure, the Buckner equation was overly conservative. Also, the development length values that resulted in hybrid failures were both conservative and unconservative.

7. Study development length values were compared to values predicted by the Lane[11] equation. The Lane equation was conservative for the development length values that resulted in bond failures. However, it was unconservative for development length values that resulted in slip/shear failures. Also, as with the Buckner equation, the development length values that resulted in hybrid failure were both conservative and unconservative.

8. Development length values in this study were compared to values predicted by the proposed development length equation. It was found that the proposed development length equation values were conservative for development lengths that resulted in slip/shear and bond failures except two values that resulted in slip/shear failure that were slightly unconservative. For the development length values that resulted in flexural failure, the proposed development length equation was not overly conservative as was the Buckner equation. Also, the proposed development length equation was not overly conservative for the hybrid failures as was the case with both the Buckner and Lane equations.

As a result of these observations, it can be said that the proposed transfer and development length equations provide more valid and verifiable predictions than the transfer and development length equation currently used by ACI 318,[1] AASHTO Standard,[8] and AASHTO-LRFD[9] and those proposed by Buckner[10] and Lane.[11]

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APPENDIX A – NOTATION

d_b = nominal diameter of prestressing strand (in.)
f'_{ci} = concrete strength at time of release (psi)
f'_c = strength of concrete at 28 days (psi)
f_{se} = effective stress in prestressed reinforcement after all prestress losses (ksi)
f_{si} = effective stress in prestressed reinforcement after short-term losses (ksi)
f_{pi} = stress in prestressing strand prior to release (ksi)
f_{ps} = stress in prestressing strand at nominal strength (ksi)
f_{pt} = initial prestress prior to release (ksi) (used in Lane equation)
f_{pu} = ultimate tensile strength of prestressing strand (ksi)
L_t = transfer length (in.)
L_{fb} = flexural bond length (in.)
L_d = development length (in.)
β_1 = ratio of depth of equivalent rectangular stress block to depth of neutral axis
ε_{ps} = strain in prestressing strand corresponding to f_{ps}
λ = variable flexural bond length multiplier
ω_p = reinforcement index