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BOND CHARACTERISTICS AND TRANSFER LENGTH OF PRESTRESSING STRAND IN PRETENSIONED CONCRETE STRUCTURES

SI N. LIM[†], YOUNG C. CHOI[††], BYUNG H. OH[*], JI S. KIM[†††], SOOBONG SHIN[††††], AND MYUNG K. LEE[†††††]

[†] Hyundai Development Co., Research Institute, Seoul, Korea
[††*]Seoul National University, Seoul, Korea
e-mail: bhohcon@snu.ac.kr
[†††] Seo Kyeong University, Seoul, Korea
[††††] Inha University, Incheon, Korea
[†††††] Jeonju University, Jeonju, Korea

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Abstract: The bond between prestressing steel and concrete plays an important role in transferring prestress force to concrete in pretensioned prestressed concrete members. The purpose of the present paper is first to identify the bond behavior between prestressing steel and concrete and then employ this bond crack model in the numerical analysis to obtain the transfer length realistically in pretensioned prestressed concrete members. For this purpose, several series of tests have been conducted in the present study. From the present tests, the bond-slip relations for pretensioned members were first obtained by measuring the strains in prestressing steel and concrete at various locations. A realistic bond-slip relation was derived from the present tests. The bond-slip model derived in the present study was then used to formulate the properties of interface element between prestressing steel and concrete. A numerical analysis incorporating smeared crack model was conducted in the present study to obtain the transfer length theoretically.The present study indicates that not only the diameter of prestressing steels and prestress intensity, but also the compressive strength and concrete cover affect greatly the transfer length in pretensioned members. The present test results indicate that the transfer length decreases with an increase of concrete cover and also decreases with an increase of concrete compressive strength. Therefore, these effects must be considered in the design code to accurately design the pretensioned concrete structures. It was shown in this study that the results of numerical analyses agree well with the test data.

1 INTRODUCTION

The pretensioning force in pretensioned concrete members is directly transferred from prestressing steel to concrete by cutting the prestressed prestressing steels at the end of the members [1-3]. Therefore, the bond between prestressing steel and concrete plays an important role in transferring prestress force to concrete in pretensioned prestressed concrete members [4-6]. On the other hand, the transfer of prestress force and the transfer length in pretensioned prestressed concrete members are of great concern because it directly affects the distribution of prestress in the pretensioned members [7, 8].

The purpose of the present paper is first to identify the bond behavior between prestressing steel and concrete and then employ this bond model in the finite element analysis to obtain the transfer length realistically in pretensioned prestressed concrete members.

For this purpose, several series of tests have been conducted in the present study. From the present tests, the bond stress-slip relations for pretensioned members were first obtained by measuring the strains in prestressing steel and concrete at various locations. A realistic bond stress-slip relation was derived from the present tests. The bond stress-slip model derived in the present study was then used to formulate the properties of interface element between PS steel and concrete.

The design provision of some design codes considers only the prestress magnitude and the diameter of prestressing steels to estimate the transfer length of prestress force in pretensioned members [1, 9]. The present study however indicates that the compressive strength and concrete cover may also affect greatly the transfer length in pretensioned members. Therefore, in addition to the diameter of prestressing steels and prestress magnitude, the concrete compressive strength and concrete cover have been also taken into account in the present tests and analyses. In this regard, the effects of these parameters on transfer length have been investigated thoroughly by analyses and tests.

Three-dimensional finite element analyses have been conducted first to obtain transfer lengths for various cases and the results of analyses have been compared with test data.

2 BOND CHARACTERISTICS OF PRESTRESSING STRANDS

2.1 Bond tests

The bond stress-slip relations have been obtained from the measurement of stresses and strains in pretensioned members. The bond stress may be obtained from the force difference of a strand between two adjacent points as shown in Figure 1. The strain gages can measure the strains at two adjacent points on a strand as shown in Figure 1 and these strains may easily be converted to forces. The steel strain gages with the length of 5mm were attached on the strand to measure the strand strains. The bond stress is then expressed as follows.

$$f_b = \frac{P_{j+1} - P_j}{\Sigma_0 \Delta l} = \frac{\Delta P}{\Sigma_0 \Delta l} \quad (1)$$

Where f_b =bond stress, ΔP =force difference between two adjacent points, Σ_0 =perimeter of a strand, and Δl =distance between two adjacent points, respectively.

The slip may also be obtained from the measurement of concrete strains at the same two adjacent points as shown in Figure 1. The slip may be written as follows.

$$s = (\varepsilon_{j+1} - \varepsilon_j)\Delta l \quad (2)$$

Where s =slip and ε_j =strain at the point j, respectively.

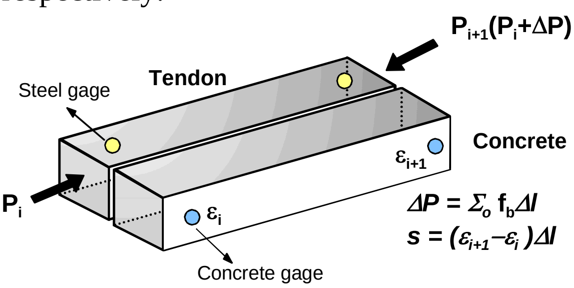

Figure 1: Measurement of bond stress and slip

2.2 Bond stress-slip relation

The bond stress and slip relations for strands have been obtained by using the above procedure and are shown in Figure 2. Figure 2 shows the bond stress and slip relations for the strand of diameter 15.2mm. This figure indicates that the bond stress increases rapidly with an increase of slip at lower slip values and then the increase of bond stress becomes lower as the slip increases. This behavior of bond stress-slip relation can be modeled by the following equation considering that the bond stress is related to concrete strength and slip values.

$$f_b(x) = \alpha \sqrt{f_{ci}'} \left(\frac{s(x)}{d_b}\right)^{\beta} \quad (3)$$

Where $f_b(x)$ =bond stress, f_{ci}' =compressive strength of concrete, $s(x)$ =slip, d_b =diameter of strand, and α and β = constants to be determined from experiments, respectively. A regression analysis has been done for the present data and the result is also shown in Figure 2. The appropriate values for the constants have been obtained from the data.

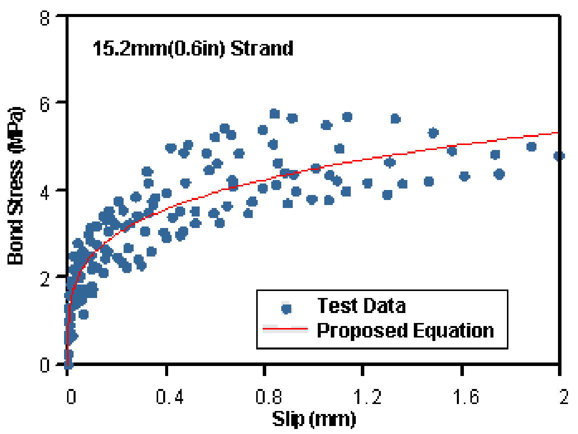

Figure 2: Bond stress and slip relation for strand

The appropriate values obtained from the total data of both strands are α =10.7 and β =0.27, respectively and thus the appropriate equation for bond stress-slip relation may be written as follows.

$$f_b(x) = 10.7\sqrt{f_{ci}^{'}}\left(\frac{s(x)}{d_b}\right)^{0.27} \qquad (4)$$

The bond stress-slip relation between strand and concrete is a required property in the finite element analysis of pretensioned concrete members because it directly relates the behavior of prestressing strand with the surrounding concrete. The above relation [Eq. (4)] has been used to characterize the property of interface element between strand and concrete.

3 TRANSFER LENGTH TESTS FOR PRETENSIOND CONCRETE MEMBERS

3.1 Test method

The transfer length can be determined by the profile of the strain distribution in pretensioned members after prestress transfer. The strains may be measured on the prestressing strand or on the concrete surface along the line of prestressing strand. However, the strain gages on the prestressing strand may be damaged during the placement of concrete in a test member and also at the time of prestress transfer. The attachment of strain gages on the strand may also hurt the adequate bonding between concrete and strand. Therefore, it was preferred in this study to measure the strains on the surface of concrete at the level of strand by mechanical strain gages. The determination of transfer length was based on the concept of average maximum strain method proposed by authors in Reference 1. The detailed procedures for measurement of strains and for determining transfer length have been summarized in Reference 1 and thus are not repeated here.

3.2 Measured transfer lengths

Figure 3 shows the measured transfer lengths obtained from the present test series. Figure 3 indicates that the transfer length decreases with an increase of concrete strength and also decreases with an increase of concrete cover. These effects of concrete strength and concrete cover on transfer length have not been considered in the design code [9]. On the other hand, the transfer length increases with an increase of strand diameter as shown in Figure 3. The detailed comparisons of transfer length with theoretical analysis will be discussed in the section 4 and section 5.

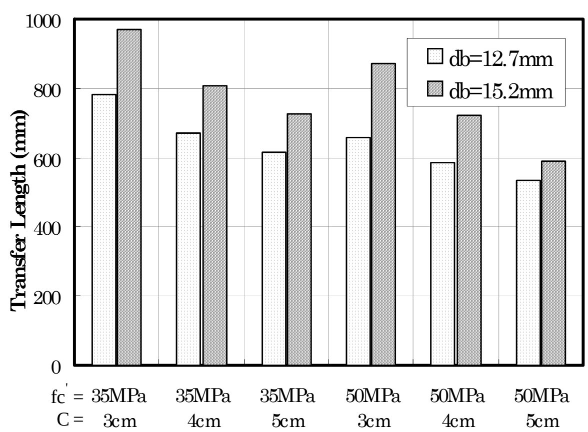

Figure 3: Measured transfer lengths for strands

4 THEORETICAL TRANSFER LENGTH

4.1 Analysis procedure and modeling

The area of a strand in pretensioned members decreases initially by prestressing due to Poisson effect and then tends to restore when prestress is transferred. This restoration effect naturally leads to lateral expansion of strand and the lateral expansion induces circumferential tensile stresses in adjacent concrete. These circumferential tensile stresses may cause cracking in concrete around the strand. This phenomenon may not be well described by two-dimensional analysis and therefore three-dimensional modeling has been implemented in this study. Figure 4 shows a detailed portion of three-dimensional modeling for strand and concrete. The solid finite elements have been used for modeling both concrete and strand.

The interface elements have been used in between strand and concrete. Only one quarter of the member may be modeled due to symmetric condition. For modeling both concrete and strand, twenty-node three dimensional solid finite elements have been used.

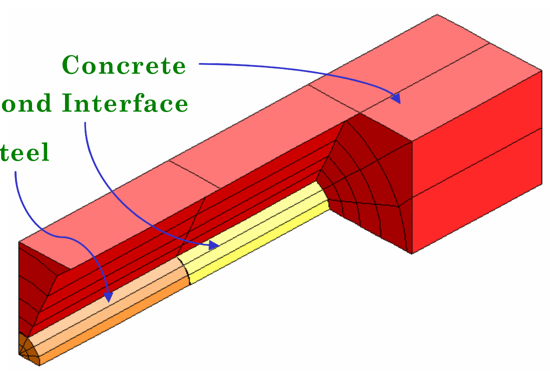

Figure 4: Three-dimensional modeling for strand and concrete in pretensioned concrete members

The smeared crack approach with a linear tension softening has been employed for modeling tensile cracking of concrete [10]. The Drucker-Prager failure model was used for compression failure of concrete. The well-known nonlinear program (DIANA) for concrete structures was used for the present finite element analysis and the Newton-Rapson method was employed for nonlinear analysis.

4.2 Interface element between strand and concrete

The interface elements have been used in this study to model the interface bond behavior between strand and concrete. The interface elements describe the interface bond behavior by modeling the relations of normal traction and displacement and also shear force and displacement at the interface. There are several types of interface elements including nodal interface element, line interface element, and plane interface element. The plane interface element has been used in this study because it is more appropriate to the real situation. Figure 5 shows the plane interface element which has eight nodes on one plane and another eight nodes on the opposite plane. The pair nodes in the interface element (i.e., node 1 and node 9, node 2 and node 10, node 3 and node 11, node 4 and node 12, node 5 and node 13, node 6 and node 14, node 7 and node 15, node 8 and node 16) share the same coordinates, respectively, although node numbers are different. The relative displacements Δu between these pair nodes may determine the tractions t_n and t_t at the interface as follows.

$$\begin{bmatrix} t_n \\ t_t \end{bmatrix} = \begin{bmatrix} D_{11} 0 \\ 0 D_{22} \end{bmatrix} \begin{bmatrix} \Delta u_n \\ \Delta u_t \end{bmatrix} \qquad (5)$$

Where $D_{22}=D_{11}/[2(1+\nu)]$ and ν =Poisson's ratio, respectively. Figure 5 shows the schematic diagram and tractions for 16-node interface element.

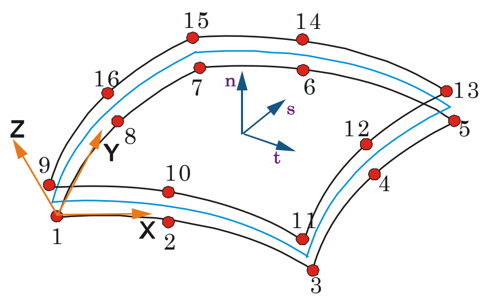

Figure 5: Schematics for 16 node interface element

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5 COMPARISON OF MEASURED AND THEORETICAL TRANSFER LENGTHS

The finite element analyses have been executed for pretensioned concrete test members and the results have been compared with test data. Table 1 shows the comparison of theoretical transfer lengths with the present test data. It can be seen from Table 1 that the analysis results agree well with test data for transfer length and the average relative ratio of analysis results to test data is about 1.025. In Table 1, the test series N-3 represents the test member with normal strength concrete (f_{ci}=35Mpa) with the cover thickness of 3cm. H-5 represents the test member with high strength concrete (f_{ci}=50Mpa) with the cover thickness of 5cm.

The design equation for transfer length in pretensioned members by ACI Code[9] may be written as $l_t = 0.048 f_{pe} d_b$ where f_{pe} is effective prestress in MPa and d_b is the diameter of prestressing strand in mm. In the present case, the transfer lengths based on ACI code for strand diameters of 12.7mm and 15.2mm are 724mm and 866mm, respectively.

It can be seen from Table 1 that the results of finite element analysis generally agree well with test data for all cases. However, the design code[9] underestimates the transfer length for the case of small concrete cover and overestimates the transfer length for the case of large concrete cover. This is because the ACI design code[9] does not consider the concrete cover in calculating the transfer length and thus gives the same transfer lengths for different concrete covers.

The test results in Table 1also indicate that high strength concrete shows smaller transfer length at the same concrete cover, but the design code shows no difference for different strengths because the code does not consider the effect of concrete strength.

Therefore, it is necessary to include the effects concrete strength and concrete cover in calculating the transfer length correctly. Table 1 also depicts that the increase of strand diameter increases the transfer length and the increase of concrete strength decreases the transfer length.

Table 1: Comparison of measured and theoretical transfer lengths

Strand Diameter d_b (mm)	Test Series	Transfer Length(mm)		
		Analysis (mm)	Test (mm)	Analysis/ Test
12.7	N-3	747	781	0.96
	N-4	661	669	0.99
	N-5	627	617	1.01
	H-3	669	658	1.01
	H-4	596	587	1.01
	H-5	562	533	1.05
15.2	N-3	975	971	1.00
	N-4	823	809	1.02
	N-5	779	727	1.07
	H-3	873	872	1.00
	H-4	735	722	1.02
	H-5	697	591	1.17

6 EFFECTS OF VARIOUS DESIGN FACTORS ON TRANSFER LENGTH

6.1 Design variables for finite element analysis

It has been shown in the previous section that the transfer lengths obtained from the above nonlinear finite element analysis agree well with test data. Therefore, comprehensive finite element analyses have been done for pretensioned concrete members in order to explore the effects of various design variables on transfer length.

Major design variables include strand diameter, magnitude of prestress, depth of concrete cover, and compressive strength of concrete, respectively. The diameters of strand are 12.7mm and 15.2mm which are most-commonly-used strands in actual construction. The magnitudes of prestress include 0.40 f_{pu}, 0.45 f_{pu}, 0.50 f_{pu}, 0.55 f_{pu}, 0.60 f_{pu}, 0.65 f_{pu}, 0.70 f_{pu}, and 0.75 f_{pu}, respectively, where f_{pu} is the ultimate tensile strength. The depths of concrete cover are 30mm, 40mm, 50mm, and 60mm, respectively. The compressive strengths of concrete are 35MPa, 40MPa, 50MPa, and 60MPa, respectively. The finite element analyses have been implemented for all those variables and the results are discussed in the following sections.

6.2 Effect of prestress intensity

Figure 6 shows the variation of transfer lengths according to the intensity of prestress. It can be seen that the transfer length increases with an increase of prestress intensity f_{pe} and that the rate of increase of transfer length is roughly proportional to the square root of prestress intensity f_{pe} .

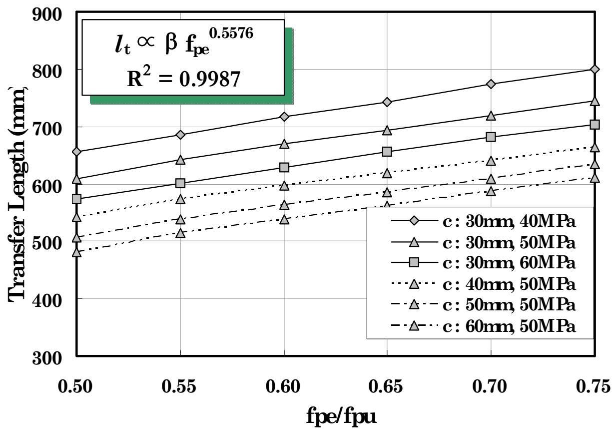

Figure 6: Comparison of transfer length according to the intensity of prestress for various concrete cover

6.3 Effect of the diameter of strand

Figure 7 shows the comparison of analyzed transfer lengths between the strand diameters of 12.7mm and 15.2mm, rspectively. It can be seen from this figure that the transfer length increases with an increase of strand diameter and the average rate of increase is about 30 percent between the strand diameter 12.7mm and 15.2mm.

Figure 7 also shows the regression line for transfer length according to the strand diameter. It is seen from Figure 7 that very good correlation has been obtained between transfer length and strand diameter.

Figure 7 indicates that the transfer length is approximately proportional to $d_b^{1.3}$ in which d_b is strand diameter.

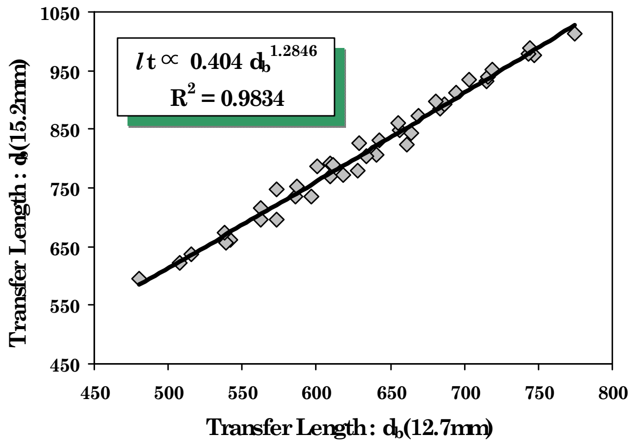

Figure 7: Variation of transfer length with strand diameter

6.4 Effect of concrete strength

Figure 8 shows the variation of transfer length according to the compressive strength of concrete. Figure 8 indicates that the transfer length decreases with an increase of concrete strength for all prestress intensities and strand diameters. This means that high strength concrete is much more effective to transfer prestress than normal strength concrete in pretensioned concrete members. Nevertheless, some design codes[1, 9] do not consider the effect of concrete strength on transfer length. Therefore, it is necessary to modify the code equation on transfer length to design pretensioned concrete members more rationally.

Figure 8 indicates that the transfer length is inversely proportional to $f_{ci}^{1/3}$ in which f_{ci} is compressive strength of concrete.

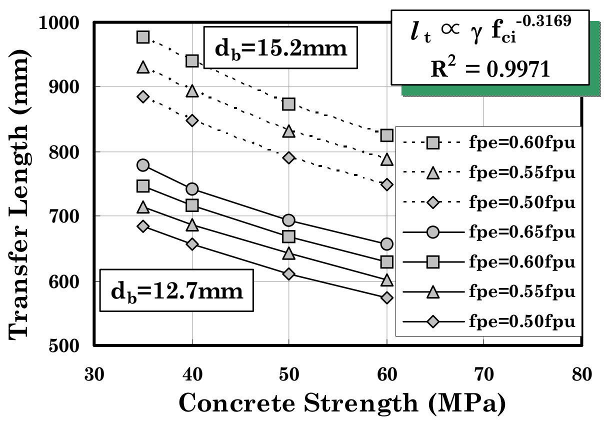

Figure 8: Comparison of transfer length according to compressive strength of concrete

6.5 Effect of concrete cover

Figure 9 shows the variation of transfer length according to the concrete cover for various prestress magnitudes.

It can be seen from Figure 9 that the transfer length decreases with an increase of cover depth for all prestress intensities.

However, some design codes do not consider the effect of concrete cover thickness on transfer length and thus provides only one constant value for all cover depths.

It can be seen from Figure 9 that the transfer length is inversely proportional to the concrete cover depth.

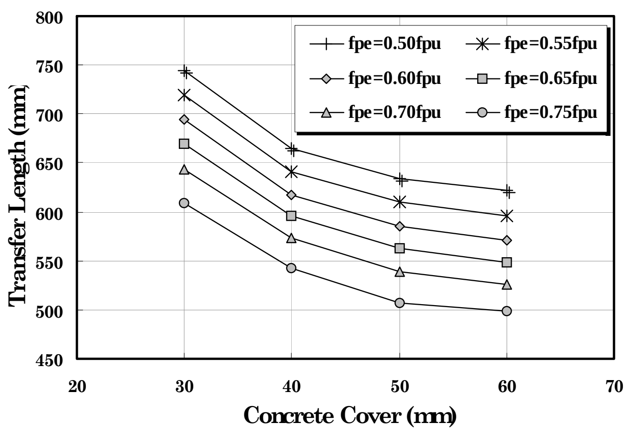

Figure 9: Comparison of transfer length according to concrete cover

7 CONCLUSIONS

In this study, the bond behavior of prestressing strands and the transfer length in pretensioned concrete members have been investigated both experimentally and theoretically. Several series of tests have been conducted to measure the transfer lengths in pretensioned concrete members. The finite element analyses have been also conducted to obtain the transfer length theoretically. The major conclusions derived from this study can be summarized as follows.

(a) A realistic bond stress-slip relation for pretensioned concrete members has been derived in this study and employed in modeling interface element for finite element analysis. The present study indicates that the analysis results agree well with the test data on transfer length.

(b) It was found from this study that the transfer length increases with an increase of prestress magnitude and that the rate of increase of transfer length is roughly proportional to the square root of prestress magnitude.

(c) The present study indicates that the transfer length increases with an increase of strand diameter and the average rate of increase is about 30 percent when the strand diameter increases from 12.7mm to 15.2mm.

(d) It is shown that the transfer length decreases with an increase of concrete strength for all prestress magnitudes and strand diameters. This means that high strength concrete is much more effective to transfer prestress than normal strength concrete in pretensioned concrete members.

(e) The present study indicates that the transfer length decreases with an increase of cover depth for all prestress magnitudes. This effect must be considered realistically in the design code for more rational design of pretensioned concrete structures.

(f) The present nonlinear analysis for pretensioned concrete members incorporating realistic bond model and smeared crack approach provides good results in determining transfer length as well as stress and strain behavior.

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