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# Transfer lengths of pretensioned concrete members reinforced with 2400 MPa high-strength prestressing tendons

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**Abstract.** High-strength prestressing tendons with a tensile strength of 2400 MPa have been recently developed in the steel industry of South Korea, and is currently being mass produced for common commercial applications in structural engineering practices. Accordingly, since most of the existing transfer length estimation models were derived based on the test results of the specimens having the prestressing tendons with a tensile strength of 1860 MPa or less, modifications of the transfer length models are now required to consider the effect of the enhanced tensile strength of the prestressing tendons. In this study, six pretensioned concrete specimens reinforced with 2400 MPa tensile strength prestressing tendons were fabricated and tested to investigate their transfer lengths. In addition, a simplified design equation for the transfer length was developed based on the assumption of the linear strain profile curves of the prestressing tendon and surrounding concrete in transfer length zone. The accuracy of the proposed equation was verified in detail by comparing a total of 215 transfer length test results with analysis results. The simplified design equation provided very accurate results on the transfer lengths of all the test specimens, regardless of the tensile strength grades of prestressing tendons.

**Keywords**: transfer length; 2400 MPa; high-strength; prestressed concrete; pretensioned concrete; slip

## 1. Introduction

In an effort to achieve an economic design for prestressed concrete (PSC) structures, high-strength prestressing tendons have been developed, and high-strength tendons with the grades of

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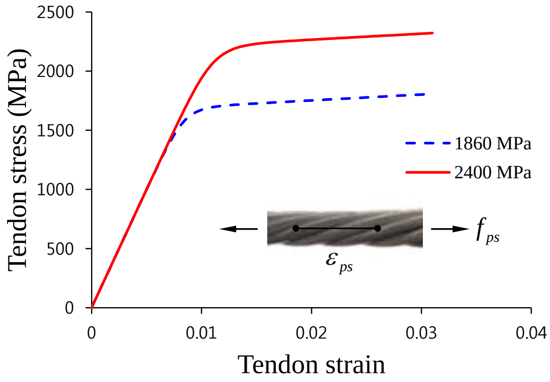



Fig. 1 Stress-strain relationship of high strength prestressing tendons

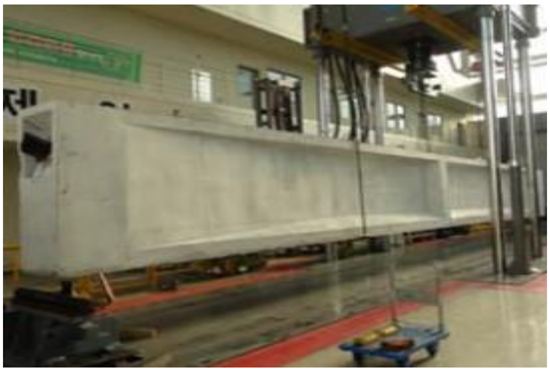


Fig. 2 Experimental study on pretentioned concrete girder using high strength prestressing strand (Kim and Lee 2013)

2160 MPa and 2400 MPa are currently available in the Japanese and South Korean industrial markets, respectively (Park *et al.* 2012, Kim and Lee 2013, Park 2015, Yang *et al.* 2016). As shown in Figs. 1-2, Park *et al.* (2012), and Kim and Lee (2013) conducted material tests of many high-strength tendons, and they also conducted flexural tests on pretensioned concrete beam members reinforced with high-strength prestressing tendons. In addition, the applicability of the current ACI318 (2011) building code provisions to PSC members reinforced with 2160 and 2400 MPa grade tendons was reviewed in detail. In ACI318 (2011) and AASHTO-LRFD Bridge Design Specification (2010), the transfer lengths of pretensioned concrete members are simply expressed, as follows

$$l_t = \frac{1}{21} f_{pe} d_b \quad \text{(ACI 318-11, mm)} \tag{1}$$

$$l_t = 60 d_b \quad \text{(AASHTO LRFD 2010, mm)} \tag{2}$$

where $f_{pe}$ is the effective prestress in the prestressing tendons, and $d_b$ is the diameter of the prestressing tendons. Eqs. (1)-(2) for calculating transfer lengths were developed for the prestressing tendons with a tensile strength of 1860 MPa or less. Thus, modifications are now

Table 1 Dimensions and material properties of test specimens

| Specimens | $b_w$ (mm) | $h$ (mm) | $A_c$ (mm$^2$) | $I_c$ (mm$^4$) | $f_{ck}$ (MPa) | $f_{ci}$ (MPa) | $f_{pu}$ (MPa) | $f_{pi}/f_{pu}$ |
|---|---|---|---|---|---|---|---|---|
| S30-0.5 | 300 | 600 | $1.8\times10^5$ | $5.40\times10^9$ | 40.0 (44.3) | 30.0 (30.0) | 2400 (2436) | 0.50 (0.50) |
| S30-0.6 | | | | | | | | 0.60 (0.59) |
| S30-0.7 | | | | | | | | 0.70 (0.66) |
| S50-0.5 | | | | | 70.0 (68.2) | 50.0 (49.5) | | 0.50 (0.51) |
| S50-0.6 | | | | | | | | 0.60 (0.63) |
| S50-0.7 | | | | | | | | 0.70 (0.72) |

* ( ): values measured from test

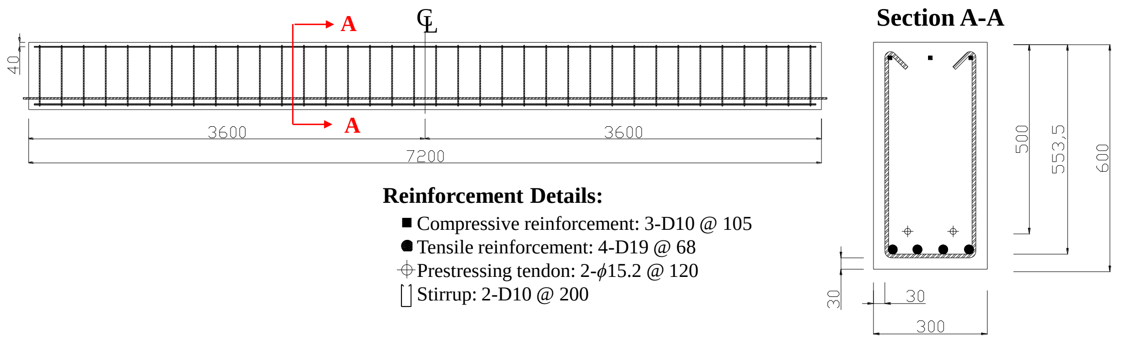
required to apply these equations or other existing models (Zia and Mostafa 1977, Mitchell *et al.* 1993, Russell and Burns 1997) to estimate the transfer lengths of the pretensioned concrete members with 2160 MPa and 2400 MPa grade tendons. Therefore, in this study, six pretensioned concrete members reinforced with the grade of 2400 MPa tendons were fabricated and tested to investigate the effect of the enhanced ultimate tensile strength on the transfer lengths. The applicability of the transfer length equations presented in ACI318 (2011) and AASHTO-LRFD (2010) were also examined, comparing the analysis results to the test results. In the authors' previous study (Han *et al.* 2016), a transfer length estimation model was proposed based on the thick-walled cylinder theory (TWCT), and its accuracy was also verified. This analysis model, called as the detailed model hereafter, was utilized in this study to derive a simple design equation of transfer length. Based on the parametric studies on the major influencing factors performed in the authors' previous study (Han *et al.* 2016), the transfer length model was simplified as a function of compressive strength of concrete at release ($f_{ci}$), magnitude of initial prestress ($f_{pi}$), and diameter of tendons ($d_b$). To verify the proposed equation, a total of 209 test results on transfer length were also collected from the literature (Oh and Kim 2000; Park 2015; Park *et al.* 2012; Park and Cho 2014; Thomas *et al.* 1990; Mitchell *et al.* 1993; Russell and Burns 1996; Martí-Vargas *et al.* 2007), and its accuracy was evaluated by comparing the analysis results with the test results.

## 2. Research significance

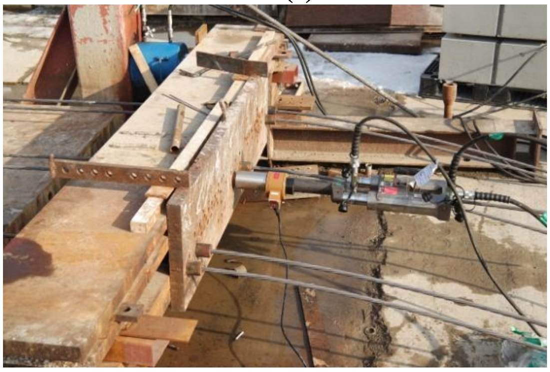
In this study, prestress transfer tests were conducted on six pretensioned concrete members reinforced with 2400 MPa grade tendons. The applicability of the transfer length equations specified in the current design codes was also reviewed in detail, and a simplified design equation was derived, which can be easily applied to estimate the transfer lengths of the pretensioned concrete members with 2400 MPa grade tendons as well as 1860 MPa grade tendons.

## 3. Experimental study

### *3.1 Experimental program*




(a) Dimensional details of test specimens (units: mm)



(b) Jacking by using hydraulic jack


(c) Test specimens

Fig. 3 Description of test specimens

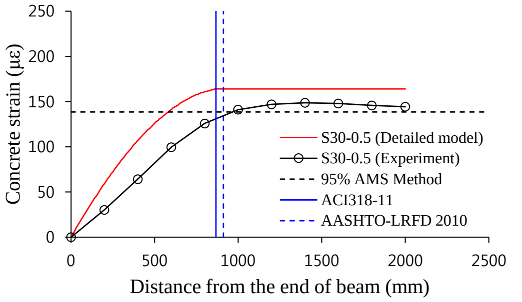
The dimensions and material properties of the test specimens are summarized in Table 1, and the reinforcing details of the test specimens are shown in Fig. 3(a). In this study, six test specimens were fabricated; their cross-section size was 300 mm×600 mm, and 2400 MPa tensile strength tendons with 15.2 mm diameter ($d_b$) were used. To investigate the effect of the initial prestress ($f_{pi}$) and the compressive strength of concrete at release ($f_{ci}$) on the transfer length, the specimens had the $f_{pi}$ levels of 0.5, 0.6, and 0.7$f_{pu}$, and had the $f_{ci}$ values of 30 and 50 MPa. Each test specimen had two tendons, and their cover thickness of concrete was 30 mm. As shown in Fig. 3(b), jacking operation was precisely controlled by placing a load-cell in front of the hydraulic jack, and all specimens were steam-cured for two days after casting concrete. As shown in Fig. 3(c), the concrete strain gauges were attached on the surface of specimens at the level of the prestressing tendons with a spacing of 200 mm in the longitudinal direction. The prestressing tendons were released using the flame-cutting method, and the compressive strengths of concrete at the transfer of the S30 and S50 series specimens were 30.0 MPa and 49.5 MPa, respectively, as shown in Table 1. In addition, the relative slips between tendons and concrete were measured at the live end of the test specimens.

### *3.2 Evaluation of transfer lengths*

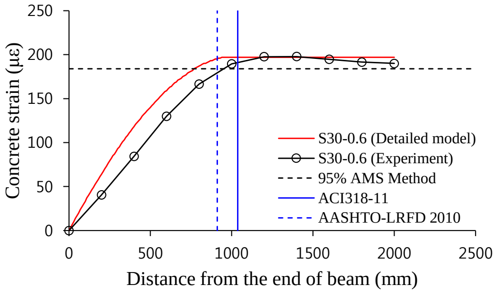
The concrete surface strains were measured at the level of prestressing tendons in the longitudinal direction, and they were calibrated using the smoothing technique proposed by

Table 2 Comparison of transfer lengths

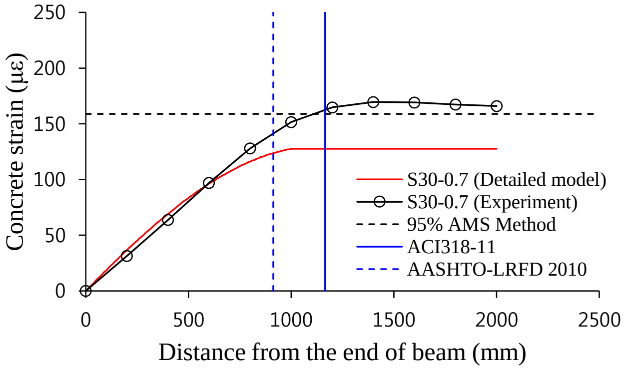
| Specimens | [1] Test Results (mm) | [2] Detailed model (mm) | [3] ACI318-11 (mm) | [4] AASHTO LRFD (mm) | Ratio [2]/[1] | Ratio [3]/[1] | Ratio [4]/[1] |
|---|---|---|---|---|---|---|---|
| S30-0.5 | 965 | 860 | 867 | 912 | 0.89 | 0.90 | 0.95 |
| S30-0.6 | 951 | 940 | 1037 | 912 | 0.99 | 1.09 | 0.96 |
| S30-0.7 | 1111 | 1010 | 1165 | 912 | 0.91 | 1.23 | 0.82 |
| S50-0.5 | 595 | 690 | 884 | 912 | 1.16 | 1.49 | 1.53 |
| S50-0.6 | 581 | 770 | 1101 | 912 | 1.32 | 1.90 | 1.57 |
| S50-0.7 | 815 | 810 | 1266 | 912 | 0.99 | 1.55 | 1.12 |
| | | Average | | | 1.04 | 1.55 | 1.16 |
| | | Standard deviation | | | 0.17 | 0.36 | 0.32 |
| | | COV | | | 0.16 | 0.26 | 0.27 |




(a) S30-0.5 specimen




(b) S30-0.6 specimen




(c) S30-0.7 specimen

Fig. 4 Transfer lengths of S30 series specimens

Russell and Burns (1993) as follows

$$\varepsilon_{c,i} = \frac{\varepsilon_{c,i-1} + \varepsilon_{c,i} + \varepsilon_{c,i+1}}{3} \tag{3}$$

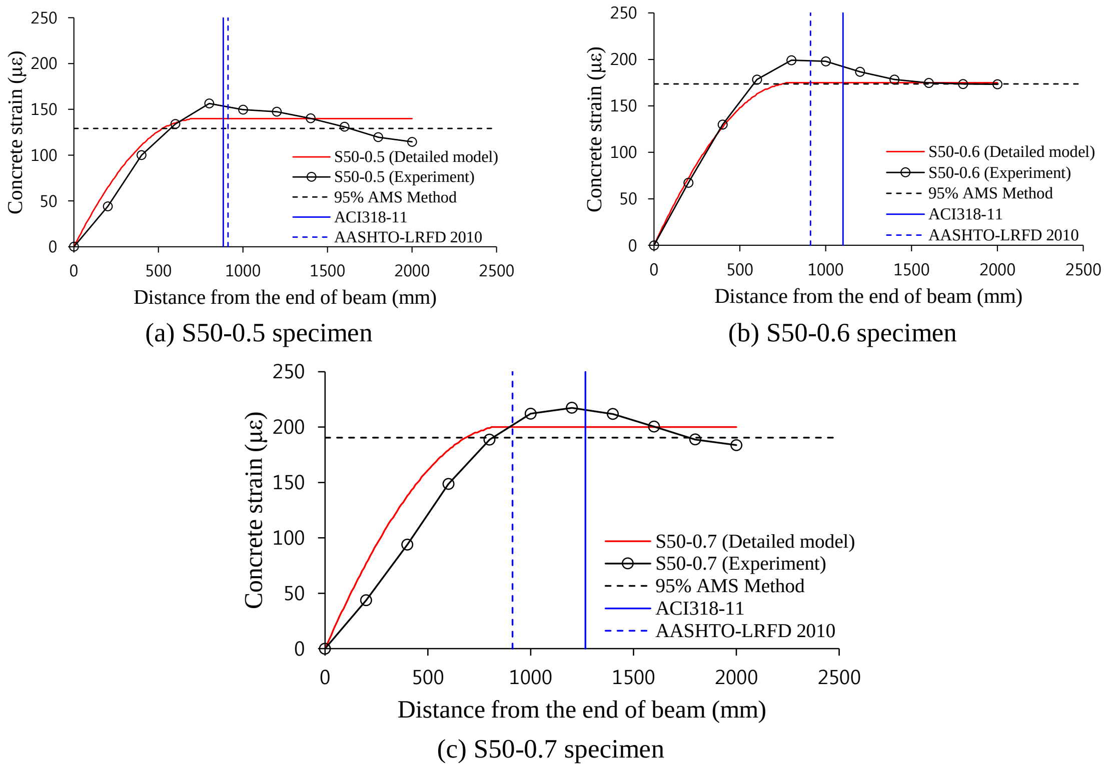
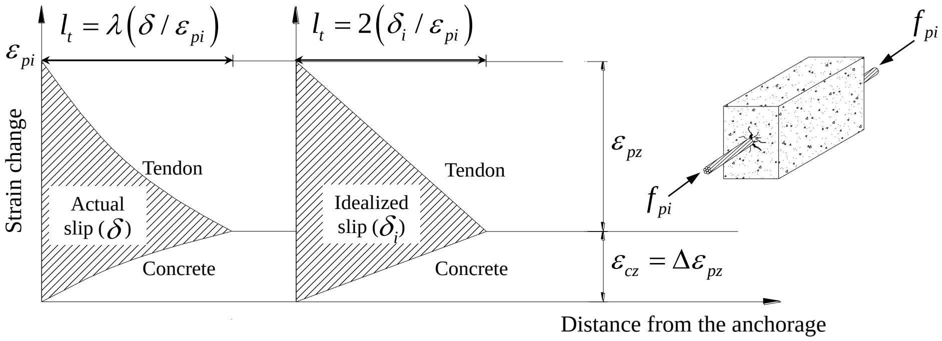


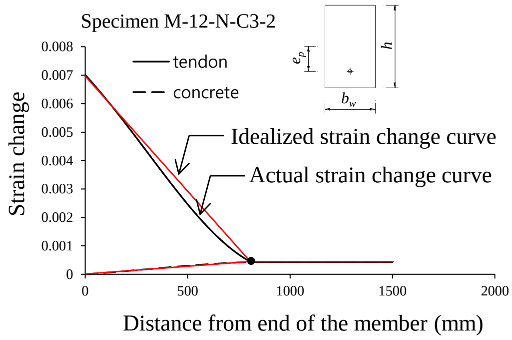

Fig. 5 Transfer lengths of S50 series specimens

where $\varepsilon_{c,i}$ is the concrete strain of the $i$-th gauge, and $\varepsilon_{c,i-1}$ and $\varepsilon_{c,i+1}$ are the concrete strains measured at the points adjacent to the $i$-th gauge. In this study, the 95% average maximum strain (AMS) method (Russell and Burns 1993) was adopted to determine the transfer lengths from the smoothed strain profile curves obtained from Eq. (3).

Table 2 and Figs. 4-5 show comparisons of the transfer lengths measured from the test and the analysis results calculated by the detailed model (Han *et al.* 2016) and the current code models specified in ACI318 (2011) and AASHTO-LRFD (2010). It is noted that the data acquisition device installed in the precast factory was unexpectedly malfunctioned when transferring the first tendon in the S30-0.7 specimen, and thus, the concrete strains induced only by the second tendon were measured for this specimen. The analysis results shown in Fig. 4(c) were also calculated by considering the effect of the second tendon only. Consequently, the concrete compressive strains of the S30-0.7 specimen at transfer were inevitably smaller than those of the S30-0.5 and S30-0.6 specimens, although the initial prestress of the S30-0.7 specimen was larger than those of the S30-0.5 and S30-0.6 specimens. Both the test and the analysis results show that the slope of the concrete strain profile curves at the transfer length zone increases as the concrete compressive strength at release ($f_{ci}$) or initial prestress ($f_{pi}$) increases. In addition, the concrete compressive strains at the strain plateau zone become larger, as the concrete compressive strength at release ($f_{ci}$) decreases or as the initial prestress ($f_{pi}$) increases. The detailed model accurately estimated the concrete compressive strains of the test specimens along the member length at the prestress transfer.




(a) Idealized strain change curve




(b) Strain change curve of specimen M12-N-C3-2 (Oh and Kim 2010)

Fig. 6 Idealized strain change curves of tendon and concrete

As shown in Table 2, the ACI318 (2011) and AASHTO LRFD (2010) models provided conservative results giving the analysis to test result ratios of 1.55 and 1.16, respectively. Their coefficients of variation (COV) were also 0.26 and 0.27, respectively, whereas the COV of the detailed model was 0.16, which means that the detailed model has much higher accuracy than the code equations. As a matter of fact, the code equations provided reasonable estimations on the transfer lengths of the S30 series specimens; however, they provided very conservative analysis results for the S50 series specimens with a high compressive strength of concrete at release ($f_{ci}$). In addition, although the ACI318 (2011) model can reflect the effects of the effective prestress in tendons ($f_{pe}$), its accuracy was significantly decreased for the S50 series specimens. This is because the ACI318 (2011) model could not reflect the effects of the concrete compressive strength at the release, which is the same for the AASHTO LRFD (2010) model.

## 4. Simplified model for practical design

### *4.1 Strain distribution of tendon and concrete*

As aforementioned, authors proposed the detailed analysis model based on TWCT in their previous study (Han *et al.* 2016), in which the bond mechanism between prestressing tendons and concrete in the transfer length zone was modeled in a theoretical manner. It was also confirmed that the proposed method can estimate the transfer lengths of pretensioned concrete members with a high level of accuracy; however, the detailed model is somewhat difficult to be used in practice due to iterative calculation procedure. On the other hand, the code models specified in ACI318 (2011) and AASHTO-LRFD (2010) have an advantage in that they can calculate the transfer lengths of prestressing tendons in a very simple manner; however, they cannot reflect the effects of the major influencing factors on the transfer length, including the grade of prestressing tendons and the compressive strength of concrete. Therefore, in this study, a simplified design equation was derived based on the analysis results of the parametric studies on the major influencing factors using the detailed model.

As shown in Fig. 6(a), the relative slip between the prestressing tendon and the surrounding concrete can be calculated by accumulating the difference between the strain changes of the tendon and the concrete within the transfer length zone. On this basis, the relationship between the transfer length ($l_t$) and the slip ($\delta$) can be expressed as follows

$$l_t = \lambda \frac{\delta}{\varepsilon_{pi}} \tag{4}$$

where $\lambda$ is the shape coefficient of the strain change curve, and $\varepsilon_{pi}$ is the initial prestrain. Guyon (1953) suggested the shape coefficient ($\lambda$) to be 2.0 by assuming the linear relationship between the transfer length and the relative slip. On the other hand, other researchers (Oh and Kim 2000; Russell and Burns 1996; Den Uijl 1998; Lopes and Carmo 2002; Brooks *et al.* 1988; Logan 1997; Steinberg *et al.* 2001; Wan *et al.* 2002; Josson 1992) proposed the shape coefficient ($\lambda$) as various values ranging from 1.5 to 3.0 based on their test results. However, as shown in Fig. 6(b), the strain change curves of the concrete and the tendon can be approximated to be the linear relations as presented by Guyon (1953), and error due to this assumption is expected to be marginal. In this study, as shown in Fig. 6(a), the shape coefficient ($\lambda$) was assumed to be 2.0. Then, Eq. (4) can be expressed as follows

$$\delta_i = \frac{\varepsilon_{pi} l_t}{2} \tag{5}$$

where $\delta_i$ is the relative slip between the prestressing tendon and the surrounding concrete estimated from the idealized strain profile curves. Mitchell *et al*. (1993) and Barnes *et al*. (2003) derived the transfer length as a function of $f_{pi} d_b / \sqrt{f_{ci}}$, while other researchers (Buckner 1995, Tadros and Baishya 1996) proposed it as being proportional to the initial prestress ($f_{pi}$) and the diameter of the prestressing tendon ($d_b$), i.e., $l_t = k f_{pi} d_b$, where $k$ is a constant. Since the compressive strength of concrete at release ($f_{ci}$), the magnitude of initial prestress ($f_{pi}$), and the diameter of the prestressing tendon ($d_b$) are directly related to the bond behavior of the prestressing tendon and the surrounding concrete, these factors have significant influences on the relative slip between them. Therefore, in this study, the relative slip ($\delta_i$) was assumed as functions of $f_{pi} d_b / \sqrt{f_{ci}}$ from the idealized strain profile curves shown in Fig. 6(a), as follows

$$\delta_i = \alpha \left( \frac{f_{pi}}{\sqrt{f_{ci}}} d_b \right)^{\beta} \tag{6}$$

Table 3 Dimensions and material properties of pretensioned concrete members used in parametric studies

| Parameters | | | |
|---|---|---|---|
| beam width ($b_w$) | 100 mm | | 200 mm |
| beam height ($h$) | 1.0 $b_w$ | 1.5 $b_w$ | 2.0 $b_w$ |
| strand diameter ($d_b$) | 9.5 mm | 12.7 mm | 15.2 mm |
| concrete compressive strength at release ($f_{ci}$) | 30 MPa | 50 MPa | 70 MPa |
| tensile strength of prestressing tendon ($f_{pu}$) | 1860 MPa | | 2400 MPa |
| magnitude of initial prestress ($f_{pi}$) | 0.5 $f_{pu}$ | 0.6 $f_{pu}$ | 0.7 $f_{pu}$ |
| clear cover thickness ($C$) | 30mm | 40mm | 50mm |
| eccentricity ratio ($e_p/h$) | | 0 ~ 0.425 | |
| Total number of members: 972 | | | |

where $\alpha$ and $\beta$ are the calibration constants that are to be determined by the regression analysis explained in the following section.

### *4.2 Determination of α and β*

As shown in Table 3, regression analyses were performed on 972 pretensioned concrete members that have various cross-sectional dimensions and material properties by applying the detailed analysis model to determine $\alpha$ and $\beta$ in Eq. (6). It should be noted that grade 1860 MPa and grade 2400 MPa prestressing tendons were considered in the regression analyses. In addition, the maximum compressive stress of concrete in the cross section at transfer was limited by $0.7 f_{ci}$ in this study, according to the allowable compressive stress specified in the ACI318 code (2011).
Fig. 7 shows the distribution of relative slips ($\delta_i$) obtained from the regression analyses with respect to $f_{pi} d_b / \sqrt{f_{ci}}$; the best-fit line was obtained when the values of $\alpha$ and $\beta$ were $2.17\times10^{-4}$ and 1.16, respectively. Thus, Eq. (6) can be re-expressed, as follows

$$\delta_i \times 10^4 = 2.17\left(\frac{f_{pi}}{\sqrt{f_{ci}}} d_b\right)^{1.16} \tag{7}$$

Assuming the elastic modulus of prestressing tendon ($E_p$) is $2.0\times10^5$ MPa, the simplified transfer length equation ($l_t$) can be derived from Eqs. (5) and (7), as follows

$$l_t = 86.8\left(f_{pi}\right)^{0.16}\left(\frac{d_b}{\sqrt{f_{ci}}}\right)^{1.16} \tag{8}$$

## 5. Verification of proposed model

### *5.1 Database of test results*

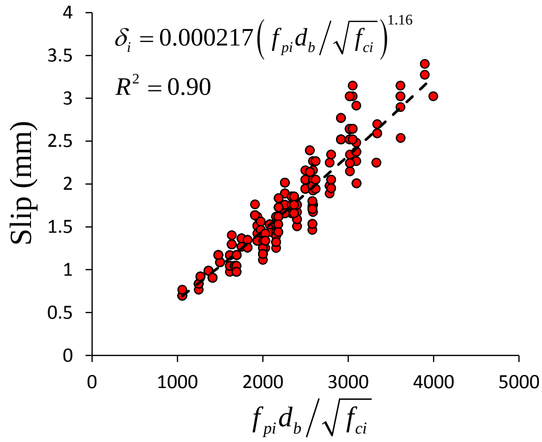



Fig. 7 Regression analysis for determining the coefficients in Eq. (6)

Table 4 Dimensions and material properties of collected specimens

| Researcher | Number of specimens | $d_b$ (mm) | $C$ (mm) | $f_{ci}$ (MPa) | $f_{pi}$ (MPa) | $e_p$ (mm) |
|---|---|---|---|---|---|---|
| Oh and Kim (2000) | 36 | 9.5 ~ 15.2 | 30.0 ~ 50.0 | 32.5~47.2 | 1,395 | 42.4 ~ 63.7 |
| Park *et al.*(2012) | 6 | 15.2 | 67.4 | 31.5 | 1,347.5 | - |
| Park and Cho (2014) | 16 | 12.7 ~ 15.2 | 52.4 ~ 68.7 | 24.5 ~ 31.5 | 930.0 ~ 1,302.0 | - |
| Thomas *et al.* (2015) | 23 | 9.5 ~ 15.2 | 39.7 ~ 68.6 | 29.9 | 1,489.6 | 25.4 ~ 38.1 |
| Russell and Burns (1990) | 18 | 12.7 ~ 15.2 | 43.4 ~ 44.7 | 19.2 ~ 30.2 | 1,168.0 ~ 1,406.0 | - |
| Mitchell *et al.* (1996) | 22 | 9.5 ~ 15.2 | 42.4 ~ 45.3 | 21.0 ~ 50.0 | 871.0 ~ 1,329.0 | 37.5 ~ 75.0 |
| Martí-Vargas *et al.*(2007) | 12 | 12.7 | 43.6 | 24.2 ~ 54.8 | 1,395.0 | - |
| Park (2015) | 76 | 12.7 ~ 15.2 | 22.4 ~ 93.7 | 29.0 ~ 46.0 | 824.0 ~ 1,681.0 | 0 ~ 150.0 |

For verification of the proposed simplified equation, a total of 215 test results were collected from various references, such as Oh and Kim (2000), Park *et al.* (2012), Park and Cho (2014), Thomas *et al.* (1990), Russell and Burns (1996), Mitchell *et al.* (1993), Martí-Vargas *et al.* (2007), and Park (2015), including the test results conducted in this study. The dimensions and material properties of the test specimens are summarized in Table 4. The compressive strengths of concrete at the release ($f_{ci}$) ranged from 19.2 MPa to 54.8 MPa, the diameters of tendon ($d_b$) ranged from 9.5 mm to 15.2 mm, the initial prestresses ($f_{pi}$) ranged from 824 MPa to 1,681 MPa, the eccentric ratios of tendon ($e_p$ / $h$) ranged from 0 to 0.38, and the concrete cover thicknesses ($C$) ranged from 22.4 mm to 93.7 mm. All the specimens had rectangular shaped sections. When multiple tendons are placed in the cross section, the concrete cover thicknesses ($C$) is affected by the tendon spacing ($s_p$). In such cases, the effective cover thickness ($C_{eff}$) proposed by Den Uijl (1998) was used, as follows

Table 5 Verification of proposed slip model

| Specimens | Test Result (mm) | Proposed Model (mm) | Ratio (Cal/Test) |
|---|---|---|---|
| S30-0.5 | 2.24 | 2.67 | 1.19 |
| S30-0.6 | 3.25 | 3.29 | 1.01 |
| S30-0.7 | 3.30 | 3.74 | 1.13 |
| S50-0.5 | 2.20 | 2.04 | 0.93 |
| S50-0.6 | 1.83 | 2.63 | 1.44 |
| S50-0.7 | 2.86 | 3.07 | 1.07 |
| Average | | | 1.13 |
| Standard deviation | | | 0.18 |
| COV | | | 0.16 |

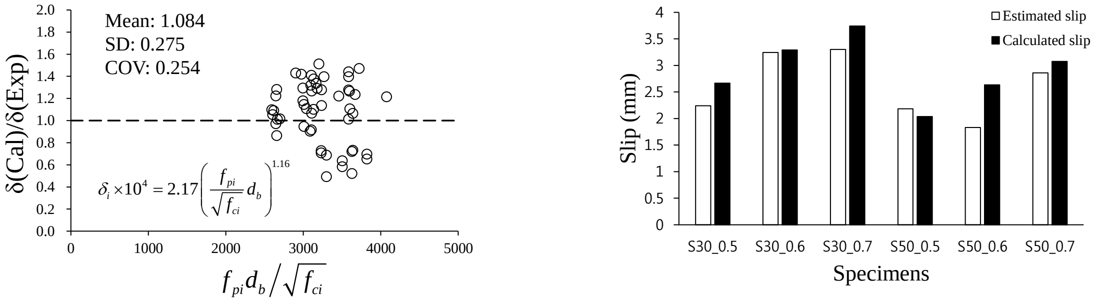
$$C_{eff} = \frac{2C + 1.5(n_p - 1)s_p}{2n_p} \tag{9}$$

where $n_p$ is the number of tendons in the row considered.

### *5.2 Verification of the proposed model*

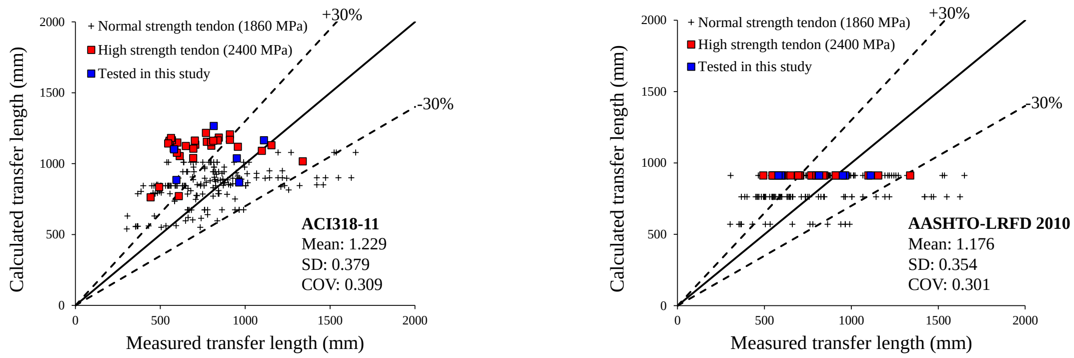
Fig. 8(a) shows comparisons of the measured tendon slips reported by Oh and Kim (2000) and Russell and Burns (1996) with those calculated from Eq. (7) proposed in this study. Eq. (7) adequately evaluated the tendon slips of the test specimens with an average of 1.084 and a COV of 0.254. Table 5 and Fig. 8(b) show a comparison of the tendon slips measured from the specimens having the grade 2400 MPa tendons tested in this study and those calculated from Eq. (7). It can be confirmed that the tendon slip increases, as the initial prestress increases, with the exception of the S50-0.6 specimen. This is because an increase in the initial prestress leads to a large strain difference between the concrete and tendon in the end region of the pretensioned concrete member, which also leads the transfer length to be larger. In addition, as the concrete compressive strength increases, the tendon slip decreased. This is because, as the concrete compressive strength increases, the confinement stresses induced by the surrounding concrete increase. This results in a large bond stress between the tendon and the concrete, and thus the transfer length of the tendon is reduced.

Fig. 9 shows comparisons between the transfer lengths of the collected test specimens and those calculated by the code equations specified in ACI 318 (2011) and AASHTO LRFD (2010). The transfer length equations presented in ACI318 (2011) and AASHTO-LRFD (2010) provided relatively conservative estimation on their transfer lengths with the averages of 1.229 and 1.176, respectively; the COVs of these code models were 0.309 and 0.301, respectively. In particular, the code models showed lower accuracy for the test specimens reinforced with the grade 2400 MPa tendons compared to those reinforced with the grade 1860 MPa tendons.



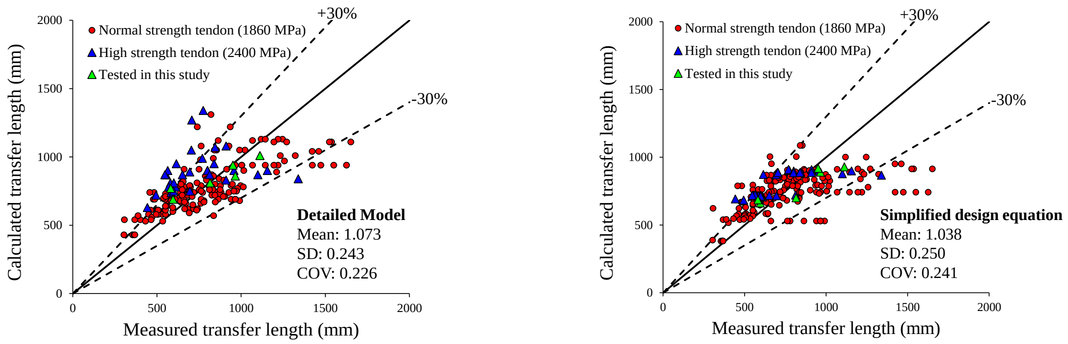

(a) Comparison with collected specimens (b) Comparison with test results in this study

Fig. 8 Verification of proposed slip function




(a) ACI318 (2011) (b) AASHTO-LRFD (2010)

Fig. 9 Verifications of code equations




(a) Detailed model based on TWCT (b) Simplified design equation

Fig. 10 Comparison of detailed model and simplified design equations

Fig. 10 shows comparisons of the detailed model presented in the authors' previous study (Han *et al.* 2016) and the simplified design equation proposed in this study. The simplified design equation provided an adequate level of accuracy comparable to the detailed model, with an average of 1.038 and COV of 0.241. Especially, the simplified design equation also provided reasonable estimations on the transfer lengths of the pretensioned concrete members reinforced with the grade 2400 MPa tendons.

## 6. Conclusions

In this study, prestress transfer tests were conducted on pretensioned concrete members to examine the transfer lengths of grade 2400 MPa prestressing tendons, and the applicability of the current code equations was also evaluated. In addition, a simplified design equation for the transfer length was proposed, and its analytical accuracy was verified by comparing with the test results. Based on this study, the following conclusions can be derived:

- The transfer length equations specified in the ACI318 and AASHTO-LRFD conservatively estimated the transfer lengths of the pretensioned concrete members reinforced with grade 2400 MPa prestressing tendons.
- The code equations provided lower accuracy on the transfer lengths of grade 2400 MPa prestressing tendons, compared to those of grade 1860 MPa tendons; this is because the code equations were developed based on the test results of grade 1860 MPa tendons or less.
- The detailed model based on the thick-walled cylinder theory proposed in the authors' previous study closely estimated the concrete compressive strain behaviors at transfer and the transfer lengths of grade 2400 MPa prestressing tendons.
- The tendon slip function derived from the regression analysis results provided reasonable evaluations of the tendon slips of pretensioned concrete members.
- The simplified design equation of the transfer lengths proposed in this study showed a good accuracy, which is comparable to that of the detailed model derived from the thick-walled cylinder theory. It also provided reasonable estimations on the transfer lengths of the pretensioned concrete members reinforced with grade 2400 MPa tendons.

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