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Transfer length of 2400 MPa seven-wire 15.2 mm steel strands in high-strength pretensioned prestressed concrete beam

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Abstract. In this study, the transfer length of 2400 MPa, seven-wire high-strength steel strands with a 15.2 mm diameter in pretensioned prestressed concrete (PSC) beams utilizing high strength concrete over 58 MPa at prestress release was evaluated experimentally. 32 specimens, which have the variables of concrete compressive strength, concrete cover depth, and the number of PS strands, were fabricated and corresponding transfer lengths were measured. The strands were released gradually by slowly reducing the pressure in the hydraulic stressing rams. The measured results of transfer length showed that the transfer length decreased as the concrete compressive strength and concrete cover depth increased. The number of strands had a very small effect, and the effect varied with both the concrete cover depth and concrete strength. The results were compared to current design codes and transfer lengths predicted by other researchers. The comparison results showed that the current transfer length prediction models in design codes may be conservatively used for 2400 MPa high-strength strands in high-strength concrete beams exceeding 58 MPa at prestress release.

Keywords: high-strength concrete; 2400 MPa prestressing strand; prestressed concrete; pretension; transfer length

1. Introduction

In order to fabricate pretensioned prestressed concrete (PSC) beams, concrete is cast around prestressing steel strands under tension. The concrete is bonded with the tendons as it cures, and when the tension is released, prestressing force is transferred to the concrete with the compression of tendons. The distance over which the strand must be bonded to the concrete in order to develop an effective prestress condition is defined as the transfer length. The theoretical transfer length refers to the distance from the end of the beam to the point at which the concrete strain converged, indicating that the strand has developed an effective prestress, and the concrete will experience no further change in the strain unless it is subjected to external loading (Pozolo and Andrawes 2011).

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The bond between the pretensioned strands and the surrounding concrete is attributed to three major mechanisms: (a) the adhesion between the steel surface and cementitious material, (b) the Hoyer effect: friction and "wedge action," which results from the dilation of the strand following release, and (c) the mechanical interlocking between the helically oriented strand wires and the concrete. In mechanics, friction is considered only in the presence of transverse compression. In pretensioned concrete beams, the radial expansion of strands described by the Hoyer effect results in significant friction and mechanical wedge action, and it also enhances the mechanical interlock effect. Similar to ordinary reinforcement, the mechanical interlock and the friction induced by the Hoyer effect are primarily responsible for the development of subsequent load-induced stresses that affect the transfer length (Briere *et al.* 2013).

The transfer length has been investigated by many researchers, who have identified the following:

1. An increase in the strand stress results in a larger transfer length (Mitchell *et al.* 1993, Oh *et al.* 2014).
2. An increase in the strand diameter results in a larger transfer length under identical stress levels (Mitchell *et al.* 1993, Oh *et al.* 2014).
3. The compressive strength of concrete (or its square root) is inversely proportional to the transfer length at the time of release (Zia and Mostafa 1977, Cousins *et al.* 1990, Balazs 1992, Mitchell *et al.* 1993).
4. The release of the flame-cutting strand for the load transfer to concrete has a larger transfer length than the gradual release of prestress about 6% to 30% (Kaar and Hanson 1975, Cousins *et al.* 1990).
5. A properly rusted strand surface enhances the bonding between the strand and the concrete because of the increased friction, and results in a smaller transfer length (Hanson 1969).
6. In recent studies, an increase in the concrete cover depth results in a decrease of the transfer length (Oh *et al.* 2014).

These studies were based on conventionally used construction materials, such as concrete strength of up to 60 MPa, and strands having nominal tensile strength values of 1860 MPa. Recently, with the increasing sizes of infrastructures, there is a greater need for higher-strength materials. Many structures adopted 80MPa or higher strength concrete and 2400MPa strand for efficient design. As a first step, Yim *et al.* (2015) studied the transfer length of 2400-MPa strands in terms of the concrete strength, detensioning method, the reinforcement of steel fibers, and stirrups. Their study was tested based on the high strength concrete up to 64 MPa and single strand members.

In this study, the transfer length of 2400 MPa, seven-wire high-strength steel strands with a 15.2 mm diameter in pretensioned prestressed concrete (PSC) beams was experimentally evaluated. High-strength concrete above 58 MPa at prestress release was used. 32 specimens, which have the variables of concrete compressive strength, concrete cover depth, and the number of PS strands, were fabricated and corresponding transfer lengths were measured. The strands were gradually released by slowly reducing the pressure in the hydraulic stressing rams. The results were compared to current design codes and transfer lengths predicted by other researchers in order to evaluate their applicability to prediction of transfer length of 2,400MPa strand in high strength over 58MPa concrete beams.

2. Experimental study

2.1 Material properties of concrete and PS strands

A seven-wire PS strand with a diameter of 15.2 mm was used. Its nominal tensile strength was 2400 MPa or 333 kN. The minimum elongation and maximum relaxation values of the strand were 3.5% and 2.5%, respectively (KS D7002, 2011). Test results obtained for the strand along with nominal values are shown in Table 1. The high strength strand has appears to be identical to the conventional 1860 MPa strand, including the surface condition and the number of twists per meter. The stress-strain curve of a new strand has almost the same features as the 1860 MPa strand in terms of the elastic modulus and yield to ultimate load behavior (Kim *et al*. 2013).

Concrete based on two different mixture proportions was prepared. They have different water-to-cement ratios of 30% and 25% for different standard design compressive strengths of 50 MPa and 80 MPa, respectively. For mixing, Type 1 Portland cement (specific gravity of 3.15), river sand (specific gravity of 2.67 in a surface-dry saturated condition) as the fine aggregate, and crushed gravel with a maximum size of 20 mm (specific gravity of 2.71 in a surface-dry saturated condition) as the coarse aggregate were used. Superplasticizer, which is a polycarboxylate-based admixture, was added as 1.5% of the cement weight to control the workability of the concrete mixture. In Table 2, mix proportions of the concrete samples used for the fabrication of the pretensioned concrete beams according to the design strength was presented. Cylindrical concrete samples upon fabrication of the pretensioned concrete beams were also prepared. These samples were used to measure the compressive strength when the prestressing force was exerted after concrete hardening. The measured average compressive strengths at prestress release were 58 MPa and 74 MPa for concrete designed with compressive strength values of 50 MPa and 80 MPa, respectively.

Table 1 Properties of PS strand

Item	Diameter (mm)	Breaking Strength (kN)	Yield Strength (kN)	Elongation (%)	Modulus of Elasticity (GPa)	Relaxation (%)
Spec.	15.0~15.6	333.0	283.0	3.5	185.0~205.0	2.5
Result	15.4	347.5	321.7	7.5	198.7	0.8

Table 2 Design strength and mix proportions of concrete samples

Design strength (MPa)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Superplasticizer (kg/m^3)
50	160	534	638	976	8.06
80	160	632	573	948	9.48

2.2 Fabrication of PSC beams

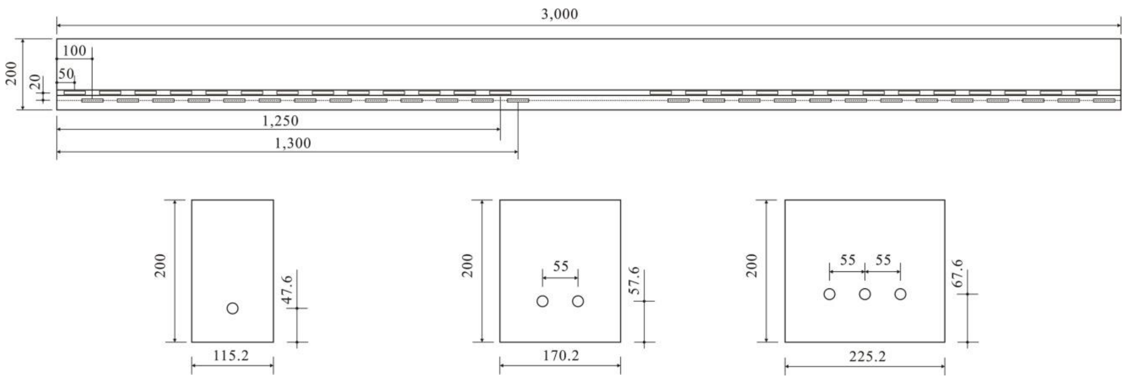
In this study, a total of 32 PSC beams were fabricated and tested in order to investigate the variables that affect the measured transfer length. The variables include the concrete compressive strength (50 MPa and 80 MPa), concrete cover depth (40 mm, 50 mm, and 60 mm), and number of strands (1, 2, and 3). These variables result in 16 combinations of PSC beams, and for each case, we use two identical beams to verify the reliability of the acquired data. As a follow-up study of the previous experiments (Yim *et al.* 2015), we applied the same design concept of PSC beams. The heights and lengths of the beams were 200 mm and 3000 mm, respectively, while the widths were 115.2 mm, 165.2 mm, and 215.2 mm, depending on the number of strands used. The bottom cover depth values were varied from 40 mm to 60 mm, but the side cover depth was fixed at 50 mm. The spacing between the strands was fixed as 55 mm because of limitations of the fabricated steel frame. Details of the beams are presented in Table 3 and Fig. 1.

Table 3 Transfer length of prestressed concrete beams (mm)

No.	Design strength of concrete (MPa)	Compressive strength of concrete at prestress release (MPa)	No. of PS strands	Concrete cover (mm)	Measured value		Averaged value		
					Prestress release end	Dead end	Prestress release end	Dead end	Ave.
#1	50	58	1	40	719	710	723	728	726
#2	50	58	1	40	727	746			
#3	50	58	1	50	739	805	664	719	692
#4	50	58	1	50	590	633			
#5	50	58	1	60	620	592	682	582	632
#6	50	58	1	60	744	572			
#7	50	58	2	40	459	543	830	736	783
#8	50	58	2	40	830	736			
#9	50	58	2	50	580	621	595	660	627
#10	50	58	2	50	610	698			
#11	50	58	3	40	881	809	896	843	869
#12	50	58	3	40	912	877			
#13	50	58	3	50	742	704	662	710	686
#14	50	58	3	50	583	716			

Continued-

#15	50	58	3	60	491	526	470	519	494
#16	50	58	3	60	449	512			
#17	80	74	1	40	710	567	588	476	532
#18	80	74	1	40	466	385			
#19	80	74	1	50	416	417	407	500	454
#20	80	74	1	50	397	583			
#21	80	74	1	60	582	499	545	495	520
#22	80	74	1	60	509	491			
#23	80	74	2	40	513	446	518	594	556
#24	80	74	2	40	523	741			
#25	80	74	2	50	484	525	467	615	541
#26	80	74	2	50	450	706			
#27	80	74	3	40	669	733	694	847	771
#28	80	74	3	40	720	962			
#29	80	74	3	50	669	834	629	711	670
#30	80	74	3	50	588	587			
#31	80	74	3	60	458	507	522	528	525
#32	80	74	3	60	587	548			



(a) (b) (c)

Fig. 1 Details of test specimens and attached locations of strain gauges: (a) #1, #2, #17, #18, (b) #9, #10, #25, #26; and (c) #15, #16, #31, #32

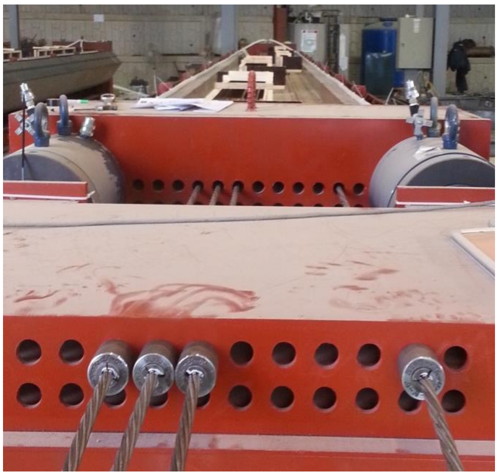


Fig. 2 Fabrication of pretensioned prestressed concrete beams on Bed-4

16 PSC beams were fabricated simultaneously on the four prestressing frames, which were prepared using a center-hole piston and hydraulic pump to stress the strand, and each frame accommodated four beams, as shown in Figs. 2 and 3. A tension of 0.75 f_{pu} (250 kN for a strand) was applied to each beam, and it was measured using center-hole load cells that were placed between the strand grip and piston. The concrete beams were steam cured for 8 hours, and formwork was removed. 16 hours later after removing the formwork, the prestressing forces were released gradually by slowly reducing the pressure in the hydraulic stressing rams. The strains on the concrete surface were measured using electrical-resistance strain gauges attached to the side surface with 50 mm spacing, as shown in Fig. 1.

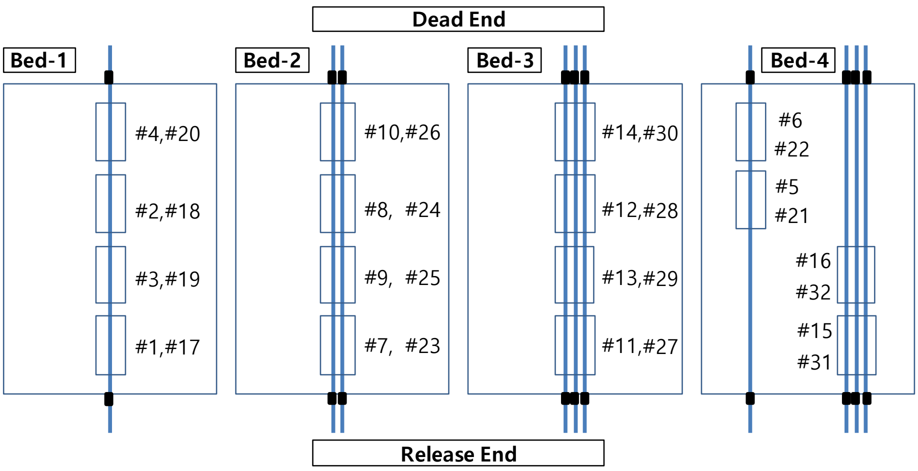


Fig. 3 Prestressing beds and fabrication scheme for test specimens

3. Test results

3.1 Evaluation of transfer length

Fig. 4 shows the representative strain result of sample #1, which was measured using the electrical-resistance strain gauges at the release and dead ends. Each measurement was carried out simultaneously after detensioning. The measured strain values increase from the end to the center of the beam, where the increased strains demonstrate the transfer of the prestress from the PS strands to the concrete. The increased strain was observed to gradually converge. These converged strain values indicate that the effective prestressing force was fully transferred to the concrete from the strand (Yim *et al.* 2015). In this study, to obtain a practical strain distribution, we calibrated the strain results based on the smoothing technique and the least-squares approximation (Russel and Burns 1996, Zi *et al.* 2007). The converged point is determined by averaged maximum strain region, which is defined that the increased ratio of strain result is lower than 5%. Accordingly, the 95% value of converged point is selected as the transfer length of PSC beam.

3.2 Transfer length

Table 3 shows the measured transfer lengths at both ends of the beams. The average transfer length of individual strand samples with a 40 mm cover depth (#1, #2) is 726 mm, which is 7~11% lower than the results at the cut ends by flame cutting, averaged 774 ~ 816 mm, of previous samples obtained by Yim *et al.* (2015). This result supports a previous study (Mitchell *et al.* 1993) conducted using 1860 MPa or lower-strength steel strands, even though the strength or prestressing stress increased by about 29%. Mitchell *et al.* (1993) reported that the measured transfer length obtained by sudden release was 6~30% higher than the value obtained by gradual release, and the detensioning method was a key factor in determining the transfer length. In the test results of Table 3, the difference at both ends of the beams is negligible, and the averaged value from both sides of two beams that have the same variables was chosen as the transfer length.

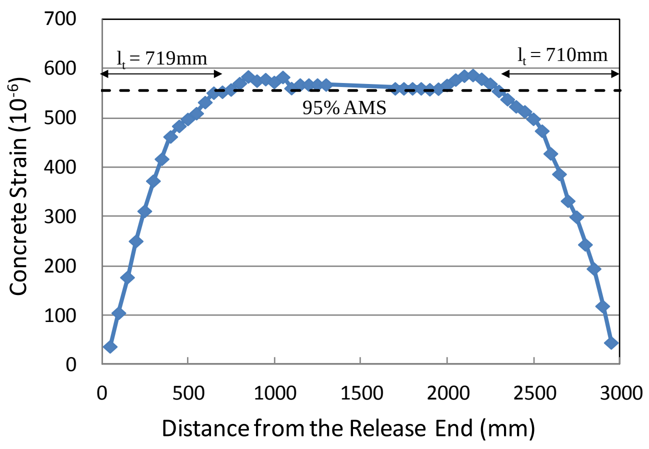


Fig. 4 Refined strain measurement and determination of transfer length (#1)

4. Discussion on transfer length

4.1 Effect of concrete strength

The averaged transfer lengths in Table 3 are presented in Fig. 5 according to the concrete compressive strength at release. Figs. 5(b) to 5(d) show transfer length changes according to concrete strength for each number of strands. The overall pattern indicates that the transfer length tended to decrease as the concrete strength was increased. This may be attributed to the increased confinement of the surrounding high-strength concrete, resulting in higher bonding between two materials and shorter transfer length. This trend is similar to what was observed in previous studies (Zia 1977, Mitchell *et al.* 1993, Oh *et al.* 2014) using 1860 MPa strands and 50 MPa or lower-strength concrete, even though prestressing force was increased about 29% (2400MPa strand) and high strength concrete over 58MPa was used in this study. The rate of reduction of the transfer length with increasing concrete strength tended to decrease as the concrete cover depth and number of strands increased. In particular, when the number of strands was three and the cover depth was 60 mm, the transfer length increased slightly. This may be due to the fact that the transfer length attains a certain value at which it is hardly affected by other variables such as the concrete strength.

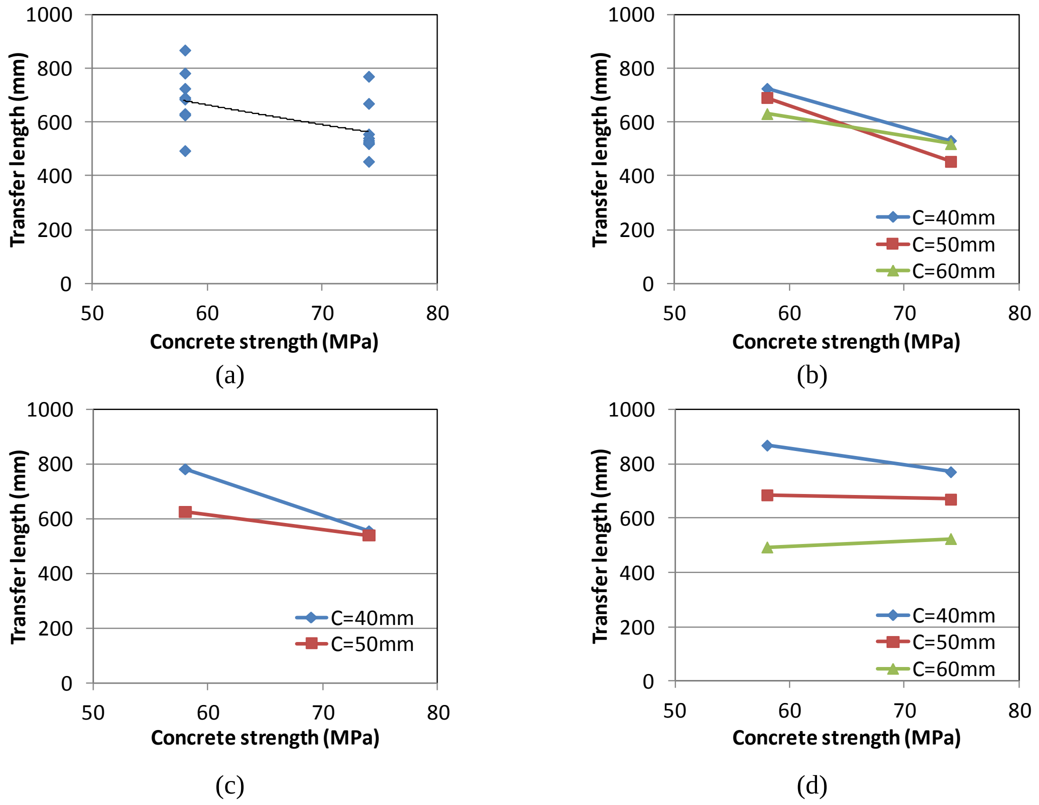


Fig. 5 Transfer length according to the concrete compressive strength: (a) All, (b) No. of PS strands = 1, (c) No. of PS strands = 2 and (d) No. of PS strands = 3

4.2 Effect of concrete cover depth

In Fig. 6, averaged transfer lengths in Table 3 were plotted according to the concrete cover depth. The transfer length tends to decrease as the concrete cover depth increases as shown in the previous study (Oh *et al.* 2014). However, the decreasing trend in high strength concrete specimens was somewhat weakened. As shown in Fig. 7, the transfer length in single-strand beams with the 58 MPa concrete decreases by 4.7% (from 726 mm to 692 mm) and 8.7% (from 692 mm to 632 mm) as the cover depth increases from 40 mm to 50 mm and 60 mm, respectively. This is due to the increased confinement by the surrounding concrete, which results in an increased cross-sectional area of concrete contributing to bonding between the concrete and strand as the cover depth increases. This result confirms that a sufficient concrete cover depth is required to enable that there is sufficient bonding of strand to concrete. In single-strand beams with 74 MPa concrete, the transfer length fluctuates with changes in the cover depth, with a decrease of 14.7% (from 532 mm to 454 mm) as the cover depth varies from 40 mm to 50 mm, and an increase of 14.5% (from 454 mm to 520 mm) as the cover depth varies from 50 mm to 60 mm. We concluded that the required concrete area for the bonding decreases as the concrete strength increases. In PSC beams having 58 MPa concrete, the effect of the concrete cover depth was relatively large when two or three strands were used. However, 74 MPa concrete beams were affected by the cover depth only when the three strands were used. This seems that the measured transfer lengths ranging from 400 to 500 mm are the minimum values under the design condition in this paper.

4.3 Effect of number of strands

Fig. 8 shows the effect of the number of strands on the transfer length of high-strength strands. As the number of strands increases, there is an increased transfer length in the 74 MPa concrete beams, and the relationship remains unclear in the 58 MPa concrete beams. However, the increase in the number of strands definitely affects the transfer length, regardless of the concrete strength when the cover depth is 40 mm, as shown in Fig. 7. This is because the increased number of strands results in a reduction in the concrete area contributing to the bonding.

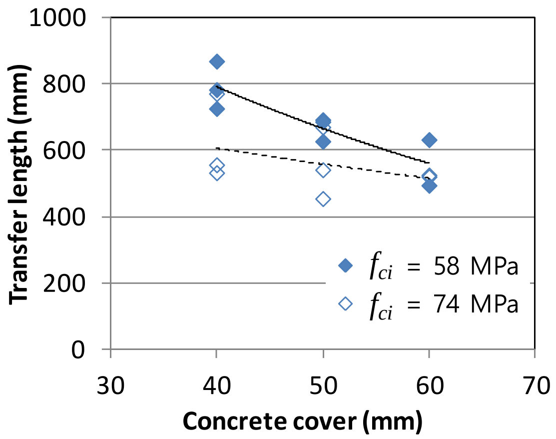


Fig. 6 Transfer length according to the concrete cover depth

The reinforcing ratio of strands increases from 0.006 to 0.008 and 0.009, and the relative concrete area decreases inversely as the number of strands increases from 1 to 2 and 3. Meanwhile, the beams with a cover depth of 50 mm and 60 mm are not affected by the number of strands. The reduced concrete area that contributes to the bonding appears to be sufficient for the bonding when the cover depth is 50 mm or larger. It can be concluded that the transfer length is interactively influenced by both the number of strands and concrete cover depth.

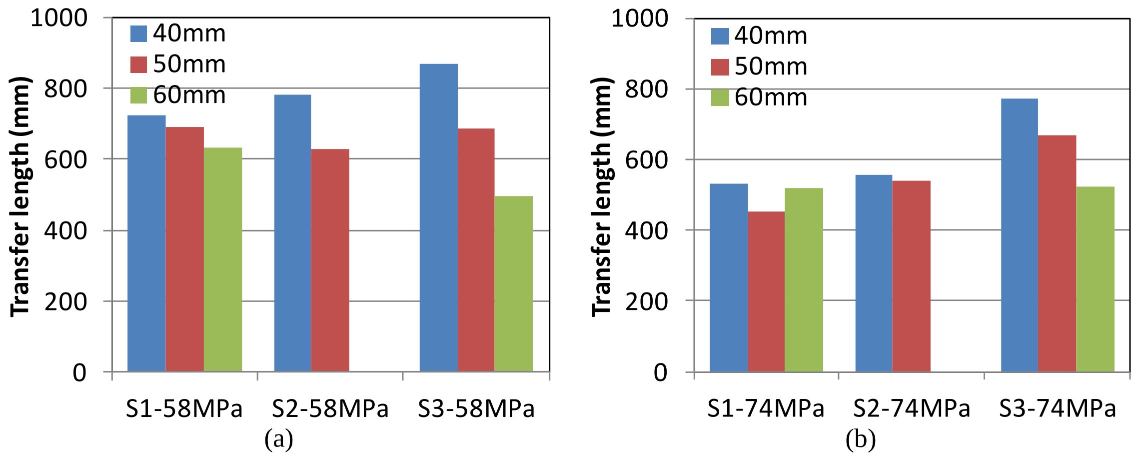


Fig. 7 Transfer length according to the concrete cover depth and the number of PS strands (S1: 1 PS strand; S2: 2 PS strands; S3: 3 PS strands): (a) concrete compressive strength of 58 MPa and (b) concrete compressive strength of 74 MPa

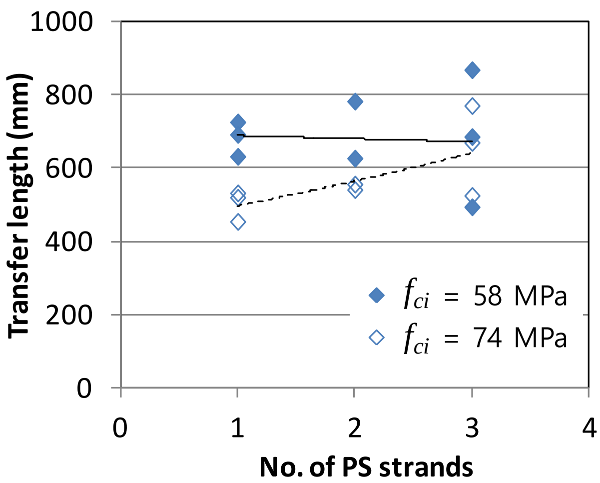


Fig. 8 Variation in transfer length according to the number of PS strands

5. Comparisons with prediction equations

The results obtained by these experiments were compared to the current design codes of ACI 318-08 and Eurocode 2 (ACI 318 2008, BS EN 1992-1-1 2004), and the transfer lengths predicted by other researchers (Mitchell *et al.* 1993, Marti-Vargas *et al.* 2007, Oh *et al.* 2014). In this comparison, the factors for safety and reliability involved in the equations are not considered.

ACI 318-08 proposed a prediction model for the transfer length of pretensioned beams based on an ordinary concrete strength with a concrete cover depth of greater than 50 mm (ACI 318 2008)

$$l_t = 0.048 f_{pe} d_b \tag{1}$$

where l_t is the transfer length (mm), f_{pe} is the effective prestress force (MPa), and d_b is the nominal diameter of the strand (mm).

Eurocode 2 (BS EN 1992-1-1 2004) considers additional factors such as the tensile strength of concrete, type of PS strands, surface condition of the PS strands, and the bonding condition of both materials, along with the prestressing force and diameter of the PS strand.

$$l_t = \alpha_1 \alpha_2 d_b f_{pi} / f_{bpt} \tag{2}$$

where α_1 is a coefficient that considers the detensioning method (gradual release: 1.0; sudden release: 1.25), α_2 is the type of tendon (0.25: circular cross section; 0.19: 3 and seven-wire strands), f_{pi} is the prestressing force at release (MPa), and f_{bpt} is the bond stress between concrete and the PS strand (MPa). The bond stress is also described as follows

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

where η_{p1} is a coefficient that considers the type of tendon and the bond situation (2.7: intended wires; 3.2: three or seven-wire strands), η_1 is the coefficient bonding condition (1.0: good bond condition; 0.7 otherwise), and f_{ctd} is the design tensile value of the strength at the time of release (MPa).

Mitchell *et al.* (1993) reported that the increased compressive strength of concrete mainly induces a decrease of the transfer length, and they proposed a modified model of the ACI code to predict the transfer length as follows

$$l_t = 0.048 f_{pi} d_b \sqrt{\frac{20}{f'_{ci}}} \tag{4}$$

where f'_{ci} is the compressive strength of concrete at release (MPa). Marti-Vargas *et al.* (2007) also proposed a modified model as follows

$$l_t = \frac{\psi f_{pi} A_p}{(4/3)\pi d_b (0.4) f'^{0.67}_{ci}} \tag{5}$$

where A_p is the cross-sectional area of the PS strand (mm^2), and Ψ is 1. Pozolo and Andrawes (2011) reported that based on their analysis of prediction models of the transfer length for the last 40 years, the prestressing force at release (f_{pi}) has been used in about 67% of the proposed models, and the effective prestressing force (f_{pe}) has been used in about 33% of the models. The models proposed by Mitchell *et al.* (1993) and Marti-Vargas *et al.* (2007) are also used as a prestressing force at release (f_{pi}) in the same manner as in Eurocode 2 (BS EN 1992-1-1 2004), instead of using the effective prestressing force (f_{pe}), because the transfer length hardly changes after release.

Recently, Oh *et al.* (2014) proposed an advanced model that was based on the theoretical and experimental results, which is determined by the prestressing force, diameter of the used tendon, compressive strength of concrete, and cover depth of concrete.

Table 4 Test to predict ratios for the transfer length

No	$l_{t,test}/l_{t,equation}$				
	ACI	Eurocode	Mitchell *et al*.	Marti-Vargas *et al*.	Oh *et al.*
#1~#2	0.59	0.89	0.94	1.12	0.87
#3~#4	0.56	0.85	0.90	1.07	0.87
#5~#6	0.52	0.78	0.82	0.98	0.82
#7~#8	0.64	0.96	1.02	1.21	0.93
#9~#10	0.51	0.77	0.81	0.97	0.79
#11~#12	0.71	1.07	1.13	1.35	1.04
#13~#14	0.56	0.84	0.89	1.06	0.87
#15~#16	0.40	0.61	0.64	0.76	0.64
#17~#18	0.43	0.72	0.78	0.97	0.69
#19~#20	0.37	0.61	0.66	0.83	0.62
#21~#22	0.42	0.70	0.76	0.95	0.73
#23~#24	0.45	0.75	0.81	1.01	0.72
#25~#26	0.44	0.73	0.79	0.99	0.74
#27~#28	0.63	1.04	1.13	1.41	1.00
#29~#30	0.55	0.91	0.98	1.22	0.92
#31~#32	0.43	0.71	0.77	0.96	0.74
Yim #1~#2 dead end	0.64	0.91	0.94	1.09	0.78
Yim #3~#4 dead end	0.65	1.01	1.08	1.31	0.86
Yim #5~#6 dead end	0.56	0.78	0.81	0.94	0.77
Yim #7~#8 dead end	0.51	0.80	0.86	1.04	0.78
Yim #1~#2 cut end	0.81	0.91	1.18	1.37	0.98
Yim #3~#4 cut end	0.74	0.92	1.23	1.49	0.98
Yim #5~#6 cut end	0.67	0.75	0.97	1.13	0.92
Yim #7~#8 cut end	0.63	0.79	1.05	1.28	0.95
Mean	0.56	0.83	0.91	1.10	0.83
Coefficient of variation	0.20	0.15	0.17	0.17	0.14

It is a unique model that uses the cover depth of concrete as a factor for the prediction of the transfer length.

$$l_t = 8\sqrt{f_{pe}}\left(\frac{1}{f_{ci}}\right)^{1/3} \mathrm{d}_b^{1.28}\left\{\frac{1}{C-20}+0.25\right\} \tag{6}$$

where C is the cover depth of concrete (mm).

A comparison analysis of the prediction models above was performed using the experimental measurements in this study. Here, the previous experimental results using a 2400 MPa PS strand (Yim *et al.* 2015) are also included and listed in Table 4. Yim *et al.* (2015) fabricated various types of PSC beams according to the prestressing force (f_{pi}): 196 kN (#1~#4) and 250 kN (#5~#8), and the compressive strength of concrete (f'_{ci}): 49 MPa (#1~#2, #5~#6) and 64 MPa (#3~#4, #7~#8).

The $l_{t,test}/l_{t,equation}$ in Table 4 means the ratio of the measured transfer length to prediction models, and represents the accuracy of the models for transfer length prediction of pretensioned concrete beam using the 2400 MPa PS strand. The ratio by ACI equation shows that the mean value is about 0.56, which is the most inaccurate result. This is due to the fact that the ACI code determines the transfer length using only two parameters, namely the effective prestressing force and diameter of the strand. However, the ACI code is widely used because of its simplicity and conservative design with respect to the transfer length. Eurocode 2 (BS EN 1992-1-1 2004) considers various parameters, and it therefore predicts transfer length more accurately than ACI code. In addition, results for different detensioning methods show comparable ratios owing to the selection of different coefficients as the detensioning method in Eurocode 2. However, for PSC beams that have a smaller concrete cover depth of about 40 mm, Eurocode 2 predicts unconservative transfer length. This is because the finding in recent studies (Oh *et al.* 2014), which is the cover depth of concrete is a significant parameter for the prediction of the transfer length, is not considered.

As can be seen in Table 4, it is concluded that existing models in the design codes can be used to predict the transfer length when 2400 MPa PS strand and high-strength concrete over 60 MPa are used in pretensioned prestressed beam with a sufficient cover depth of concrete of over 50 mm. However, existing models have determined that the transfer length of PSC beams is a more conservative value of about 5%~20% and 10%~21% when using high-strength concrete and 2400 MPa PS strands, respectively. This implies that existing models were proposed without experimental data using high-strength concrete and 2400 MPa PS strands. Furthermore, a greater Hoyer's effect, which is induced by an increased extension of high-strength PS strands under the same prestressing stress condition (f_{pi} /f_{pu}), has not been considered in existing models. Accordingly, existing models should be modified to determine the effect of various parameters on the transfer length of PSC beams when high-strength construction materials are used.

From the comparison results presented in Table 4, the model proposed by Mitchell *et al.* (1993) shows the most accurate prediction of the transfer length with a mean comparison ratio of 0.91. However, this model was obtained based on the experimental results with gradual release for detensioning, so the transfer length obtained using the sudden-release method is not very accurate. Marti-Vargas' model (Marti-Vargas *et al.* 2007) shows unconservative prediction results. Comparison ratios are higher than the value of 1.0, with the exception of the specimens having 60-mm cover depth.

Oh's model (Oh *et al.* 2014) appears to be the most reasonable model for the prediction of the transfer length because it has conservative comparison ratios for all specimens, and has the lowest coefficient of variation due to considering the cover depth of concrete. Especially, the transfer length at the cut end (Yim #1~#8 cut end) has a comparison ratio of about 0.96, this is because Oh's model was obtained based on the experimental results with sudden release for detensioning. In order to improve the accuracy of the Oh's prediction model, the expression of existing parameters should be modified based on the experimental results obtained for high-strength construction materials, and additional parameters such as the spacing between strands and the detensioning method should be considered.

6. Conclusions

In this study, the transfer length in pretensioned PSC beams fabricated by high-strength concrete above 58 MPa at prestress release and 2400 MPa PS strands was measured. A total of 32 PSC beams that have different factors which affect the transfer length, such as the compressive strength of concrete, cover depth of concrete, and the number of PS strands, were prepared for the transfer length measurement. Based on a comparison analysis with previous models used to predict the transfer length in PSC, the measured transfer length of high-strength construction materials was discussed, and the following conclusions were made:

1. The transfer length of PSC beams that were fabricated by high-strength concrete above 60 MPa and prestressing force was 29% higher than that in previous studies, decreased as the compressive strength increased. However, other parameters can reduce the influence of the concrete strength on the transfer length of PSC beams.
2. The transfer length decreases as the bottom cover depth increases, but the rate of this decrease slows down with high-strength concrete.
3. When more than two PS strands were used, the transfer length increased for the 40 mm bottom cover depth as the number of used PS strands increased, but it is not represented in PSC beams having a bottom cover depth of 50 mm. The bottom cover depth and the spacing between strands are complementary parameters that may be used to determine the transfer length.
4. From the comparison analysis, existing models in the design codes showed conservative results, and therefore can be used to predict the transfer length for the pretensioned prestressed beams utilizing 2400 MPa PS strand and high-strength concrete over 58 MPa at prestress release.
5. The transfer length model proposed by Oh *et al.* (2014) appears to be the most reasonable model in terms of accuracy and variation, but to improve its accuracy as a prediction model, existing parameters should be modified based on the experimental results obtained for high-strength construction materials, and additional parameters such as the spacing between strands and the detensioning method should be considered.

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