Investigation of Bond Tests to Transfer Performance of Prestressing Strand

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ABSTRACT

Extensive research has been reported on the bond between pretensioned strand and concrete, and it is commonly classified into three distinct mechanisms including adhesion, Hoyer effect and mechanical interlock. Hoyer claimed that, after the release of the prestressing force, even an extreme small swelling of the pretensioned wire could produce a very high radial pressure on the surrounding concrete within the anchorage zone, thereby causing a large friction forces if sliding movement occurred. It was assumed that most of the transfer bond was probably from Hoyer effect because mechanical interlocking had not been fully developed. However, the relative contribution of each bond mechanism was uncertain. In particular, the previous claims were made based on the test with smooth wires which have been replaced by seven-wire strands. In this paper, the bond mechanism will be investigated through a series of pullout tests. The specimen will be divided into three types: pretensioned strand with Hoyer effect, pretensioned strand without Hoyer effect, and non-pretensioned strand. The relationship of the pullout force and the relative slip will be studied. The relative contribution of each bond mechanism will be evaluated through the comparison of the pullout test results.

Keyword: Prestressing strands, Bond mechanism, pullout tests

INTRODUCTION

Pretensioned members rely on the bond performance between the prestressing strands and the surround concrete in the end anchorage zone. Prestress transfer bond is present from the end of a pretensioned concrete member to the transfer length, where the concrete compression stress is constant and the prestressing force is fully effective. Although extensive experimental tests and mathematical formulas have been presented to study the transfer length, the bond behavior in the end zone has not been fully understood. The strength of this bond is commonly considered to be developed from three distinct mechanisms: adhesion, Hoyer effect and mechanical interlock. However, there are few efforts to quantify the relative contribution of each bond mechanism for the pretensioned members. For mildly reinforced (non-prestressed) concrete members, the bond behavior is typically investigated based on the slip-stress relationship through pull-out tests. And the similar pullout tests were introduced for the pretensioned members in the previous research (Brearley and Johnston, 1990, Morcous et al, 2012). However, the strands embedded in concrete were not pretensioned in these tests. It is questionable that the bond behavior is the same between the non-pretensioned members and the pretensioned members. In other words, the non-pretensioned pullout tests result is not appropriate to demonstrate the prestress transfer bond behavior. It is more reliable to understand the bond characteristics based on the pullout tests of the pretensioned members.

The objective of this research is to introduce a series of small-scale tests to determine the bond stress-slip response for pretensioned strands embedded in concrete along the transfer length, to understand how much influence that each bond mechanism may contribute to the end transfer.

BOND MECHANISM

Russell and Burns (1993) have categorized the bond between the strand and concrete into three bond mechanism: adhesion, Hoyer effect and mechanical interlocking. They did not list friction as a separate mechanism. Instead, they claimed that friction was a component and contributor to both Hoyer effect and mechanical interlocking. The loss of friction will result in the loss of Hoyer effect and decrease of mechanical interlocking. In this research, this categorization will be used to study the bond mechanism.

Adhesion is the glue between strand and concrete. The adhesion will disappear once the relative slip occurs. Because the transfer zone is characterized by strand slip, adhesion contributes nothing to the prestress transfer bond. On the contrary, the adhesion does exist if the strand embedded in concrete is not pretensioned or if there is no relative slip between the pretensioned strand and concrete. Hoyer (1939) pointed out that, upon release of the wire from its temporary anchorage on the prestressing bed, the end of the wire swells as a result of the recovery of the lateral contraction and develops a wedge effect because the prestressing force must diminish to zero at the free end of the wire. This is known as the Hoyer effect, as shown in Figure 1. Although the swelling of the wire is only a few thousandths of a millimeter, it may produces a very high radial pressure on the surrounding concrete, thereby giving rise to a large frictional forces if sliding movements occur. The hardened concrete will have enveloped the pretensioned strand and mimic its shape. If the strand attempts to pull through the concrete without twisting, movement is resisted by mechanical interlocking due to the concrete ridges acting on the outside surfaces of the strand.

Russell and Burns (1993) proposed an idealized bond mechanism in the anchorage end zone. As shown in Figure 2, the bond for the transfer of pretensioned force is from Hoyer effect and mechanical interlocking. Janney's test results (Janney, 1954) supported that most of the transfer bond developed due to the Hoyer effect, because the smooth wires were used in his transfer length experiments and thus mechanical interlocking could not contribute to bond. As for the pretensioned seven-wire strand, the relative contribution of each bond mechanism is unknown, although Russell and Burns (1993) claimed that most of the transfer bond probably was from Hoyer effect because mechanical interlocking had not been fully developed.

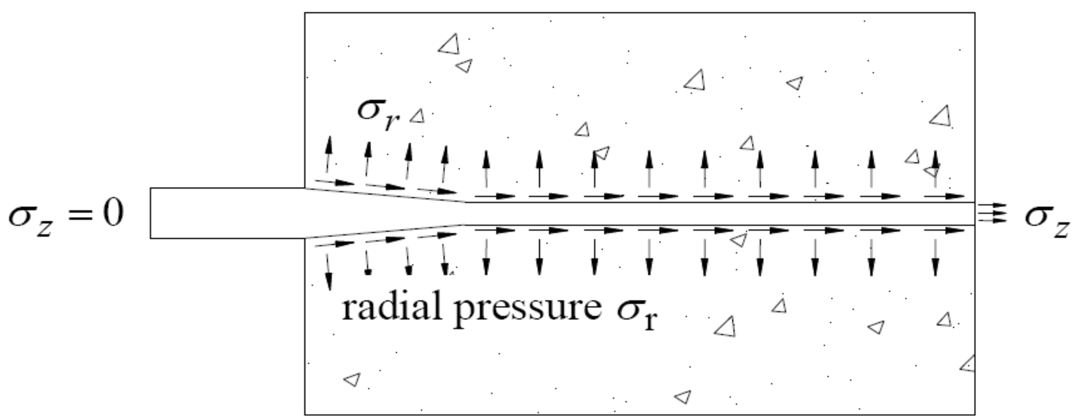


Figure 1 The Hoyer Effect (courtesy of Burgueno and Sun)

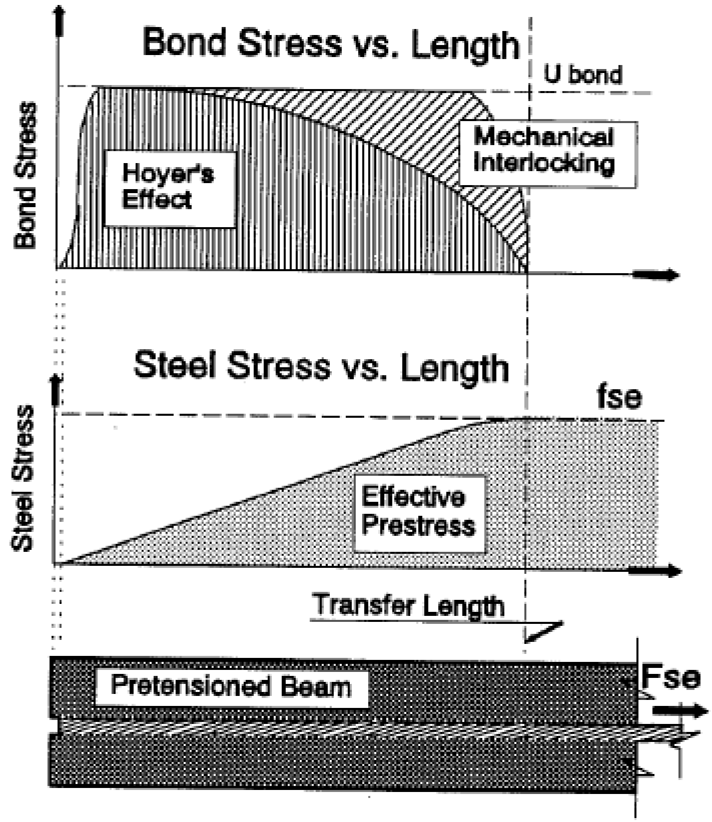


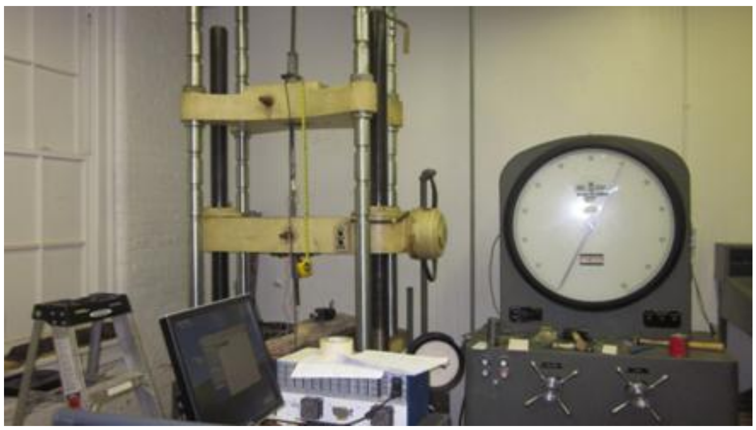
Figure 2 Idealization of Bond Mechanics in Transfer Zones (courtesy of Russell and Burns, 1993)

TEST PLAN AND PROCEDURE

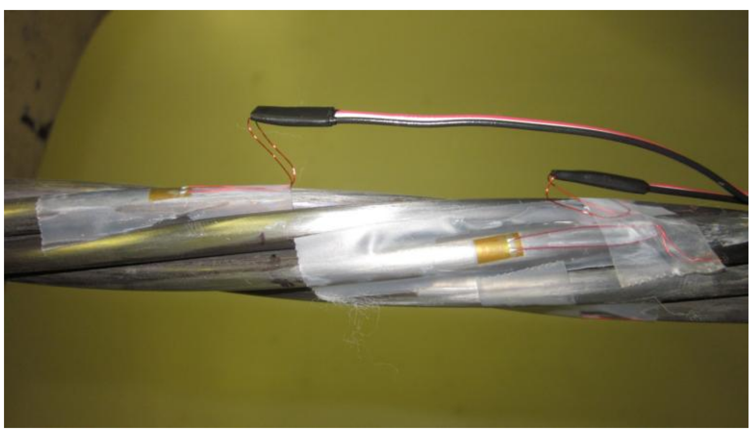
The main objective is to investigate the contribution of each transfer bond mechanism. Eleven pairs (A/B) of specimens will be cast as shown in Table 1. The 0.7-in. low-relaxation strand (Grade 270) is used as a reference strand, and the typical concrete strength (except ID 6) is 9 ksi at the pullout test day. All specimens are 6 in. diameter cylinders. The strand is located at the concrete center through the length of the specimen. For the pretensioned members, the strand will be released one day after the concrete cast. For all specimens including the non-pretensioned members (Test ID 4 and 5), the pullout test will be conducted two days after the concrete cast.

Before the pullout test, the strand tension tests have been conducted as shown in Figure 3 (a). As shown in Figure 3 (b), the electrical strain gauges are attached to the outside wires of the strand in the twisted longitudinal direction. The relationship of the longitudinal strain, the elongation and the tension force is established through the strand tension test. Before the strands yield (the yield strength is 90% of the ultimate strength), the strain and the elongation are proportional to the tension force. In the pullout test, only the strand strain can be measured for the embedded part and the two ends strand slips can be obtained. Thus, this

relationship will help in understanding the stress distribution in the strand embedded in concrete.
For the pullout tests, the electrical strain gauges will be attached to the strand surface in the longitudinal direction every 4 in. along the specimen and the DEMEC strain gauges will be attached to the surface of the concrete at the centerline of the strand every 4 in. along the specimen. These strain gauges will provide the information of strain distribution of the strand and concrete along the specimen. LVDT will be used to measure the slip of the strand during the pullout tests. Load cell will be used to record the pullout force. Thus, the distribution of the strand stress and the concrete stress, the relation among the pullout force, the bond stress development and the relative slip of the strand, and the failure mode of the specimen will be investigated.



(a) Strand Tension Test Setup



(b) Strain Gauges attached to the Strand
Figure 3 Stand Tension Test

Pullout Test Procedure and Comparison

1) Measurement of transfer length Lt. Test ID 1 and 2 will be conducted before other tests. 0.7-in. strand will be pretensioned. The strand will be released one day after the concrete cast. There are two Hoyer effects in Test ID 1. The transfer length can be measured in the two end zones. Thus, the transfer length will be obtained accurately. The difference of ID 1 and ID 2 is that the middle part of the strand will be debonded in the latter. Thus, the total length of ID 2 will be composed of two transfer lengths in the end zones and one debonding length in the middle of the member. Thus, the difference of the bond in the pullout tests is that there is mechanical interlocking in the middle of the specimen for ID 1 while no interlocking for ID 2. The slip-stress relationship and the bond stress distribution along the specimen are expected to be different in Test ID 1 and ID 2.

2) Test ID 3, ID 4 and ID 5 will be compared to investigate the Hoyer effect contribution to the transfer bond in the end zone. The length of the specimen is the transfer length measured from ID 1. It is noted that, at the beginning of the pullout test, there is adhesion bond in Test ID 4 and ID 5 because there is no relative slip between the strand and concrete.

   a. ID3 (pretensioned strand with one Hoyer effect). As shown in Figure 4, an II-shape horizontal steel frame is anchored to a strong floor. Two chucks (Chuck A and B) are used in both ends of the strand. Through the screw of the Nut A, the strand will be pretensioned. The Load Cell A against the Chuck A will provide the value of the pretension force. Plate C is fixed to the frame. The concrete specimen will be cast using Plate C as an end form plate. One day after the concrete cast, the strand will be cut at the right cut point. The stand in the right free end will lose the initial prestress and swell, resulting in a Hoyer effect. In the pullout test, the pullout force will be caused by the movement of the Nut A toward the left direction. The load cell behind the Chuck A will record the pullout force, LVDT 2 record the slip of strand in the left dead end and LVDT 1 record the slip of strand in the right free end.

   b. ID 4 (pretensioned strand without Hoyer effect). In this test, the strand will also be pretensioned, but the strand will not be cut. Thus, at the beginning of the pullout test, the prestress force will not transfer to the concrete and there will be no Hoyer effect in the specimen, because there is no bond stress at the concrete-strand interface and no relative slip occurs. Both Chuck A in the left and Chuck B in the right will be used for the pullout test. The pullout force will be the difference of the force in Load Cell A and B.

   c. ID 5 (non-pretensioned strand). The strand will not be pretensioned. The pullout test is the same as that for the reinforcement concrete members. The difference between ID 4 and ID 5 is that the pretensioned force may result in the stronger friction interaction (tighter contact) among strand wires, the decrease of strand diameter, and the shape change of the strand (the change of strand wire twist angle). Accordingly, the mechanical interlocking force for ID 4 and ID 5 may be different.

3) Concrete strength effect. In Test ID 6, the concrete compression strength is 4 ksi. The modulus of elasticity increase with the concrete compression strength. The bond behavior is related to the relative stiffness ratio of the concrete and the strand. Concrete with higher compression strength will restrain the swelling of the pretensioned strand and “hold” the strand more tightly, contributing stronger bond. The pullout test of ID 6 will be compared to ID 3.

4) Initial pretension force. In Test ID 7 and ID 8, the pretension stress is 20% and 40% percent of the ultimate strength of the strand. For other tests, the pretension level is 60%. The change of the diameter of the pretensioned strand depends on the pretension force. The higher pretension level is assumed to cause stronger Hoyer effect. Also, the transfer length may decrease with the lower pretension force. The pullout test of ID 7 and ID 8 will be compared to ID 3.

5) Type of pretensioned strand. The pretensioned strand sizes include 0.5 in., 0.6 in. and 0.62 in. According to AASHTO equation, the transfer length is proportional to the diameter of the strand. Thus, in the Test ID 9, ID 10, and ID 11, the length of the specimen decrease, accordingly. It is noted that, the 0.62-in. strand is Grade 330 ksi and the others are Grade 270 ksi. The effect of the type of strands on the bond will be investigated by comparison of Test ID 3, ID 9, ID 10, and ID 11. The detailed information of the strands is listed in Table 2.

DISCUSSION

The objective of this research is to investigate the transfer bond behavior. The specimens include three types: pretensioned strand with Hoyer effect, pretensioned strand without Hoyer effect, and non-pretensioned strand. The comparion of these three types of pullout tests will help to understand the relative contribution of the Hoyer effect and the mechanical interlocking. Also, several parameters will be considered such as the concrete compression strength, the pretension level and the type of the pretensioned strand. The distribution of the strand stress and the concrete stress along the specimen and their change with pullout force, the relation between the pullout force and the relative slip of the strand, and the failure mode of the specimen will be analyzed to better understand the bond behavior in the transfer end zone.

ACKNOWLEDGEMENTS

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Table 1 Test Plan

Test ID	Strand D (in)	Test Type	Release Type	Specimen	Length (ft)	Initial Tension /0.6 fpu(kips)	Test objectives
1	0.7	Two Hoyer Effects	Two Ends release	07-1A/B	8	47.6	Lt from Strand Stress/Concrete Strain, Bond Response
2	0.7	Mid-Debonding	Two Ends release	07-2A/B	Two Hoyer Lt + Debonding Length=8	47.6	Bond Response
3	0.7	One Hoyer Effect	One End release	07-3A/B	Lt	47.6	ID 3,4&5 compare Hoyer effect, Bond Response
4	0.7	No Hoyer Effect	No End release	07-4A/B	Lt	47.6	
5	0.7	No Prestress	No Pre-Tension	07-5A/B	Lt	0	
6	0.7	One Hoyer Effect	One End release	07-6A/B	Lt	47.6	ID 3&6 compare concrete strength, Bond Response
7	0.7	One Hoyer Effect	One End release	07-7A/B	Lt	15.9(0.2 fpu)	ID 3,7&8 compare strand effective stress, Bond Response
8	0.7	One Hoyer Effect	One End release	07-8A/B	Lt	31.7(0.4 fpu)	
9	0.5	One Hoyer Effect	One End release	05-3A/B	Lt*5/7	24.8	ID 3,9,10&11 compare strand diameter and stress level, Bond Response
10	0.6	One Hoyer Effect	One End release	06-3A/B	Lt*6/7	35.2	
11	0.62	One Hoyer Effect	One End release	062-3A/B	Lt*(62/70)	45.8	

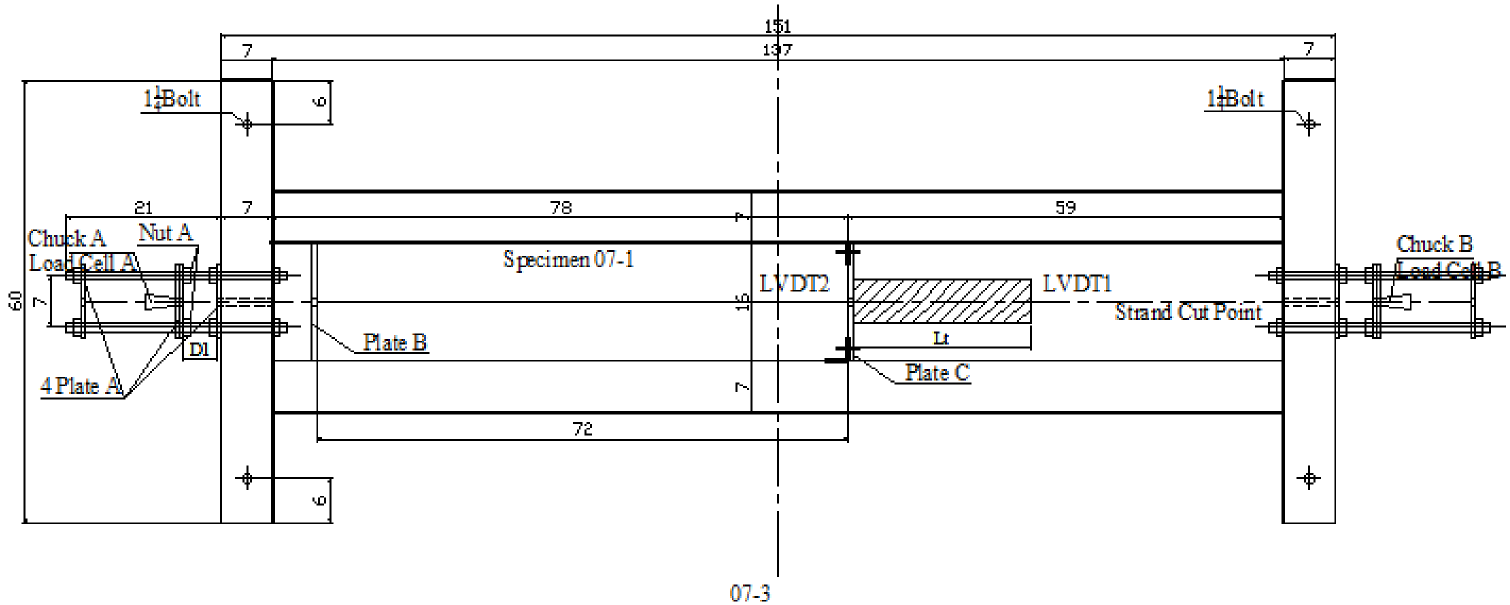

Figure 4 Pullout Test Setup for Test ID 3 with One Hoyer Effect

Table 2 Information of Strands

Strand diameter (in)	Grade (ksi)	Nominal area (in^2)	Nominal strength (klb)	75% nominal strength(klb)	60% nominal strength(klb)	Modulus of elasticity (Mpsi)	Yield Point (klb)	Break strength (klb)	Ultimate elongation (%)	Manufacturer
0.5	270	0.153	41.31	30.9825	24.786	28.7	39.5	44.1	6	SWPC
0.6	270	0.217	58.59	43.9425	35.154	28		61.8	4.78	Martin
0.62	330	0.2314	76.36	57.27	45.816	28.08		76.551	7.49	Sumiden Wire
0.7	270	0.294	79.38	59.535	47.628	29		82.413	5.73	Insteel Wire