Bond Performance of Pretensioned Concrete Systems

Prabha Mohandoss, Sriram K. Kompella and Radhakrishna G. Pillai

Abstract Prestressed concrete technology has revolutionized the infrastructure growth in many countries, especially that of the bridge sector. The bond between prestressed strand and concrete is very important for achieving good structural performance. However, some of the codal provisions have not given enough consideration to the bond strength of pretensioned concrete system in design. This paper presents the results from a preliminary experimental program on the bond strength of 7-wire strands embedded in M35 and M55 concretes. A pull-out test method was developed, and the same was used to determine the bond strength. The bond behavior and the mechanisms at the strand–concrete interface are also discussed. Bond strength of 7-wire strand in M55 concrete is found to be about two times more than that in M35 concrete.

Keywords Pretensioned concrete · Pull-out test · Bond strength
Bond-slip · Strand–concrete interface

1 Introduction

In India, for the past five decades, the applications of prestressed concrete have been predominant in the field of bridge constructions, overpasses/flyovers, metro rail projects, commercial buildings, nuclear containment vessels, pavements, railroad sleepers, poles, piles marine structures liquefied gas, and oil storing vessels.

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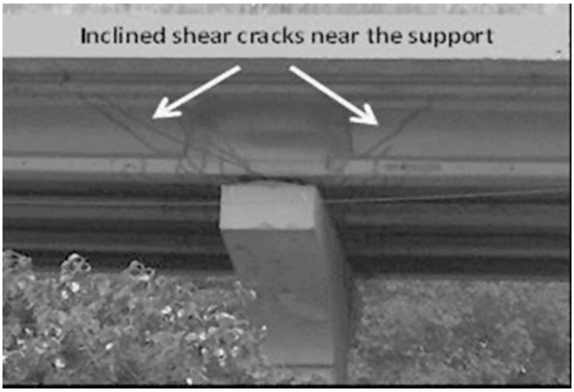

Fig. 1 Shear cracks in bridge girders due to poor bond

Moreover, bridges and railway sleepers have the most widespread application of the pretensioned concrete among all the fields.

In a pretensioned concrete (PTC) systems, prestress is transferred through a bond from the strand to the surrounding concrete. Hence, the bond between the prestressed strand and concrete is more important for its structural performance. If the bond of PTC member is not good or inadequate, then it can lead to poor structural performance leading to shear failure at the ends and cracks in the member. In India, similar types of issues have been observed in a highway bridge girder as shown in Fig. 1. One of the main reasons for this poor bond performance is the presence of the residue of the colorless, shiny, and dry lubricant on the strands. Calcium stearate (CaSt) and sodium stearate are the most commonly used dry lubricants to ease the process of cold drawing of wires during the strand manufacturing and to meet the site inspectors' demand of corrosion free strands. However, there is no test method to quantify the quality of the bond between the strand and concrete to produce the better quality product. Therefore, this study attempts to study the bond strength and bond behavior between the strand and concrete.

1.1 Bond Mechanisms

Bond mechanism of PTC systems is mainly contributed by three factors: adhesion, mechanical interlock, and friction [1]. Adhesion plays a minimal role in PTC system. Mechanical interlock and friction play a significant role in the PTC systems [2]. Mechanical interlock occurs due to the spiral twisting of the outer wires that form the strand. This helical shape of the strand results in bearing stress between the strand and concrete. Friction is attributed to concrete confinement and Hoyer effect. Hoyer effect is the expansion of strand in the transfer zone after releasing the prestress due to Poisson's effect. The bond between the strand and concrete can also be influenced by many factors such as compressive strength of concrete, type/diameter/surface condition of the strand, amount of prestress applied, etc. [3].

1.2 Bond Test Methods

Typically, the bond strength between strand and concrete is determined by using pull-out test. Many pull-out tests have been developed to determine the bond strength of strand. The Moustafa pull-out test [4] was one of the earliest test methods. It was developed to quantify the bond capacity of strands for lifting loops. In this test method, strands were pulled out from the large concrete block using a jack. Another test method is the North American Strand Producers (NASP) bond test [5], in which the strand is pulled out from the mortar. The contemporary version of the NASP bond test is adopted by American Society for Testing and Materials (*ASTM A1081 Standard test method for evaluating the bond of seven wire prestressing strand*) [6, 7]. However, none of these test methods represent the actual behavior of PTC (the bond behavior between the stressed strand and concrete), where the strands are pretensioned to certain stress level (say, 0.75 f_{pu}). Moreover, these test methods use only the unstressed strand, which may lead to wobbling issue during specimen preparation since the strands are not perfectly straight and stressed as in the field structures.

Performing pull-out test for a fully pretensioned strand member is not easy due to the requirement of long specimen length to transfer the applied pretension from the strand to concrete and the machinery required. Later, ECADA test method was developed by Marti-Vargas et al. (2006) [8] to determine the bond performance between the prestressed strand and concrete by representing the actual behavior of PTC.

This study focuses on the pull-out testing, bond strength, and bond behavior of taut strands embedded in concrete. The taut specimen is the specimen with minimal prestress—applied to keep the strands straight and avoid the wobbling effect.

2 Experimental Program

Figure 2 provides a schematic of the pull-out test specimen with a taut 7-wire strand embedded in concrete prism (500 × 100 × 100 mm in size). High strength, low-relaxation 7-wire strand of 12.7 mm diameter was used. The modulus of elasticity of the 7-wire strand was 196 MPa. The ultimate tensile strength (f_{pu}) of the 7-wire strand was 1770 MPa. Four specimens each with M35 and M55 grade

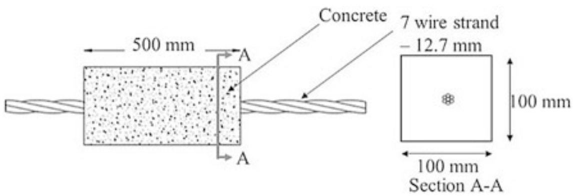

Fig. 2 Schematic of the pull-out test specimen with taut strand embedded in concrete prism

concrete with 40–50 mm slump were cast and tested. The average 28-day compressive strength of M35 and M45 concretes were 41 and 58 MPa, respectively. As shown in Fig. 2, the length of the concrete prism was 500 mm. The length of bond breaker placed inside the specimen was 50 mm. Therefore, the actual embedment length (l_e) of the strand is 450 mm.

2.1 Specimen Preparation

2.1.1 Initial Stressing

The length of the strand to be used for stressing is decided based on the length of the strand embedded in the specimen, the length of strand inside the hydraulic jack, load cell, and the thickness of the endplate including the screws. Based on this, 6 m long, 7-wire strands (12.7 mm dia.) were kept straight in the prestressing bed. Then, a hydraulic jack was used to apply a minimum load just to keep the strand straight and to avoid the wobbling effect. Before placing the wedges and tensioning the strand, a 5 cm long PVC pipe was kept around the strand (as bond breaker) near the pulling end. This was done to avoid the stress concentration in this region during the pull-out test. The wedge and barrel were placed outside the two end brackets of the prestressing bed—to maintain the stress. Also, a stress releasing system with a nut-bolt system was placed at the releasing end—to facilitate gradual release of the prestress.

2.1.2 Casting of Concrete

Fresh concrete was prepared using laboratory scale pan mixer and placed inside the specimen molds, which are placed on the prestressing bed. Concrete was hand-compacted using a standard procedure—to ensure uniformity in the concrete properties. Along with the pull-out specimens, three companion cube specimens were also cast to determine the compressive strength of concrete at the time of pull-out testing. After 24 h, the specimens were demolded, and the stress in the specimen was released. The strand was cut at both ends of the specimen—leaving 350 mm length of the strand at one end and 150 mm long at another end of the specimen. This was done to facilitate the placement of LVDTs and grip the strand at pulling end during the pull-out testing. Then, the specimens were cured for 28 days to achieve the desired concrete properties, prior to the pull-out test.

2.2 *Pull-Out Test Procedure*

2.2.1 Pull-Out Test Setup

Figure 3 shows the schematic of the pull-out test setup. In this, a 40 mm thick top and bottom steel plates of the frame are connected using four tension members (1.4 m long and 36 mm diameter steel rods). The center of the bottom steel plate of the frame has a 16 mm diameter hole to place the strand through and grip it using the hydraulic V-grips of the universal testing machine. One end of the hanging rod is gripped inside the upper wedge of the machine. Another end of the hanging rod has hemispherical shape to lock with the top plate of the frame to provide a swivel arrangement, which allows the free rotation of the frame while testing and avoids any torsion.

After fixing the pull-out frame on the machine, the pull-out specimen is placed in the pull-out frame. The bottom end of the strand is gripped in the MTS machine and that end is called as the live end where the load is applied. The top portion of the strand is free and known as a free end.

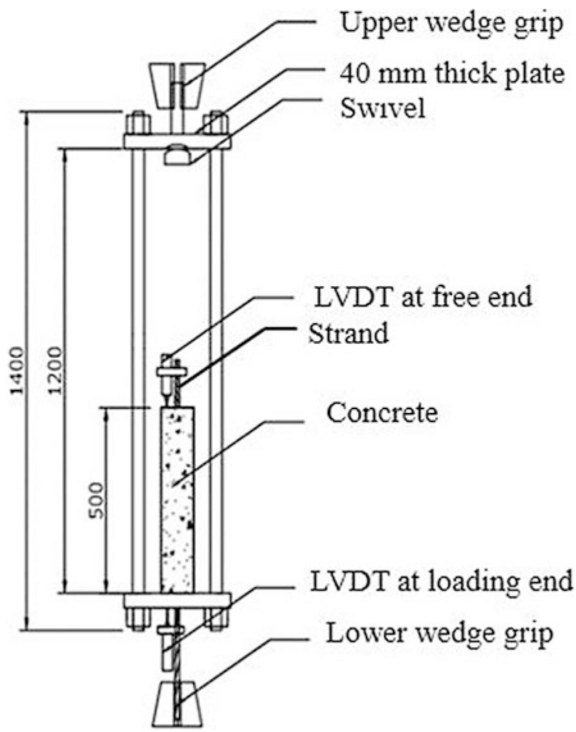

Fig. 3 Schematic of the pull-out test setup

2.2.2 Instrumentations

Two LVDTs were used. One LVDT was placed at the live end and another LVDT was placed at the free end of the strand, as shown in Fig. 3—to measure the slip of the strand with respect to the concrete during testing. An L-shaped plate of a smooth surface is placed on the surface of concrete at the free end of the specimen to place the LVDT in a position to get a uniform reading. Load was applied at the rate of 2 mm/min. Two LVDTs and the load cell of the machine were connected to a data acquisition system, and the time elapsed, load, and displacement data were recorded.

3 Results and Discussions

The bond stress-slip behavior (τ–s curve) of 12.7 mm strand embedded in M35 and M55 grade concretes is shown in Fig. 5a, b. The bond surface area is calculated as the circumference of the strand (p) multiplied by the actual embedment length (l_e). The bond strength (τ_b) is calculated as follows:

$$\tau_b = \frac{P_u}{p l_e} \tag{1}$$

where P_u is the ultimate load (or peak load).

As discussed in Sect. 1.1, the bond mechanism in PTC is governed by three factors: (i) adhesion, (ii) mechanical interlock, and (iii) friction. Hence, the bond-slip curve can be divided into three regions as follows.

- Region 1: Linear region, which is governed by the adhesion mechanism. Once adhesion is lost, then the mechanical interlock and friction are mobilized.
- Region 2: Mainly governed by mechanical interlock, which gives resistance to slip.
- Region 3: Mainly governed by friction between the strand and concrete, after the peak load.

Two types of behaviors or bond-slip patterns are observed: (i) smooth pattern and (ii) stick-slip pattern. The specimens with smooth pattern exhibited splitting and cracking of concrete, as seen in Fig. 4. The specimens with stick-slip pattern exhibited pulling-out of the strand (without the splitting and cracking of concrete).

Fig. 4 Longitudinal cracks along the 7-wire strand in M55 grade in concrete

3.1 Bond Strength and Slip

Figure 5a, b shows the τ–s curves of taut strands in M35 and M55 concretes, respectively. As shown in Fig. 5, two specimens with M35 concrete and all the specimens with M55 concrete are exhibiting the smooth pattern. This happens when the concrete confinement is good. In such case, the concrete will resist the movement of the strand, resulting in an increase in the stress developed, which in turn results in longitudinal cracks in concrete (Fig. 2).

Specimens A2 and A3 in Fig. 4a exhibited the stick-slip pattern. It seems that this pattern is more predominant in the case of low strength concrete (say, below M35 concrete). When the concrete strength is low, the grooves may fail in shear and allow the strand to slide from one groove to the next one (in the longitudinal direction)—resulting in the stick-slip pattern. Also, 25°–40° rotation of strands (as they are pulled out) was observed at the peak of the τ–s curve.

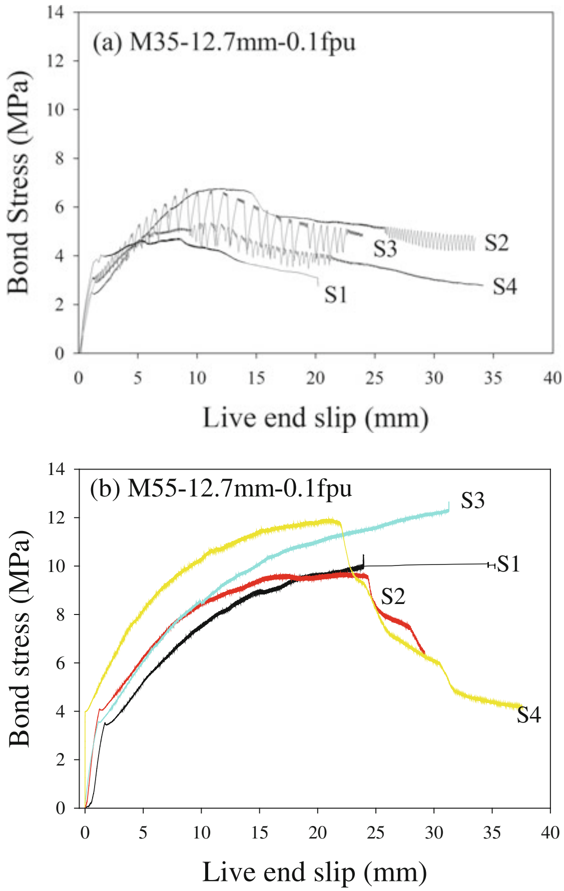

Fig. 5 Bond behavior in **a** M35 grade and **b** M55 grade concretes

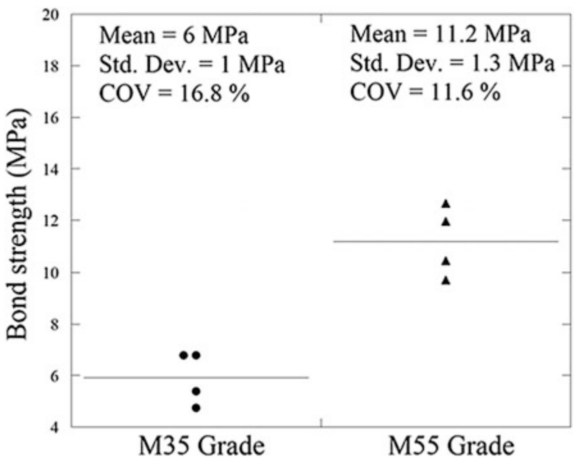

Fig. 6 Bond strength of PTC specimens as a function of compressive strength of concrete

Table 1 Bond stress values of 12.7 strands

Specimen no.	Grade of concrete	f'_c (MPa)	$\tau_{2.5}$ (MPa)	τ_{max} (MPa)	Slip at τ_{max} (MPa)
A1	M35	44.1	4.03	4.74	8.4
A2		43.8	3.04	6.77	11.9
A3		43.7	3.74	6.77	9.10
A4		42.9	3.36	5.40	11.2
B1	M55	63.1	3.65	10.50	24.0
B2		61.8	4.65	9.72	22.0
B3		60.2	4.30	12.66	31.2
B4		60.2	6.26	11.80	20.7

The measured bond strength τ_{max} of pull-out specimens is shown in Fig. 6. The term τ_{max} is defined as the maximum bond stress observed in the τ–s curves, as shown in Fig. 6. For the eight specimens tested here, the τ_{max} occurred at a slip ranging from 8 to 30 mm. However, in ASTM 1018, bond strength is calculated as the bond stress corresponding to 2.5 mm. Hence, the maximum bond stress (τ_{max}) and bond stress at 2.5 mm ($\tau_{2.5}$) are calculated and shown in Table 1. Also, the slip corresponding to τ_{max} is shown in the last column of Table 1. It can be seen that these values are in the range of 8–30 mm (i.e., greater than the design slip value of 2.5 mm).

It is observed that average $\tau_{2.5}$ is approximately half the value of τ_{max}. Also, when the grade of concrete increased from M35 to M55, the τ_{avg} increased from 6 to 11 MPa—about twofold increase.

4 Preliminary Findings

- As the characteristic compressive strength of concrete increases from 35 to 55 MPa, the average bond strength increase by about two times.
- A stick-slip τ–s behavior is observed when the strand is pulled out of the concrete with relatively low strength (say, M35).
- A smooth τ–s behavior is observed when the bond failure is due to concrete cracking or splitting.

5 Notations

d_b	Nominal diameter of strand (mm)
l_e	Embedded length of the strand in the concrete (mm)
p	Circumference of the strand in the concrete (mm)
A_b	Bonded area of the embedded length of the strand (mm^2)
P_u	Ultimate load (kN)
f'_c	Compressive strength of the concrete at the time of testing (MPa)
τ_{max}	Measured bond strength of the strand (MPa)
τ_{avg}	Average measured bond strength (MPa)
$\tau_{2.5}$	Measured bond stress at 2.5 slip (MPa)
S	Slip of the strand (mm)

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