Experimental investigation of 0.6 in. diameter strand lifting loops

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- An experimental testing program was conducted to expand the knowledge of pullout capacity of prestressing strand lifting loops. The paper also reviews past data available on the topic.
- Pullout tests were conducted on strand lifting loops with 0.6 in. (15.24 mm) diameter, 270 ksi (1860 MPa) strand with both straight and bent loop configurations. Embedment depths of the test specimens were varied. Most tests exhibited pullout failure modes and adequate ductility.
- Additional design parameters are proposed to support future research and testing of lifting loops.

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Unused lengths of prestressing strands[1] are often embedded in precast concrete members and used to lift precast concrete elements at the casting yard and project site. These pieces of strands are mechanically bent into loops and cast into the concrete at the necessary embedment and projection above the surface to ensure safe lifting of the element (**Fig. 1**). The load capacity of lifting loop depends on a variety of parameters. The key parameters seem to be the strength and condition of the strand, the length and configuration of the embedment, the diameter of the rigging element engaging the loop, the type and strength of concrete, and the lifting angle. Precast concrete manufacturers are typically responsible for ensuring an adequate anchor design by implementing a safety factor of at least 4 to prevent strand slippage and strand failure.[2,3] In the absence of published data, precast concrete producers' proprietary tests and experiences currently dictate strand loop capacities and detailing. In 2019, as part of their PCI Dennis R. Mertz Fellowship project, the authors conducted an industry survey[4] to understand standard lifting loop procedures used in PCI-certified plants. In coordination with that effort, this paper summarizes the results of an experimental testing program to assess the lifting loop capacity of single, 0.6 in. (15.24 mm) diameter strand lifting loops. It considers 13 tests of straight- and bent-leg configurations at different embedment depths. The research is primarily geared toward bridge products, but the results are also applicable to other commercial products.

Bridge beam suspended
from crane with lifting loops

Lifting loops prior to concrete casting

Figure 1. Lifting loop configurations.

Background

As girder spans have increased due to new girder types and other advances in precast concrete design, there is an increasing need to ensure safe lifting practices. Despite the prevalence of prestressing strand lifting loops, the current editions of the *PCI Bridge Design Manual*[3] (MNL 133) and *PCI Design Handbook: Precast and Prestressed Concrete*[2] (MNL 120) provide limited guidance on how precasters should design and detail these loop configurations. The *PCI Design Handbook* has recommendations for lifting loop design in lieu of full-scale physical testing. These recommendations include using a 24 in. (609.6 mm) minimum loop leg embedment, a hook diameter of at least four times the diameter of the strand, and a minimum bend diameter of 2 in. (50.8 mm) (Fig. 1). A safe load of 10 kip (44.48 kN) is specified for ½ in. (12.7 mm) diameter, 270 ksi (1862 MPa) strand loop that satisfies the aforementioned recommendations. No guidance is provided for safe working loads for 0.6 in. (15.24 mm) diameter strand, which is commonly used in precast, prestressed concrete bridge construction.

Very little experimental data pertaining to lifting loop capacity have been published.[5,6] A study was published by Concrete Technology Associates in a technical bulletin in 1974.[5] This work, which will be referred to as the Moustafa study, included strand pullout tests using concretes with compressive strengths of 6000 psi (41.4 MPa) for 192 tests and 3000 psi for 80 tests. In addition to ½ in. (12.7 mm) diameter strand, 7⁄16 in. (11.1 mm) and ⅜ in. (9.525 mm) diameter strands were also tested; however, 0.6 in. (15.24 mmm) diameter strand was not tested because this strand size did not exist at the time. The tests considered different surface conditions (bright and rusted), development lengths, and strand embedment configurations (straight, broom, and 90-degree bend). All of the Moustafa study tests mentioned here were performed on single-leg strand with different end conditions of straight, broom, or bend. These tests were not performed on lifting loops, which have two legs; however, limited studies on multiple loops as well as inclined loads were also conducted. In addition, nine tests were performed to evaluate the influence of pin diameter on the strength of strand lifting loops to resist strand rupture.

Kuchma and Hart[6] conducted an experimental test program to evaluate the performance and capacity of lifting loops in deck beams that were shallower than 24 in. (609.6 mm). A number of parameters were explored, including loop shape, embedment depth, side edge distance, number of strands per loop, multiple loop conditions, and angle of pull. Test results were used to bolster the Illinois Department of Transportation's *Bridge Manual*[6] design requirements for lifting loops in deck beams with a minimum 60-degree lift angle, a minimum 6 in. edge clearance, and an embedment depth equal to or greater than the member depth minus 4 in. (101.6 mm).

Strand bond behavior

Prestressed strand bonds to the surrounding concrete via three mechanisms: Hoyer effect, adhesion, and friction.[8–11] The Hoyer effect refers to the expansion of strand diameter upon release of prestressing force; however because lifting loops are not prestressed, their bond mechanisms are composed of just adhesion and friction. The bond capacity of prestressing strand depends primarily on the strand surface condition, confinement of strand, and concrete strength at the time of load application and, secondarily, on aggregate hardness. Significant variations in strand and concrete bond quality were demonstrated in a 1997 PCI study among strand producers,[12] which motivated the development of a method to evaluate bond performance. The strand surface condition as manufactured is controlled by the strand manufacturer and verified by standardized bond tests conducted in accordance with ASTM A1081.[13] The strand surface condition can also be affected by weathering between the time of manufacture and the time of use. Typically, weathered strand would be expected to have better bond properties than as-manufactured strand as long as the weathered strand is not contaminated.

The type of aggregate used in precast concrete mixtures varies depending on the plant location as well as whether the concrete is normalweight or lightweight, with aggregates ranging from hard limestone to crushed granite to river gravel. The different aggregate types and, in particular, their hardness can influence the pullout capacity of the strand. Round-robin pullout testing performed by Russell and Paulsgrove[9] included pullout values determined using the aforementioned Moustafa test procedure.[5] The same tests were performed in three different locations, and the test facility that used soft limestone aggregate was found to consistently achieve lower pullout values than the other facilities. It has been postulated that aggregate modulus may contribute to bond performance.[14] In lieu of aggregate modulus tests, which would be difficult to administer, Mohs hardness tests are an easy alternative approach to measuring coarse aggregate hardness.[14] A further discussion of the role of concrete toughness on the pullout capacity of strand lifting loops is provided in the appendix.

Experimental program

In the study, 13 full-scale pullout tests were performed to evaluate the behavior, strength, and ductility of 0.6 in. (15.24 mm) diameter strand lifting loops. Lifting loops were cast into concrete block specimens, and a steel test frame was placed on top of the block (**Fig. 2**). The test frame, consisting of two back-to-back channels with stitch plates and two rectangular hollow structural sections, was self-equilibrating. The base plate of the hollow structural section columns bears on top of the concrete block without a direct connection and was moved and centered around the test loop. Additional steel bracing (shown in red in Fig. 2) was installed prior to each test to ensure stability of the system during testing.

Loading was applied to the loops using a hydraulic cylinder placed on top of the test frame, which was connected to the loop using a pullout assembly of a rod, clevis, and pin (Fig. 2). The clevis and pin were ASTM A36 and A572 Grade 50 (345 MPa) steel, respectively, and were designed by performing finite element analyses in Abaqus software to ensure elastic behavior and minimal deformations. The diameter of the pin was 3 in. (76.2 mm). Although this pin diameter is larger than the standard pin diameter of 2.0 to 2.8 in. (50.8 to 71.1 mm) reported in the industry survey,[4] it was used due

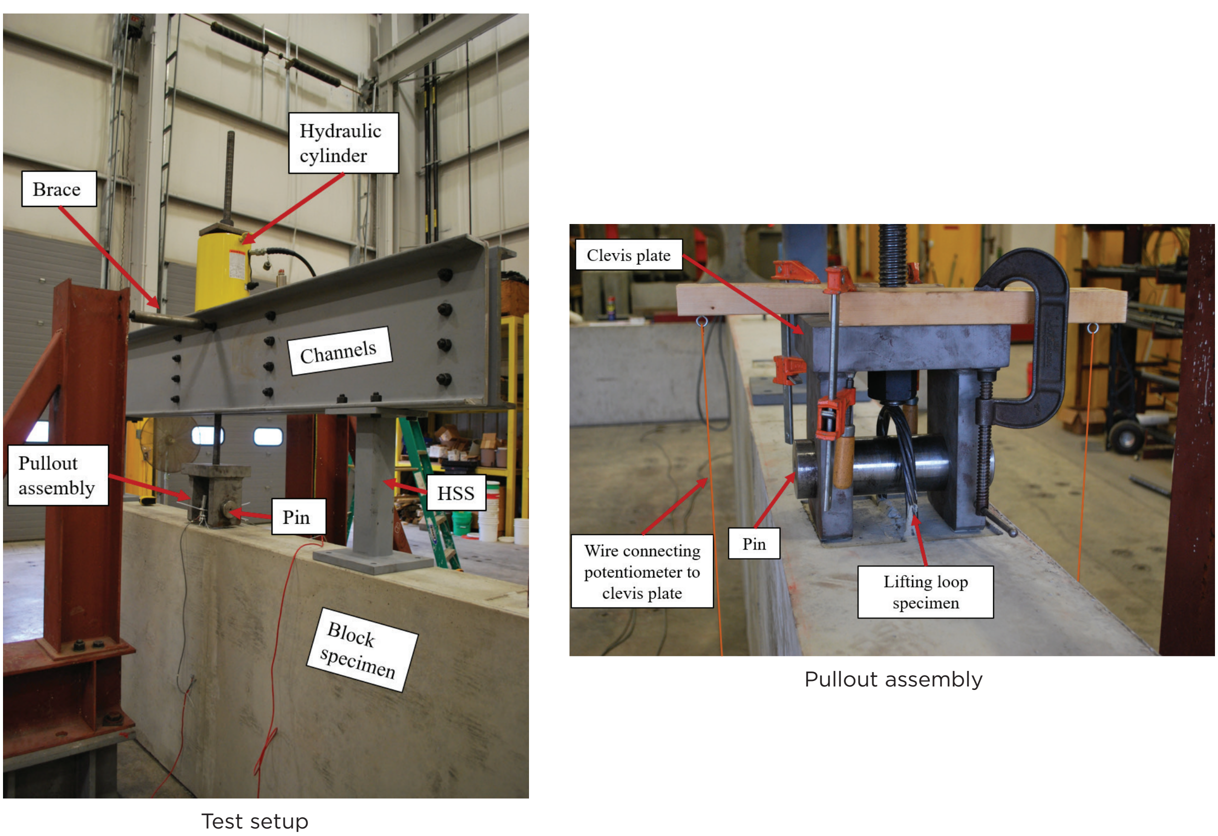


Figure 2. Pullout test setup. Note: HSS = hollow structural section.

to the span of the pin and the need for it to remain elastic through multiple rounds of testing. At the start of each test, the pin was fit snugly against the lifting loop. **Figure 3** shows a schematic of the concrete block with test loop specimens with bent-end conditions. The lifting loops on either end of the block were used to lift and transport the specimens, but they were not tested.

Instrumentation

The test lifting loops were pulled out of the concrete using monotonic, near-static loading until failure at a rate of approximately 6 kip (26.7 kN) per minute. A calibrated pressure transducer was used to measure the pullout force applied by the hydraulic cylinder. Two displacement string potentiometers were placed on the test floor at opposite sides of the concrete block to measure the vertical displacement of the pullout assembly (the clevis). The wires from the string potentiometers were connected to the base plate of the clevis (Fig. 2). It is acknowledged that these recorded deformations could include slight deformations in the clevis and pin, but the approach was deemed sufficiently accurate for this testing. By averaging the string potentiometer output, any rotation of the clevis was compensated.

Concrete block specimens

Five normalweight concrete blocks were designed by the research team and fabricated by Coreslab (INDIANAPOLIS). Each concrete block specimen consisted of two or three test lifting loops of the same embedment and orientation (Fig. 3). The test lifting loops were spaced within the concrete block at distances approximately equal to two times their embedment depth to limit the influence of the test frame on lifting loop pullout behavior. The blue region in Fig. 3 shows the zone of compression resulting from the bearing of the test frame on top of the test specimen, which was presumed to act at a 45-degree angle. The spacing of the hollow structural section columns in the test frame could be adjusted to accommodate variable spacing of the lifting loops.

All blocks used the same cross-sectional dimensions (12 in. [304.8 mm] wide by 44 in. [1117.6 mm] deep) for ease of fabrication. The width of the block was narrowed as much as possible to limit the edge distance; ultimately, widths less than 12 in. were not considered due to potential stability issues. The 12 in. width is consistent with the Moustafa[5] testing. The height of the blocks was dictated by the deepest loop embedment plus at least 2 in. (50.8 mm) of concrete cover. Two no. 8 (25M) longitudinal bars were provided at the top and bottom, and no. 4 (13M) stirrups were provided at 12 in. spacing to prevent shear and flexural failures in the block. Minimal reinforcement was used to avoid overconfining the concrete.

Concrete block material properties **Table 1** presents the average compressive strength f_c' of three cylinders for each block and, correspondingly, each test series. The target compressive strength of the blocks was between 3000 and 4000 psi (20.7 and 27.6 MPa). To achieve a low early-strength concrete, a conventional ready-mixed concrete was designed with a 6 to 7 in. (152.4 to 177.8 mm) slump and 6% air using a high-range water-reducing admixture and an air-entraining admixture. The mixture contained 530 lb/yd^3 (314 kg/m^3) of Type I cement, 1320 lb/yd^3 (782 kg/m^3) of natural river sand, 1770 lb/yd^3 (1049 kg/m^3) of ¾ in. crushed limestone, and 267 lb/yd^3 (158 kg/m^3) of water. The concrete was placed in the

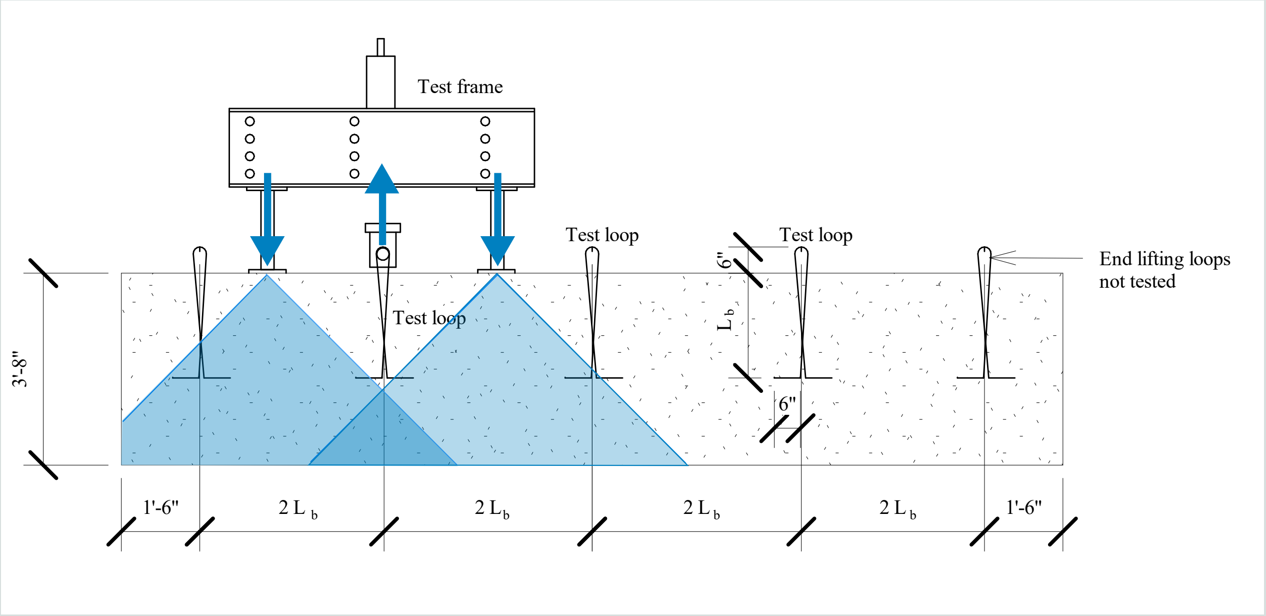


Figure 3. Block elevation showing loop layout to avoid test frame compression zone. Note: L_b = embedment depth. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

forms and vibrated to consolidate. Due to an unforeseen delay in shipping the first concrete block, the compressive strength of the S36 specimens exceeded the target range. All tests were performed within 36 hours of casting. In addition to concrete compressive strength tests, one series of split tension tests was completed using concrete from the B24 test series. The ratio of tension to compression strength was approximately 9.5%. Naming conventions are explained in the "Lifting Loop Specimens" section.

Mohs hardness A Mohs hardness test, which provides an indicator of the relative hardness of concrete aggregate, was performed for this study. A ¾ in. (19.05 mm) maximum crushed limestone material with uniform gradation was used in the concrete blocks. The average hardness was reported as 3.6 and 3.8 using two different test kits. The typical Mohs value for hard limestone is 5. The lifting loop tests were deemed conservative because hardness of 3.8 is softer than typical hard limestone or other aggregates in mixtures used by many precasters. For Mohs hardness values less than 3.6, alternative safe lifting loop values will need to be considered. Aggregate with Mohs hardness values greater than 3.6 can conservatively use the findings from this study.

Lifting loop specimens

Thirteen lifting loops were tested at different embedment depths in concrete. **Table 2** shows the test series name, embedment depth L_b, end condition of strands, and number of tests conducted. Tests labeled B or S indicate the bent- or straight-end conditions, respectively. The number designation (for example, 24 or 30) indicates the embedment depth in inches. The S36 loops were oriented in the transverse direction, indicated by a T in the loop designation. Two or three tests were conducted for each type of specimen. Each specimen was a single-strand loop; multiple loops were not considered in this study and should be considered in future work. Embedment depths and end conditions of the lifting loops were selected based on results from Moustafa's ½ in. (12.7 mm) diameter strand tests.[5] Those tests determined the following development lengths for ½ in. diameter strand in 3000 psi (20.7 MPa) concrete: 36 and 24 in. (914.4 and 609 mm) embedment depths for straight and bent configurations, respectively. Those values were used to extrapolate a variety of embedment depths for the 0.6 in. (15.24 mm) diameter strand in this test.

The lifting loops had straight ends and 90-degree bent ends, which reflect common industry practices.[4] Grade 270 ksi (1860 MPa) seven-wire steel strand[1] at 0.6 in. (15.24 mm) diameter was used for all 13 tests. All lifting loops came from the same reel of strand. The reel was new and had been stored away from weathering, resulting in bright strand. The pitch of the strand was 8.15 in. (207 mm), and the lay (handedness) was left. The steel strand elongated 5% (24 in. [609.6 mm] gauge length) at rupture. The recorded yield strength value was 57.0 kip (253.5 kN) at 1% elongation and 61.8 kip (274.9 kN) at rupture, as reported by the manufacturer.

Figure 4 shows the lifting loops in straight and bent configurations. Bent loops included legs with a 6 in. (152.4 mm) bend at the end of each lifting loop strand. The loops were tied approximately 4 to 6 in. (101.6 to 152.4 mm) from the base. In some real-world cases, loops are not tied but bent in a configuration where the strand legs are parallel to one another. Kuchma and Hart[6] compared the pullout capacities of parallel legs and the tied configuration similar to what was used in this test program. They found that the parallel legs performed better than the tied legs, which means that the tested loops in this study are likely representing lower-bound capacity.

Strand bond behavior The intention of this testing program was to use conservative, lower-bound values of bond performance. This required soliciting information from strand

Table 1. Average compressive and tensile strengths of concrete

Test series	f'_c, psi	f_{ct}, psi
B24	3030	288*
B30	3300	—
S32	3080	—
S36	4460	—
S42	3300	—

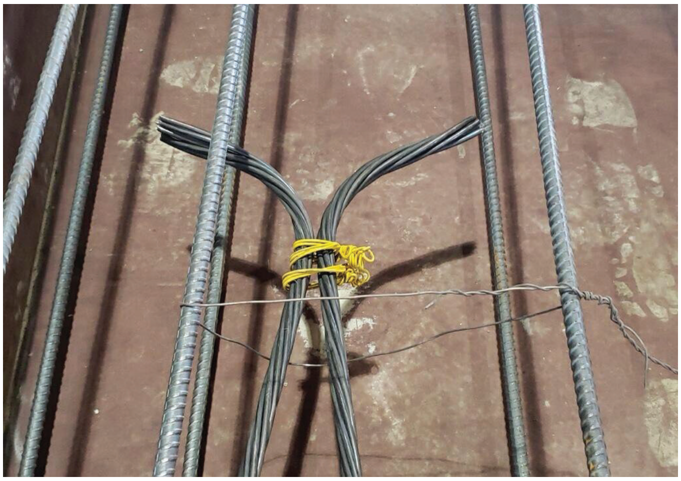
Note: B24 = bent loop test series with 24 in. embedment depth; B30 = bent loop test series with 30 in. embedment depth; f'_c = average compressive strength of concrete; f_{ct} = average splitting tensile strength of concrete; S32 = straight loop test series with 32 in. embedment depth; S36 = straight loop test series with 36 in. embedment depth; S42 = straight loop test series with 42 in. embedment depth. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.
*One split tensile test was conducted in order to quantify the tensile strength of the concrete mix.

Table 2. Lifting loop test matrix

Test series	Embedment depth, in.	End condition	Number of tests
B24	24	Bent	2
B30	30	Bent	3
S32	32	Straight	3
S36	36	Straight	3
S42	42	Straight	2

Note: B24 = bent loop test series with 24 in. embedment depth; B30 = bent loop test series with 30 in. embedment depth; S32 = straight loop test series with 32 in. embedment depth; S36 = straight loop test series with 36 in. embedment depth; S42 = straight loop test series with 42 in. embedment depth. 1 in. = 25.4 mm.

Straight lifting loop in place prior to casting



Close-up of bent ends of lifting loops

Figure 4. Lifting loops prior to casting.

producers to gauge the typical bond performance of their strand, and the strand with the lowest bond strength characteristics was selected. The ASTM A1081[13] bond testing protocol was performed on the strands used in the experimental test program. Six specimens were tested, and the average tensile force was 18.2 kip (80.95 kN) at 0.1 in. (2.54 mm) slip (452 psi [3116.5 kPa] on the contact surface). The PCI Strand Bond Task Group recently published "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand,"[15] which establishes minimum and high bond ASTM A1081 values for strand. For 0.6 in. (15.24 mm) diameter strand, the minimum value is 16.8 kip (74.7 kN) and the high bond value is 21.6 kip (96.1 kN). Hence, the strand used in this study is intermediate between minimum and high bond.

Test results and discussion

Bent (hooked) loops

Five bent loop tests were conducted: two from test series B24 (24 in. [609.6 mm] embedment) and three from test series B30 (30 in. [762 mm] embedment). B24-1 and B24-2 represent the first and second tests conducted in the B24 series, and B30-1, B30-2, and B30-3 represent the first, second, and third tests in the B30 series, respectively. **Table 3** presents the peak load P reached during testing for each loop. These loads are also recorded relative to peak bond stress τ_p and ultimate strength of the strand $P/2P_u$, where P_u represents the measured ultimate strength of the strand and $2P_u$ is used because there are two strand legs per loop. The load at first cracking P_1 is also recorded, as well as the bond stress at first cracking τ_1. The first cracking load occurred when cracking along the surface or sides of the concrete was first observed. In most instances, first cracking occurred when there was a slight drop in load; however, test B24-1 did not experience this drop in load. Test series B24 exhibited an average peak bond stress of 420 psi (2896 kPa) and an average bond stress at first cracking of 343 psi (2365 kPa). Test series B30 exhibited a higher average peak bond stress of 431 psi (2972 kPa) and a lower bond stress at first cracking of 291 psi (2006 kPa). The variation of bond stress between B24 and B30 was likely due to edge effects.

Failure modes Both tests in the B24 series failed in pullout at comparable peak loads of 62.9 and 64.0 kip (279.8 and 284.7 kN), respectively. **Figure 5** shows the cracks observed at the end of the B24 tests, which reflect hybrid failure in bond and surface concrete breakout cone failure at the surface. This type of behavior is commonly observed in adhesive anchor experiments.

The average lifting loop capacity for the B30 series was 78 kip (346.9 kN). All three tests in the B30 series failed by side-face blowout. The strand ends of the B30-3 loop were exposed during testing as the concrete spalled (Fig. 5) and the clear cover could be measured. The side-face blowout failure was at least partly due to the inclined position of the loops (**Fig. 6**).
During fabrication, the loops were unintentionally inclined

Table 3. Results of bent loop specimen tests

Label	Embedment depth L_b, in.	Total loop embedment L,* in.	Load at first cracking P_1, kip	Peak load P, kip	Failure type	$P/2P_u$	Bond stress at first cracking τ_1, psi[†]	Peak bond stress τ_p, psi[‡]
B24-1	24	60	51	62.9	Pullout	0.51	340	417
B24-2	24	60	52	64.0	Pullout	0.52	345	424
B30-1	30	72	53	75.8	Side-face blowout	0.61	293	419
B30-2	30	72	56	79.3	Side-face blowout	0.64	309	438
B30-3	30	72	49	78.8	Side-face blowout	0.64	271	435
Average	n/a	n/a	52	72.2	n/a	0.58	312	427

Note: B24-1 = first test in bent loop test series with 24 in. embedment depth; B24-2 = second test in bent loop test series with 24 in. embedment depth; B30-1 = first test in bent loop test series with 30 in. embedment depth; B30-2 = second test in bent loop test series with 30 in. embedment depth; B30-3 = third test in bent loop test series with 30 in. embedment depth; n/a = not applicable; P_u = ultimate strength of one strand = 61.8 kip. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

* Total loop embedment $L = 2(L_b + L_{bend})$, where L_{bend} is the length of bent ends of strand.

† Bond stress at first cracking $\tau_1 = P_1/A_{bond}$, where A_{bond} is the surface area of the strand in square inches, which is measured as the strand circumferential perimeter ($4/3\pi d_b$ = 2.51 in.²/in.) × embedment length L, where d_b is the diameter of the strand.

‡ Peak bond stress $\tau_p = P/A_{bond}$.

B24-2 plan view

B24-1 elevation

Close-up of side face blowout in B30-1

B30-1

Figure 5. Failure modes observed in bent loop specimens. Note: B24-1 = first test in bent loop test series with 24 in. embedment depth; B24-2 = second test in bent loop test series with 24 in. embedment depth; B30-1 = first test in bent loop test series with 30 in. embedment depth. 1 in. = 25.4 mm.

out of plane at an angle of approximately 6 degrees. This led to a clear cover of only about 2.5 in. (63.5 mm) at the end of the loops. A triangular portion of concrete also broke out at the top surface of the concrete specimen in all three B30 tests. Crack patterns at the top surface of the concrete would have presumably been more symmetric had the loops been placed without an incline. It is also likely that pullout failure may have occurred had placement been more accurate.

Load-displacement behavior **Figure 7** shows the applied force-displacement response for the tests in the B24 and B30 series. Both loops B24-1 and B24-2 failed in pullout at comparable peak loads and exhibited the same initial stiffness. B24-2 exhibited a slight drop in load at 51 kip (226.8 kN) (at 0.6 in. [15.24 mm] displacement), which was when first cracking at the surface of the concrete occurred. The typical formation of first cracking is shown in **Fig. 8**. The cracks have been emphasized (traced) for clarity in the photo.

All three B30 tests shared similar stiffness and peak loads. When cracking occurred, each test also experienced a slight drop in load: 53 kip (235.7 kN) at 0.43 in. (10.9 mm), 56 kip (249.1 kN) at 0.45 in. (11.4 mm), and 49 kip (217.95 kN) at 0.39 in. (9.9 mm) in B30-1, B30-2, and B30-3, respectively. These values can be used as reasonable upper-bound capacities for the B30 specimens in lieu of first-slip data, which could not be obtained from this testing.

The B24 tests did not reach peak capacities as large as the B30 tests, but they exhibited greater ductility. In this case, ductility is meant to imply that there will be warning signs prior to failure. A brittle anchor design may not provide adequate warning of failure. More than 2.4 in. (60.96 mm) of maximum displacement was recorded for both B24 tests. Measurement error and a lack of sufficient stroke for the clevis kept these displacements from being larger. The B30 tests, however, which failed in side-face blowout, experienced 1.3, 1.0, and 1.4 in. (33.02, 25.4, and 35.6 mm) of displacement upon sudden loss of strength.

Figure 9 shows the recorded force-displacement behavior of the bent specimens relative to the ASTM A1081[13] criteria, which record tensile force in the strand corresponding to a displacement of 0.1 in. A pullout force of approximately 16 kip (71.2 kN) was determined at 0.1 in. (2.54 mm) displacement after correcting for strand deformation. Because each loop has two strands, this equates to 8 kip (35.6 kN) per strand, which is very low relative to ASTM A1081[13] tests for 0.6 in. (15.24 mm) diameter strand, as explained earlier in the strand bond behavior section. It is theorized that marginal bond of the strand, a low Mohs hardness, and low concrete

Figure 6. Inclined position of B30 loops. Note: B30 = bent loop test series with 30 in. embedment depth. 1 in. = 25.4 mm.

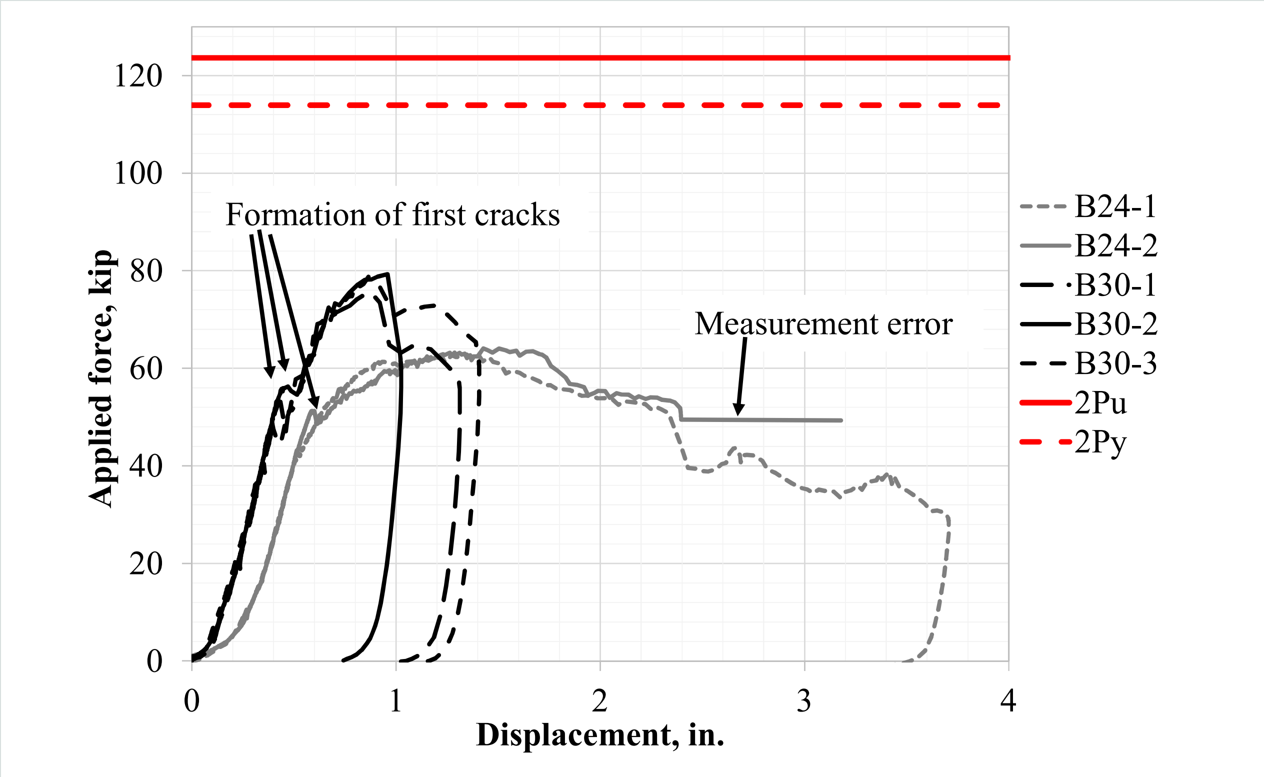


Figure 7. Applied force versus displacement curves for bent loop specimens. Note: B24-1 = first test in bent loop test series with 24 in. embedment depth; B24-2 = second test in bent loop test series with 24 in. embedment depth; B30-1 = first test in bent loop test series with 30 in. embedment depth; B30-2 = second test in bent loop test series with 30 in. embedment depth; B30-3 = third test in bent loop test series with 30 in. embedment depth; P_u = ultimate tensile strength; P_y = tensile yield strength. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

Figure 8. Initial cracking for B24-2. Cracks have been emphasized (traced) for clarity. Note: B24-2 = second test in bent loop test series with 24 in. embedment depth. 1 in. = 25.4 mm.

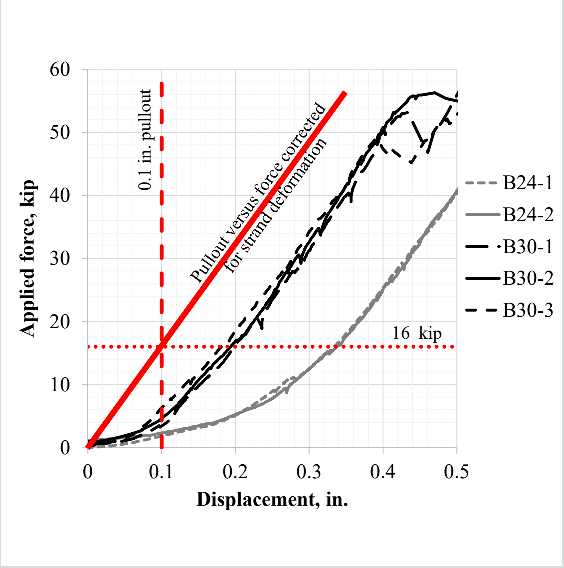


Figure 9. Applied force versus displacement curves for bent loop specimens relative to ASTM A1081 criteria. Note: B24-1 = first test in bent loop test series with 24 in. embedment depth; B24-2 = second test in bent loop test series with 24 in. embedment depth; B30-1 = first test in bent loop test series with 30 in. embedment depth; B30-2 = second test in bent loop test series with 30 in. embedment depth; B30-3 = third test in bent loop test series with 30 in. embedment depth. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

strength all contributed to result in this very conservative value for pullout.

Straight loops

Eight tests were conducted on straight loop configurations: three S32 tests (32 in. [812.8 mm] embedment), three S36 tests (36 in. [914.4 mm] embedment), and two S42 tests (42 in. [1066.8 mm] embedment). These specimens did not have the 6 in. (152.4 mm) leg bends that were present in the bent test series (Fig. 4). The concrete block for the S36 series had a higher concrete strength of 4460 psi (30.75 MPa) (Table 1). The S36 loops were also installed in the transverse orientation (**Fig. 10**). This led to a reduced edge distance for the S36 specimens relative to the other specimen series.

Table 4 presents the peak load P reached by the loops in each test. This peak load is also reported as a ratio of the ultimate strength of the loop $P/2P_u$ and as a bond stress τ_p. For test series S32, S36, and S42, the average peak bond stresses were 432, 364, and 334 psi (2979, 2510, and 2303 kPa), respectively. Load at first cracking P_1 is also presented for the S32 and S42 specimens, as well as the bond stress at first cracking τ_1. The average bond stress at first cracking was 330 psi (2275 kPa) for S32 specimens and 230 psi (1586 kPa) for S42 specimens. Peak loading and load at first cracking for test S42-1 were lower than expected. These results may have been due to improper consolidation of concrete.

Table 4. Results of straight loop specimen tests

Label	Embedment depth L_b, in.	Total loop embedment L,* in.	Load at first cracking P_1, kip	Peak load P, kip	Failure type	$P/2P_u$	Bond stress at first cracking τ_1, psi	Peak bond stress τ_p, psi
S32-1	32	64	50	65.0	Pullout	0.53	311	404
S32-2	32	64	54	82.0	Pullout	0.66	336	510
S32-3	32	64	55	61.3	Pullout	0.50	342	381
S36-1T†	36	72	NR	71.6	Pullout	0.58	—	396
S36-2T†	36	72	NR	68.6	Pullout	0.56	—	379
S36-3T†	36	72	NR	57.3	Pullout	0.46	—	317
S42-1	42	84	39	67.0	Pullout	0.54	185	317
S42-2	42	84	58	74.2	Pullout	0.60	275	351
Average	n/a	n/a	51	68.4	n/a	0.55	290	382

Note: n/a = not applicable; NR = not recorded; P_u = ultimate strength of one strand; S32-1 = first test in straight loop test series with 32 in. embedment depth; S32-2 = second test in straight loop test series with 32 in. embedment depth; S32-3 = third test in straight loop test series with 32 in. embedment depth; S36-1T = first test in straight loop test series with 36 in. embedment depth; S36-2T = second test in straight loop test series with 36 in. embedment depth; S36-3T = third test in straight loop test series with 36 in. embedment depth; S42-1 = first test in straight loop test series with 42 in. embedment depth; S42-2 = second test in straight loop test series with 42 in. embedment depth. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

* Total loop embedment $L = 2L_b$.

† T indicates loops oriented transversely to the block direction.

The average lifting loop capacity for the S32 series was 69.4 kip (308.7 kN); however, there was notable variability between the peak load in specimen S32-2 (82.0 kip [364.7 kN]) and the values obtained in specimens S32-1 (65.0 kip [289.1 kN]) and S32-3 (61.3 kip [272.7 kN). Despite these differences, the coefficient of variation of this test series was 0.13, which is within reason for typical coefficient of variation values observed during the experimental testing of anchors.

Failure modes All eight of the specimens in the straight configuration failed in pullout (Table 4). Figure 10 shows the typical concrete cracks formed at the end of pullout loading for each test, which was consistent with the previous pullout results observed in the B24 test series. The twisting of the loop observed in the figure was a consequence of unloading of the clevis; it did not occur during loading.

All three loops in the S36 series resulted in pullout failure (Fig. 10). The average lifting loop capacity for the three S36 tests was 66 kip (293.6 kN). Despite having a higher concrete strength than the other test series, these specimens did not exhibit higher pullout capacities, which was likely due to the transverse orientation of the loops, resulting in a smaller edge distance. Test S36-3T (Fig. 10) experienced a more pronounced effect of combined pullout–concrete breakout relative to the more traditional ductile pullout modes observed in specimens S36-1T and S36-2T (Fig. 10).

The S42 series had an average pullout capacity of 70.6 kip (314 kN). This was not substantially different from the S32 series, which had a 69.4 kip (308.7 kN) average capacity despite having embedment depths that were 10 in. (254 mm) shorter than those in the S42 tests. Failures observed in the S42 series were very similar in behavior to the S32 tests (Fig. 10).

Load-displacement behavior Figure 11 shows the applied load relative to recorded displacement for the tests in the S32, S36, and S42 series. Data for specimen S36-1T are excluded because of measurement errors during testing. Specimens S32-1 and S32-3 experienced a drop in load at 50 kip (222.4 kN) (0.67 in. [17 mm]) and 54 kip (240.2 kN) (0.93 in. [23.6 mm]), respectively, when cracking at the top surface of the concrete occurred. S32-2 did not experience this drop in load. Given the differences in peak capacity observed in the S32 series, an investigation was conducted after testing to expose the embedded ends of the lifting loops to verify that the loops were installed at the same embedment. All were found to be installed at the same embedment, despite noticeable differences in peak capacities. These specimens all experienced similar initial stiffnesses and overall ductility. The S36 specimens experienced the same initial stiffness but

Figure 10. Failure modes of straight loop test specimens. Note: S32-2 = second test in straight loop test series with 32 in. embedment depth; S36-2T = second test in straight loop test series with 36 in. embedment depth; S36-3T = third test in straight loop test series with 36 in. embedment depth; S42-2 = second test in straight loop test series with 42 in. embedment depth. 1 in. = 25.4 mm.

slightly different peak capacities and very different ductility. Neither S36 specimen experienced a first-cracking drop in load. The average lifting loop capacity for the S36 specimens was 66 kip (293.6 kN). Specimen S42-1 experienced a drop in load at 39 kip (173.5 kN) (0.54 in. [13.7 mm]), but S42-2 did not experience this drop in load. The average lifting loop capacity for S42 specimens was 70.6 kip (314 kN).

Most of the straight specimens were able to sustain load at a displacement in excess of 3.8 in. (96.5 mm). It should be noted that for these tests, the displacement would have been greater had there been enough stroke to continue testing. The displacement of the clevis was limited by the presence of the test frame and could not be pulled more than approximately 4 to 5 in. (101.6 to 127 mm). S36-3T was the only test in the S36 series that experienced an unanticipated level of low ductility. This test experienced more of a combined pullout-breakout failure than the other tests in the series, which were classic pullout failures. This difference could be due to any number of small differences between the test specimens, such as improper consolidation around the strand and slight skews or offsets of the loop location. The S36 tests also had the loops oriented in the transverse direction where the edge distance of the strand legs was much smaller than the 6 in. (152.4 mm) used in the other tests. It is plausible that low levels of ductility can be expected for lifting loops with edge distances less than 6 in. because combined pullout-breakout failure modes may begin to govern over traditional pullout failures. For bridge applications, bridge members typically have wider top flanges than those used in these specimens, and the wider flange would help restrain lateral forces from the strand as it pulls out.

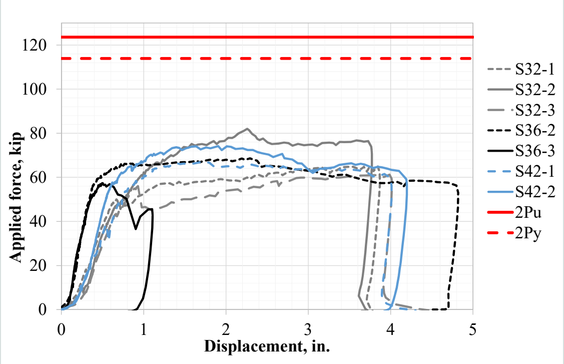


Figure 11. Applied force versus displacement curves for straight loop specimens.
Note: S32-1 = first test in straight loop test series with 32 in. embedment depth; S32-2 = second test in straight loop test series with 32 in. embedment depth; S32-3 = third test in straight loop test series with 32 in. embedment depth; S36-2T = second test in straight loop test series with 36 in. embedment depth; S36-3T = third test in straight loop test series with 36 in. embedment depth; S42-1 = first test in straight loop test series with 42 in. embedment depth; S42-2 = second test in straight loop test series with 42 in. embedment depth; P_u = ultimate tensile strength; P_y = tensile yield strength. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

Project limitations and future needs

This research study provides important data on the pullout capacity of 0.6 in. (15.24 mm) diameter strand lifting loops; however, the findings from this study are somewhat limited by the scope of work. Additional experimental testing is needed to obtain additional statistically significant results and consider additional design parameters. The following are considerations for future work:

- The use of conduit or pipe and multiple loops: Conduit or pipe is typically used around lifting loops.[4] If used properly, this shield is expected to reduce concentrated loads on the individual wires in the strands or among multiple loops in one location. The use of these shields, including the procedure for selecting and installing them, should be studied in future work, particularly for multiple loops in one location where there is the potential for individual loops to get overloaded.

- Edge distance: An edge distance of approximately 6 in. (152.4 mm) was used in this study, as in the work performed by Moustafa;[5] however, the edge distance of a lifting loop can vary greatly based on the element the loop is anchored to. For instance, double tees and wide flange shapes have narrow webs, which would result in smaller lifting loop edge distances than what was available in this testing. Additional work is needed to fully understand the influence of edge conditions on the lifting loop capacity.

- Pin diameter: A 3 in. (76.2 mm) pin diameter was selected to ensure that the pin could remain elastic through multiple rounds of testing. Although 3 in. diameter hardware is within reasonable dimensions of typical hardware currently being used,[4] the use of a 3 in. diameter pin is not conservative relative to 1 or 2 in. (25.4 or 50.8 mm) diameter hardware. The standard hardware geometry used in practice varies widely and is often hooked and not round. These factors would reduce the strand capacity and should be considered when extrapolating the findings of this work to other applications.

- Strand bond: The bond behavior of strands can vary among strand producers.[12] The strand used in this study was conservatively chosen because it offers a lower bond strength (per ASTM A1081[13] testing) than many other strands made in North America; however, it does not necessarily represent the lowest quality of strand bond available. Strand producers should confirm, using ASTM A1081 testing, that their 0.6 in. (15.24 mm) diameter strand has a capacity equal to or greater than 18.2 kip (90.95 kN). If their A1081 bond strength is less than 18.2 kip, the findings cannot be conservatively used and the precaster should determine alternative safe lifting loop values for the concrete used in their products to be lifted.

- Concrete aggregate hardness: The Mohs hardness of the aggregate can also affect the bond capacity of lifting loops. The findings from this test report may not conservatively

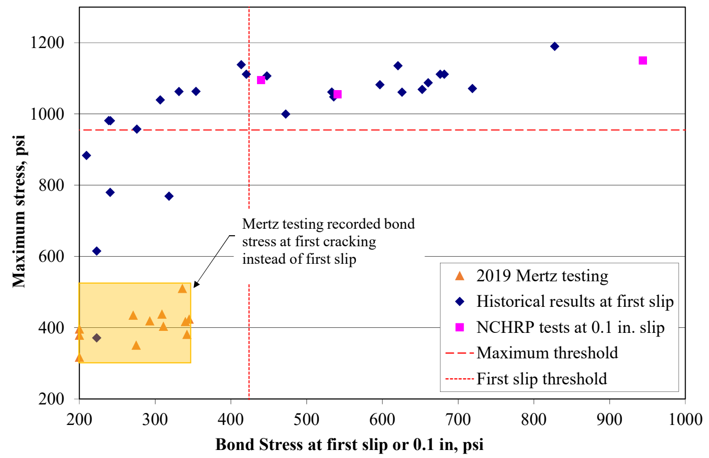


Figure 12. Correlation between maximum stress and first slip for historic and recently manufactured strand.
Source: Historical data from Osborn, Lawler, and Connolly (2008).
Note: NCHRP = National Cooperative Highway Research Program. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

apply to soft aggregates (such as soft limestone used by some Florida producers). In addition, sanded lightweight concrete aggregate should be considered carefully.

Conclusion

The following qualitative recommendations can be made based on the experimental test results:

- When embedment depth cannot be increased, strands should be bent at their ends to provide additional pullout capacity relative to straight-end loops.

- Edge distance should be carefully considered when determining loop capacity because the failure mode (pullout, combined pullout-breakout, or even side-face blowout) and anchor capacity can be influenced by an edge distance less than 6 in. (152.4 mm).

- Proper placement of the loop is essential to ensuring adequate capacity of the loop. This was shown in the B30 tests, which experienced premature side-face blowout failure due to the out-of-plane skew of the loop.

The pullout tests reflected calculated uniform bond stress values as low as 317 psi (2186 kPa) at peak load. The overall measured average bond stress at failure was approximately 400 psi (2758 kPa) ±110 psi (758.45 kPa). At first cracking, the average observed bond stress was 290 psi (1999.55 kPa) and the minimum bond stress was 185 psi (1276 kPa). It is presumed that the low-strength concrete and the low Mohs hardness, as well as choosing a strand with a marginal bond, resulted in these relatively low-bond stresses. These bond levels represent very low levels of bond strength relative to previous testing of Moustafa,[5] and large concrete block pullout tests and can be deemed very conservative. This comparison is shown in **Fig. 12**, where the range of bond stresses observed in this test program is shown in yellow and compared with previous test results recorded in the National Cooperative Highway Research Program (NCHRP) test report 621.[14] The results from this study were plotted with the maximum stress relative to the stress at first cracking; the NCHRP test results were plotted with the maximum stress relative to the first slip stress. This study found low values of peak stress as well as serviceability limits (first cracking) relative to the NCHRP testing.

As outlined previously, the *PCI Design Handbook*[2] currently recommends a safe load of 10 kip (44.48 kN) for ½ in. (12.7 mm) diameter, 270 ksi (1860 MPa) strand with a 24 in. (609.6 mm) minimum loop leg embedment. This corresponds to a safe uniform bond stress of 100 psi (689 kPa). This bond stress is well below the minimum observed bond stress of 317 psi (2186 kPa) at failure, but it is close to the minimum observed first cracking bond stress of 185 psi (1276 kPa). Based on these results, a safe uniform bond stress of 100 psi was deemed a reasonable recommendation for 0.6 in. (15.24 mm) diameter strand. This equates to a safe load of 12 kip (53.4 kN) for 24 in. embedded strand. To apply these recommendations, the strand used should have a minimum equivalent ASTM A1081[13] pullout value of 18.2 kip (81 kN) and the concrete to be lifted should have a minimum compressive strength of 3000 psi (20.7 MPa) at time of lift.

Acknowledgments

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Notation

A_{bond} = surface area of the strand = $\frac{4}{3}\pi d_b L$

d_b = nominal diameter of the prestressing strand

f_c' = average compressive strength of concrete

f_{ct} = average splitting tensile strength of concrete

L = total loop embedment = $2(L_b + L_{bend})$

L_b = embedment depth

L_{bend} = length of bent ends of strand

P = peak load recorded from experimental testing

P_u = ultimate tensile strength of one 0.6 in. (15.24 mm) diameter strand

P_y = tensile yield strength of one 0.6 in. (15.24 mm) diameter strand

P_1 = load at first cracking recorded from experimental testing

τ_p = measured peak bond stress of prestressing strand = P/A_{bond}

τ_1 = measured bond stress of prestressing strand at first cracking = P_1/A_{bond}

Appendix: Concrete toughness

Donald R. Logan

Concrete toughness refers to concrete's ability to resist the pullout of prestressing strands in tests of lifting loops as well as in large block pullout tests (LBPTs). Lifting loop tests were conducted by Saad Moustafa[1] at Concrete Technology Associates in 1974 and 1993. In these tests, the concrete used in the test blocks was Concrete Technology's hard rock structural mixture. The coarse aggregate was Steilacoom gravel, a very hard crushed gravel with a Mohs hardness that most likely exceeded 6.0.

Stresscon has conducted LBPTs since the early 1990s and researched the capability of the test to provide consistent pullout values on samples from a specific strand test reel varying the concrete mixture as well as the test sites. The approximate Mohs hardness of Stresscon's coarse aggregate had been greater than 6. The embedment of the ½ in. (12.7 mm) diameter strands tested is 18 in. (457.2 mm), and the maximum pullout value typically ranged from 37 to 40 kip (165 to 178 kN) for typical high-bond-quality strand.

In LBPTs conducted at other sites, it was immediately noted that the pullout value of high-bond-quality strand varied significantly depending on the toughness of the concrete mixture, and it was then determined that the toughness was directly related to the hardness of the coarse aggregates, which can be measured using the Mohs hardness test. **Table A.1** presents examples.

Pullout values at other sites with crushed gravel compared closely with Stresscon's typical pullout values. These observations led to a formalization of the toughness by Bob Peterman[1] (now at Kansas State University), acting on a suggestion by Andrew E. N. Osborn of Wiss, Janney, Elstner Associates. Mohs hardness of the coarse aggregates in six different concrete mixtures was measured, and LBPTs were performed on samples of high-bond-quality, ½ in. (12.7 mm) diameter strand from the same test reel. Figure A.1 compares maximum pullout load to Mohs hardness of coarse aggregate for each source. These tests were conducted by Peterman and examined the reproducibility of LBPT with varying mixture proportions and Mohs hardness values of coarse aggregates. High-bond-quality, ½ in. diameter strand samples were the same for each pullout test.

Implications for Mertz Fellowship lifting loop project

Pullout test result application Peterman tested the Mohs hardness of the coarse aggregate used in the project. In two different tests, the Mohs hardness value was determined to be 3.6 and 3.8. ASTM A1081 tests on the 0.6 in. (15.24 mm) diameter strand found an average pullout capacity of 18.2 kip (81 kN). Thus, the authors concluded that the pullout test results are applicable to coarse aggregate Mohs values of 3.6 and greater and 0.6 in. (15.24 mm) diameter, 270 ksi

Table A.1. Selected large block pullout tests

Study	Test number	Coarse aggregate	Pullout value, kip
Norm Scott and Ron Hielbron, late April 1997, Coreslab (MIAMI)	1	Nova Scotia granite	39.3
	2	Florida limestone	21.3
	3	Florida limestone	27.0
Bob Peterman, September 18, 1997, Purdue University	1	Crushed gravel	38.9
	2	Hard limestone	31.4
Carl Buchman, Spancrete, November 1997, Cornell University	1	Crushed gravel	39.3
	2	Hard limestone	32.6

Note: 1 kip = 4.448 kN.

(1860 MPa) ASTM A1081 values of 18.2 kip (81 kN) and greater.

Extrapolation of pullout test results to coarse aggregates with lower Mohs hardness values

Based on reduced pullout values from late 1990s LBPTs of ½ in. (12.7 mm) diameter strand, the authors speculated that there may be a reduction of pullout values of approximately 20% to 25% when comparing pullout values from hard limestone to Florida limestone. The test results from the Mertz Fellowship project may not be sufficiently conservative for use by Florida girder producers or for products with sanded lightweight concrete. Therefore, the testing program should be expanded to include pullout testing of concrete with lower Mohs hardness values.

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Donald R. Logan is president of Logan Structural Research Foundation and founder and former CEO/president of Stresscon Corp. in Colorado Springs, Colo. He served as an advisory committee member for the Dennis R. Mertz Fellowship lifting loop project.

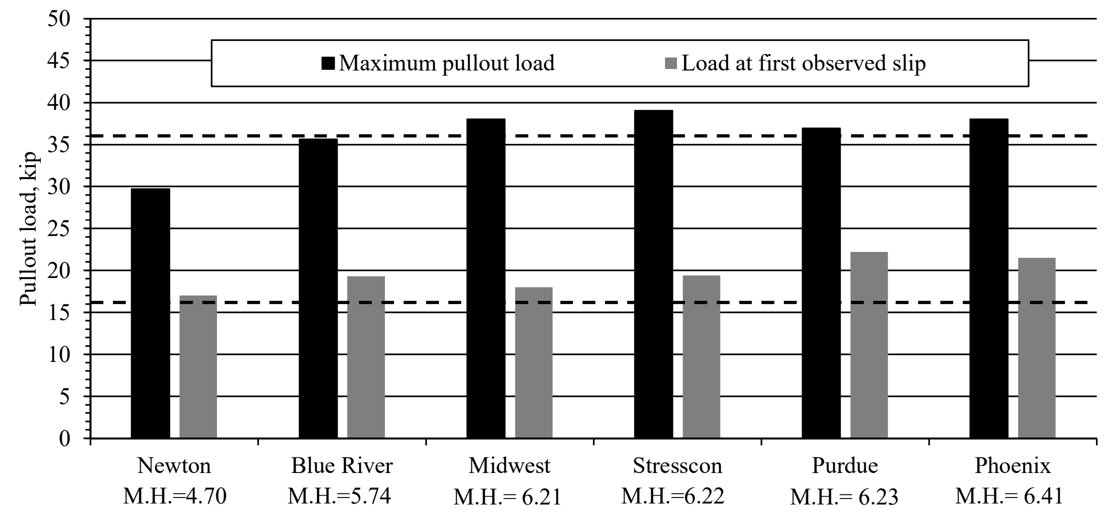

Figure A.1. Maximum pullout load compared with Mohs hardness of coarse aggregates used in each concrete mixture source. Note: M.H. = Mohs hardness. 1 kip = 4.448 kN.

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Abstract

Very little experimental data have been published relating to the pullout capacity of prestressing strand lifting loops. To address this gap in knowledge, 13 pullout tests were conducted on strand lifting loops with 0.6 in. (15.24 mm) diameter, 270 ksi (1860 MPa) strand. Straight and bent orientations were tested for single loops at different embedment depths. Loops were embedded in 12 in. (304.8 mm) wide and 44 in. (1117.6 mm) deep concrete blocks and subjected to monotonic, static loading until failure. Marginal bond quality of the strand (18.2 kip [81 kN]), Mohs hardness (3.6), and concrete strength (3000 psi [20.7 MPa]) resulted in an average bond stress value of 400 psi (2758 kPa) at failure. Most tests exhibited pullout failure modes and adequate ductility. Three loops tested at 32 in. (812.8 mm) embedment with 6 in. (152.4 mm), 90-degree bends experienced brittle side-face blowout failures. These failures were due to inclination of the lifting, which led to a reduced edge distance. A safe uniform bond stress of 199 psi (1372 kPa) is recommended for 0.6 in. diameter strand.

Keywords

Anchorage, bond behavior, lifting loop, prestressing strand, pullout capacity.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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