Experimental investigation of multiple-strand lifting loops

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- This research investigates prestressing strand loops used to lift and transfer precast concrete. In the experimental program, tests were conducted to determine the load-carrying capacity of prestressing strand lifting loops.

- Test parameters included the number of strands in the lifting loop, sleeve type, vertical offset and splaying of strands, and lifting device.

- Test results summarize failure modes, average peak load, ratio of peak load to ultimate strength of the strand, and peak bond.

Prestressing strand lifting loops are used to lift and transfer precast concrete components from the manufacturing plant to the truck bed and from the truck bed to the structure. These lifting loops, bent from ASTM A416[1] strand, are commonly used because they are readily available, cost effective, strong, and ductile and offer the flexibility to easily create loops of varying lengths and configurations. The load capacity of lifting loops depends on a variety of parameters, including, but not limited to, strength and condition of the strand, length and configuration of embedment, diameter of the rigging element engaging the loop, the type and strength of concrete, and lifting angle.

Limited studies have been conducted on lifting loops. Moustafa[2] conducted pullout tests with several parameters: strand diameters of 3⁄8, 7⁄16, and 1⁄2 in. (9.5, 11.1, 12.7 mm); embedment depths of 12, 18, 24, and 30 in. (305, 457, 610, and 762 mm); straight, bent, and broomed end configurations; bright and rusted surface finishes; and concrete strengths of 6000 and 3000 psi (41 and 21 MPa). These tests involved a single straight strand embedded in a 12 in. wide concrete block. Testing of a strand loop was not performed. Safe lifting loads were recommended. In addition, the breaking strength of the strand for different pin diameters was evaluated.

Kuchma and Hart[3] tested lifting loops in deck beams with depths less than 24 in. (610 mm). The parameters tested were concrete strength, loop shape (parallel, tie, or splayed legs), loop embedment depth, number of loops, multiple loop bundles at a single lifting point, lifting device, side edge distance, and angle of pull. Strands of ½ in. (12.7 mm) diameter were tested. Among other conclusions, the work determined that hooks lower the capacity of the lifting loops relative to lifts performed using shackles (pins).

The Kansas Department of Transportation provides a design example in its 2009 *Bridge Design Manual*[4] for determining the number and depth of ½ in. (12.7 mm) diameter strand lifting loops. It references Salmons' work,[5] which provides relationships between maximum force (stress) and embedment length of untensioned prestressing strand. This calculation for determining lifting-loop capacities is the only one known to be published, as most of the guidance is empirically based.

Typical lifting-loop practices as determined from an industry survey are presented in previous work by Chhetri et al.[6] To date, precast concrete producers have primarily based their lifting-loop designs on limited guidance provided in the *PCI Design Handbook: Precast and Prestressed Concrete*[7] and previous experience. The eighth edition of the handbook specifies a safety factor of 4 against slippage and breakage of the strand and the use of a hook or pin (shackle) with a diameter at least four times the diameter of the prestressing strand. A minimum embedment of 24 in. (610 mm) is recommended for ½ in. (12.7 mm) diameter, 270 ksi (1862 MPa) strand loops. When embedment is 24 in. or greater, a safe working load of 10 kip (44.5 kN) can be used. If double- or triple-strand loops are used, the stated safe load is multiplied by 1.7 or 2.2, respectively. By dividing the safe working load by the circumferential area of the strand embedded in the concrete, the safe working bond stress could be calculated to be approximately 100 psi (689 kPa) for single-strand loops, 85 psi (586 kPa) for double-strand loops, and 73 psi (503 kPa) for triple-strand loops. The *PCI Design Handbook* does not provide guidance for 0.6 in. (15.2 mm) diameter strand; however, research by Chhetri et al.[8] was conducted to determine the safe lifting load of single 0.6 in. diameter strand loops. A safe working load of 12 kip (53 kN) was proposed. Additional single-loop test results (with stainless steel loops and in lightweight concrete) can be found in work by Chhetri.[9]

This paper fills existing gaps in knowledge on the strength of multiple 0.6 in. (15.2 mm) diameter strands in one location.

Experimental program

Table 1 summarizes the experimental test matrix and testing parameters evaluated in this study. All 28 tests were conducted with 0.6 in. (15.2 mm) diameter, 270 ksi (1862 MPa) strand embedded 36 in. (914 mm) into the concrete with 6 in. (152 mm) bent ends (**Fig. 1**). The strand was embedded in a vertical orientation instead of a tied or inverted-vee configuration. The primary test variables were as follows:

Table 1. Experimental test matrix

Number of strands in loop *n*	Sleeve type	Other parameters	Lifting device	Number of tests
1	None	n/a	2.4 in. diameter pin	3
		n/a	Hook	1
2	Crushed conduit	n/a	2.4 in. diameter pin	2
		n/a	3 in. diameter pin	2
		n/a	Hook	2
3	Crushed conduit	n/a	3 in. diameter pin	2
	Crushed pipe	n/a	3 in. diameter pin	2
		n/a	Hook	2
	None	½ in. vertical offset from one another (maximum offset of 1 in.)	3 in. diameter pin	2
		½ in. vertical offset from one another (maximum offset of 1 in.)	Hook	1
	Crushed conduit	12 in. top of concrete	3 in. diameter pin	1
4	Crushed conduit	Splay, 12 in. top of concrete	3 in. diameter pin	2
	Crushed conduit	12 in. top of concrete		2
	Crushed pipe	6 in. top of concrete	3 in. diameter pin	2
	Crushed conduit	Splay, 18 in. top of concrete	3 in. diameter pin	2

Note: n/a = not applicable. 1 in = 25.4 mm.

- number of strands in a loop: 1, 2, 3, or 4
- sleeve: conduit, pipe, or no sleeve
- lifting device: 2.4 in. (61 mm) pin diameter, 3 in. (76 mm) pin diameter, or hook
- loop projection from top of concrete: 6, 12, or 18 in. (152, 305, 457 mm)

Splaying and vertical offsets were also tested. These parameters are explained in more detail in the following sections.

Sleeve

When multiple strands are used in a loop, the strands must be placed at the same elevation to ensure equal loading among all strands. Failure to place the strands in this manner could lead to overloading of one strand, which could cause progressive failure of the remaining strands. This equal distribution of loading can be achieved through precise placement of the individual strand loops at the same elevation. An easier and more common approach is to place the strands in a sleeve (typically electrical conduit or pipe) before the loop is bent (**Fig. 2**). For this method to be effective, the sleeve must be

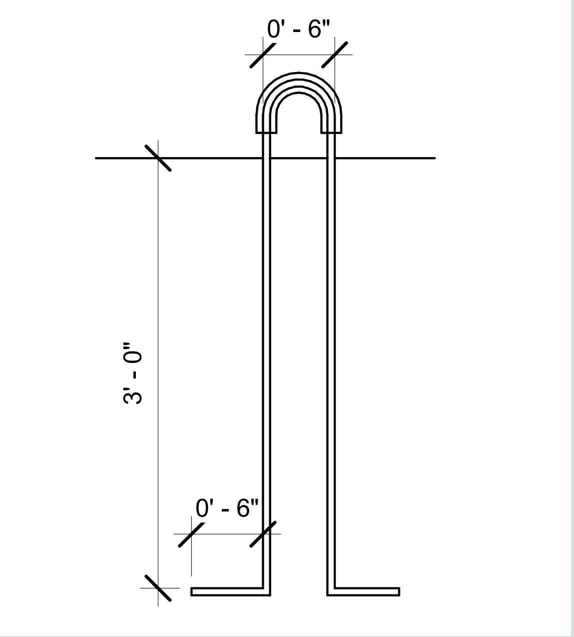
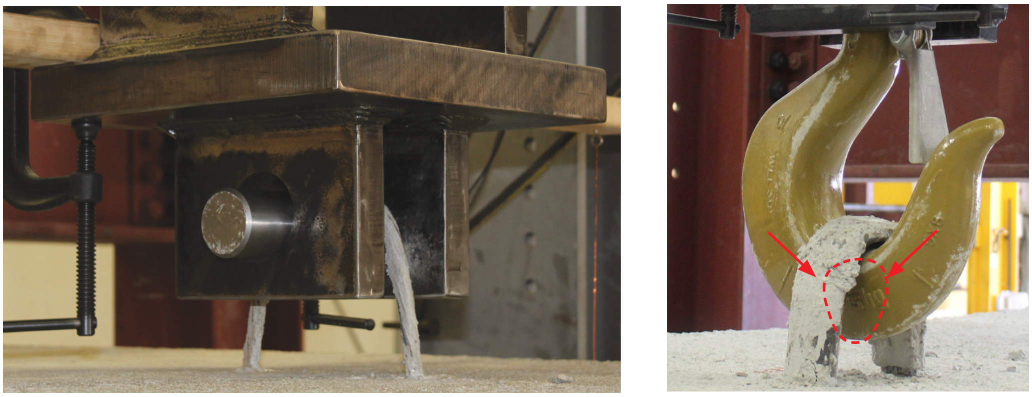


Figure 1. Typical lifting loop orientation. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

Figure 2. Sleeve and vertical offset details. Note: 1" = 1 in. = 25.4 mm. Photo courtesy of Mark Combs, Prestress Services Inc.



3 in. diameter pin (shackle)

20-ton eye hook showing locations of stress concentration in cross section

Figure 3. Lifting devices. Note: 1" = 1 in. = 25.4 mm; 1 ton = 0.907 tonnes.

crushed prior to bending to facilitate even distribution of loading. The strands in the uncrushed sleeve are not evenly distributed, whereas the crushed sleeve allows each strand to maintain the same elevation. Uncrushed sleeves should not be used for multiple-strand lifting loops. This study only tested crushed sleeves using Schedule 40 pipe and thin-walled electrical metallic tubing (also known as conduit). Sleeves with diameters of 1¼ in. (31.75 mm) were used for all multiple-strand cases, whereas 1½ in. (38 mm) pipe was used for the four-strand cases. Crushed sleeves were not used in single-strand test cases or when a vertical offset was intentionally created (Fig. 2). The vertical offset was 1 in. (25.4 mm) between the shortest and tallest strands in a three-strand loop.

Lifting device

Hooks and shackles are commonly used to lift precast concrete elements. Research has shown that the size and shape of the lifting device can influence the capacity of the lifting loop. Moustafa[2] demonstrated that smaller pin diameters result in lower strand capacity. The work described in this paper used two different pin diameters of 2.4 and 3 in. (61 and 76 mm) (**Fig. 3**). The selected diameters represent the diameters of pins in shackle lifting devices. The *PCI Design Handbook*[7] recommends a minimum pin diameter of four times the diameter of the strand, which is why this study used a minimum diameter of 2.4 in. In addition, the study used a 20-ton (18-tonne) Crosby carbon eye hook, which had a diameter of 3 in. (76 mm). Kuchma and Hart[3] observed decreased strengths with hooks because of stress concentrations associated with the nonrounded nature of the hook cross section (Fig. 3).

Loop projections

Most of the tests had the loops placed approximately 6 in. (152 mm) from the top of the concrete (**Fig. 4**). However, 12 and 18 in. (305 and 457 mm) projections were also tested. Longer projections above the concrete result in lower strains in the strands, thereby decreasing the likelihood of strand rupture of the loop.

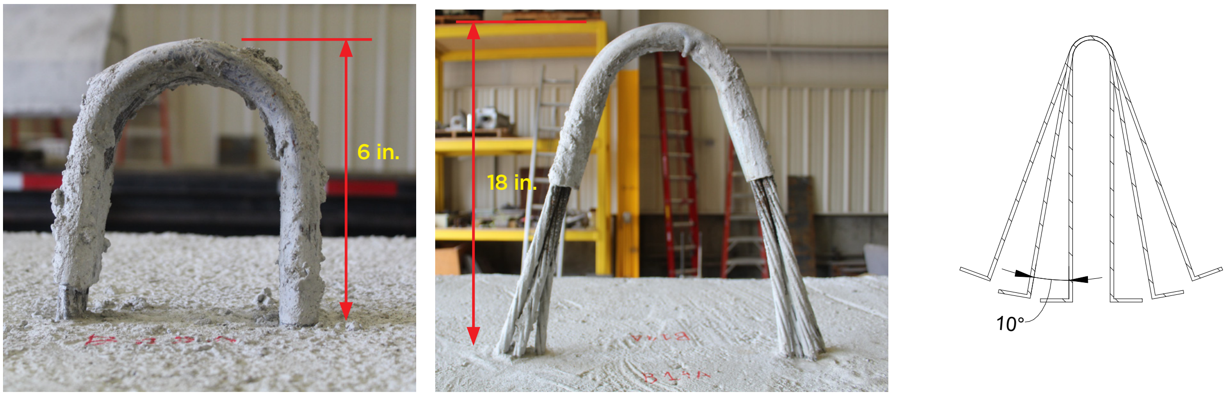
Splaying strand ends

The strand legs were oriented vertically within the concrete (Fig. 1) in nearly all test cases. However, the strand ends were splayed for four test specimens (Table 1). The strand legs were splayed at approximately 10 degrees from one another (Fig. 4).

Test setup

All specimens were tested using the setup shown in **Fig. 5**. The lifting-loop specimens were embedded in an Indiana I-beam, and a central test frame was used to load them. A hydraulic cylinder hung from the central test frame and pulled the test lift loop up using a customized clevis assembly, which was rigidly attached to the ram (**Fig. 6**). The exterior frames on either side of the test lift loop were used to hold down the I-beam as load was applied to it. These exterior frames were placed 6 ft (1.8 m) from the location of the test loop to prevent compressive stresses in the test loop region due to the bearing of the exterior frames on the concrete beam. Monotonic, near-static loading was applied until failure at a rate of approximately 6 kip (26.7 kN) per minute. Force was measured using a calibrated pressure transducer. Vertical displacement of the pullout assembly was measured using string potentiometers on both sides of the concrete beam (Fig. 6). This displacement included potential slip or elongation of the strand as well as very minor deformations in the pullout assembly itself and the Indiana I-beam.

Test loops were embedded into 54 in. (1372 mm) deep Indiana I-beams with a 42 in. (1067 mm) wide top flange and 7 in. (178 mm) web. Each beam was lightly reinforced



6 in. loop projection

18 in. loop projection

Strand legs splayed in concrete at 10 degrees

Figure 4. Loop orientations. Note: 1 in. = 25.4 mm.

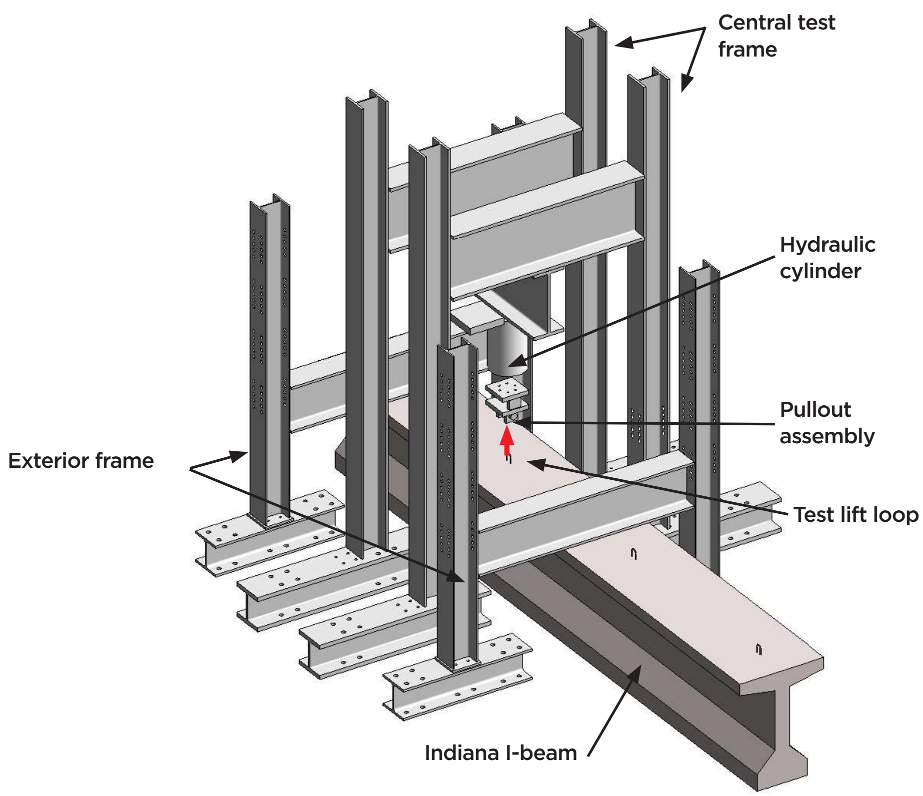


Figure 5. Schematic of test setup.

with only mild steel reinforcement to avoid overconfinement of the loop. As a conservative measure, prestressing was not applied to the I-beams to avoid adding compressive stresses that could result in larger pullout capacities. **Figure 7** shows a cross section of the beam. Two test loops were cast into each beam and spaced approximately 8 ft (2.4 m) apart from one another to prevent cracking or damage from a previous test affecting subsequent test results. The beams were cast using conventional ready-mixed normalweight concrete with Type III cement and crushed bourbon limestone.[9] To generate

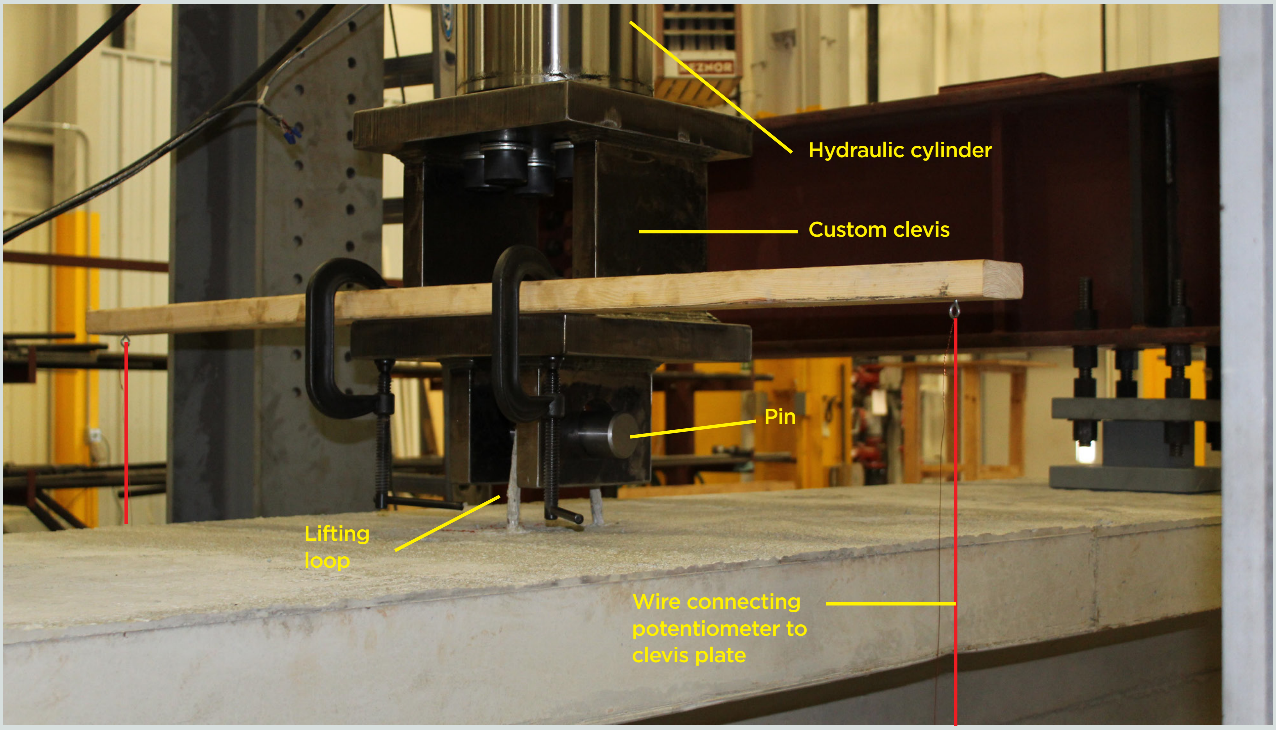


Figure 6. Pullout assembly and instrumentation (wires drawn for emphasis).

conservative test results, a target compressive stress of approximately 4000 psi (27.6 MPa) was desired and an average compressive stress of 4210 psi (29.0 MPa) was achieved. To maintain these low concrete strengths, the testing took place within 36 hours of concrete casting. The hardness of aggregate, which can be measured using Mohs hardness testing, has been shown to influence the bond capacity of strand.[8] The bourbon limestone aggregate in this testing had a Mohs hardness of 3.5. Lifting loops cast in concrete with softer aggregates (with lower Mohs hardness values) may produce lower pullout capacities.[8]

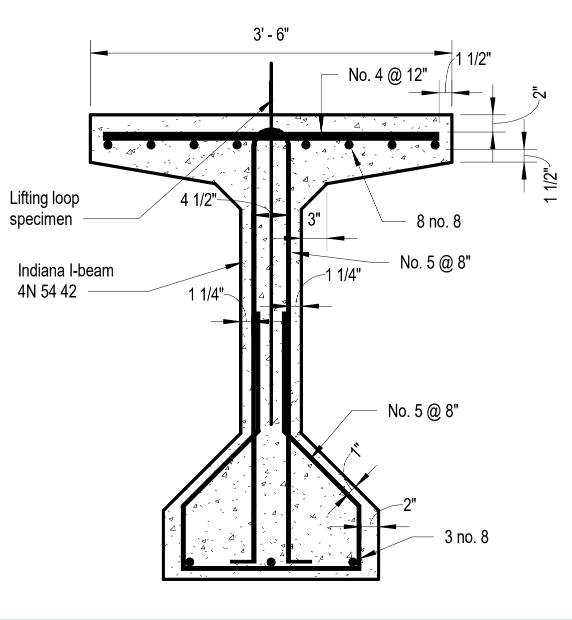


Figure 7. Beam cross section and reinforcement layout. Note: no. 4 = 10M; no. 5 = 16M; no. 8 = 25M. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

The strand lifting loops were fabricated using ASTM A416[1] 0.6 in. (15.2 mm) diameter, Grade 270 (1860 MPa), seven-wire strands. These prestressing strands were produced by two different manufacturers. Strands for the tests using crushed pipe were provided by one manufacturer, whereas all other tests used the other manufacturer's material. To characterize the bond quality of the strand, ASTM A1081[10] bond testing was performed on each strand type using the same laboratory and materials. The average tensile forces of the crushed pipe and conduit strands were 14.94 and 19.06 kip (66.46 and 84.78 kN) , respectively, at 0.1 in. (2.54 mm) slip, which corresponds to uniform bond stresses of 372 and 475 psi (2565 and 3275 kPa).

Test results and discussion

Table 2 summarizes the average test results for each test series. The failure mode, average peak load P, ratio of peak load to ultimate strength of the strand $P/2nP_u$, and peak bond stress τ_p are presented in the table. The variable n represents the number of strands in a loop bundle. P_u represents the measured ultimate strength of the strand, and $2nP_u$ is used

Table 2. Summary of multiple-loop test results

Number of strands in loop *n*	Number of tests	Lifting device*	Sleeve type	Other parameters	Failure type	Average peak load *P* kip	*P*/*n*, kip	$P/2nP_u$	Peak bond stress† τ_p, psi
1	3	2.4 in.	None	n/a	SR	84.9	84.9	0.68	403
1	1	Hook	None	n/a	SR	69.3	69.3	0.56	329
2	2	2.4 in.	Crushed conduit	n/a	SR	170.7	85.3	0.69	405
2	2	3 in.	Crushed conduit	n/a	SR	188.2	94.1	0.76	446
2	2	Hook	Crushed conduit	n/a	SR	166.6	83.3	0.67	395
3	2	3 in.	Crushed conduit	n/a	PO + SBO	271.2	90.4	0.73	429
3	2	3 in.	Crushed pipe	n/a	PO + SBO	246.7	82.2	0.67	390
3	2	3 in.	None	1 in. vertical offset	SR	189.1	63.0	0.51	299
3	1	3 in.	Crushed conduit	12 in. projection	SR	259.7	86.6	0.7	411
3	1	Hook	None	1 in. vertical offset	SR	129.9	43.3	0.35	205
3	2	Hook	Crushed pipe	n/a	SR	211.7	70.6	0.58	335
4	2	3 in.	Crushed pipe	n/a	PO + SBO	304.4	76.1	0.62	361
4	2	3 in.	Crushed conduit	12 in. projection, 30 in. embedment	PO + SBO	245.6	61.4	0.49	339
4	2	3 in.	Crushed conduit	12 in. projection, 30 in. embedment, splayed ends	PO + SBO	246.7	61.7	0.5	341
4	2	3 in.	Crushed conduit	18 in. projection, 24 in. embedment	PO + SBO	214.6	53.7	0.43	356

* 2.4 in. and 3 in. represent 2.4 in. and 3 in. diameter pins as the lifting device. The hook was a 20-ton Crosby eye hook.

† Bond stress $\tau_p = P/nA_{bond}$, where *P* is the average peak load among tests in that series; *n* is the number of strands in loop; and A_{bond} is the strand circumferential perimeter = ($4/3\pi d_b$ = 2.51 in.²/in.) × *L*, where d_b is the nominal diameter of prestressing strand and *L* is the total loop embedment = $2(h_{ef} + L_{bend})$, where h_{ef} is embedment depth = 36, 30, or 24 in. and L_{bend} is the length of the bent ends of strand = 6 in. For failures due to strand rupture, these values represent the maximum bond stress achieved prior to strand rupture, not the maximum possible bond stress.

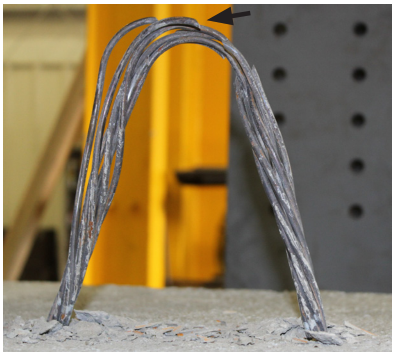
Note: n/a = not applicable; PO = pullout; SBO = side-face blowout; SR = strand rupture. 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; 1 kip = 4.448 kN; 1 psi = 6.895 kPa; 1 ton = 0.907 tonnes.

because there are two strand legs per loop of strand. The peak bond stresses provided in the table are the maximum bond stress values achieved before lifting-loop failure. These stresses ranged from 205 to 446 psi (1413 to 3075 kPa). For tests that failed in strand rupture, these peak bond stress values represent the maximum bond stress achieved before strand rupture, not the maximum possible bond stress of the strand. The average and median peak bond stresses among all of the tests were 370 and 375 psi (2551 and 2585 kPa), respectively, with a standard deviation of 55 psi (379 kPa). These mean peak bond stresses are comparable to the average peak bond stress of 400 psi (2758 kPa), which was observed in a previous study.[8] The low values of bond stress are attributed to small edge distances, the use of loops with vertical offsets, and in some cases, the use of hooks instead of pins. The multiple-strand loops failed by strand rupture, pullout, and concrete side-face blowout when subjected to vertical loading.

Failure modes

Single-strand testing previously conducted by Chhetri et al.[8] primarily resulted in pullout failures; however, because the strands in this more recent study were embedded 36 in. (914 mm) into the concrete with 6 in. (152 mm) bent ends, the pullout failure mode was nearly precluded. Most of the test specimens in this recent testing experienced strand rupture, which can be seen most easily in the single-strand tests, which did not have a sleeve. Partial (individual-wire) or full (seven-wire) rupture occurred (**Fig. 8**) for the single- and double-strand tests. Combined pullout and concrete side-face blowout failure occurred in many of the triple-strand tests and all of the quadruple-strand tests. In general, concrete spalling occurred around the strand on the top of the beam, as is often seen in a typical pullout failure (Fig. 8); however, there were scenarios where large and wide concrete cracks, which signify splitting cracks, formed on the beam's top surface (Fig. 8). In addition, side-face blowout occurred along the side of the beam in some tests. The damage to the concrete initiated around the embedded loop ends (Fig. 8). Concrete failure—in particular, side-face blowout—was dominant in tests with three or more strands. With multiple-strand loops, the loads were distributed among the individual strands so strand rupture did not always occur; however, because of the large loading occurring along the loops with a small edge distance from the loop to the edge of the beam web, concrete failures occurred instead. The test beam had a web thickness of 7 in. (178 mm), which led to an edge distance of less than 3.5 in. (89 mm) for the loops centered within the web. The recommended edge distance from loop to concrete surface is 6 in. (152 mm) whenever possible.[3,8] The smaller edge distance initiated side-face blowout and reduced the vertical lifting capacity. It is expected that embedding the ends of the loop into the bottom flange of the concrete beam (instead of the web) would have increased the capacity of the loops.

Figure 9 shows the applied force-displacement responses for the single-strand, double-strand, triple-strand, and quadruple-strand tests. The applied force was measured using a calibrated pressure transducer, and the displacement of the clevis was measured using the wire potentiometers (Fig. 6). The measured displacement did not solely represent strand elongation and slip but also included any minimal deformation within the clevis or the I-beam or within both. In this study, P_y represents the measured yield strength of the strand, $2nP_y$ represents the yield strength based on the total number of strand legs in the loop, and P_u represents the measured ultimate strength of the strand. "PCI safe load" indicates a



Partial strand rupture

Full (seven-wire) strand rupture

Pullout

Splitting/side-face blowout (top)

Side-face blowout (elevation)

Figure 8. Typical failure modes observed.

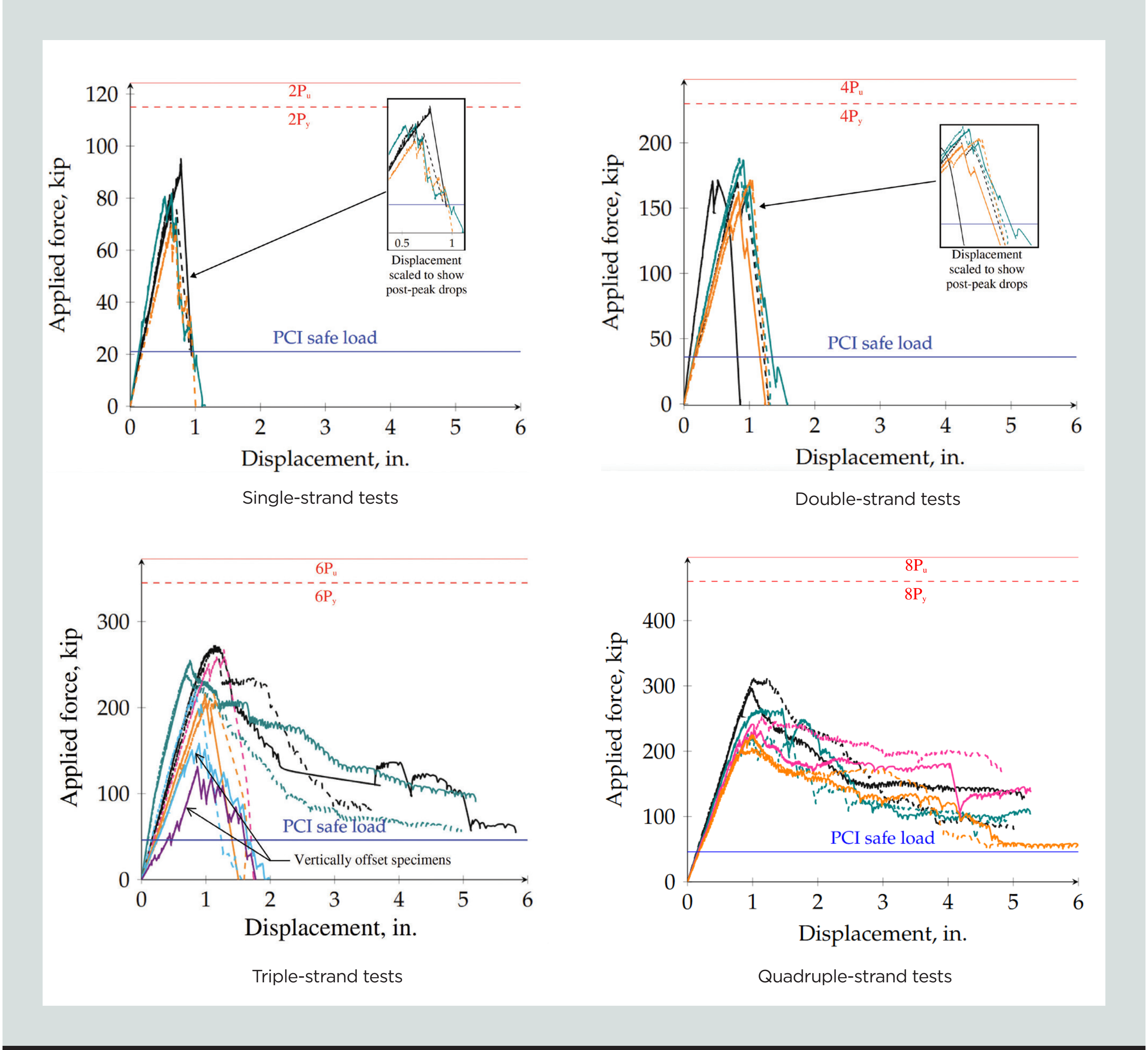


Figure 9. Vertical displacement versus vertical force of the clevis on the hydraulic cylinder. Note: P_u = ultimate tensile strength; P_y = tensile yield strength. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

calculated safe load for the given loop embedment based on the previously mentioned uniform bond stresses obtained from the *PCI Design Handbook*[7] (100 psi [689 kPa] for single-strand loops, 85 psi [586 kPa] for double-strand loops, and 73 psi [503 kPa] for triple-strand loops). In each of these tests, the specimens' peak loads were less than the yield strength of the strand but were significantly higher than the safe loads recommended in the *PCI Design Handbook*. This finding is to be expected because of the incorporation of the factor of safety of 4 for lifting devices.[7]

Sudden drops in load for the single-strand tests represent the strand rupture failures that occurred (Fig. 9). Multiple minor load drops in tests indicated rupturing of individual wires of the strand. Strand rupture occurred at displacements of approximately 1 in. (25.4 mm). Such behavior indicates that strand rupture is a brittle and instantaneous failure, which does not provide ample warning relative to other possible failure modes.

In the double-strand tests (Fig. 9), the strand wires broke in a progressive fashion, which can be seen by the multiple load drops in the force-displacement curves after peak loading. The first drop in load signaled the start of strand rupture. Notably, the curve shown in black in Fig. 9 has a different stiffness than the other test curves. The specimen represented by the black curve was initially loaded up to 80 kip (356 kN); however, due to an unforeseen issue during testing, this specimen had to be unloaded. When it was tested again two weeks later, the strength reached 6000 psi (41.4 MPa). The black curve represents the force-displacement response of this second loading with a higher concrete strength.

Many of the triple-strand loops (Fig. 9) experienced strand rupture. In these tests, the strand wires broke in a cascading manner, which can be seen by multiple load drops in the force-displacement curves. The vertically offset test cases labeled in the graph experienced more load drops than the strand loops without vertical offsets. This result was due to the progressive failure of the individual wires and, subsequently, strands due to the offset creating uneven loading among the strands, which caused a cascading failure. The tests in which more than 2 in. (50.8 mm) of vertical displacement occurred before failure were the cases of combined pullout and side-face blowout.

The quadruple-loop tests (Fig. 9) exhibited concrete failure (combined pullout and side-face blowout). The post-peak decline of load was gradual in these tests relative to the strand-rupture cases. The specimens in these tests were able to undergo larger displacements, reaching up to 6 in. (152 mm) of vertical displacement. Owing to stroke limitations on the hydraulic cylinder, the specimens could not be displaced more than approximately 6 in.

Influence of lifting device on loop capacity

The type of lifting device (pin or hook) had an effect on the load-carrying capacity of the loops. Compared to the hook, the pin had a rounder surface, which caused no pinching and delayed the breakage of strands; however, a smaller shackle pin diameter resulted in a lower loop capacity. There was an 8% increase in capacity after the diameter of the pin was changed from 2.4 to 3 in. (61 to 76 mm).

The hook further reduced the lifting performance of the strand loops. The edges of the hook caused the pinching of strands and stress concentrations, which, in turn, led to early strand rupture. The hook caused the strands to break early and reach only 60% of their guaranteed breaking strength ($2P_u$). In contrast, the loops reached 74% of their guaranteed breaking strength when loaded by the 3 in. (76 mm) diameter pin. There was a 12% decrease in lifting-loop capacity when the hook was used instead of the 2.4 in. (61 mm) diameter pin. Note that the lifting-loop capacity reductions associated with the hook are specific to the type and size of hook used in this study, which was a 20-ton (18-tonne) Crosby eye hook. The effects of other hook types may need to be evaluated. The work by Kuchma and Hart[3] also showed lifting loop capacity reductions when hooks were used.

Figure 10 shows the influence of the lifting device by plotting the loop-breaking strength (that is, strand rupture load) relative to the size and type of lifting device. The results for 0.6 in. (15.2 mm) diameter strand determined from this testing study are drawn in black. The other curves are reproduced from the Moustafa study[2] for smaller-diameter strand.

Influence of strand vertical offset on loop capacity

Figure 9 displays the difference between triple-strand loops with a 1 in. (25.4 mm) vertical offset and all other triple-strand loop cases that did not have an intentional offset. The 1 in. vertical offset resulted in an average reduction in load-carrying capacity of 42% relative to the triple-strand cases without offsets. The loops with a vertical offset of 1 in. achieved an average peak load of 157.3 kip (700 kN) and an average peak bond stress of 249 psi (1717 kPa). The vertical offset between the individual loops initiated early strand rupture and reduced the lifting capacity of the loop. The loop with the 1 in. vertical offset that was loaded using a hook

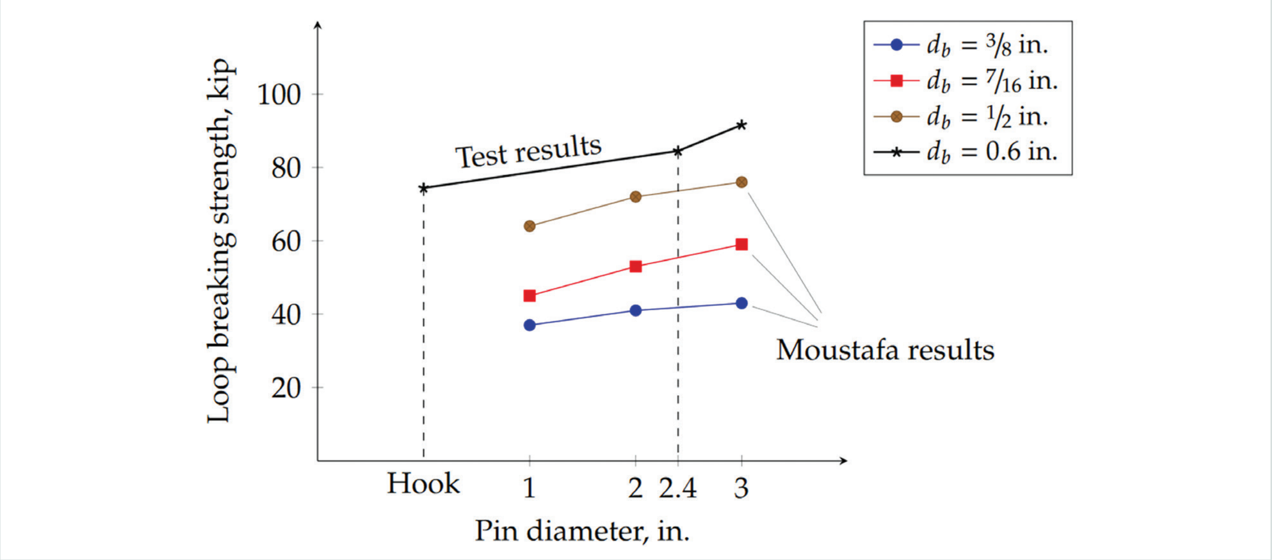


Figure 10. Impact of lifting device on loop breaking strength. Note: d_b = nominal diameter of prestressing strand. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

failed at a peak load of 129.9 kip (578 kN) and a peak bond stress of 205 psi (1413 kPa). This setup had the lowest capacity of all the triple loops tested in this experimental program. The combination of hook and vertical offset adversely affected the lifting performance of this specimen. Efforts should be made to limit vertical offsets to ensure even distribution of load among all loop strands. As discussed previously, even load distribution can be achieved through careful placement of the strands or, more commonly, through a crushed sleeve around the strands.

Bond stress comparison with *PCI Design Handbook* guidelines

Table 3 presents a summary of the test results for 0.6 in. (152 mm) diameter strand loops relative to the guidelines in the eighth edition of the *PCI Design Handbook*.[7] The column for "safe load per *PCI Design Handbook*" presents the loads that can be assumed for single-, double-, triple-, and quadruple-strand loops based on the current guidance in the handbook to use a 10 kip (44.5 kN) safe load for single-strand loops and multipliers of 1.7 and 2.2 for two- and three-strand loops, respectively. The "safe load per bond stress" is the load calculated based on a 100 psi (689 kPa) uniform bond stress assumption. This 100 psi assumption includes a factor of safety of 4. Thus, the safe load per bond stress is multiplied by a factor of safety of 4 to determine the expected capacity of the loops. These values can be compared with the actual peak load observed during testing. The ratio of the actual load obtained from testing and the expected capacity is provided in the final column of the table. Values greater than 1.0 indicate that the 100 psi safe bond stress assumption is conservative

Table 3. Summary of test results for 0.6 in. diameter loops (embedded 36 in. with bent ends) compared with *PCI Design Handbook* guidance

Number of strands in loop *n*	Safe load per *PCI Design Handbook*,* kip	Safe load per bond stress,† kip	Safe load per bond stress times factor of safety (expected capacity),‡ kip	Actual peak load from testing, kip	Ratio of actual peak load to expected capacity
1	10	21	84	84.9	1.01
1	10	40	84	69.3	0.83 (hook used)§
2	17	40	160	170.7	1.07
2	17	40	160	188.2	1.18
2	17	40	160	166.6	1.04
3	22	58	232	271.2	1.17
3	22	58	232	246.7	1.06
3	22	58	232	189.1	0.82 (1 in. vertical offset)§
3	22	58	232	259.7	1.12
3	22	58	232	129.9	0.56 (hook with offset)§
3	22	58	232	211.7	0.91 (hook used)§
4	22	58	185	304.4	1.65
4	22	58	185	245.6	1.33
4	22	58	185	246.7	1.33
4	22	58	185	214.6	1.16
Average					1.08

Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 psi = 6.895 kPa.

* Using 10 kip safe loads and multipliers of 1.7 and 2.2 for two-strand and three- or four-strand loops in one location. These values apply to 0.5 in. diameter strand but are used here because there is no guidance in the eighth edition of the *PCI Design Handbook* for 0.6 in. diameter strand or quadruple-strand-loop multipliers.

† Safe load calculated using the 100 psi bond stress previously calculated based on the safe loads provided in the *PCI Design Handbook* for 0.5 in. diameter strand. Multipliers of 1.9 for double-strand loops and 2.8 for triple- and quadruple-strand loops were used, as determined from this study, instead of the 1.7 and 2.2 multipliers in the eighth edition of the handbook.

‡ Factor of safety of 4 maintained per the *PCI Design Handbook*.

§ Ratios less than 1.0 are considered unconservative.

relative to the actual loads determined from testing. Most tests have ratios greater than 1.0. Those that are unconservative (less than or equal to 1.0) are noted. These four cases applied when a hook was used or when a vertical offset was intentionally created. Thus, if shackles are used instead of hooks and if vertical offsets are avoided through use of crushed sleeves or careful placement of the strands, the 100 psi safe bond stress assumption can be conservatively used. Note that the 100 psi value for assumed bond stress applies to the data presented in this study, and this bond assumption may not apply to all cases. Possible factors that could affect this assumption include, but are not limited to, inadequate embedment, smaller edge distances, the use of more than four strands, lower concrete strengths, lower Mohs hardness, inadequate strand bond, and lifting at angles.

Multiple-strand multipliers

Table 4 presents an evaluation of the multipliers that can be used for double-, triple-, and quadruple-strand loops relative to the multipliers found in the eighth edition of the *PCI Design Handbook*.[7] The average peak loads among single- and multiple-strand tests are reported from the test results. Note that cases with vertical offsets and the use of the hook lifting device were not included in these averages. Because the single-strand tests used 2.4 in. (61 mm) diameter pins and the other tests used 3 in. (76 mm) diameter pins, the averages reported for the multiple-strand cases were adjusted to account for a 2.4 in. diameter pin so that a comparison between single- and multiple-strand cases could be directly compared without consideration of the lifting device. Each of the multiple-strand cases were then compared with the single-strand case to determine the loop multiplier. Multipliers of 1.95, 2.8, and 3.3 were calculated for double-, triple-, and quadruple-strand loops, respectively. These are higher multipliers than the recommendations of 1.7 and 2.2 from the *PCI Design Handbook*. It is presumed that these previously established multipliers may have been developed for building applications where the precast concrete components were not very deep and, thus, the loop embedment depths were not as deep as those tested in this test program. For strands embedded deep enough to preclude pullout or other concrete failures, the multipliers are closer to the number of strands (2, 3, or 4) because they are dictated by strand rupture; however, the multiplier for quadruple-loop cases was only 3.3 because of concrete failure modes. These newly developed multipliers ought to only be used when strands are evenly loaded, embedded deep enough to preclude pullout, and have adequate edge distances. The fact that the multipliers were found to be close to the number of strands also shows that the crushed sleeves provided adequate, even distribution of loading among all strands.

Other potential influences and future work

Some additional parameters were briefly studied in this test program, but they would need to be studied further to make any definitive conclusions. For example, the projection of the loop above the concrete surface (Fig. 4) could not be adequately studied. Projections of 12 and 18 in. (305 and 457 mm) were considered in addition to the typical projection of 6 in. (152 mm). The loops should have been embedded at 36 in. (914 mm) for all cases regardless of projection, but the specimens with longer projections resulted in shorter embedment depths. Thus, direct comparisons could not be made among the 6, 12, and 18 in. projection cases. It is believed that longer projections would increase the loop capacity because

Table 4. Multipliers for single-, double-, triple-, and quadruple-strand loops

Number of strands *n*	Failure modes observed	Average peak load derived from direct test results		Average peak load adjusted for 2.4 in. diameter pin*		*PCI Design Handbook*†
		Kip	Multiplier (× 1 strand)	Kip	Multiplier (× 1 strand)	Multiplier (× 1 strand)
1	Strand rupture	84.9	1.0	84.9	1.0	1.0
2	Strand rupture	179.5	2.1	165.1	1.95	1.7
3	PO + SBO, strand rupture	259.2	3.0	238.5	2.8	2.2
4	PO + SBO	304.4	3.6	280.0	3.3‡	n/a

Note: n/a = not applicable; PO = pullout; SBO = side-face blowout. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

* A 2.4 in. diameter pin was used for single-strand loop cases, and a 3 in. diameter pin was used for the double-, triple-, and quadruple-strand cases. Loads determined from 3 in. diameter pin tests were converted to 2.4 in. diameter pin loads based on the pin diameter–to–load relationship (a loop pulled with a 2.4 in. diameter pin can achieve approximately 92% of the load of a 3 in. diameter pin test).

† Recommendations from eighth edition of the *PCI Design Handbook* for single, double, and triple strands. The handbook does not provide guidance for quadruple strands.

‡ The capacity of four loops was limited by concrete failure mode (PO + SBO).

these loops would have a longer length over which to accommodate the displacement from the loading.

Additional testing would also be needed to adequately investigate the impact of splaying of the strand ends (Fig. 4). It is generally believed that splaying the legs will provide consolidation of concrete around each strand leg and increase the bond capacity around each strand; however, in the limited testing conducted in this study, there was not a notable change in loop capacity. Designers should consider the strand bond quality and the Mohs hardness of the concrete when evaluating the safe lifting load for their lifting loops. In addition, a web width of 7 in. (178 mm) was used in this testing. Smaller edge distances could affect the lifting load capacity. Finally, additional studies should be conducted to consider inclined lifts. Only vertical lifts were tested in this study.

Conclusion

The following conclusions and recommendations can be made based on the results of the experimental testing program.

- The type of lifting device plays a role in determining the capacity of the lifting loop. Hooks (in this case, a 20 ton [18 tonnes] Crosby eye hook) reduced the loop capacity by approximately 12% relative to the 2.4 in. (61 mm) diameter pin.

- Pin diameter also influences the capacity of the lifting loop. The 2.4 in. (61 mm) diameter pin reduced the loop capacity by approximately 8% relative to the 3 in. (76 mm) diameter pin. The guidance from the *PCI Design Handbook*[7] to not use a pin diameter smaller than four times the diameter of the strand should be maintained.

- Vertical offset may affect the overall stiffness and strength of the loops. In this testing program, a vertical offset of 1 in. (25.4 mm), which was approximately two times the diameter of the strand, resulted in a strength reduction of approximately 42%. It is critical that efforts are made to ensure loops are located at the same elevation. Otherwise, progressive failure of the loops will likely result.

- If loops are embedded deep enough to prevent bond failure (as is common in deep bridge girders), multipliers of approximately 2 and 3 can be appropriately used for double- and triple-loop configurations. Values of 1.9 and 2.8 are recommended. For triple-loop bundles and larger, edge effects may begin to play a role and minimize the capacity. In these cases, the multipliers recommended herein may not be applicable.

- While the use of crushed versus uncrushed conduit or pipe was not specifically evaluated in this test program, Fig. 2 showed the impact of crushing the sleeve before the strand bundle is bent. It can be seen that, compared with an uncrushed sleeve, a crushed sleeve does a far better job of reducing vertical offsets between the strands. The significant impact of vertical offsets was shown in this study, and these offsets should be avoided. Uncrushed pipe or conduit should not be used in lifting loops.

While not tested as a design parameter within this study, it is known that soft coarse aggregates (that is, aggregates with low Mohs hardness) and marginal bond quality from ASTM A1081 testing[10] will decrease the lifting-loop capacity.[9] If using the test results in this study to predict lifting-loop capacities, one must be aware of the Mohs hardness of the coarse aggregate and the bond quality being used in the design. Values that are lower than those determined in this test program may be unconservative.

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Notation

A_{bond} = surface area of the strand

d_b = nominal diameter of the prestressing strand

h_{ef} = embedment depth

L = total loop embedment

L_{bend} = length of bent ends of strand

n = number of strands in loop

P = average peak load recorded from experimental testing

P_u = ultimate tensile strength of strand

P_y = tensile yield strength of strand

τ_p = measured peak bond stress of prestressing strand

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Abstract

An experimental investigation of 28 tests was conducted to determine the load-carrying capacity of 0.6 in. (15.2 mm) diameter prestressing strand lifting loops. The parameters studied were number of strands in a loop (1, 2, 3, or 4), lifting device (shackle or hook), vertical offset or use of a crushed sleeve, projection of loop from the top of the concrete, and splaying of strand legs. Strand rupture was the primary failure mode, though pullout and side-face blowout became prominent modes in multiple-strand cases. A uniform bond stress of 100 psi (690 kPa) can be used to determine a safe load. Multipliers of 1.9, 2.8, and 3.3 were determined for double-, triple-, and quadruple-strand loops. Hooks decreased the loop's capacity by approximately 12% relative to a 2.4 in. (61 mm) diameter pin. A vertical offset of 1 in. (25.4 mm) decreased the loop's capacity by approximately 42%. Efforts should be made to ensure even loading of the multiple strands within a loop.

Keywords

Anchorage in concrete, bond behavior, lifting devices, lifting loops, prestressing strand, pullout capacity.

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