Unbonded seven-wire prestressing strands provide the primary reinforcement in post-tensioned concrete slabs. Strand corrosion can result in broken wires, which require expensive inspections and strand replacements.

During these inspections, strands that are suspected of being corroded are exposed and inspected visually and a screwdriver penetration test is performed. Penetration of the screwdriver between any two adjacent wires is an indication that one of the wires may be broken or that the strand is unstressed or de-stressed.

In this study, penetration tests were conducted on corroded strands with broken wires. The purpose of the study was twofold: to determine the distance from an inspection location where a wire break may be detected using penetration tests and to determine how corrosion products between the wires of a strand affect the accuracy of the penetration tests.

During testing, corroded strands were stressed to typical service-load levels and the load and boundary conditions of an unbonded, post-tensioned concrete slab were simulated. Two outer wires were cut in succession, and penetration tests were performed along the strand. It was observed that penetration can be achieved between a broken and an unbroken wire within a region where the strain in the broken wire is less than about 200με.
North America now has more than 1 billion ft$^2$ (93 million m$^2$) of unbonded, post-tensioned concrete construction, and seven-wire prestressing strands provide the primary reinforcement in these structures.

In some cases, concerns have been raised because water entering into the plastic sheathing surrounding unbonded tendons has caused corrosion, wire breakage, and strand rupture, leading to a loss of prestressing force. Inspection of unbonded, post-tensioned concrete slabs to determine strand corrosion is challenging because the strands are inaccessible to visual inspection and external evidence of deterioration is seldom apparent.

Currently, many unbonded, post-tensioned concrete buildings suspected of having corroded strands are assessed using the screwdriver penetration test (SPT). Figure 1 shows an SPT being conducted. During an SPT, the concrete cover is removed over an 8 in. to 12 in. (200 mm to 300 mm) length, the post-tensioning sheathing is cut open, and the strand is exposed. The operator then attempts to drive a screwdriver tip between individual wires of the strand. Penetration of the screwdriver tip into the wires indicates a lack of full tension in the strand or individual wire breakage. The common version of the SPT utilizes a simple carpenter’s hammer to strike a screwdriver. A more sophisticated version of the SPT, shown in Fig. 1, delivers a consistent impact to the strand each time the test is conducted.

**SPT ACCURACY**

The SPT is a simple and economical test for inspecting unbonded strands during the preliminary stages of a structural assessment of a post-tensioned building. Much of the published literature does not address the accuracy of the method, and the SPT has been criticized as relying too heavily on the skill and the strength of the operator. Two primary variables, the impact force of the hammer and the subjective judgment of the operator as to the wire resistance, are thought to affect the SPT results. In addition, it is thought that the SPT will not detect wire breaks if breakage occurs some distance from the inspection location. Bonding of the strand due to corrosion or intermediate anchorages also may mask the presence of broken wires.

The objective of this work is to understand the efficacy of the SPT in finding wire breaks or lower values of prestressing in seven-wire prestressing strands. In the test program, corroded strands are tensioned to service-load levels typical of unbonded, post-tensioned concrete slabs. Individual wires are cut to simulate breakage in a deteriorating, unbonded, post-tensioned slab. Finally, the SPT is performed along the length of the strands to determine whether the broken wire can be differentiated from the unbroken wires. The distance from the test site that breaks may be accurately determined is also studied.

**STUDIES OF SPT EFFICACY**

Literature has reported limited test results on the detection of post-tensioning strands with broken wires. In deriving a Baysian model for optimiz-
ing the inspection of unbonded, post-tensioned concrete slabs, Pandey and Nessim assumption that the SPT could detect wire breakage that occurred 60 ft to 90 ft (20 m to 30 m) from the inspection location, an assumption also suggested by Webster.6

MacDougall and Bartlett7,8 derived and experimentally verified a model for the behavior of unbonded, post-tensioned, seven-wire strands with wire breaks. Figure 2 shows the predicted wire strain distribution in a seven-wire strand with two diametrically opposed wire breaks. Within the affected length $L_a$, the strain in the broken wires $\varepsilon_b(x)$ increases exponentially while the strains in the unbroken wires $\varepsilon_u(x)$ decrease exponentially with distance from the break. Beyond the affected length, the strains in the broken and unbroken wires are equal. The affected length is governed primarily by the coefficient of friction among the wires and the space between outer wires. As friction increases (due to corrosion, for example), the affected length decreases. It is believed that the SPT will detect broken wires only if it is performed within the affected length, though this has not been verified through experiments.

Figure 2 also shows the predicted strains in a tendon with one broken wire. Behavior similar to that shown for the two diametrically opposed broken wires is exhibited. However, the strains in the unbroken wires within the affected length are not equal. To distinguish the relative position of the broken wire to the various unbroken wires, the classification shown in Fig. 3 is employed. The wires adjacent to the broken wire are labeled $W_{60}^\circ$, the wire opposite the broken wire is $W_{180}^\circ$, and the other two wires are $W_{120}^\circ$. Similarly, the strain in these wires is $\varepsilon_{60}^\circ$, $\varepsilon_{180}^\circ$, and $\varepsilon_{120}^\circ$, respectively.

### EXPERIMENTAL METHODS

In this study, three 0.375 in. (9.5 mm) nominal diameter and three 0.5 in. (13 mm) nominal diameter, low-relaxation, seven-wire strands were tested. Each strand had a nominal ultimate strength of 270 ksi (1860 MPa) and a modulus of elasticity of 28,000 ksi (190 GPa). Table 1 summarizes the geometric properties of all tested strands.

Each strand was unraveled into seven individual wires and immersed in a 5% (by weight) salt solution for about 21 days to accelerate corrosion. The seven wires were then raveled back into strands. The entire strand was again put into the salt solution and corroded for 17 to 19 days. The strand was removed from the saline solution and stored in lab air until testing. Figure 4 illustrates the typical level of corrosion. Heavy rust was observed along the outer surface of all of the strands, and pits of about 0.04 in. (1.0 mm) in diameter were observed on the wire surface when an area of the surface was cleaned. The purpose of the procedure was to increase interwire friction by creating a uniform level of corrosion on the surface of each wire along the inside of the strand. The study is not intended to simulate a specific level of damage in post-tensioned concrete slabs.

Table 1. Strand Geometric Properties

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>0.125</td>
<td>0.130</td>
<td>4.9</td>
</tr>
<tr>
<td>0.5</td>
<td>0.167</td>
<td>0.173</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Note: $p = \text{lay length (longitudinal distance along the length of the strand required for a complete helical wrap of one of the outer wires).}$ 1 in. = 25.4 mm.
Bearing plates are provided at each end of the beam. The strand is gripped by wedges at the dead end of the beam while the strand is gripped and elongated by a hydraulic jack at the live end of the beam. Each strand was instrumented with 19 foil strain gauges mounted on the wires as indicated in Fig. 6. A linear variable differential transducer, shown in Fig. 7, was used to measure total tendon elongation, and a load cell, shown in Fig. 8, was used to measure total tendon load.

Two penetration tests for detecting wire breaks were considered. The first test used a conventional SPT with a flat-blade screwdriver and hammer. There are no published standards for this test, but Harder et al.\(^1\) describe the procedure. The second approach, called the modified penetration test (MPT), used the modified Schmidt hammer shown in Fig. 9. The plunger was modified to incorporate a tip with a blade thickness of 0.04 in. (1.0 mm) and a width of 0.25 in. (6.4 mm). The Schmidt hammer employs an internal mass attached to a spring. The spring is elongated and then released to provide a more consistent impact force in testing.

Before the wires were cut, each strand underwent three cycles of tensioning to evaluate the strand stiffness. In general, the loss in axial stiffness due to the unraveling and corrosion of the wires, compared with the as-received strands, was 1% to 8%.\(^12\) The strand was then elongated about 4 in. (100 mm), corresponding to a strand stress of 56% of the nominal ultimate stress \(f_{pu}\). This is a typical strand stress at service after losses and relaxation. The elongation was then held for at least one hour to ensure consistent readings from the instrumentation.

One outer wire was cut at midspan using a handheld cutting wheel. Care was taken to ensure that the surrounding wires were not damaged during this process. The strand was held in this condition for about one hour to allow any further relaxation to take place. Wire strain and strand load readings were then recorded. During impact, the screwdriver tip or the Schmidt hammer tip must be held pointing straight to the center of the strand cross section. Penetration was found when a distinct popping-in of the screwdriver tip occurred between the two wires. In penetration, the wires were clearly separated by about 0.04 in. to 0.08 in. (1.0 mm to 2.0 mm) and the screwdriver could be held in place by the forces of the wires of the strand. The screwdriver had to be pried from between the wires following penetration. If no penetration occurred, the operator felt a strong resistance from the impacted tip and the tip would slip away from the wires. Once the penetration tests were completed, a second outer wire—diametrically opposite the first wire—was cut and the strand was once again left for one hour. Wire strains and strand load were again recorded, and penetration tests were repeated along the length of the strand.

**TEST RESULTS**

Figure 10 presents a typical strain distribution for a 0.375-in.-diameter (9.5 mm) tendon with a single broken wire. The dashed horizontal line indicates the average outer-wire strain...
before the wire was cut. The strain distribution is symmetrical about the wire break location,\textsuperscript{7,8} so only the strains on one side of the strand are shown. Close to the wire break, the strains in wires $W_{\pm60^\circ}$ were about 15% higher than the strains in the same wires before the wire break occurred. The strain in wires $W_{\pm60^\circ}$ decreased with distance from the wire break. The strain in wires $W_{120^\circ}$ was similar to the wire strain before the wire break and stayed relatively constant with distance from the wire break. The strain in wire $W_{180^\circ}$, about 3.9 ft (1.2 m) from the wire break, was about 24% less than the wire strain before the wire break occurred; the strain in this wire increased with distance from the wire break.

Finally, the broken wire itself had strains less than 1000\(\mu\varepsilon\) within 40 in. (1000 mm) of the wire break. With increasing distance from the wire break, the strain in the broken wire rapidly increased due to the friction between the wires. About 6.7 ft (2.0 m) from the wire break, the broken wire recovered its share of the tendon strain, and the strains in all six outer wires were approximately equal to their respective wire strains before the wire break occurred. Thus, the affected length $L_a$ for this tendon was 13.3 ft (4.1 m).

Figure 11 shows the strain distribution in the wires after a second wire ($W_{180^\circ}$) was cut. The horizontal dashed line is the average outer-wire strain before breaking the wires. For this case, the strains in the four unbroken wires ($W_{60^\circ}$ and $W_{120^\circ}$) were all equal at each location beyond the wire breaks. At the wire-break location, the strains in these wires were about 35% greater than the strains before the wires were broken.

The strains in the unbroken wires decreased with distance from the wire break. Alternatively, the strains in the two broken wires were equal to each other at a given location beyond the breaks. The strains in these wires were close to zero at and increased with distance from the break location. At about 5.8 ft (1.8 m) from the wire breaks, the strains in the broken and unbroken wires were again equal to each other and approximately equal to the strain before the wires were cut. Thus, with two broken wires, the affected length was 11.7 ft (3.6 m).

The 0.5-in.-diameter (13 mm) tendons did not exhibit clear affected lengths within the 60 ft (18 m) length of the test beam. Figure 12 plots a typical distribution of outer-wire strains for a 0.5-in.-diameter (13 mm) tendon with two broken wires. The strain data points for the unbroken wires, though scattered, are for the most part greater than the strain before the wires were broken. The only exception is the strain value for wire $W_{120^\circ}$ at 300 in. (7.6 m) from the wire break. This value is significantly lower than the prebreak average strain. Other than this value, there was no evidence of the unbroken wire strains decreasing with distance from the wire breaks. The strains in the broken wires

---

**Fig. 10.** Distribution of outer-wire strains for 0.375-in.-diameter strand with one broken wire. See Fig. 3 for strand nomenclature. Note: 1 in. = 25.4 mm.

**Fig. 11.** Distribution of outer-wire strains for 0.375-in.-diameter strand with two broken wires. Note: 1 in. = 25.4 mm.
were all close to zero, and strains did not increase with distance from the wire break.

Table 2 summarizes the observed affected lengths based on the strain distribution measurements. The 0.5-in.-diameter (13 mm) strands had affected lengths that exceeded the 60 ft (18 m) length of the test beam. The 0.375-in.-diameter (9.5 mm) strands had affected lengths that varied from 10 ft (3.0 m) to 30 ft (9.0 m). Generally, the affected lengths observed for the 0.375-in.-diameter strand were about 30% longer after two wires were broken than after a single wire was broken. This result is consistent with observations made by MacDougall and Bartlett.8

Following the cutting of each wire, penetration tests were performed between each broken and unbroken wire along the entire length of the strand. SPTs and MPTs were both attempted. It was observed that penetration could not be achieved between any two adjacent unbroken wires anywhere along the length of the strand. Penetration was only achieved between a broken and unbroken wire and only within a region of low broken-wire strain. Comparison with the wire strain data indicated that penetration was not achieved over the entire affected length but rather in a region where the broken wire strains were close to zero or up to 4 to 8 × 10^-6 in./in. (100 to 200 × 10^-6 mm/mm). As the broken-wire strains began to increase, penetration could no longer be achieved.

Table 3 summarizes the results of the penetration tests. For strands 5 and 6, penetration was achieved for the broken wires along the entire length of the strand. This is consistent with the observed affected lengths. For strand 4, penetration was achieved over a length centered at the wire break of 33 ft (10 m) and about 43.3 ft (13.2 m) following one and two broken outer wires, respectively. An affected length could not be determined from the strain data for strand 4. The penetration test results, however, suggest that the wire strains would likely equalize just beyond the 60 ft (18 m) length of the test beam. The MPT was capable of detecting the broken wires over a greater length of the strand than the conventional SPT. The MPT detection length for the 0.375-in.-diameter (9.5 mm) strand tests was from 10% to 50% greater than the SPT detection length.

An important parameter for engineers assessing unbonded, post-tensioned concrete slabs is the prestressing force loss following wire breaks. Table 4 summarizes the strand load measured

![Graph](image_url)

**Fig. 12.** Distribution of outer-wire strains for 0.5-in.-diameter strand with one broken wire. Note: 1 in. = 25.4 mm.

**Table 2. Measured Affected Lengths \( L_a \) from Strain Gauge Measurements**

<table>
<thead>
<tr>
<th>Strand</th>
<th>Diameter, in.</th>
<th>( L_a ) - One Broken Wire, ft</th>
<th>( L_a ) - Two Broken Wires, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.375</td>
<td>10</td>
<td>13.3</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
<td>23.3</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
</tbody>
</table>

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.

**Table 3. Penetration Test Limits**

<table>
<thead>
<tr>
<th>Strand</th>
<th>Diameter, in.</th>
<th>One Broken Wire</th>
<th>Two Broken Wires</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SPT, ft</td>
<td>MPT, ft</td>
</tr>
<tr>
<td>1</td>
<td>0.375</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
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<td>8.3</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
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<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
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<td>43.3</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
</tbody>
</table>

Note: MPT = modified penetration test; SPT = screwdriver penetration test. 1 in. = 25.4 mm; 1 ft = 0.3048 m.
before any wires were cut $F_{sb}$, the load following the first wire cut $F_{b1}$, and the load following the second wire cut $F_{b2}$. The remaining prestressing load fractions $r_{b1}$ and $r_{b2}$ are the ratios of the strand load after the wire breaks to the strand load before the wire breaks occurred. Results indicate that the load in strands 1, 2, and 3 was reduced only 2% to 5% following the first wire break and only 8% to 12% following the second wire break. If there was no friction between the wires, the expected strand load reduction would be about 14% (one-seventh) and 28% (two-sevenths) following one and two wire breaks, respectively. The prestressing force losses for strands 4, 5, and 6 were significantly greater than those for the 0.375-in.-diameter (9.5 mm) strands: 14% to 18% and 22% to 28% following one- and two-wire breaks, respectively.

### DISCUSSION

Previous work by MacDougall and Bartlett\(^7,8,13\) investigated seven-wire strands with broken wires loaded in a quasi-static manner. Wires were cut before the strand was tensioned. In a concrete slab in the field, the strands are in tension when corrosion takes place and the wires break. The tests in the present study verified several important aspects of strand behavior when wires break while the strand is tensioned.

In particular, it was found that if the interwire friction is high enough due to corrosion, as it was with the 0.375-in.-diameter (9.5 mm) strands, an affected length of low broken-wire strain is formed after each wire break. It was verified, as the work of MacDougall and Bartlett\(^8\) suggests, that the strains in the unbroken wires after a single wire breaks are not uniform along the affected length. The strains in the unbroken wires adjacent to the broken wire $W_{adj}$ were up to 15% higher than those in the unbroken wires before the wire break occurred.

This is important because it suggests that after the first wire breaks, the adjacent wires are likely to break soon thereafter due to elevated strains. In addition, strains in the broken wires increase and strains in the unbroken wires decrease with distance away from the break within the affected length.

Some promising findings regarding penetration tests for finding wire breaks in seven-wire strands were made. First, penetration tests were quite effective at distinguishing between broken and unbroken wires provided that the strain in the broken wires is low. Tables 5 and 6 compare the penetration limits and the observed affected lengths. Because the affected lengths exceeded the length of the strand for the 0.5-in.-diameter (13 mm) strands, only the results for the 0.375-in.-diameter (9.5 mm) strands subjected to the SPT are shown. Results for the MPT are similar. The SPT can penetrate more than 13% to 33% of the affected length for strands with a single wire break and more than 43% to 69% of the affected length for strands with two wire breaks. This detection length corresponds to broken-wire strains of less than about 200 με. For steel wires with a modulus of elasticity of about 29,000 ksi (200,000 MPa), this corresponds to a stress of 5.8 ksi (40 MPa).

In the field, penetration tests are also used to find strands that have not been properly tensioned during construction. This finding suggests that penetration tests will not penetrate wires unless the strand stress is less than 5.8 ksi (40 MPa). Further investigation of a penetration device with an impact force that can penetrate unbroken wires at a much higher strand stress could be useful for finding strands that have not been

| Table 4. Load Fractions for Strands after Cutting Wires |
|---|---|---|---|---|---|
| Strand | Diameter, in. | $F_{sb}$, kip | $F_{b1}$, kip | $F_{b2}$, kip | $r_{b1}$ | $r_{b2}$ |
| 1 | 0.375 | 11.5 | 11.1 | 10.6 | 0.97 | 0.92 |
| 2 | 0.375 | 11.3 | 10.7 | 10.0 | 0.95 | 0.88 |
| 3 | 0.375 | 11.5 | 11.2 | 10.7 | 0.98 | 0.93 |
| 4 | 0.5 | 16.2 | 13.7 | 12.6 | 0.85 | 0.78 |
| 5 | 0.5 | 19.8 | 16.2 | 14.2 | 0.82 | 0.72 |
| 6 | 0.5 | 19.3 | 15.8 | 13.8 | 0.82 | 0.72 |

Note: $F_{sb}$ = strand load before any wires were cut; $F_{b1}$ = load after first wire cut; $F_{b2}$ = load after second wire cut; $r_{b1}$ and $r_{b2}$ = ratio of strand load after wire break to load before wire break. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

| Table 5. Comparison between Observed Penetration Limits and Affected Lengths for One Broken Wire |
|---|---|---|---|
| Strand | SPT Limit, in. | Affected Length $L_{am}$, in. | SPT Limit/$L_{am}$, % |
| 1 | 40 | 120 | 33 |
| 2 | 90 | 280 | 32 |
| 3 | 20 | 160 | 13 |

Note: SPT = screwdriver penetration test. 1 in. = 25.4 mm.

| Table 6. Comparison between Observed Penetration Limits and Affected Lengths for Two Broken Wires |
|---|---|---|---|
| Strand | SPT Limit, in. | Affected Length $L_{am}$, in. | SPT Limit/$L_{am}$, % |
| 1 | 110 | 160 | 69 |
| 2 | 220 | 360 | 61 |
| 3 | 70 | 160 | 44 |

Note: SPT = screwdriver penetration test. 1 in. = 25.4 mm.
properly tensioned at construction.

Conventional penetration tests have been criticized as depending heavily on the strength of the operator. In this study, Li conducted all of the conventional penetration tests. A Schmidt hammer was used to conduct a second set of penetration tests using a consistent impact force. The results in Table 3, comparing the SPT and MPT, show that the conventional SPT provides results remarkably similar to those of the MPT. However, the length of the strand over which the MPT is able to detect the broken wire is about 10% to 50% greater than that for the SPT. Further work is needed to compare SPT results among a variety of operators to determine whether consistency can still be achieved.

There was a wide range in observed affected lengths (Table 2). In particular, the affected lengths of the 0.5-in.-diameter (13 mm) strands all exceeded 60 ft (18 m), while the affected lengths of the 0.375-in.-diameter (9.5 mm) strands varied from 10 ft to 30 ft (3.0 m to 9.0 m). To understand differences in the affected lengths observed for the six strands and under different testing conditions, it is important to recognize the role of strand geometry and interwire friction on material behavior as wires break. MacDougal and Bartlett6 derived expressions for the affected length. However, for strands of nominal diameter of 0.375 in., 0.5 in., or 0.75 in. (20 mm) that are subjected to an uplift force typical of an unbonded, post-tensioned concrete slab, the affected length can be approximated as:12

$$L_a = \frac{12p}{\mu}$$  \hspace{1cm} (1)

where

$L_a$ = affected length of post-tensioning strand

$p$ = lay length (longitudinal distance along the length of the strand required for a complete helical wrap of one of the outer wires)

$\mu$ = coefficient of interwire friction

The error in the predicted affected length using Eq. (1) is about 5%. Equation (1) suggests that for two strands with the same $\mu$, the strand with the greater lay length will have an affected length larger by the ratio of the lay lengths. Thus, for the strands examined in this study, it would be expected that the 0.5-in.-diameter (13 mm) strands should have affected lengths of 1.45 times (7.1 in./4.9 in.) longer than the 0.375-in.-diameter (9.5 mm) strands. Results presented in Table 2 indicate, however, that the 0.5-in.-diameter strand affected lengths were much greater than 1.45 times longer than the 0.375-in.-diameter strand affected lengths. The corrosion between adjacent wires significantly affects the coefficient of interwire friction.13

Although each strand was nominally subjected to the same accelerated corrosion environment, corrosion is highly variable and even small differences in the coefficient of interwire friction will significantly affect the strand response. It was observed that corrosion product seemed to fill the small inner gaps between the wires of the 0.375-in.-diameter (9.5 mm) strands. This was not observed for the 0.5-in.-diameter (13 mm) strands, which have much larger gaps between the wires. The filling of these gaps could increase the friction between the wires and, therefore, reduce the affected lengths of the 0.375-in.-diameter strands.

The finding that the 0.375-in.-diameter (9.5 mm) strands had higher interwire friction is confirmed by the remaining prestress fraction results (Table 4). The 0.375-in.-diameter strands had much higher remaining prestress fractions than did the 0.5-in.-diameter (13 mm) strands. In fact, the remaining prestress fractions for the 0.5-in.-diameter strands approached the theoretical lower limit that would be expected if there was no friction between the wires. More testing and analysis to further understand these differences are clearly needed.

Webster6 and Pandey and Nessim5 suggested that the SPT can detect wire breaks that occur about 60 ft to 90 ft (20 m to 30 m) away from an inspection location. The results presented in this study suggest that for cases of high interwire friction, such as in the 0.375-in.-diameter (9.5 mm) strands, these limits are overly optimistic and more inspection locations than suggested by Pandey and Nessim5 would be needed to find strands with broken wires.

Alternatively, 0.375-in.-diameter (9.5 mm) strands are rarely used for post-tensioned concrete slabs, and the results for the more-common 0.5-in.-diameter (13 mm) strands showed that the SPT can accurately distinguish between broken and unbroken wires over at least 60 ft (20 m), which is certainly in the range of previous research. It should also be emphasized that the corrosion process in this study is extreme; the wires were corroded over their entire length and over the inner surfaces.

In practice, it is usually observed that corrosion is highly localized and tends to occur at the low points in the drape of strands or close to the anchorages where water enters a duct.4 The interwire friction would be high in the corroded region but low in the uncorroded region. Unless the broken-wire strains increased rapidly within the corroded zone, it is likely that the strand behavior will be dominated by the much longer uncorroded region, leading to longer affected lengths.

An estimate of the critical length of corroded zone is 10 ft (3.0 m), the shortest affected length measured (Table 2). Harder et al.3 suggest that a few strands should be extracted for their full length during an inspection of a post-tensioned concrete slab. Inspection of these strands would give evidence as to whether the corrosion tends to occur over the entire length or over localized patches. This evidence, in turn, will give engineers an estimate of the distances over which they can expect the SPT to detect broken wires for other inspections. Again, further testing of strands with localized corrosion is clearly needed to further clarify the detection limits of the SPT.

A final comment is warranted regarding the observed remaining prestress fractions (Table 4). It may appear that for the 0.375-in.-diameter (9.5 mm) strands, friction plays a beneficial role because it prevents the broken wires from losing all of their strain, and the prestress loss is only 2% to 5% for each wire break, rather than 14%. It must be emphasized, however, that engineers counting on this effect are essentially relying on corrosion for prestressing the slab. Corrosion also makes it more difficult to find broken wires during an inspection.
CONCLUSIONS

This study has furthered the understanding of the mechanics of unbonded seven-wire strands as wires break due to corrosion. In addition, the understanding of the detection limits of penetration tests has also been advanced. It should be noted that in practice, corrosion locations are usually localized, such as at low points in tendon drapes. Thus, the uniform interwire corrosion induced in the test strands is a more severe case than that typically encountered in the field.

This work led to specific conclusions:

• Following a single wire break, strains in the unbroken wires are not uniform within the affected length. The strains in the unbroken wires adjacent to the broken wire are up to 15% higher than they were before the wire break occurred.

• The affected lengths of the 0.5-in.-diameter (13 mm) strands all exceeded 60 ft (18 m), while the affected lengths of the 0.375-in.-diameter (9.5 mm) strands varied from 10 ft (3.0 m) to 30 ft (9.0 m).

• For the 0.375-in.-diameter (9.5 mm) strands, the SPT and MPT are capable of detecting broken wires, provided that the strain in the broken wires is less than about 200 με. This condition corresponds to penetration of 13% to 33% of the affected length for strands with a single wire break and over 43% to 69% of the affected length for strands with two wire breaks. The tests were not able to penetrate between any two unbroken wires tensioned up to about 56% $f_{pu}$.

• For the 0.375-in.-diameter (9.5 mm) strands, wire detection results using a handheld hammer and screwdriver were similar to the results using the modified Schmidt hammer. The length of the strand over which the modified Schmidt hammer was able to detect the broken wire, however, was about 10% to 50% greater than that for the tests using the handheld hammer and screwdriver.

• Further investigation of a penetration device with an impact force that can penetrate unbroken wires at a much higher strand stress could be useful for finding strands that have not been properly tensioned during construction.

ACKNOWLEDGMENTS

The authors thank Queen’s University, the Ontario Graduate Scholarship, and the Natural Science and Engineering Research Council of Canada for providing the funding necessary for this study and Pre-Con Inc. for generously providing the seven-wire strands. The authors extend their appreciation to the PCI Journal reviewers for their constructive comments.

REFERENCES


APPENDIX: NOTATION

$f_{pu}$ = ultimate strength of a seven-wire strand

$F_{bn}$ = axial force in a strand with broken wires

$F_{ab}$ = axial force in a strand with unbroken wires

$L_a$ = affected length of post-tensioning strand

$p$ = lay length of a seven-wire strand

$r$ = remaining prestressing strand force fraction

$W_{\pm 60^\circ}$, $W_{\pm 120^\circ}$, $W_{180^\circ}$ = unbroken outer wires oriented ±60°, ±120°, and 180°, respectively, from the broken wire (Fig. 3)

$\varepsilon_{a}(x)$ = axial strain in broken wire at distance $x$ from break

$\varepsilon_{a}(x)$ = axial strain in unbroken wires for tendon with symmetric break

$\varepsilon_{a}(x), \varepsilon_{b}(x), \varepsilon_{c}(x)$ = axial strains in unbroken outer wires oriented ±60°, ±120°, and 180°, respectively, from the broken wire

$\mu$ = coefficient of interwire friction