Deterioration, Evaluation, and Repair of Post-Tensioned Condominium Structures

GENERAL
Building Services

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Post-tensioning

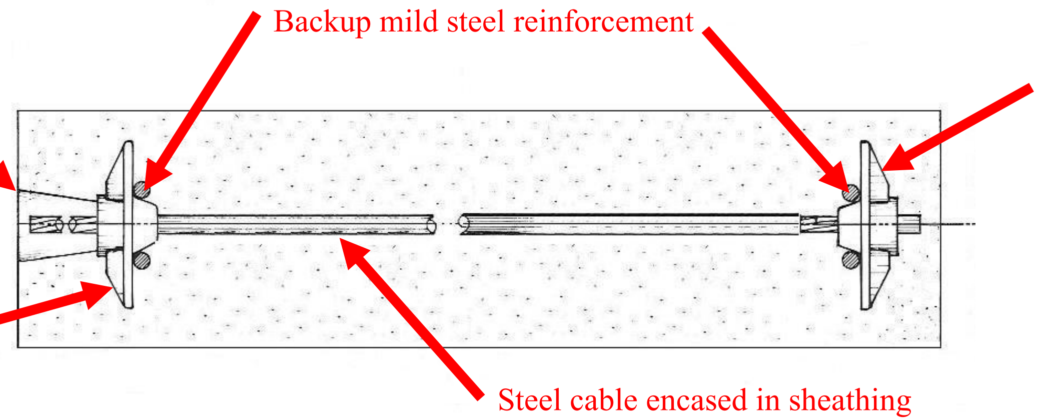
- Definitions
- Two-way slab
- Terminal anchors
- Strand
- Cable sheathing

Definitions

- Add tendons – Usually short in length, added and placed in specific locations, to increase the local prestressing force.
- Anchor: A device used to transfer cable force to the concrete. Anchors are found at each end, and sometimes intermediate on long span lengths.
- Backup bars: Mild steel reinforcement installed parallel to slab edge used to resist tensile forces in the concrete caused by the application of tensioning force.
- Cable: Same as strand, in condominium construction, they are typically a ½" diameter seven wire prestressing steel that conforms to ASTM A416/A416M, encased in sheathing and covered with corrosion inhibiting grease.
- Lock-off anchor: (also known as Trouble-shooting Anchor) A special temporary anchor used for the repair of existing unbonded single strand tendons.
- Post-tensioning (PT) – A method of structural reinforcement using prestressing steel cables, and which is tensioned after the concrete has hardened. Cables remain unbonded to the structural concrete member.
- Prestressed concrete – A method of structural reinforcement using prestressing steel cables, and which is tensioned before the concrete has hardened. Cables are bonded directly to the structural concrete member.
- Prestressing steel – High-strength steel used to prestress concrete, consisting of seven-wire strands, bars, wires, or groups of such elements.

Definitions

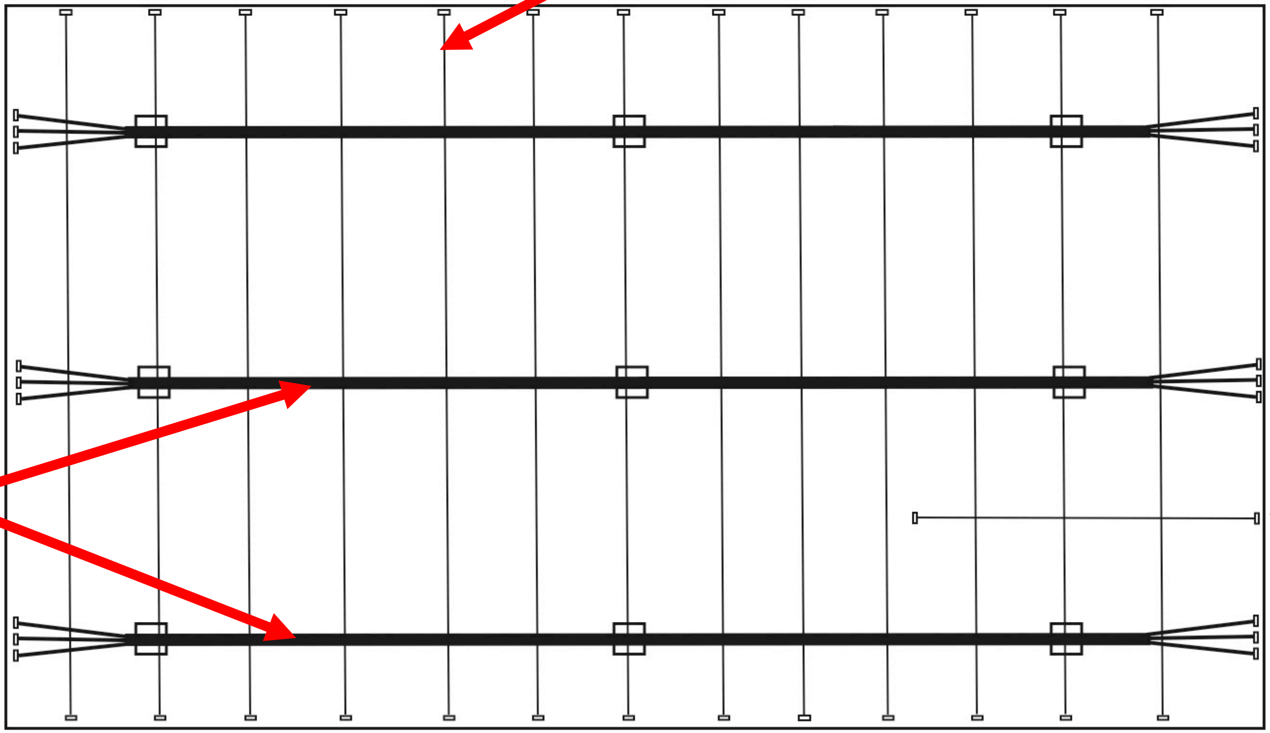
- Sheathing: Polyethylene or plastic (sometimes paper) casing surrounding the steel strand, to provide protection of the cable, and which is used to create an unbonded tendon condition in the concrete.
- Strand: Same as cable.
- Stressing pocket – The recess created by the pocket former between the stressing or intermediate anchorage and the edge of the concrete to allow the nosepiece access for stressing.
- Tendon: Is the complete assembly of anchors, splice couplers, duct, and strand encased in sheathing.
- Post-Tensioning Institute (PTI) is the governing body that provides all forms of official certification related to the post-tensioning industry. https://www.post-tensioning.org



Typical Two-Way PT Slab

Plan view of typical slab

Uniform or Distributed tendons are usually single tendons that are uniformly spaced in one direction, typically perpendicular to banded tendons or beams.



Banded tendons are tightly spaced bundles of cables that are often centered over column line.

Add tendons are usually short cables added to a specific location to increase localized PT forces

Terminal Anchors

- Anchors are found at the ends of each cable and transfer force into the concrete.

- **Bare cast iron anchors**
  - ✓ Provides no corrosion protection of the anchor or strand. Highly prone to corrosion.
- **Encapsulated anchors**
  - ✓ Polyethylene encapsulation of the cable, anchor, and end pockets can provide a measure of corrosion protection, but only if properly installed. Improper installation of the stressing anchor pocket seal and grout are a common failure, and will allow moisture to enter tendon and lead to corrosion damage.

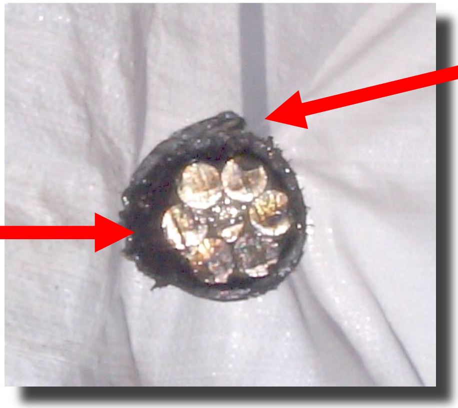
Post-Tensioned Strand

- Post-tensioned cables are made of high strength steel wires twisted around a center wire.
- ½” diameter seven wire post-tensioned cables have been used extensively in residential structures constructed since the 1990’s (particularly in coastal areas).
- Cables are stressed to 80% of the specified tensile strength of the strand, which is 33 kips for ½” diameter cables.

Cable Sheathing

➢ Heat-sealed plastic

- ✓ Found in older structures (pre-1980's).
- ✓ Uses a flat plastic strip and a heat-sealed seam to create a round cable sheathing.
- ✓ It is common for the seam to fail and allow water to enter the cable.
- ✓ Sheathing is larger in diameter and a void exists along cable length. Will retain water.
- ✓ Structures with this type of sheathing should be examined closely for cable corrosion.
- ✓ Corrosion can affect the cables anywhere along their length, and far from any concrete spalling at the terminal anchors.



Larger diameter of sheathing leaves a void that can hold moisture

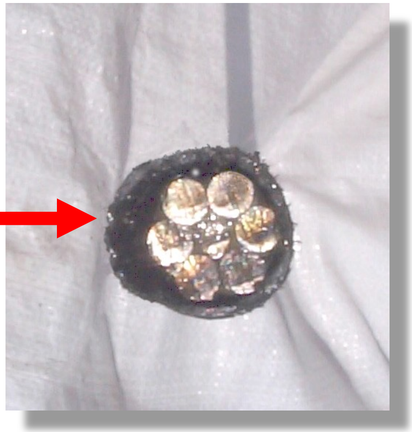
Overlapping heat-sealed seam can fail and permit moisture to infiltrate the cable

Cable Sheathing

Push through plastic

- Found in older structures (pre-1980's).
- Uses extruded plastic to create the cable sheathing.
- This sheathing is larger in diameter and a void exists along cable length. Will retain water.
- Structures with this type of sheathing should be examined closely for cable corrosion.
- Corrosion can affect the cables anywhere along their length, and far from any concrete cracking or spalling.

Larger diameter of sheathing leaves a void that can hold moisture



Cable Sheathing

Extruded plastic

- The PTI currently certifies the use of this type of sheathing.
- Method of assembly leaves minimal void between cable and sheathing, which is filled with corrosion inhibiting grease (effectively eliminating any voids).
- Can be watertight when used with an encapsulated anchor system.
- Cables are still susceptible to localized damage conditions, but less to systemic problems.

Improved sheathing will protect the cables from moisture

Causes of Damage

- Embedded rebar corrosion
- Water infiltration
- Construction defects
- Strand corrosion
- Cutting & drilling into strands
- Bonded strand corrosion

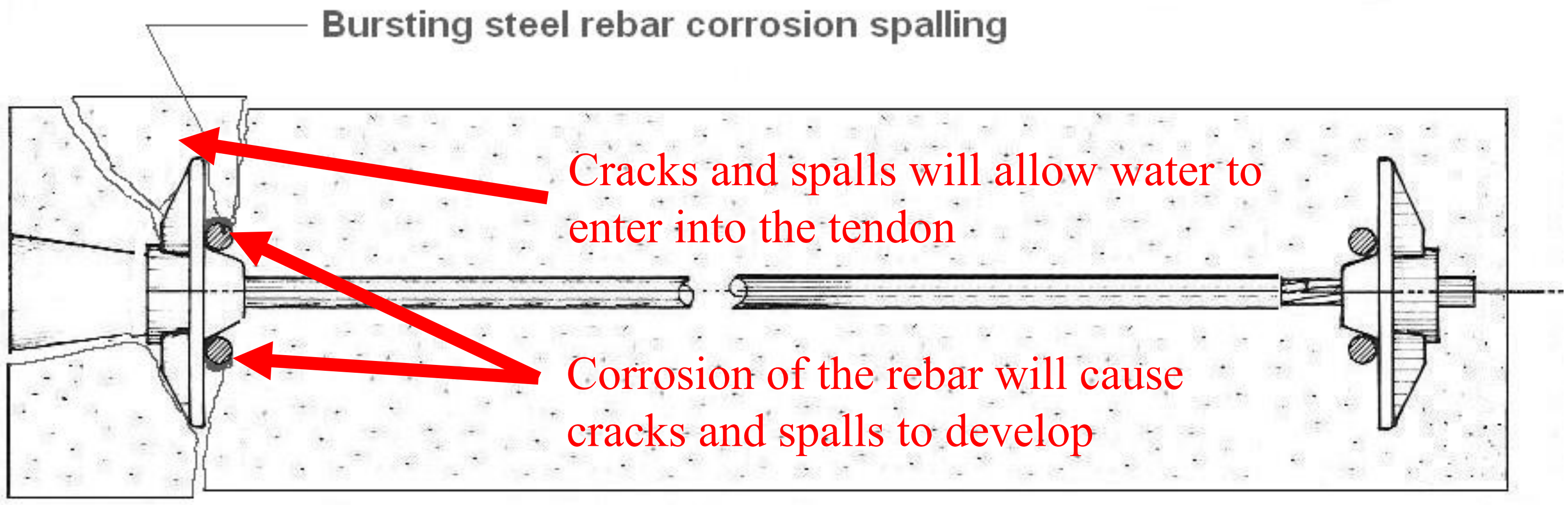
Damage

Embedded rebar corrosion

- It is common for residential structures in coastal regions to experience corrosion of the steel reinforcement embedded in the exterior concrete members, typically within the first 20-30 years, and then in decreasing cycles. This is the result of aggressive electrochemical corrosion due to the exposure to salt and moisture in the environment.
- Post-tension cable anchors are typically found within the structural elements that are most exposed to the corrosive effects of the salt leaden environment, and are therefore at a heightened risk of failure resulting from corrosion..
- Once cracks and spalls develop at the slab edges, this can allow water to enter into the anchor and/or strand, which can lead to corrosion, and ultimately failure of the tendon.

Damage

- Embedded rebar corrosion



Damage

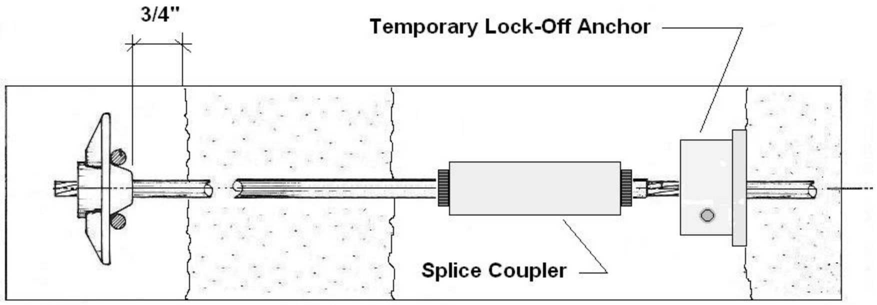
Result of improper repair is failure

- While the International Concrete Repair Institute developed a "Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion" in the late 1990's, these industry standards are routinely circumvented in the repair of post-tensioned structures. This results in structures undergoing short term patching, rather than durable repairs.
- The failure of improper concrete patching over PT anchors is a developing phenomena that some in the repair industry have not yet fully recognized.
- Incorrect repair geometry (usually recommended to reduce the financial cost of the project) will actually lead to the development of a highly active corrosion cell, and which results in accelerated corrosion (and ultimate failure) of the embedded mild steel and post-tension elements.
- As an important footnote, it has been observed that it is rare to find post-tensioning that has failed as the result of corrosion when structures are undergoing concrete structural repairs for the first time.
- Conversely, cable corrosion failures in projects with a history of improper slab edge patching is very high.
- In structures with a history of improper patching, it is not uncommon to find localized conditions with up to 50% to 80% of the cables that are broken as the result of corrosion.

Damage

Correct repair geometry

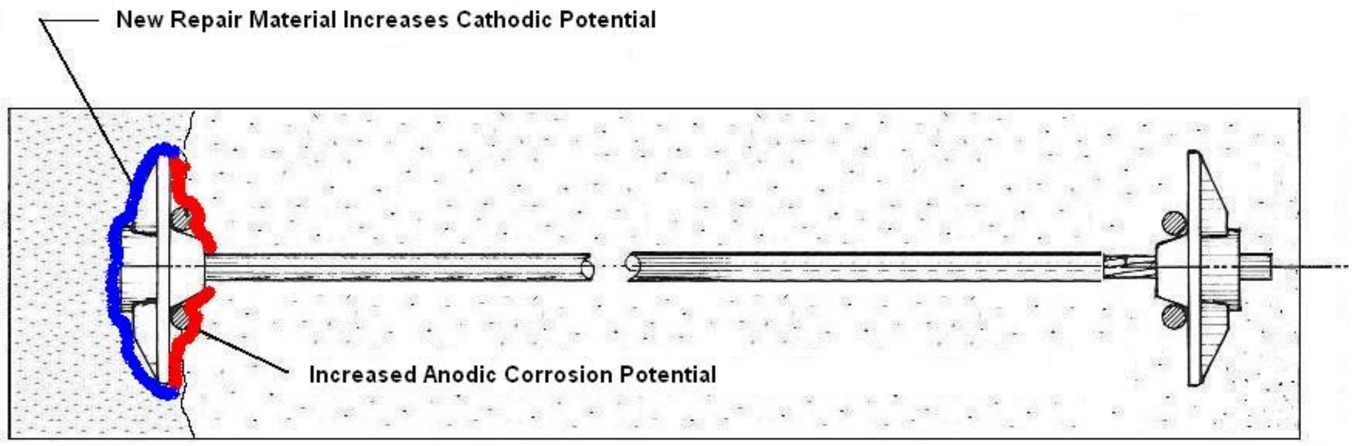
- When performing concrete structural repairs, the ICRI Guideline No. 03730 "Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion" requires a "minimum ¾ inch (19mm) clearance between exposed rebars and surrounding concrete or ¼ inch (6mm) larger than the largest aggregate in the repair material, whichever is greater."
- However, the concrete excavation recommended by the ICRI will occur behind the post-tensioned tendon anchors, and within the anchorage high-stress zone. In order to perform this work safely, the tension load on existing anchors must be temporarily relocated to a new temporary anchor.



Damage

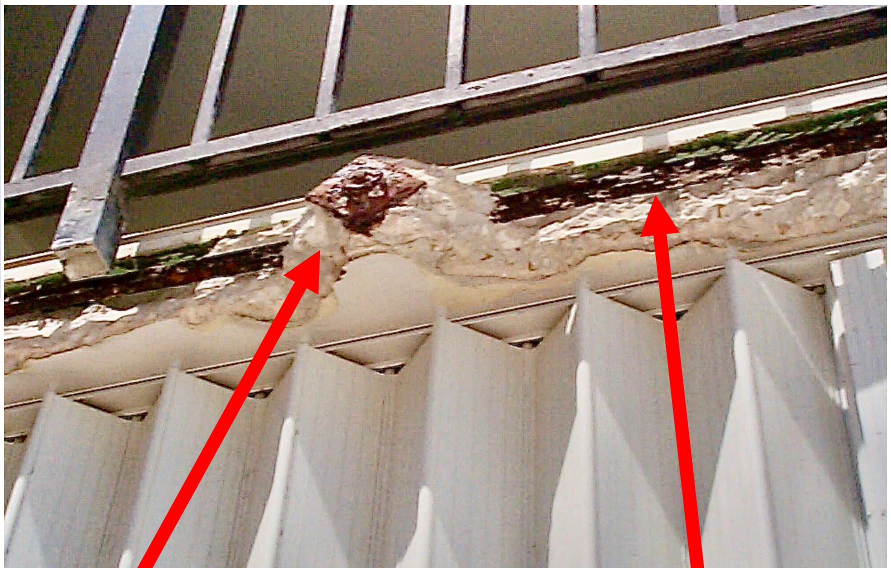
Incorrect repair geometry

- When cracked and spalled concrete is removed only from the face of the anchors and/or rebar, this causes the embedded steel elements to become “sandwiched” between the existing concrete and new concrete.
- This creates a macroscopic corrosion cell with increased corrosion potential and causes the embedded steel to corrode at a rapid rate.



Damage

- Incorrect repair geometry



Rebar continues through existing concrete behind the PT anchor, which creates an electrochemical corrosion hot spot.

Rebar has not been fully excavated, which will sandwich it between the existing concrete and new concrete on the face.

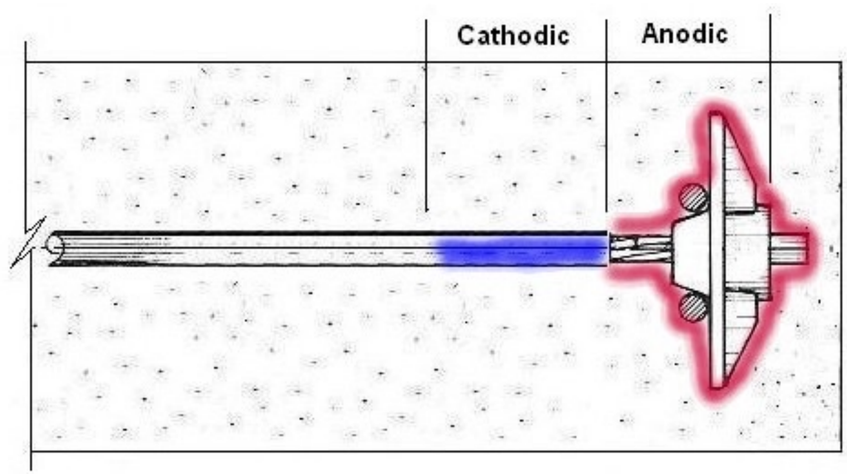
Note advanced state of rebar corrosion where it was sandwiched between old and new concrete.

Note less rebar corrosion where it remained fully embedded in the old concrete.

Damage

Improper repair cable corrosion potential

- TheElectrical continuity exists between the rebar and tendon components. It is recognized that electrochemical corrosion of steel elements that are embedded in the concrete will see an increase in Anodic corrosion potential.
- One explanation for the corrosion damage found on the portion of the cable that's isolated in sheathing is that this increase in Anodic potential of the connected elements that are in embedded in concrete, may cause the adjoining strand to become increasingly Cathodic.
- This may result in the development of an embrittlement condition in the strand, leading to its failure.



Damage

Improper repair cable corrosion potential

- In the American Concrete Institute (ACI) Committee Report 546R-96 CONCRETE REPAIR GUIDE, it is stated in section 2.4 that "The most inexpensive (on a short-term basis) and common approach to repair of deterioration resulting from reinforcement corrosion is to replace concrete only where spalls or delaminations have occurred. Generally, this approach leaves chloride-contaminated concrete surrounding the repaired area which is highly conductive to corrosion. The repairs may actually aggravate corrosion in the area adjacent to them."

- It is further stated in section 3.2 of another ACI Committee Report, 222R-96, CORROSION OF METALS IN CONCRETE, that when "some of the steel is in contact with chloride-contaminated concrete while other steel is in chloride free concrete … this creates a macroscopic corrosion cell that can possess a large driving voltage and a large cathode to small anode ratio which accelerates the rate of corrosion."

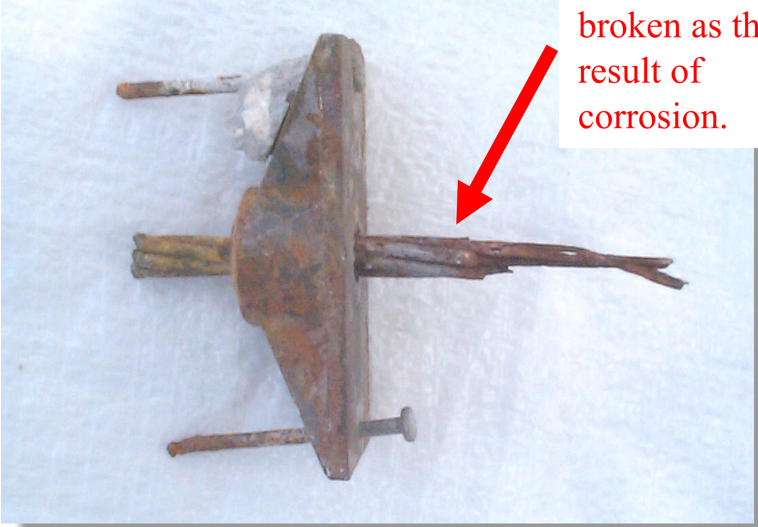
Damage

- Consequence of improper repairs are tendon failure
  - The increased corrosion potential caused by improper concrete patching (particularly at the anchorage), can lead to two types of tendon failures.
  - One is the failure of the supporting concrete around the anchors, which can allow the anchors to rupture from the concrete. Second is the corrosion of the cable itself. In either case, the result is a loss of post-tensioning.

Continued corrosion of rebar after patching resulted in spalling of the concrete around the anchors.

Failure of the patching resulted in failure of the post-tensioning.

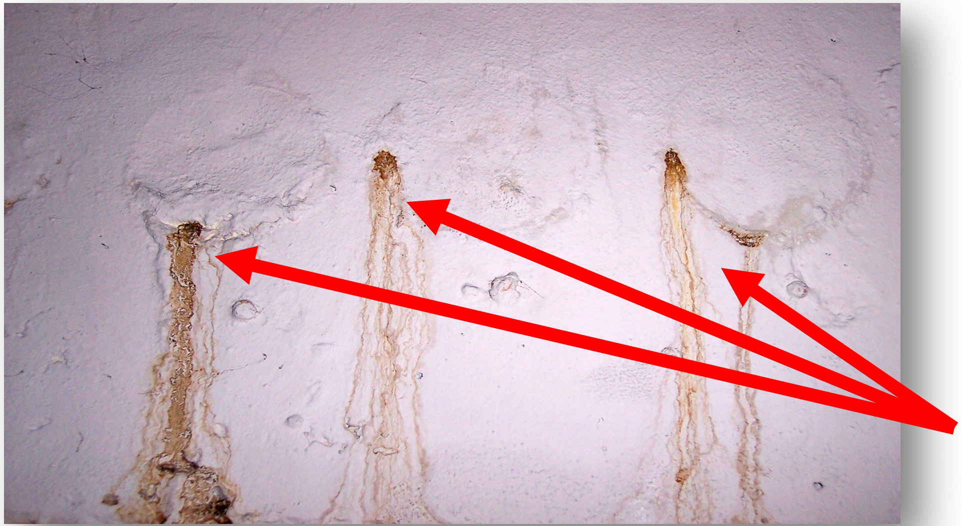
Cable has broken as the result of corrosion.



Damage

➢ Corrosion due to water infiltration

- ✓ The introduction of water into any part of a post-tensioned tendon (either the cable, anchors, and wedges) will ultimately result in a failure of the cable from corrosion.
- ✓ Cable failures result in a complete loss of post-tensioned reinforcement across the entire span of the affected tendon and resulting structural member..
- ✓ Water can enter through cracks, spalls, and other inclusions anywhere along the length of the tendon span, and at the stressing pockets.
- ✓ As buildings age, they are increasingly at risk of strand corrosion.



Water leaking from the anchor pockets is a serious concern.

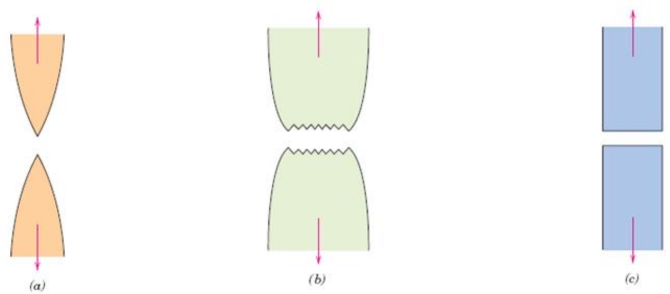
Damage

➢ Stress corrosion

- ✓ Stress corrosion is an anodic process, whereas hydrogen embrittlement is a cathodic process. However, both can cause corrosion induced cable failure.
- ✓ Stress corrosion cracking results from the combined effects of corrosion and static tensile stress. It is highly localized and results in a sudden brittle failure.
- ✓ Cable breakage can occur with minor pitting / negligible section loss, due to reduced ductility of the steel resulting from corrosion.

Ductile Fracture

The ends of cable wires can show how they failed

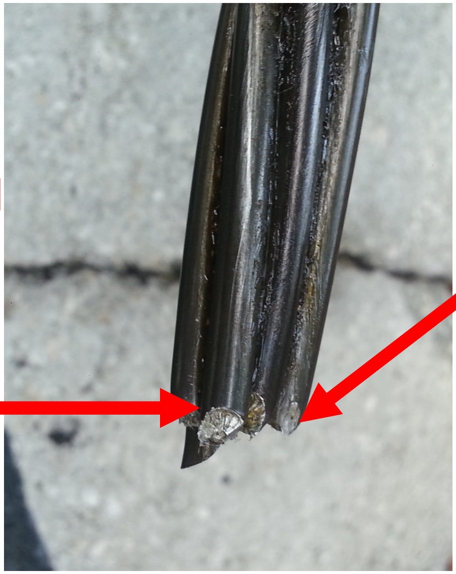


(a) Highly ductile fracture in which the specimen necks down to a point.

(b) Moderately ductile fracture after some necking.

(c) Brittle fracture without any plastic deformation.

Blunt end indicates this wire was cut or possible brittle fracture



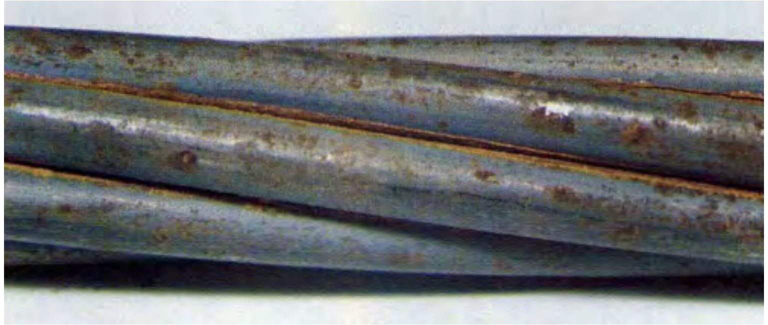
Necking is evidence of a ductile failure of wire

Damage

Pitting Corrosion

- This is a localized form of corrosion that is visible on the strand surface. Moisture within the tendon sheathing will lead to the development of corrosion of the strand.
- Corrosion will cause a loss of section and/or the development of brittle fracturing, which will result in failure of the cable.
- Some in the concrete repair industry will treat post-tensioned cable damage the same as mild steel reinforcement, with an emphasis on loss of cross section. However, this fails to recognize that cable breakage can occur with minor pitting and negligible section loss. Failure occur due to reduced ductility of the steel resulting from corrosion (embrittlement), not from loss of section.
- OPINION: The ICRI Guide for Evaluation of Unbonded PT uses the ASTM G 46 pitting scale, which applies to mild steel, not prestress steel. This focuses more on the loss of section, and overlooks the relationship between pitting and brittle failure of prestress steel.

Minor pitting



Advanced pitting

Damage

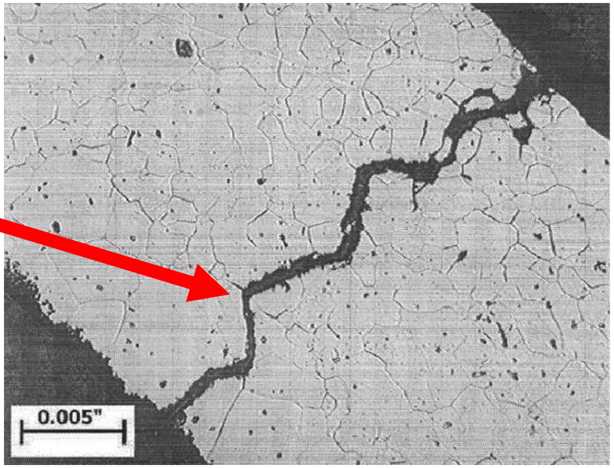
- Hydrogen Embrittlement and cathodic protection
  - The National Association of Corrosion Engineers (NACE International) Committee Report on Cathodic Protection (CP) of Prestressed Concrete Elements states that: …"areas of prestressing steel for which the cathodic current density is low (Galvanic CP) are likely to be under-protected and can corrode, whereas those that are over-protected (relatively high current density – Impressed Current CP) can be subject to hydrogen embrittlement.
  - Given this relationship between CP and the potential for post-tensioned cable damage; special consideration should be given to structures that have undergone both concrete restoration and impressed current cathodic protection.

Damage

Hydrogen Embrittlement

- This is a somewhat rare form of damage, and it is often associated with impressed current cathodic protection of prestressed concrete structures. It's not likely to be encountered on post-tensioned structures, unless an impressed current cathodic protection system has been installed on the building.
- Occurs when atomic hydrogen finds its way between the grains of the steel and forms molecular hydrogen, which has a much greater volume and causes cracking.
- It reduces ductility of steel & results in sudden brittle failure.

Microscopic image of brittle failure crack in wire

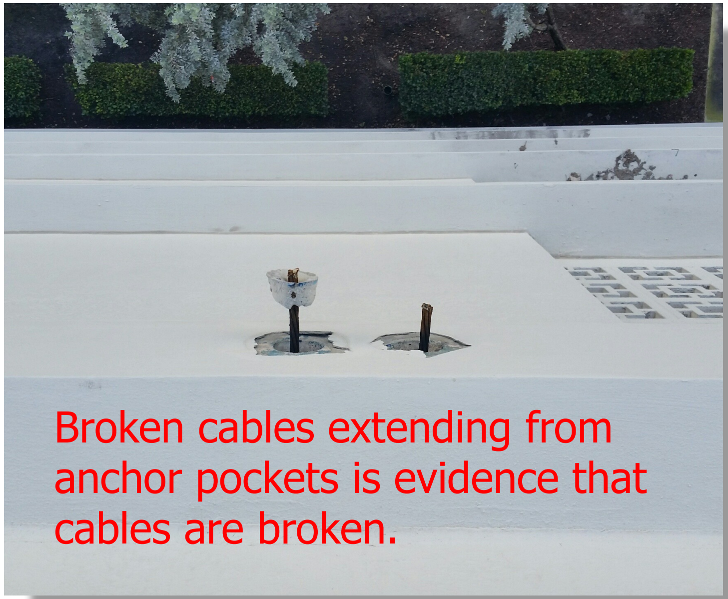


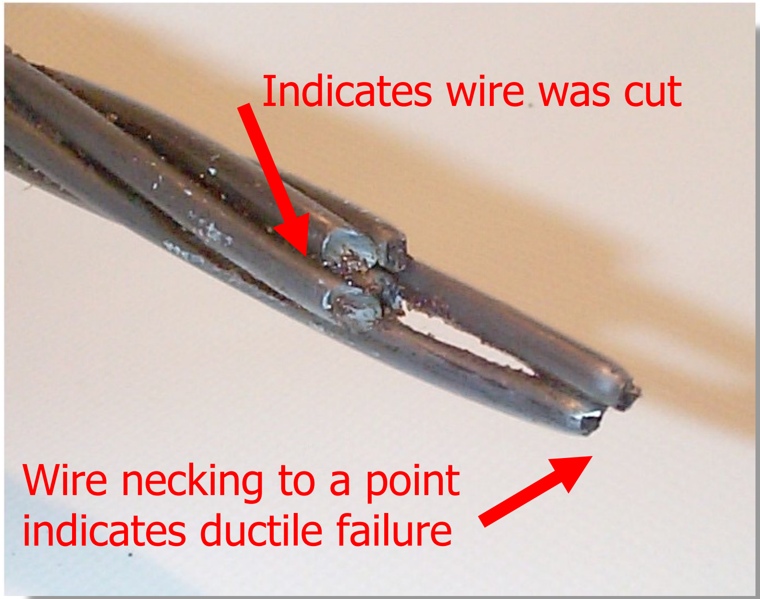
Microscopic image of brittle failure at the end of wire

Damage

➢ Accidental cutting of cables

- ✓ Given that post-tensioned cables are stressed to 80% of their ultimate tensile strength, they can fail if only 1 out of the 7 wires are cut.
- ✓ Strands are often damaged by trades that cut or drill into the structure (plumbers, shutter installers, electricians, etc.)
- ✓ Unfortunately, broken cables rarely give visible evidence of their failure because the structure will usually absorb the release of energy without damage.





Damage

Broken cables / warning Signs

- Experience has shown that few (often less than 1%) of broken tendons will result in a visible sign of failure. Unfortunately, broken cables rarely give visible evidence of their failure because the structure will absorb the release of energy without allowing the cable to rupture.
- Depending on its design, a high number of cables may break before the structure shows outward signs of distress.
- This requires monitoring of the building for signs of structural distress, such as shear or flexural cracking, which can be evidence of a localized loss of multiple post-tensioned cables that has placed the structure at risk.
- Depending on the building design and other factors, the accumulated loss of a post-tensioned reinforcement in a localized area may result in sudden structural failure with little warning.



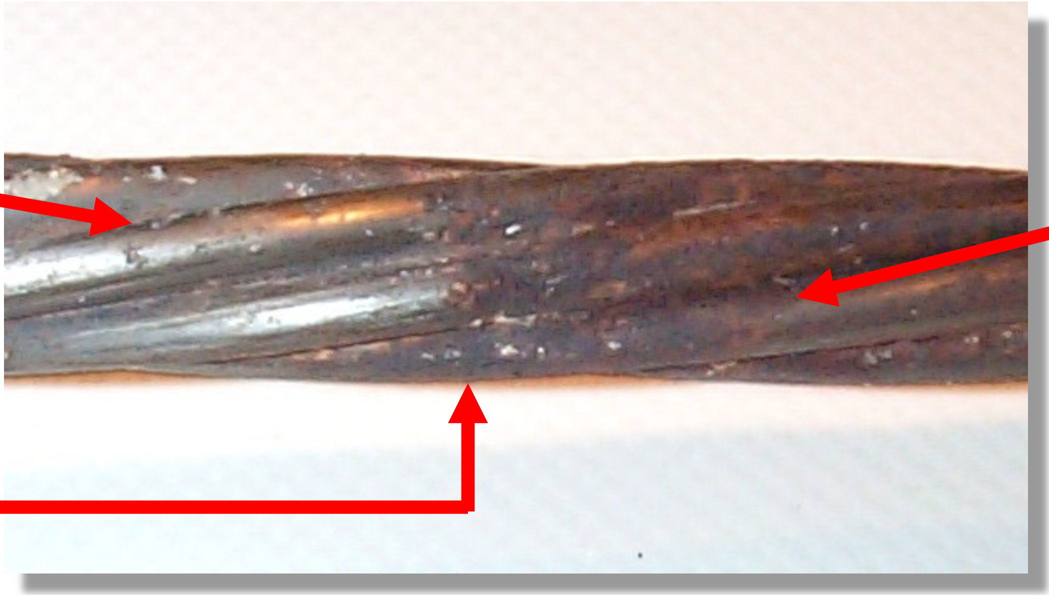
Damage

Bonded strand corrosion

- Any part of the strand that is in direct contact with concrete (without sheathing) is subject to the same electrochemical corrosion that affects mild steel embedded in concrete.
- Prior to the adoption of encapsulated PT tendon hardware, it was common for PT contractors to remove sheathing at dead-end anchors in order to create a short length of bonded cable to help hold the cable at the dead-end anchor during cable stressing.
- Corrosion of the portion of the cable embedded in concrete can cause it to break.

This part of the cable was encased in sheathing and was protected from exposure to corrosion.

Termination point of cable sheathing. Anticipate this to be where the cable will break.



This part the of cable was stripped of sheathing and fully embedded in the concrete, resulting in corrosion.

Damage

Insufficient hairpin reinforcement failure

- The PTI requires the use of hairpin reinforcement to control shear forces that develop within the concrete due to a lateral sweep of the cables off centerline.
- This type of failure usually dates back to the buildings' original construction, and occurs when the post-tension cables are placed without sufficient hairpin reinforcement. Repair will require the installation of additional reinforcement to remediate this condition.

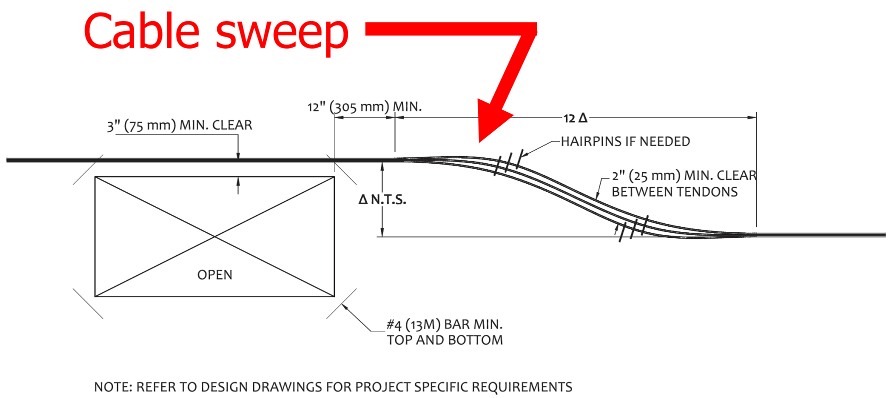
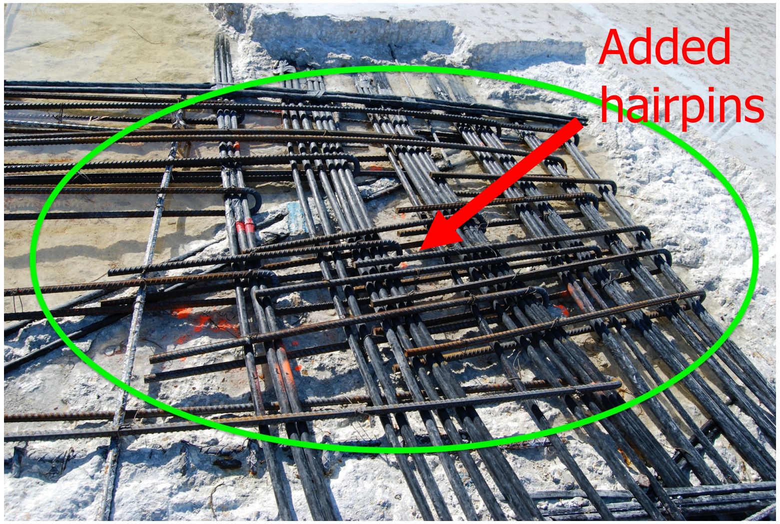


Fig. 4-6 —Typical detail of tendons deviating around an opening and tendon sweeps.



Post-tensioning Institute: Field Procedures Manual for Unbonded Single Strand Tendons, PTI M10.3-16, PTI M-10: Unbonded Tendon Committee

Damage

- Inadequate concrete coverage
  - During concrete placement, cables can be knocked off their chair supports, or pushed to the surface if not tied to support reinforcement. This leaves the cables without adequate concrete cover, making them more susceptible to water infiltration and corrosion damage.

Inspection & Evaluation

- PTI publications
- Shop drawing plan review
- Visual inspection
- Destructive inspection
- Non- destructive techniques

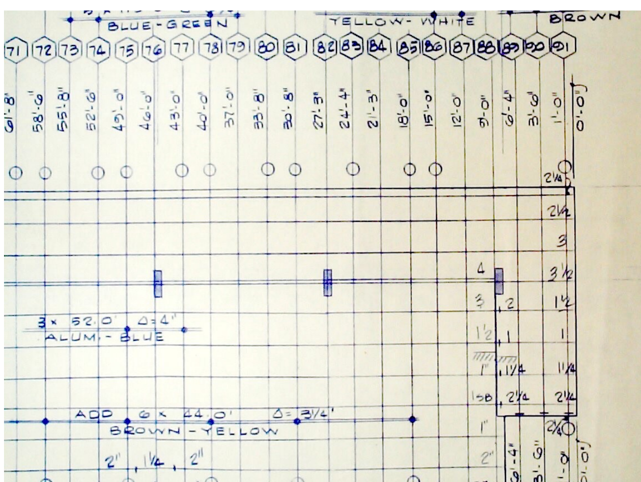
Inspection & Evaluation

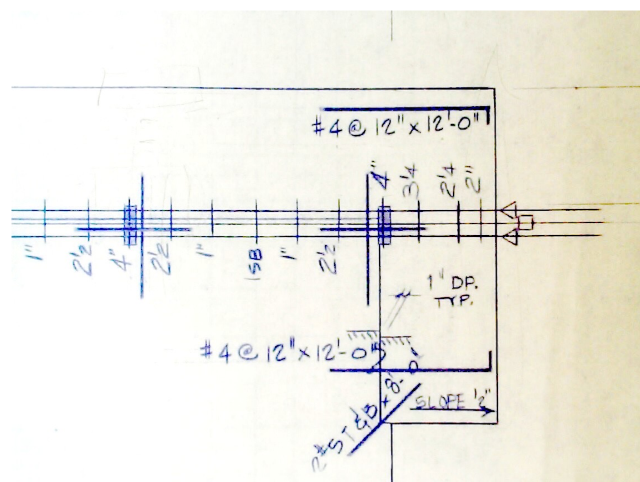
- The Post-Tensioning Institute has produced several publications that examine the deterioration and repair of post-tensioned structures:
- ✓ Guide for Evaluation and Repair of Unbonded Post-Tensioned Concrete Structures PTI DC80.3-12/ICRI 320.6
- ✓ Guide Specification for Unbonded Post-Tensioning Repair PTI DC80.4-18
- ✓ Available at: https://www.post-tensioning.org

Inspection & Evaluation

➢ Shop drawing plan review

- ✓ The starting point of any inspection on a post-tensioned structure should begin in the plan room. The post-tensioned shop drawings or the structural drawings will help determine the quantity and location of post-tensioning.
- ✓ The tendon layout will help to correlate all visible signs of damage with the known location of existing tendons.

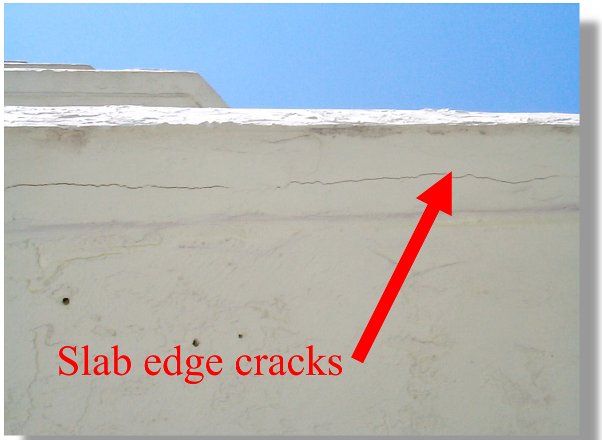


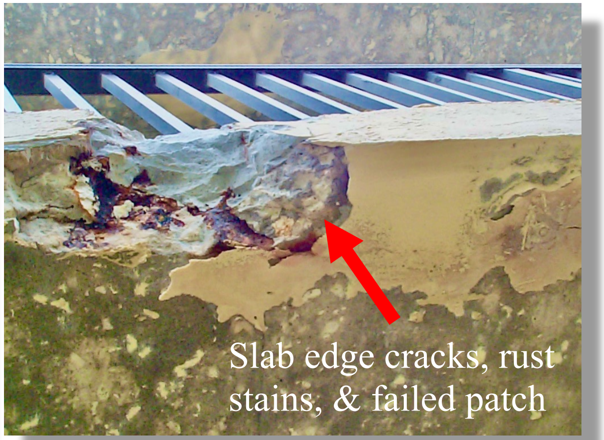


Inspection & Evaluation

Visual inspection

- In most cases, an investigation can focus on three issues simultaneously. Look for obvious evidence of damaged post-tensioning (ruptured cables), look for signs of corrosion damaged concrete (cracks, spalls, or rusty stains), and any signs of structural distress that could be signs of a loss of post-tensioning (flexural or shear cracks).
- Be mindful that it's nearly impossible to determine the precise condition of a tendon with only a visual inspection, and conditions may warrant the use of additional evaluation methods.



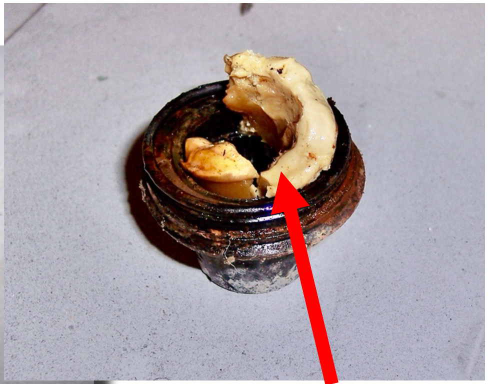


Inspection & Evaluation

Destructive inspection

- If water intrusion is suspected, it may be useful to examine the low points of a tendon for evidence of water and/or corrosion. Opaque grease can be a sign of water intrusion. May be more useful on older PT systems with heat sealed or push through sheathing, because modern extruded sheathing will impede water infiltration.
- Some engineers have determined it useful to remove the stucco and grout in order to inspect the anchor pockets for evidence of corrosion. However, it is impossible to accurately correlate the condition of the strand tail in the pocket to the tensioned portion of the cable.

Opaque grease is a sign of water intrusion

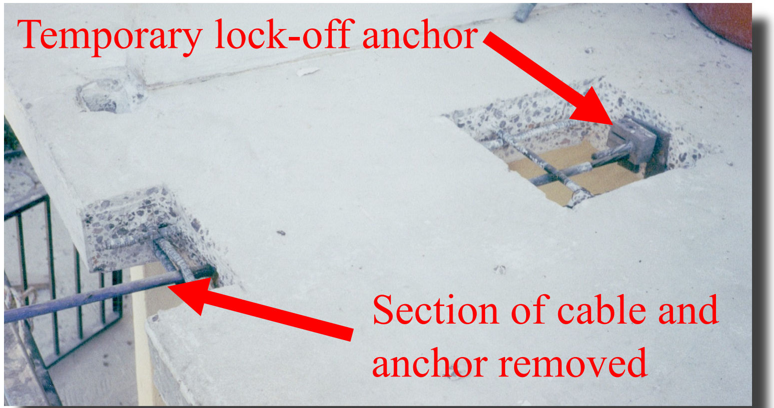


Opaque grease is a sign of water intrusion

Inspection & Evaluation

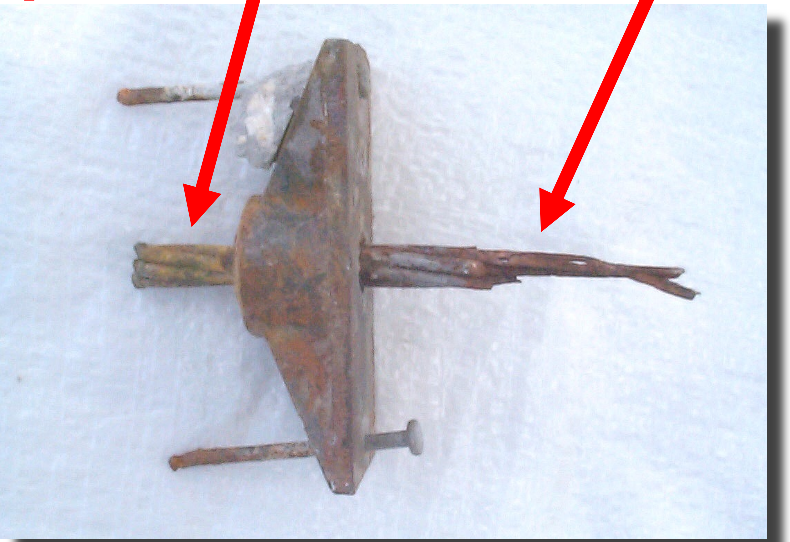
Strand / Anchor Extraction

- In some cases, it may be determined necessary to remove and examine samples of the tendons on a limited basis.
- Removal of a length of strand allows for examination for evidence of corrosion and / or failure



Relative absence of corrosion on cable tail in pocket…..

Removal of sample shows failure of tendon due to corrosion



Non Destructive Testing

Dry gas testing (Post-Tech PT Corrosion Evaluation)

- Formerly known as Corrosion Potential Evaluation (CPE) uses dry nitrogen gas to measure relative humidity within tendon to determine corrosion potential.
- However, the accuracy of evaluation is debated, and the cost of testing is equal to the cost of repair…. Leaving the question of what's the benefit of testing.

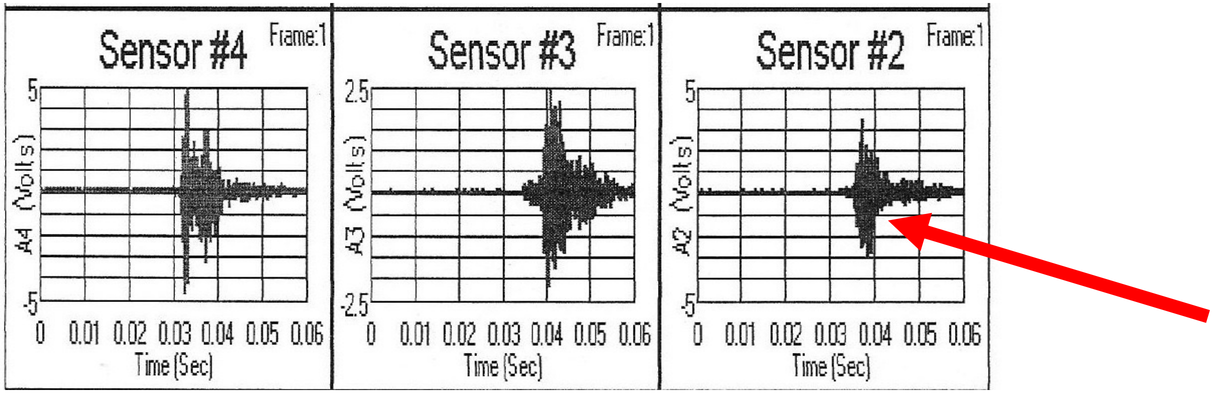
Electromagnetic inspection

- Utilizes an analysis of the tendons electromagnetic field in order to determine the presence of tension on the cable.
- Is of limited use because it requires unrestricted access to the entire length of the tendon from anchor to anchor, which limits the accuracy of the testing.

Non Destructive Testing

Acoustic monitoring

- ✓ Utilizes accelerometers bonded to the post-tensioned structure on 1,000 SF centers to monitor the acoustic footprint of the shear wave energy generated by wire or strand failures.
- ✓ Acoustic events are recorded by on site computer and then analyzed by a trained structural engineer.
- ✓ Requires a significant capital investment in the equipment and installation.
- ✓ Requires the continued investment in long term monitoring and evaluation services.



Files showing acoustic events recorded during monitoring

Non-Destructive Testing

Less effective methods

There are other types of non-destructive testing methods, but they are generally not practical for use in the evaluation of post-tensioned deterioration. These include:

- ✓ Impact echo testing will indicate the presence of voids within the concrete, but can not detect strand corrosion
- ✓ X-ray testing will provide strand location, but can not detect corrosion
- ✓ half cell testing measures corrosion potential in concrete / rebar composite structures, but is not effective in post tension evaluation due to isolation of the strand by the sheathing

Tendon Repairs

- Cable Replacement
- Single cable lock off with temporary anchor
- Cable splicing with couplers
- Multiple cable lock off with temporary anchor
- Cable splicing with LokCouplers / Grabits
- Cable grout injection

Tendon Repairs

Cable Replacement

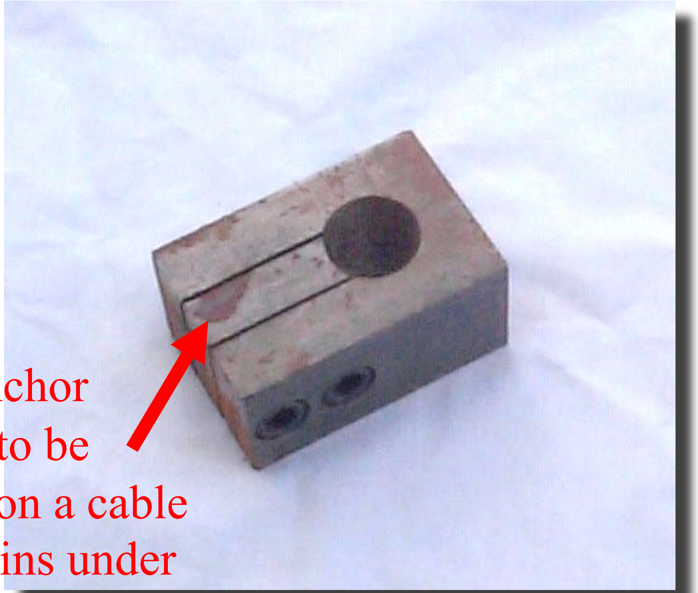
- When it is not possible, practical, or cost effective to repair damaged or broken tendons using a splice repair, then replacement of the tendon may be necessary.
- Is often done when the cables are damaged or broken within the building interior, making demolition of the concrete to expose and repair the damaged cable difficult.
- These repairs can be complicated due to field conditions, such as corrosion of cable, sheathing damage, or other obstructions.



Tendon Repairs

➤ Single cable lock-off anchors

- ✓ The troubleshooting anchor is used to provide a temporarily anchor at a new location on an existing tendon.
- ✓ Allows the post-tensioned forces to be temporarily removed from a limited portion of a tendon span, usually for repairs.

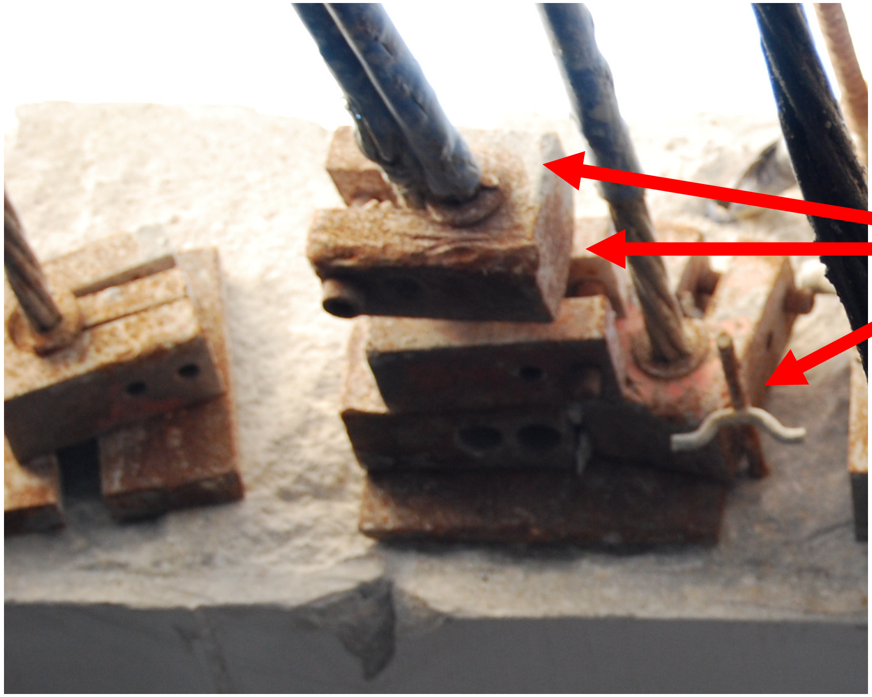


Slot in anchor allows it to be installed on a cable that remains under tension.

Tendon Repairs

Multiple cable lock-off anchors

- The installation of temporary anchors on bundles of multiple cables using single cable anchors can be extremely difficult and dangerous. A failure can result in injury, damage, and a significant loss of post-tensioning in a localized area, which is structurally significant.

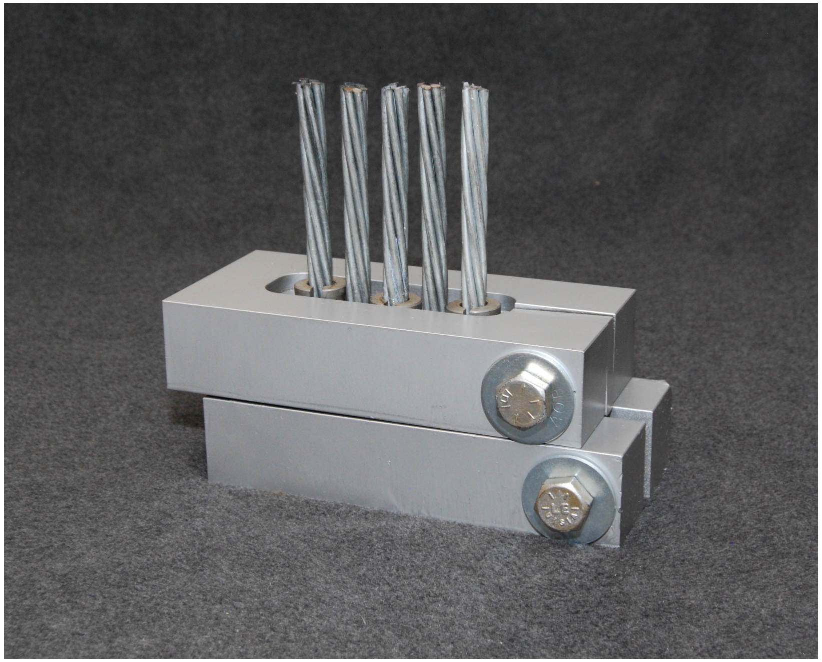


Stacked lock-offs are highly unstable and should be avoided

Tendon Repairs

➢ Patented Multi-Cable Anchor

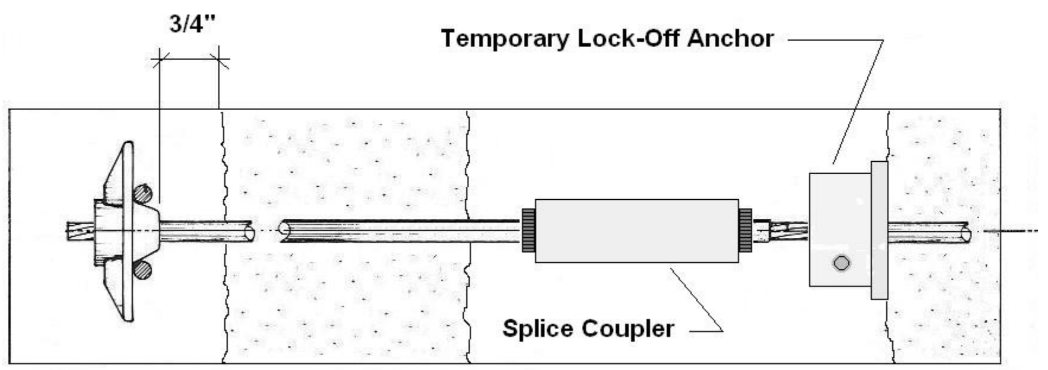
- ✓ Locking off multiple cables with single cable anchors can be extremely difficult and dangerous.
- ✓ Any failure during the repair process can result in injury, damage, and a significant loss of post-tensioning in a localized area.
- ✓ This device is used to lock-off multiple cables and is safer than stacking up multiple single cable anchors.



Tendon Repairs

One time use splice couplers

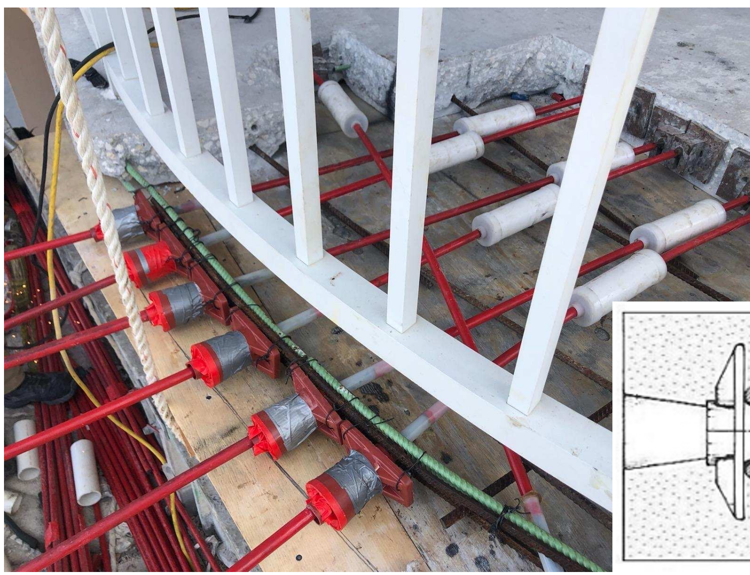
- Used for joining a section of new strand to an existing cable at some point along the tendon span.
- Requires access to a terminal end anchor in order to re-establish tension.

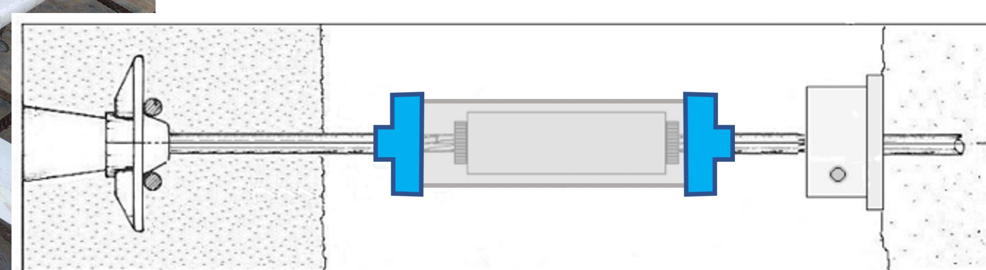


Tendon Repairs

Splice coupler encapsulation

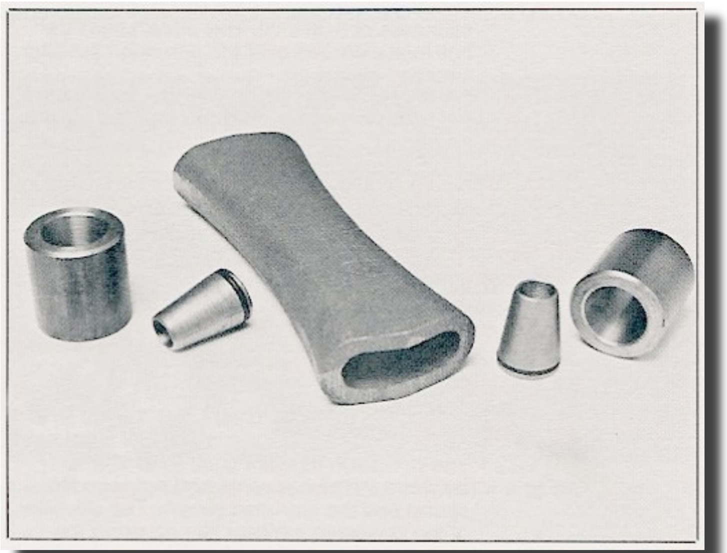
- Cable splices should be encapsulated using PVC or HDPE pipe and sealed with Splice Caps (Post-tensionProducts.com).





Tendon Repairs

- Cable tensioning with a stressing splice
  - ✓ Typically used for splicing damaged cables along their length.
  - ✓ Trade names such as LokCouplers / Grabits.
  - ✓ Does not require access to the stressing end anchors for reestablishing tension of the repaired cable.



Tendon Repairs

Cable grout injection

- An injected grout material claimed to fill any interior voids between the cable and the sheathing.
- The grout used is a low viscosity two component hydrophobic urethane grout that is injected using a proprietary (licensed) injection process.

Limitations

- Current methods of assembling cable and sheathing leave no interior voids. That can limit the cable grout injection method to older sheathing systems with adequate interior space between the cable and sheathing.
- Corrosion damage to strand may already have occurred, so benefit of remediation is limited.

Deterioration, Evaluation, and Repair of Post-Tensioned Condominium Structures

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