EFFECTS OF MARINE ENVIRONMENT ON UNGROUTED AND STRESSED STRANDS INDUCTS

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The examination of the effects of the stress condition and environmental exposure on the durability of post-tensioned strands during ungrouted periods was performed. Ungrouted exposures for periods of up to 4 weeks of stressed strand placed in tendon ducts embedded in concrete and sealed with caps to represent normal practice and without any trapped water did not result in any appreciable deterioration as evaluated by standardized mechanical tensile testing. These results were observed at both an inland and a seashore test sites. There was, however, notable surface rusting of the strand if water was trapped in the ducts or if the steel was exposed to moderate salt spray precipitation, and especially with both factors concurrently.

KEYWORDS

bonded tendons; 1080 carbon steel; detensioning; mechanical tensile testing; salt spray.

INTRODUCTION

The post-tensioned (PT) form of prestressing uses tendons consisting of strands placed through sheaths/ducts previously embedded in the concrete (internal tendons) or extending through the space between different parts of the structure (external tendons). The precompressive force is then applied to the concrete structure by tensioning the steel strands with hydraulic jacks. The strands are anchored by wedges in the anchorages on the ends of the tendons.

Bonded post-tensioning is a PT system with typically bundles of strands in a galvanized metal or polymer duct. After the tendons are stressed, cementitious grout is injected into the ducts; the grout protects the strands from corrosion and provides bond between the stressed stands and the surrounding concrete.[1]

The period of time tendons are ungrouted during construction is limited by construction standards to a relatively short window before temporary corrosion protection is necessary (permissible intervals between prestressing steel installation and grouting for high-humidity areas > 70% is only 7 days).[2,3] Often, unintended longer exposures can take place due to erection delays and other construction schedule constraints. Unprotected strand can corrode[4,5] and there are limits to what level of corrosion might be acceptable.[6]

In one notable case, strands in a major bridge project (San Francisco Bay Bridge Skyway, CA) were exposed to a potentially highly aggressive condition, including standing water and contact with galvanized steel for periods that exceeded 1 year.[7] There is increasing interest in determining to which extent the ungrouted period can be prolonged without adverse corrosion consequences, with a view to possibly relax the present specification requirements for ungrouted exposure period and thus accommodate other construction requirements. This issue has received little attention in the technical literature and is a central justification for the subject of this research.

DESIGN OF DETENSIONING PILES

The concept drawing of the detensioning pile system is shown in Fig. 1. The system allows testing, removal, and evaluation of PT strands from the ducts after each exposure period. Steel plates with welded-in tubes were used to allow PT bars to slide into the tubes during detensioning. The steel plates were also used to form the larger and smaller pile sections and to secure the anchor and duct assemblies in place. Holes were made in the steel plates to allow the pretensioning strands to run through the entire length of each two part pile. The detensioning pile system provides a means of detensioning the strands in the ducts by loos-

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ening four hex nuts on four PT bars, which are between the smaller and larger pile sections. This mechanism was used to prevent strand damage/failure due to "overstressing" required for detensioning by other methods. The hex nuts on the PT bars bear against the face plate of the smaller pile section, which prevents its movement during stressing and the stressed exposure period of strands in the duct.

The casting of the pretensioned piles was performed at a precast yard with a 14 in. (356 mm) casting bed, which provided access to the University of South Florida (USF) as well as materials and labor for pile construction. All of the 12 piles were cast in one casting bed, with the pretensioning strand for the piles stressed at one end of the bed and anchored at the other. After 1 week, the pretensioning strands were cut, and the piles were removed from the forms and transported to the inland location at USF and the marine location, Sunshine Skyway Bridge (SSK). Piles were arranged in an alternating pattern to allow better access to the detensioning mechanism. Piles were placed on two dunnage piles to allow the small portion of the pile to move per design and the piles were leveled using concrete blocks.

Once the piles were in place, a series of maintenance and cleanup steps were done. First, the extra strand length, extending outside the piles for the pretensioning of the piles, was removed. Then, the steel plates used to hold the anchor assembly in place was removed on the ends where possible, or left in place in cases where it was not possible. The ducts were cleared out by compressed air to remove any water or dirt that may have entered into the ducts. The ends of the ducts were closed with plastic caps and sealed with weatherproof silicon. Rust inhibitor was applied to the exposed steel. Weatherproof silicon was applied to any joints of steel to concrete to prevent crevice corrosion. The prestressing steel used was ASTM A416,[8] seven-wire steel strand, 0.50 in. (12.7 mm) in diameter.

The end caps from the PT anchor manufacturer were not compliant with FDOT specifications in terms of corrosion resistance. A custom end-cap design was proposed to provide both adequate seal and corrosion protection in lieu of employing the manufacturer's cap. The design includes a standard 4 in. (101.6 mm) polyvinyl chloride (PVC) slip cap held by a retaining bar and ring, which are secured by threaded rods to the anchor. All metallic elements of the end cap are stainless steel. A rubber O-ring groove is made by machining the PVC cap to form a seal between the PVC cap and the cast-iron wedge plate. The placement of the end caps ensured an airtight connection but required that the strand be cut close to the wedges to avoid interference between the strand ends and the cap.

STRANDS STRESSING PROCEDURE

The stressing jack was calibrated to correlate the jacking force to the hydraulic pressure gauge. The ratio of the stress on the strand to the hydraulic pressure was found to be 0.03 ksi/psi (2.07×10^{-4} GPa/MPa). Elongation measurements were in general agreement with the estimated stress levels. The jack was fitted with a custom retention ring to ensure adequate wedge set. Applying pressure to obtain a strand stress of 229.20 ksi (1.58 GPa) and removing jack pressure resulted in a stress of 220.8 ksi (1.52 GPa) or $0.82f_{pu}$ after wedge set. It was decided to use a regular stressing procedure with an initial gauge pressure of 1000 psi (6.89 MPa) to remove any slack from the strand and then

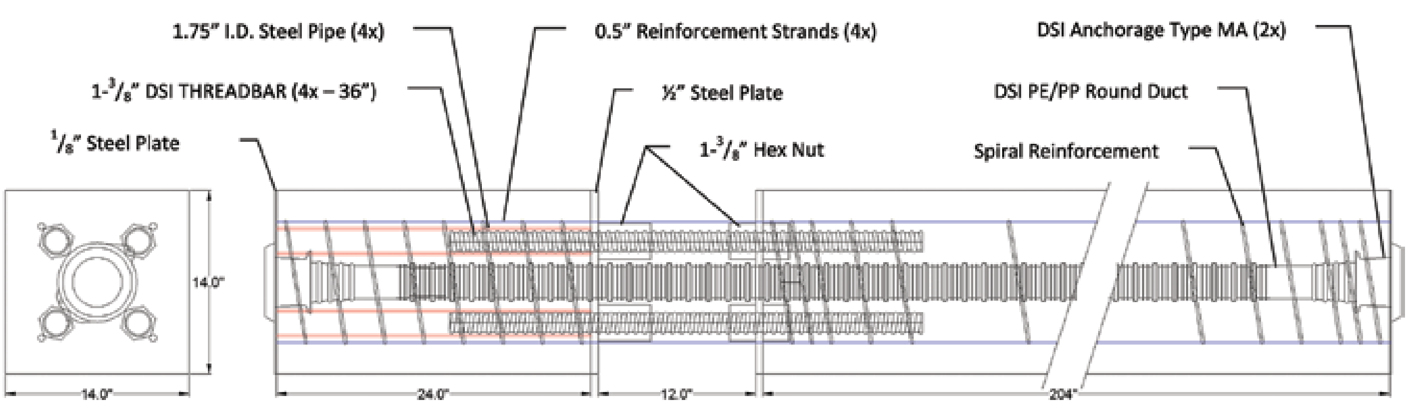

Fig. 1—Detensioning pile system design. PVC and flexible connection removed for clarity. (Note: 1 in. = 25.4 mm.)

increasing the gauge pressure to 8000 psi (55.16 MPa) (a nominal strand stress of 243.9 ksi (1.68 GPa), or $0.90f_{pu}$), so that upon removal of the pressure and subsequent wedge set, the final strand stress level of approximately $0.87f_{pu}$ would exist. While the code requires the jacking force not to exceed $0.94f_{py}$ or $0.8f_{pu}$ (which should then result in a final stress of $0.7f_{pu}$), all specimens were jacked to a level high enough to overcome large wedge seating losses (due to short strands) and to leave the strand at a higher than normal stress during the exposure ($>0.8f_{pu}$ instead of $0.7f_{pu}$). This resulted in a more aggravated stress state that offered a greater opportunity of revealing any adverse effect of stress corrosion interactions during the ungrouted period.

RESEARCH SIGNIFICANCE

Relating the rusting or cross section loss, and the mechanical tensile test data over the tested period of time allows for extrapolating the results over an extended time frame, such as over 100-year design service life of marine structures in Florida. The ability to determine susceptibility to corrosion of carbon steel strand over construction exposure period enhances the construction planning and procedure of various structures using prestressed concrete worldwide.

EXPERIMENTAL INVESTIGATION

Testing setup

Each pile had two stressed strands and one unstressed strand in ducts. The strands were cut to a length of 23 ft (7.01 m) and encoded with the appropriate paint label. A measuring tape was placed alongside each strand and each approximately 12 in. (305 mm) length of strand was photographed. Once the preparation of a set of specimens for either the USF or SSK locations was completed, the specimens were bundled together, covered to prevent salt or dirt from depositing on the surface, and stored until placement and stressing.

Selected sets of strand specimen were sprayed with salt solution 1 day before stressing. Care was taken to separate salted from unsalted strands to prevent cross-contamination. Only pre-salted strands were transported in the container used for salted specimens.

For placement in the piles, the strands were removed from their storage container pushed through the ducts, crossing the two stressed strands by appropriate placement in the wedge plates at opposite ends. Thus, a crossover contact was created near the center of the pile to increase the chances of crevice corrosion effects or adverse condensation of moisture in the area of contact. The wedges were then placed on both ends of the strands to be stressed and pre-seated by hand. The unstressed control strand was placed in the duct and through the wedge plate holes, but no wedges were placed. The stressing of the two stressed strands was performed one strand at a time using a monostrand jack. Stressing was performed by placing the jack at the end of the pile farthest away from the pile segment break and, once stressed the excess strand length was cut away. Strand samples were left stressed and ungrouted for 1-week, 2-week, and 4-week periods, with some of them salted and wetted, some just wetted, and some others left in the original condition. After the period of exposure, the ends were uncapped, the four hex nuts were loosened one at a time in small increments to ensure uniform detensioning, and a winch was used to pull the smaller pile section close enough to the larger pile section to allow the cutting of the strands in front of the wedge plates. Once the strands were separated from the wedge plates, the strands were removed from the ducts and relabeled on site.

The strands were then brought to the laboratory at USF, where they were photographed in segments as before to document changes in the surface of the strand due to the exposure conditions, stress condition, and duration. The strands were then cut into segments for mechanical testing.

Mechanical testing

The strand tested—seven-wire strand, ASTM A416,[8] 270 ksi (1.86 GPa)—was required to pass the tensile testing method detailed in ASTM A1061[9] in terms of yield strength, elongation, and breaking strength. The testing was to determine to what extent the strand in the post-exposure condition would satisfy the specification. A 50 in. (1270 mm) segment was cut from the center of each strand specimen for tensile testing. To improve gripping, silicon carbide powder was glued 8 in. (203 mm) from the ends of the 50 in. (1270 mm) specimen. These specimens were then transported to the FDOT State Material Office for tensile testing using the pull testing machine. Typically, the specimen broke at the center point between the grippers. Once the tensile test was complete, the two separate specimen pieces were secured together and transported back to USF for analysis and storage.

DISSCUSSION AND RESULTS

Mechanical testing results

The mechanical tests show that none of the strands failed to meet the ASTM requirement for load at failure (Fig. 2), load at 1% extension (Fig. 3), or total elongation (Fig. 4). It is noted that of the 216 strands tested, nine of them had slip occur in the grippers during testing, invalidating those results (shown as red-filled squares in the figures). Based on the evidence examined, there was no clear or significant differentiation in the tensile strength between stressed and unstressed companion strands. Tests performed with four specimens cut from new, never exposed strands (blue triangles in the figures) showed no differentiation from the exposed specimens. Figures 5 through 7 show a comparison between the salted and wetted, unsalted and wetted, and unsalted and closed (dry) conditions. These figures were each focused on a relatively small range of values around the median to better uncover possible differentiation between conditions. The graphs showed only minor deviations in the distribution of the results, not following any clearly identifiable pattern. For example, while the median value of load at 1% extension (Fig. 6) was slightly greater for the unsalted wetted than for the salted wetted specimens—an expected outcome—an opposite and comparable minor difference was observed in the total elongation values (Fig. 7). It was thus concluded that those apparent minor differences reflected only natural scatter of results.

In general, the mechanical testing results show that none of the strands exposed in the test piles, even in the most severe test conditions (ungrouted for 4 weeks with salt previously sprayed on them and water placed in the duct) would have failed to qualify per the ASTM tensile testing requirements.

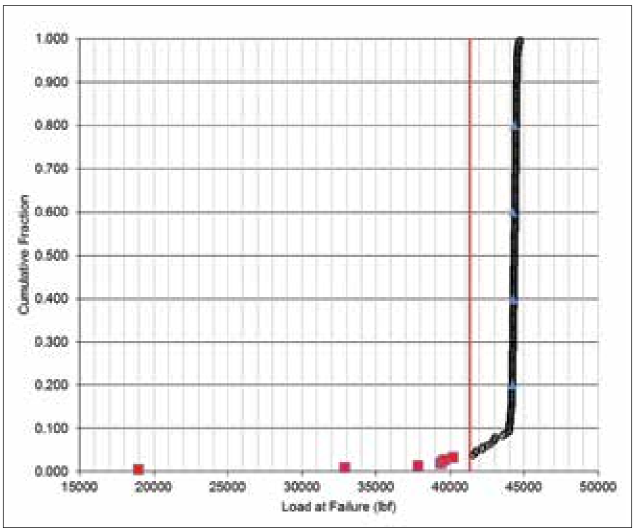

Fig. 2—Cumulative fraction of load at failure for all 216 strands. red line indicates ASTM specification requirement. Red square symbols are indicative of invalid tests. Blue triangle symbols are for unexposed controls.

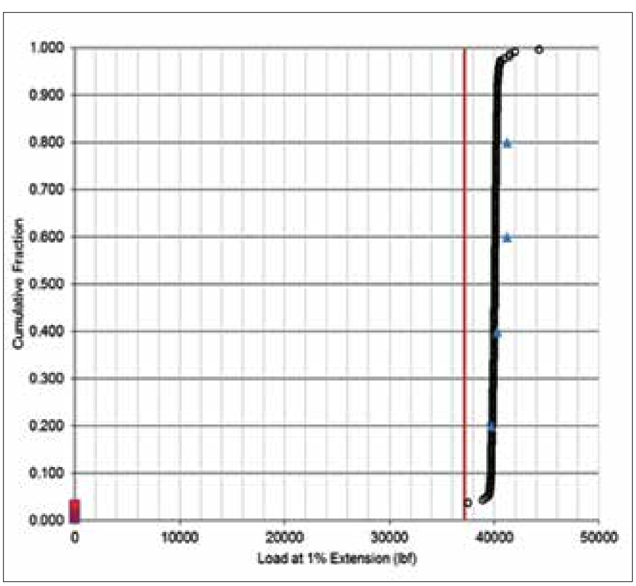

Fig. 3—Cumulative fraction of load at 1% extension for all 216 strands. Red line indicates ASTM specification requirement. Red square symbols are indicative of invalid tests. Blue triangle symbols are for unexposed controls.

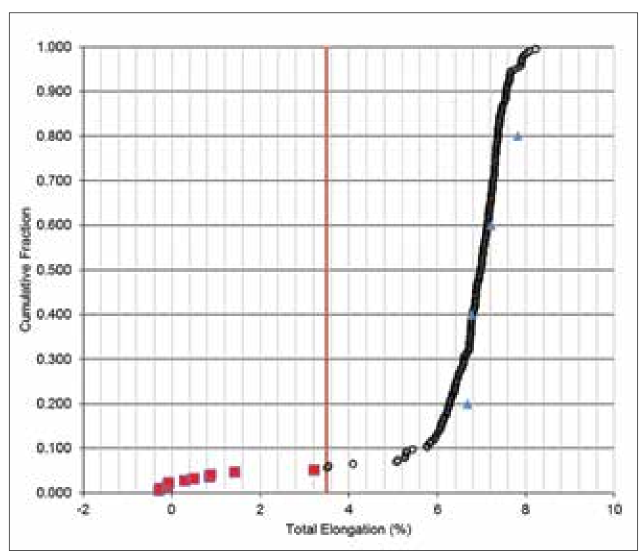

Fig. 4—Cumulative fraction of total elongation for all 216 Strands. Red line indicates specification requirement. Red square symbols are indicative of invalid tests. Blue triangle symbols are for unexposed controls.

While it is not realistic for the strand to fail due to loss of cross section within the period tested, caution applies as to the possibility of failure modes not directly addressed by the ASTM testing procedure, such as hydrogen embrittlement. No strands failed during the stressed and ungrouted period.

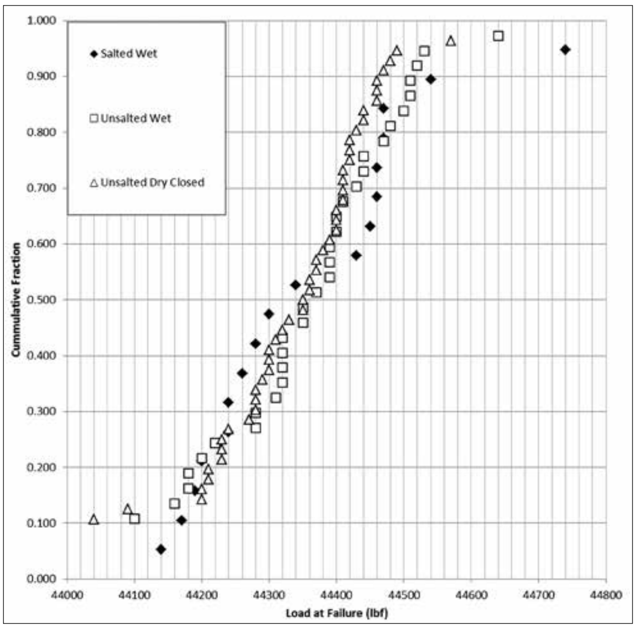

Fig. 5—Cumulative fraction of load at failure for all 216 strands comparison between salted and wetted strands, unsalted but wetted strands, and unsalted and dry strands.

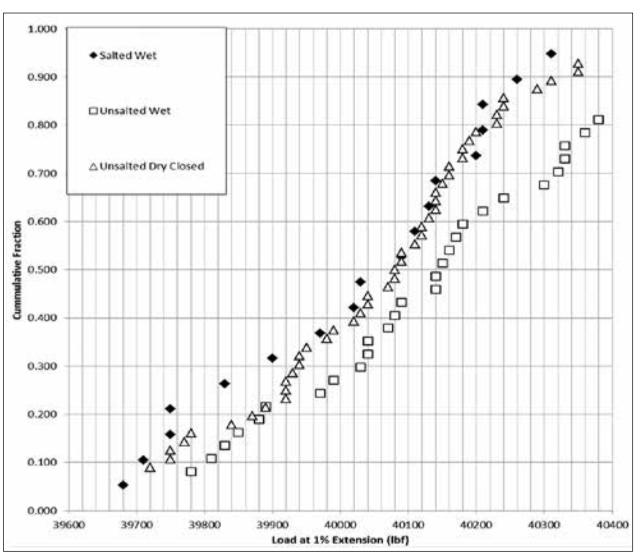

Fig. 6—Cumulative fraction of load at 1% extension for all 216 strands comparison between salted and wetted strands, unsalted but wetted strands, and unsalted and dry strands.

Extrapolation of ideal conditions (2 weeks, closed with no water or salt) to the design service life of 100 years shows little concern for failure over that time frame, as little to no corrosion and successful testing performance indicate. In nonideal cases (4 weeks, salted or wetted), the corrosion observed and the possibility of other failure modes occurring can lead to failure. Conservative estimate leads to the recommendation of a maximum 2-week period of ungrouted exposure for sealed tendons, with water and salt intrusion controls in place.

CONCLUSIONS

1. Exposures for periods of up to 4 weeks of stressed strand placed in ducts embedded in concrete, sealed with anchorage end caps and without any trapped water (closed, non-wetted condition), representing normal practice, did not result in any appreciable deterioration as evaluated by standardized mechanical tensile testing. These results were observed at both the inland and the seashore test sites.
2. If conditions were the same as in Item 1, except for the anchorage end caps not in place but the anchorage area protected from rain (open, non-wetted condition), the performance was similar to that indicated previously at both test sites. This

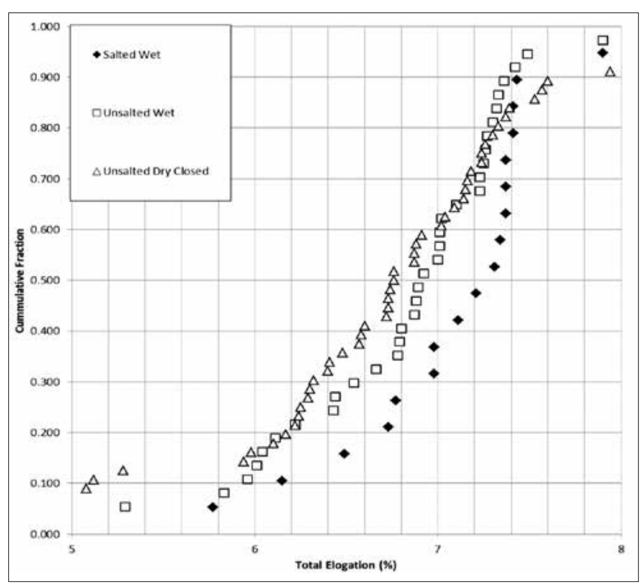

Fig. 7—Cumulative fraction of total elongation for all 216 strands comparison between salted and wetted strands, unsalted but wetted strands, and unsalted and dry strands.

finding, however, must not be interpreted as an indication that capping the ends is not important, as data from a construction site indicated an instance of increased humidity in an open duct during a rain event.

3. For the capped condition indicated in Item 1 but including a modest amount of trapped water in the capped tendon (closed, wetted condition), the tensile test performance was not significantly affected.
4. Application of salt deposit on the strand, simulating a 1-day near-seashore exposure prior to placement in the ducts, generated surface corrosion on the strands. Mechanical performance per the standardized tensile tests, however, was not appreciably degraded.
5. No clear difference between the behavior for the stressed strands and the unstressed strands exposed in the same ducts was observed in the tests.
6. Under the examined conditions, the propensity for brittle behavior was quite limited as suggested by the absence of any spontaneous stressed strand failures and the absence of any consistent indication of loss of strength or ductility in the tensile tests, even after 4 weeks of sustained stress of multiple specimens of sizable length in the more aggressive exposure combinations.
7. The results suggest that ungrouted exposures of up to 2 weeks with strict water intrusion control and prevention of any salt deposit on the steel during installation have no detrimental effect.

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