



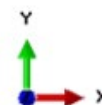
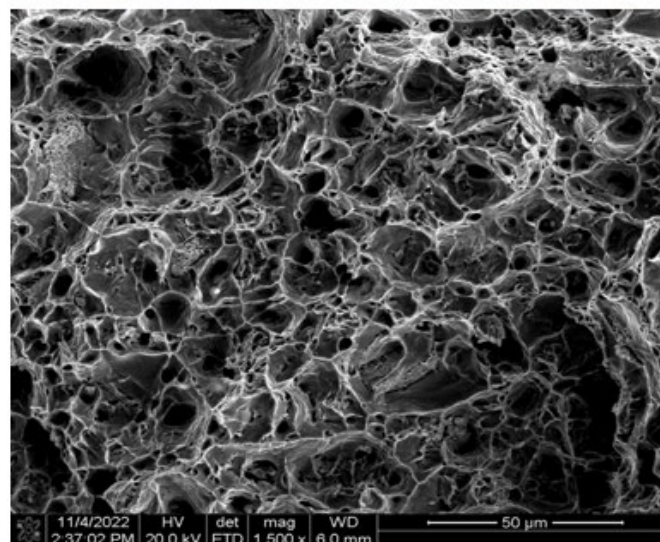
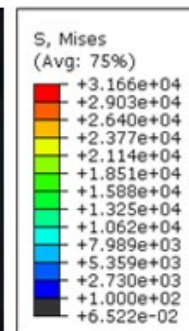
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Finite Element, Petrographic, and Mechanical Analyses of Field-Cored Concrete Fairlead Beam Anchor Rods from Luke Air Force Base

Webster C. Floyd, Kyle P. Dunsford, Andrew B. Groeneveld,
and Kyle L. Klaus

May 2024



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*US Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199*

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Abstract

The fairlead beam is used to accomplish installation of the Barrier Arresting Kit 12 energy absorber for setback aircraft arresting system (AAS) installations at permanent operating facilities. Typical fairlead beams are affixed to a Portland cement concrete (PCC) foundation pad by a series of anchor assemblies made up of steel anchor rods set in grout inside galvanized pipe sleeves. US Air Force Civil Engineering Center (AFCEC) subject matter experts have identified a pattern of premature failures in these steel anchor assemblies when they are nondestructively inspected during AAS overhauls. The US Army Engineer Research and Development Center was tasked by AFCEC to investigate potential reasons for these premature failures. This report outlines methods and results of a finite element analysis of the anchorage, a visual and petrographic analysis of field-cored PCC anchor rods from Luke Air Force Base, and a mechanical analysis of specimens taken from the anchor rods within the PCC cores. Multiple modes of PCC distress were observed, and corrosion was evident in and around the anchor assemblies. Mechanical testing of specimens from the anchor rods indicated that an inferior grade of steel was used to fabricate these particular assemblies. Finally, observed deviations from design intention are discussed.

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Preface

This study was conducted for the US Air Force Civil Engineer Center (AFCEC) and was funded by MIPR number F4ATA49126JW01. The technical monitor for this study was Dr. Barry Mines (AFCEC, Operations Directorate, Engineer Division).

This work was performed by the Airfields and Pavements Branch (GMA) and the Concrete Materials Branch (GMC) of the Engineering Systems and Materials Division (ESMD), US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). In addition, work was performed by personnel from the Structural Engineering Branch (GSS) of the Geosciences and Structures Division (GS) of ERDC-GSL. At the time of publication, Ms. Anna M. Jordan was chief, GMA; Dr. Jameson D. Shannon was chief, GMC; Ms. Mariely Mejias was chief, GSS; Mr. Jeffrey G. Averett was acting chief, ESMD; Mr. James L. Davis was chief, GS; and Mr. R. Nicholas Boone was the technical director for Force Projection and Maneuver Support. The acting deputy director of ERDC-GSL was Mr. Justin S. Strickler, and the acting director was Mr. Charles W. Ertle II.

COL Christian Patterson was the commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

Operations at military airfields require arrestment of aircraft for a variety of potential reasons including emergency landings, aborted takeoffs, pilot arrestment certifications, and contingency operations on shortened runway surfaces. In some cases, net-style barriers are employed to capture aircraft, but the primary means of arrestment of landing aircraft is engagement of the aircraft's arresting hook with a hook cable assembly stretched across the runway. The hook cable is fastened to a nylon arresting tape with a mechanical connection, the tape connector. A length of arresting tape is held in two identical aircraft arresting system (AAS) units installed one on each side of the runway. After arresting hook engagement, the kinetic energy associated with the forward velocity of the arrested aircraft is absorbed in the rotary friction brakes of the AAS energy absorber during tape payout. The Barrier Arresting Kit 12 (BAK-12) energy absorber is the most prevalent energy absorber employed by the DoD.

These energy absorbers can be installed permanently, as is common at main operating bases, or temporarily for short-term use or contingency operations. Permanent AAS installations generally require that the energy absorber be housed within concrete chambers adjacent to the runway surface. Figure 1 shows a BAK-12 absorber unit being lowered into its installation location during a permanent AAS installation.

Figure 1. Barrier Arresting Kit 12 being lowered into an installation pit.



Most US Air Force (USAF) airfields are required to support operations of multiple airframes to include fighter aircraft as well as wide-bodied aircraft. These wide-bodied aircraft, such as the C-17 cargo aircraft, require larger wingtip clearance distances for obstructions near the minimum aircraft operating strip. In these cases, the energy absorber is required to be set back farther from the runway centerline. For permanent setback AAS installations, a fairlead beam edge sheave system is typically installed in both edges of the runway surface to prevent erratic movement in the arresting tape and reduce the tape sweep area during aircraft engagement events. Figure 2 shows an example of a permanent fairlead beam installation.

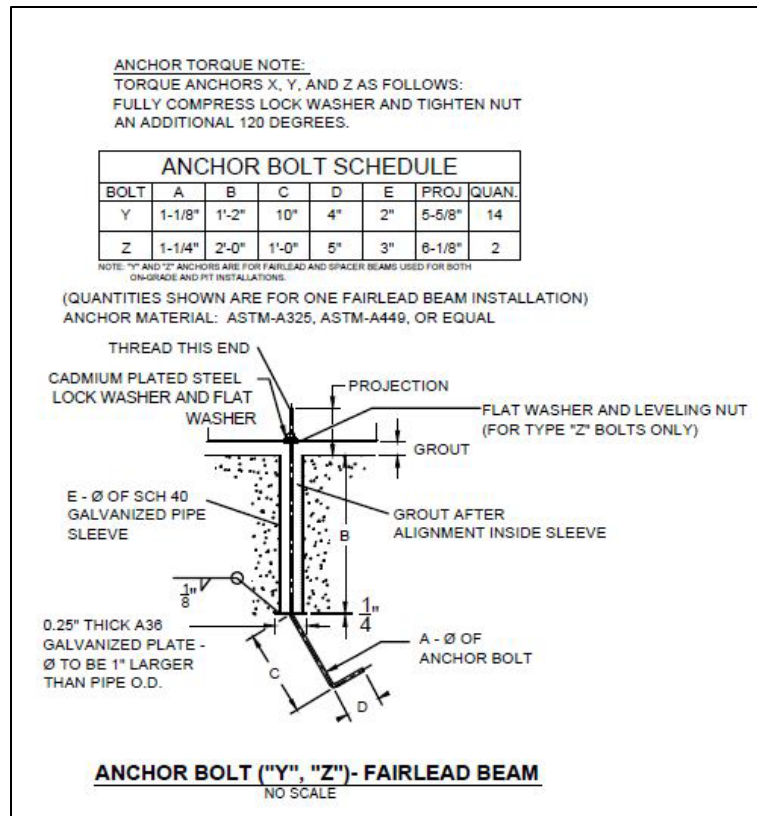
Figure 2. Permanent fairlead beam installation.



Requirements for permanent installation of fairlead beams are provided in USAF Drawing Number 67F2013A (Department of the Air Force, n.d.). For these permanent fairlead beam installations, a 54 in.* deep, 3,000 psi compressive strength concrete foundation with steel reinforcement (rebar) is cast beneath the desired placement location of the fairlead beam. This concrete foundation serves as the substrate for anchorage of the fairlead beam. Each fairlead beam is secured to its concrete foundation by 10 Y-bolt and 2 Z-bolt anchors, as detailed in Figure 3.

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Figure 3. Fairlead beam Y- and Z-bolt anchor detail.



The rebar reinforcing cage within the fairlead beam foundation pad is tied in place prior to the placement and consolidation of the concrete mixture. According to Drawing Number 67F2013A, a 1/2 in. thick plywood template of the fairlead beam base with anchor locations can be used to hold anchors in place while the concrete is placed for the foundation pad. Drawing notes stop short of prescribing a detailed, step-by-step process for tying the anchor assemblies to the steel reinforcement prior to placing the concrete mixture or outlining consolidation requirements near the anchors. Dialogue with USAF Air Force Civil Engineering Center (AFCEC) subject matter experts revealed that ideally, the concrete foundation pad would be placed first with the anchor assemblies in place. At a later date, the grout inside the galvanized pipe sleeve would be placed simultaneously with the leveling layer of grout across the concrete foundation pad's surface (which would coincide with the time of placement of the fairlead beam itself).

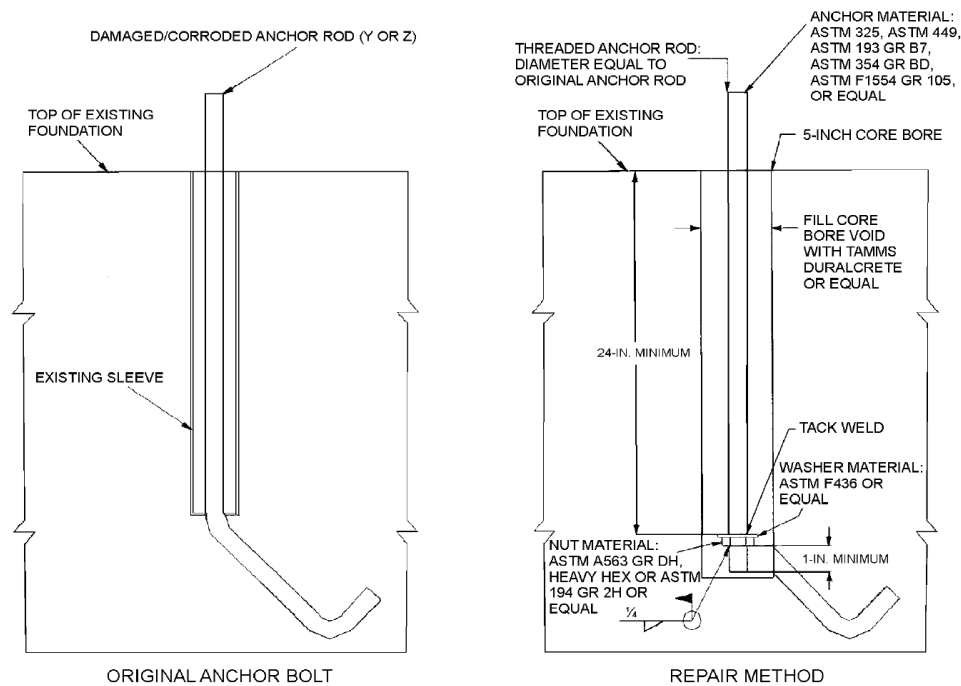
The method for inspection of fairlead beam anchor bolts is given in Section 5.30 of USAF TO 35E8-2-5-3 (Department of the Air Force 2018). The nondestructive inspection procedure outlined in USAF TO 35E8-2-5-3 consists of an ultrasonic inspection using a USN 52 Krautkramer Branson

inspection unit. Procedures for preparing the bolt head and calibrating the unit are provided. The document also outlines inspection unit outputs that indicate whether a defect is present in the bolt, requiring further inspection or repair. According to this document, “Y bolt circumferential fatigue cracks may occur anywhere along the entire length of the anchor bolts with particular attention to the exposed threaded end of the bolt in the nut and washer areas to a depth of approximately 6 in. ... and also at a depth of approximately 20 in. to include the 1/4 in. steel plate area but not to include areas below the first bend area” (Department of the Air Force 2018). There is no mention of anchor bolt material degradation related to corrosion—only cracking.

Those anchor bolts that are determined via nondestructive investigation to have defects are required to be reported to WR/ALC-542 Combat Sustainment Wing/642 CBSSS/GBZO-ENI Engineering for determination of any further action. If a determination is made that repair of the anchor rod is required, then a repair method is provided in USAF TO 35E8-2-5-3 (Department of the Air Force 2018). Figure 4 provides a schematic of this repair method.

A maximum of five anchor rods are allowed to be replaced by this method, implying that if more than five of the anchor rods must be replaced, then the entire foundation for the fairlead beam must be reconstructed unless a waiver is received from the USAF Life Cycle Management Center.

Figure 4. Fairlead beam anchor rod repair.



1.1 Background

Fairlead beams at USAF airfields are slated for overhaul on a recurring basis. To accomplish these overhauls, the setback device is removed and replaced with a new or recently serviced unit from the depot. The fairlead beam to be overhauled is then sent off for service and repair. During the overhaul process, and while the previously installed fairlead beam is removed from its foundation, the grout bed and anchor bolts on the concrete foundation pad are inspected. The anchor bolt inspection process follows the nondestructive method described previously in this section. Reports from field personnel and AFCEC subject matter experts responsible for reviewing anchor bolt inspection results and overseeing repair work indicate that the failure rate, in accordance with the nondestructive inspection method, is higher than desired.

An overhaul of the AAS on the north end of Runway 03R-21L at Luke Air Force Base (AFB), Arizona, was completed in December 2020. Most of the anchor bolts beneath the two fairlead beams did not meet the nondestructive inspection requirements and, therefore, were selected for removal and replacement with the repair method shown in Figure 4. Four of the field-cored anchor rods were delivered to the US Army Engineer Research and Development Center (ERDC) for evaluation to investigate whether these

anchors did not meet inspection requirements because of overloading of the anchor rod during arrestment, materials-related distresses (i.e., corrosion), or some other reason.

1.2 Objective

The objective of this report is to present the methods and results of a finite element analysis of the loading condition of the fairlead beam Y-bolt anchor, a visual inspection and petrographic analysis of the field cores, and a mechanical analysis of specimens taken from the anchor rods within the concrete cores. Furthermore, discussion is given for each of the analyses, and conclusions and recommendations are provided.

1.3 Approach

Section 2 of this report provides the setup and results of a finite element analysis of the loading condition of the fairlead beam Y-bolt. Section 3 describes the methods and results of a visual inspection and petrographic analysis of the concrete field cores. Section 4 presents the method and results of a mechanical analysis of specimens taken from the anchor rods within the field cores. Discussion of results is provided in Section 5. Finally, recommendations and conclusions are presented in Section 6.

2 Finite Element Analysis

This chapter presents the model inputs and results of a finite element analysis of a fairlead beam Y-bolt in Portland cement concrete (PCC). The objectives for the finite element analysis were as follows:

- To obtain a better understanding of single-anchor response to monotonic load
- To provide insight as to whether Y-bolt failures during nondestructive testing inspections were load-related
- To compare behavior of the repaired bolt assembly to that of the original Y-bolt assembly

This analysis was performed early in the project to inform the investigation. Note that detailed dimensions and material property test data were not available at the time of the analysis. Therefore, existing plans and generic material properties were employed based on engineering judgment.

2.1 Y-Bolt Stress Analysis

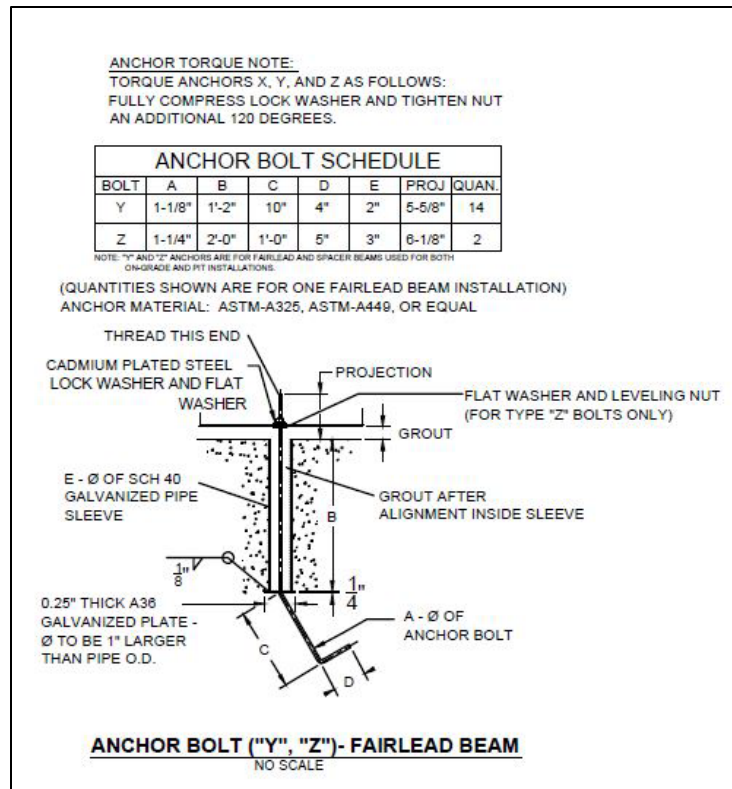
2.1.1 Model Setup

A finite element model of a Y-bolt assembly was constructed using the Abaqus/CAE (computer-aided engineering) preprocessor based on a detail drawing of the anchorage (Department of the Air Force, n.d.). The model included the Y-bolt, schedule 40 pipe, grout (infill and leveling pad), and concrete slab shown in Figure 5. Not all dimensions were specified, and some had to be assumed:

- The diameter of bends at the bolt centerline was assumed as 1.5 times the bolt diameter ($1.5 \times 1.125 \text{ in.} = 1.6875 \text{ in.}$).
- Portion “C” of the bent bolt was measured at approximately 30 degrees with respect to vertical.
- The grout layer used for leveling was assumed to be 1 in. thick.

Note that the hooked portion of the bolt is oriented perpendicular to the applied load, so symmetry cannot be used to simplify the model.

Figure 5. Anchor bolt for a fairlead beam.



A cross section of the model, showing the bent portion of the bolt, is presented in Figure 6. The concrete block containing the anchor was $72 \times 72 \times 36$ in. (length $\times$ width $\times$ depth). The Y-bolt was constrained to the grout and concrete by using the embedded element technique. Tied constraints were used to join the other parts. This modeling approach assumes perfect bond, which may not be realistic. The full list of constraints used is given below:

1. Embed the part of the bolt above the plate into grout.
2. Embed the plate and the part of the bolt below the plate into slab.
3. Tie the grout to the inner surface of the pipe.
4. Tie the pipe outside to the concrete.
5. Tie the bolt plate to the bottom of the grout.
6. Tie the bottom of the pipe to the bolt plate.
7. Tie the top of the slab to the bottom of the grout bed layer.

Figure 6. Cross section of the Y-bolt model.

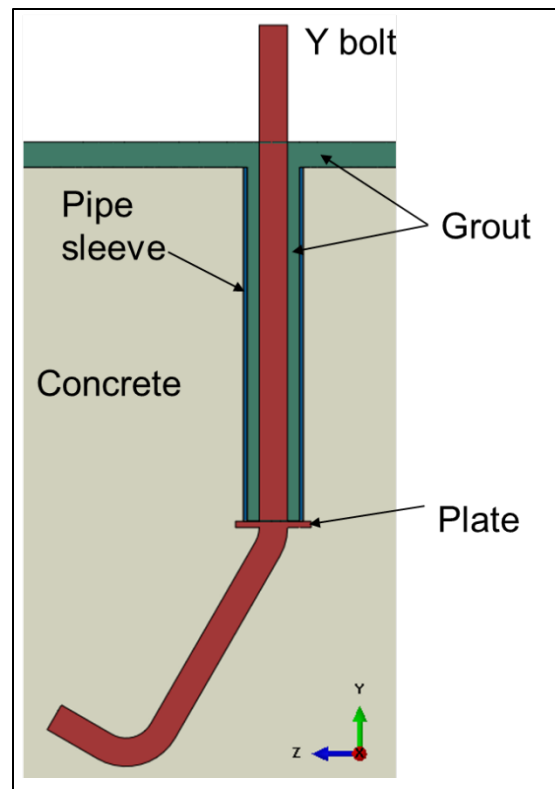
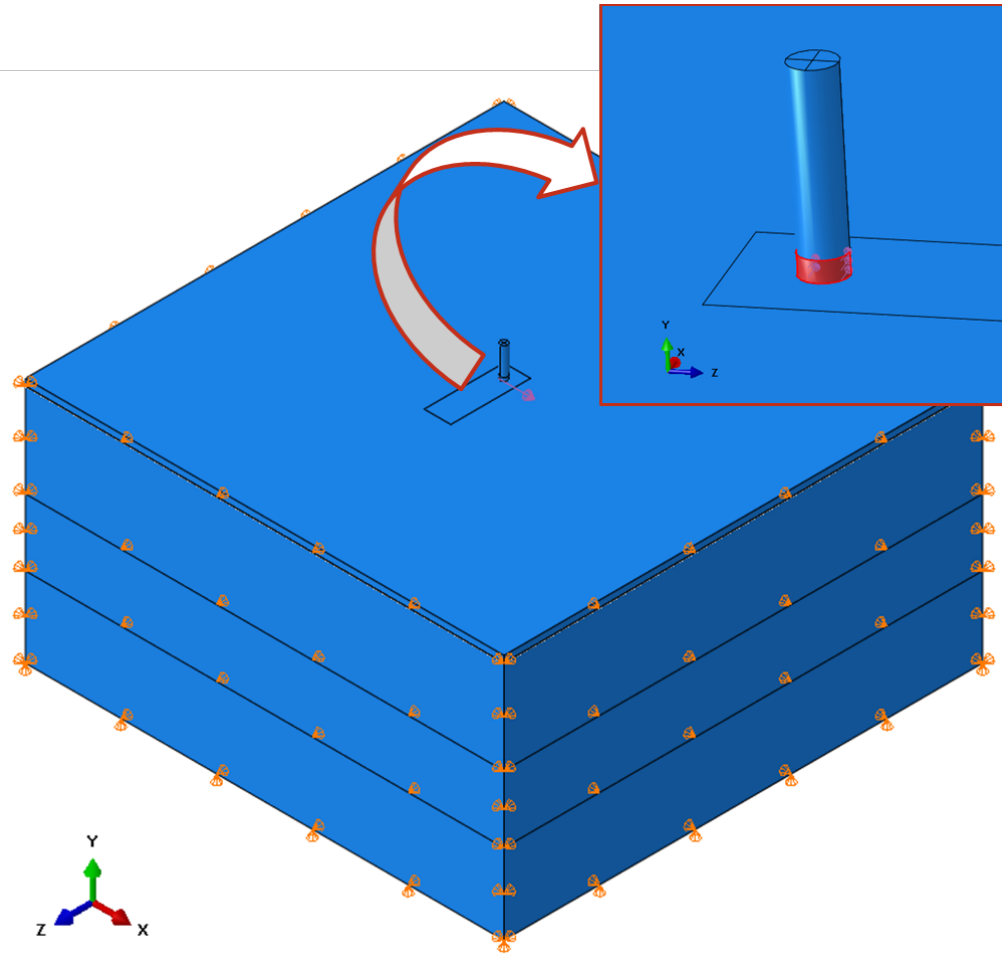


Figure 7 illustrates the boundary conditions and loading that were applied to the Y-bolt model. Five faces of the concrete slab ($-x$, $+x$, $-y$, $-z$, and $+z$) were restrained against displacement in the normal direction. The load was applied as a surface traction acting in the positive x -direction. The surface traction was applied over a 1/2 in. high region on the rear half of the bolt (see inset in Figure 7). The traction magnitude was 12,449.4 psi to obtain a total horizontal load (on one bolt) of 11,000 lbf. This load is the tape-breaking strength (110,000 lbf) divided by the number of Y-bolts (10) and conservatively neglects the resistance provided by the 2 Z-bolts.

Figure 7. Boundary conditions and load application region for the Y-bolt model.



Analysis was performed by using Abaqus/Standard V6R2018 (Dassault Systemes Simulia Corporation 2018) for implicit static analysis. The iterative solver was used in parallel with two cores. Default settings were applied.

Linear elastic, small-displacement theory was assumed. The mesh comprises solid (continuum), 3D, eight-noded linear brick (hexahedral), reduced integration elements with hourglass control (type C3D8R). Typical mechanical properties for concrete, grout, and steel were used (see Table 1). The elastic modulus of concrete was approximated using $E_c = 57000\sqrt{f'_c}$, where $f'_c = 5,000$ psi, and E_c is in units of psi. This results in $E_c = 4,031$ ksi, which was rounded to 4,000 ksi. The elastic modulus of the grout was based on the requirement of an $f'_c = 10,000$ psi minimum, non-shrink machinery grout. Utilizing this same relation between E_c and f'_c yields an E_c of approximately 5,700 ksi. The Poisson's ratio was taken as 0.15 for the concrete and the grout.

Table 1. Material properties for Y-bolt stress analysis.

Material	Elastic Modulus (ksi)	Poisson's Ratio
Concrete	4,000	0.15
Grout	5,700	0.15
Steel	29,000	0.30

A preliminary study on mesh density led to the selection of the mesh shown in Figure 8. The mesh on the bolt and pipe is refined, with the adjacent elements in the concrete and grout refined also (see close-up at the right of Figure 8). This model contained a total of 1,670,903 elements and 1,718,368 nodes, resulting in 5,160,000 degrees of freedom (DOFs). Details are shown in Table 2.

Figure 8. Mesh of the Y-bolt model with a close-up view of mesh refinement around the bolt.

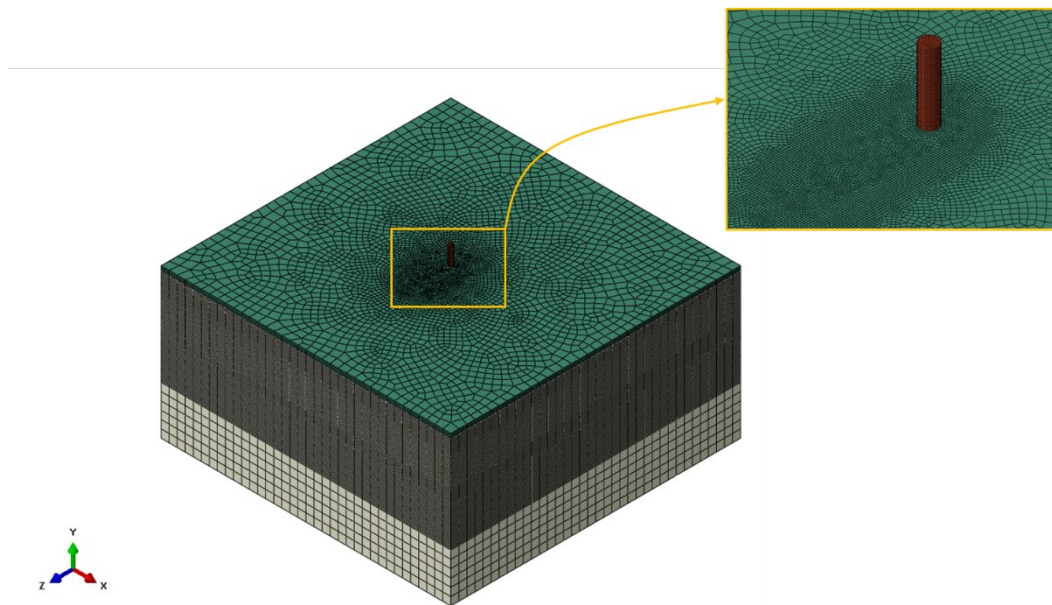


Table 2. Y-bolt mesh details.

Part	Elements	Nodes	Approximate Element Size (in.)
Pipe sleeve	12,276	16,544	0.15 (with 3 elements through thickness)
Y-bolt	30,272	35,911	0.11
Grout	97,299	111,092	0.15 (near bolt), 2 (far from bolt)
Slab	1,531,056	1,554,821	0.15 (near bolt), 2 (far from bolt)

2.1.2 Results

Under an 11-kip load, the maximum von Mises stress in the bolt was approximately 31.7 ksi, occurring at 0.1 in. above the top of the grout pad (or 4.5 in. below the top of the bolt). The maximum von Mises stress occurred on the side of the bolt (approximately ± 90 degrees from the direction of applied loading). This indicates that the bolt was primarily stressed in shear. The corresponding displacement at the top of the bolt head was 0.009 in. Figure 9 shows the von Mises equivalent stress, σ_{vm} , distribution in the Y-bolt. For purposes of visualization, deformations are scaled by a factor of 50. All areas with $\sigma_{vm} < 100$ psi are colored dark gray. The lowest point where $\sigma_{vm} > 100$ psi is 10.5 in. below the top of the bolt (4.9 in. below the surface of the concrete).

Figure 9. Von Mises equivalent stress (pounds per square inch) in the Y-bolt (deformations scaled 50×).

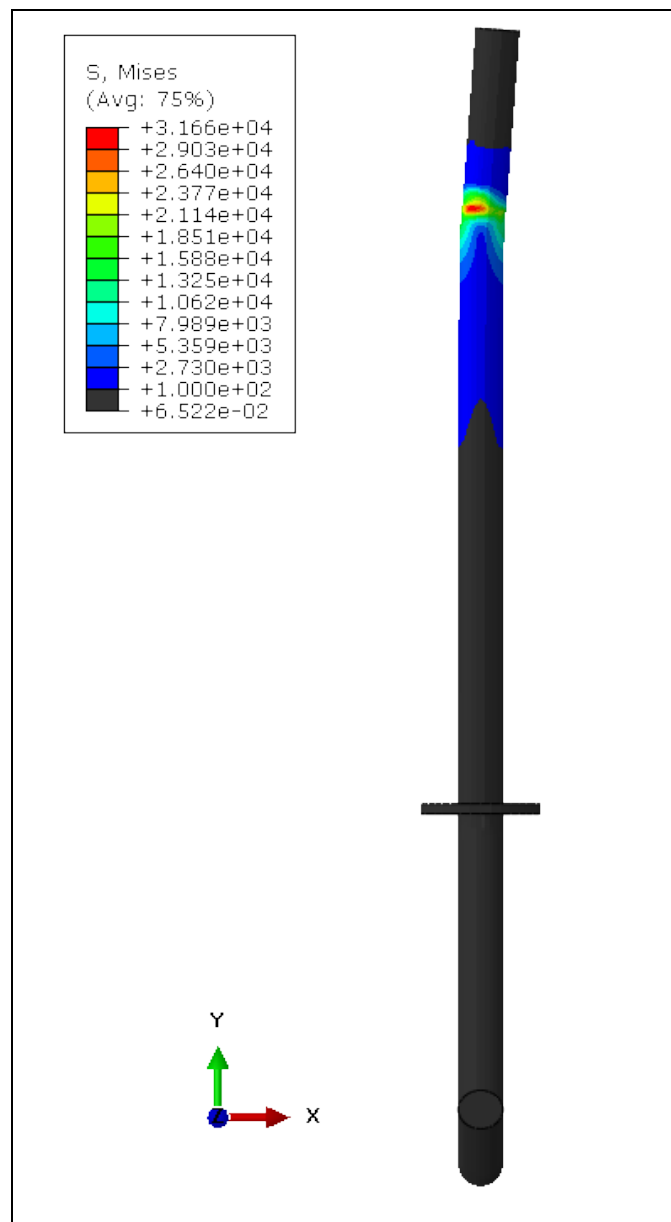


Figure 10 is a plot of von Mises stress along a path running down the rear ($-x$) face of the Y-bolt. Note that stress is plotted on a logarithmic scale to better show the decay of stress to low levels in most of the bolt.

Figure 10. Von Mises stress along the bolt (logarithmic scale for stress axis).

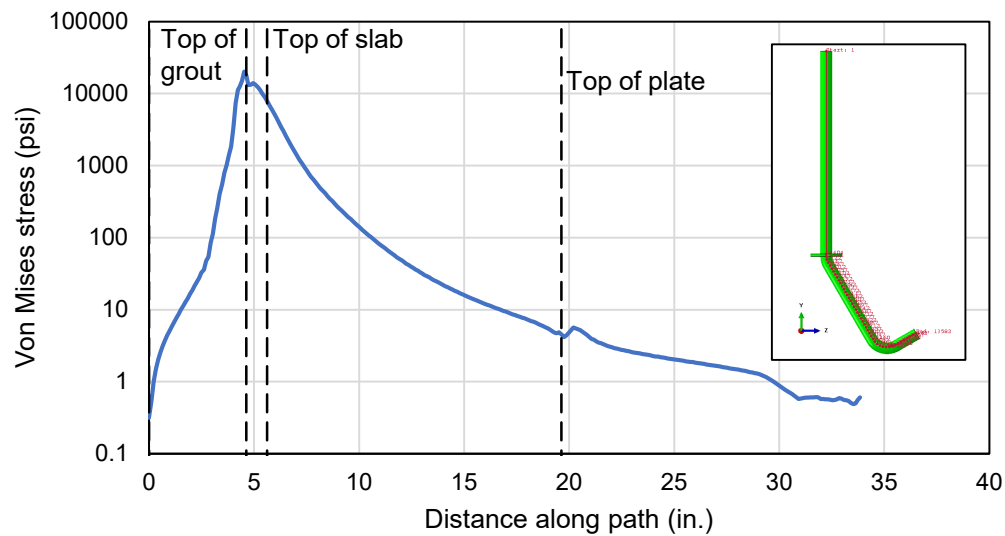
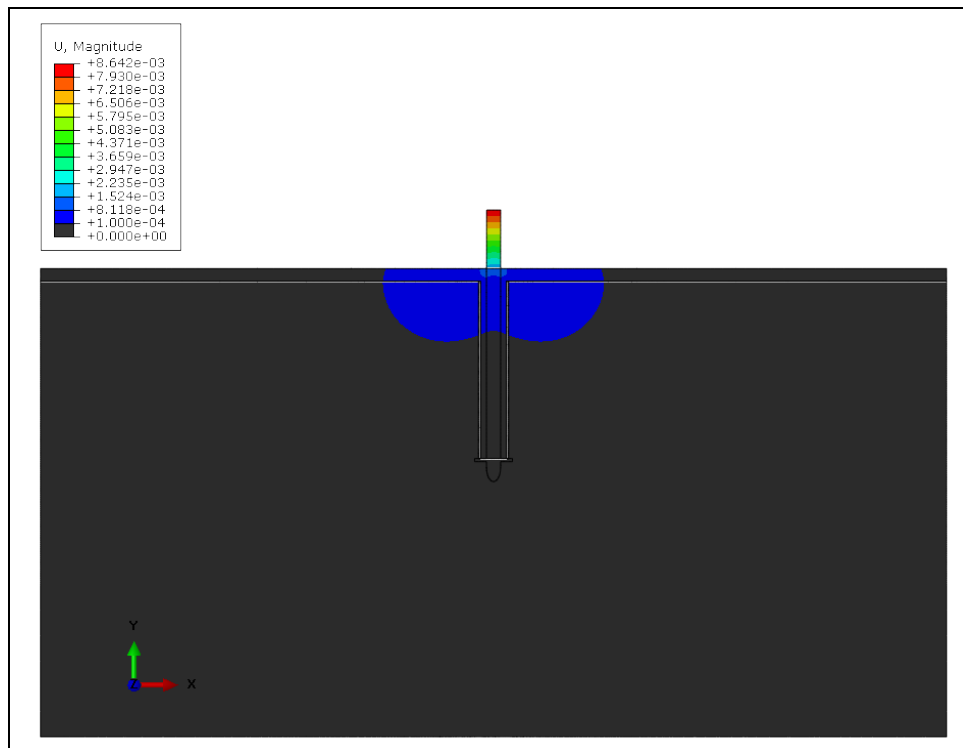


Figure 11 is a cross section through the model showing displacement magnitude. Any area with displacement magnitude less than 0.0001 in. is colored dark gray.

Figure 11. Displacement magnitude (inches) at a cross section of the Y-bolt model.



2.2 Repaired Y-Bolt Anchor Stress Analysis

2.2.1 Model Setup

A finite element model of a repaired Y-bolt assembly was constructed using the Abaqus/CAE preprocessor based on a detail drawing (Department of the Air Force 2018). The model included the anchor bolt, epoxy grout, and concrete slab shown in Figure 12. A cross section of the model with dimensions is shown in Figure 13. The concrete block containing the anchor was $72 \times 72 \times 36$ in. (length $\times$ width $\times$ depth). The anchor bolt was constrained to the epoxy grout by using the embedded element technique. Tied constraints were used to join the other parts. This modeling approach assumes perfect bond, which may not be realistic.

Figure 12. Schematic of the repaired Y-bolt anchor.

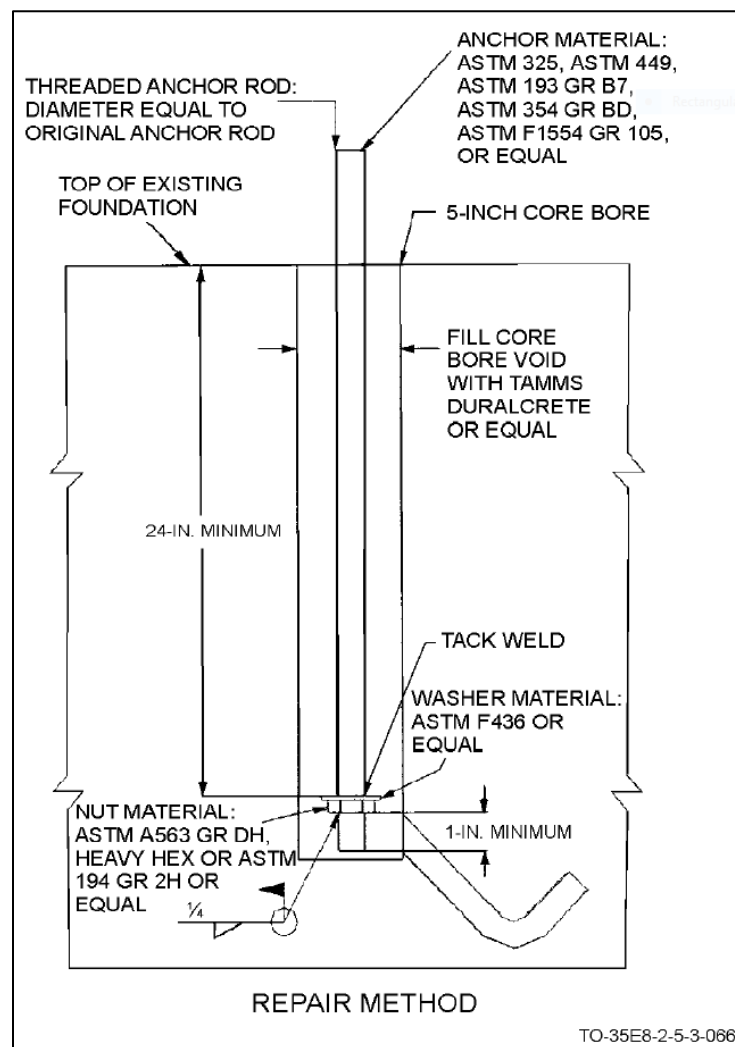


Figure 13. Cross section of the repaired Y-bolt anchor model.

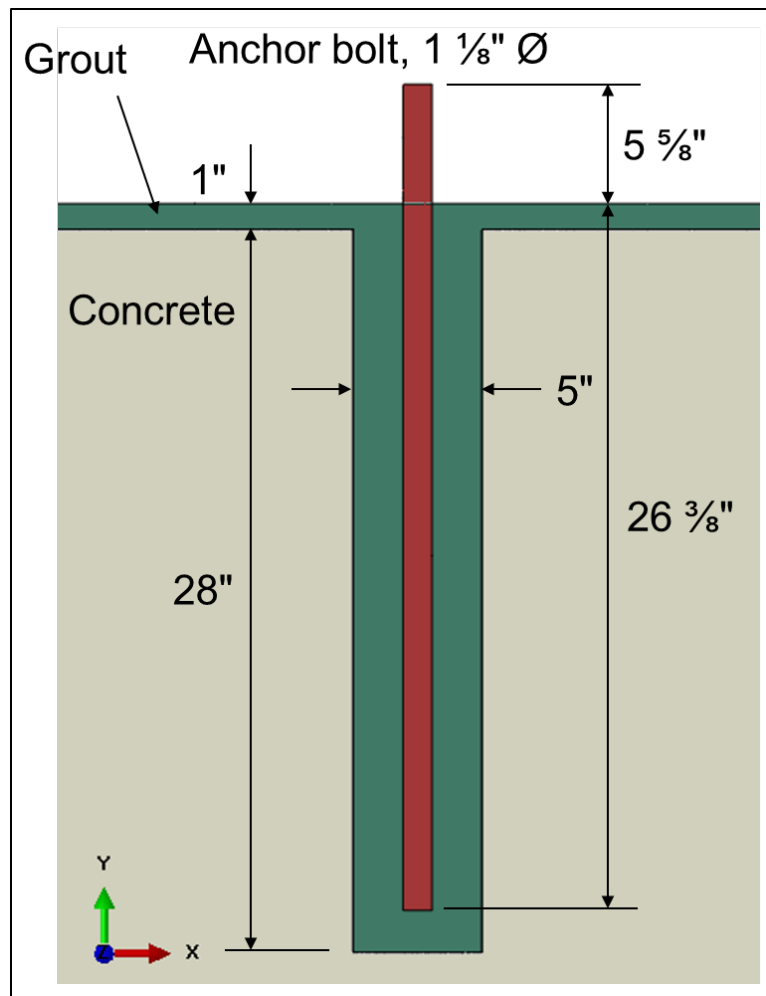
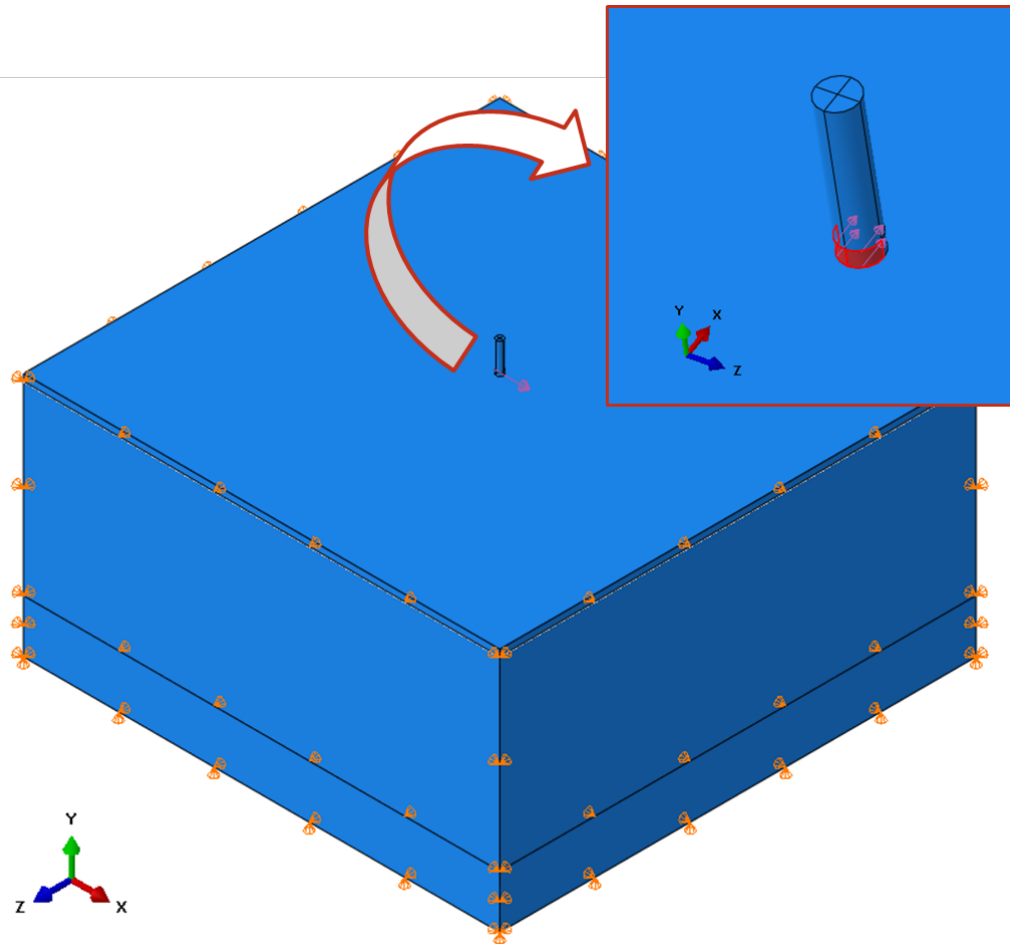


Figure 14 illustrates the boundary conditions and loading that were applied to the repaired anchor bolt model. Five faces of the concrete slab ($-x$, $+x$, $-y$, $-z$, and $+z$) were restrained against displacement in the normal direction. The load was applied as a surface traction acting in the positive x -direction. The surface traction was applied over a 1/2 in. high region on the rear half of the bolt (see inset in Figure 14). The traction magnitude was 12,449.4 psi to obtain a total horizontal load (on one bolt) of 11,000 lbf. This load is the tape-breaking strength (110,000 lbf) divided by the number of Y-bolts (10) and conservatively neglects the resistance provided by the 2 Z-bolts.

Figure 14. Boundary conditions and loads applied to the repaired anchor model.



Analysis was performed by using Abaqus/Standard V6R2018 (Dassault Systemes Simulia Corporation 2018) for implicit static analysis. The iterative solver was used in parallel with two cores. Default settings were used. Linear elastic, small-displacement theory was assumed. The mesh comprises solid (continuum), 3D, eight-noded linear brick (hexahedral), reduced integration elements with hourglass control (type C3D8R). Material properties were the same as those used for the Y-bolt stress analysis (see Table 1) except for the grout. For the repaired Y-bolt anchor, an epoxy grout was utilized. The elastic modulus of the epoxy grout was based on data for Duralcrete Epoxy, which has $E_g = 330$ ksi in compression and $E_g = 439.8$ ksi in tension. Due to variability in values for other epoxies, $E_g = 400$ ksi was chosen as a ballpark value. In the absence of more refined data, the Poisson's ratio for epoxy grout was taken as 0.3.

Element sizes were selected based on the mesh refinement study conducted for the Y-bolt model. Due to simpler geometry, the mesh for the repaired anchor model (Figure 15) had 4.24M DOFs. This model contained a total of 1,360,933 elements and 1,413,769 nodes. Details are given in Table 3.

Figure 15. Mesh of the repaired Y-bolt anchor model.

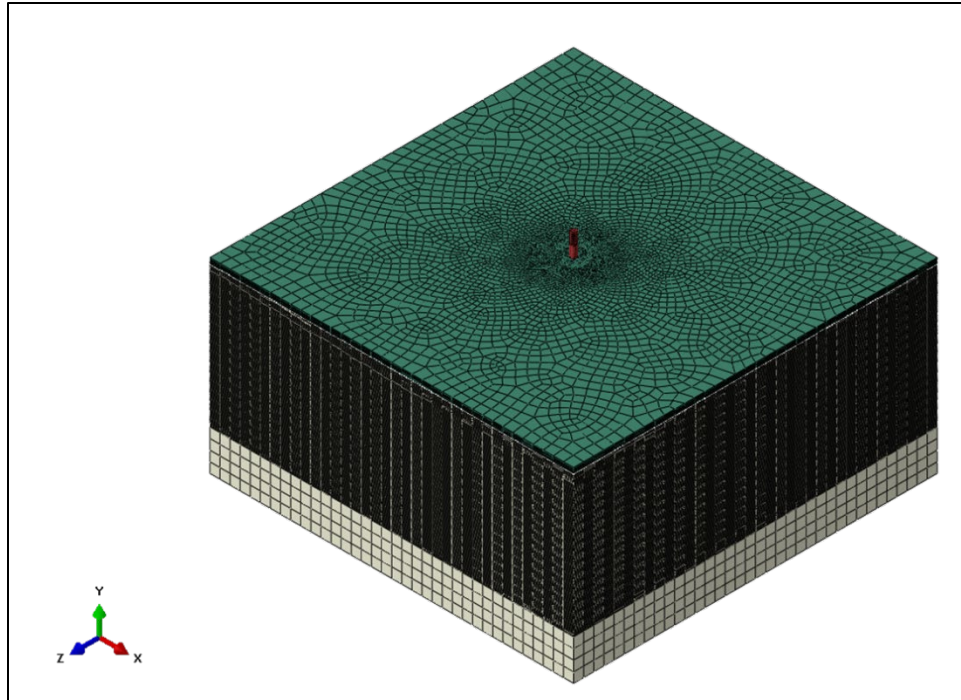


Table 3. Repaired Y-bolt mesh details.

Part	Elements	Nodes	Approximate element size (in.)
Rod	28,032	33,109	0.11
Grout	275,308	292,942	0.15 (near bolt), 2 (far from bolt)
Slab	1,057,593	1,087,718	0.15 (near bolt), 2 (far from bolt)

2.2.2 Results

Under an 11-kip load, the maximum von Mises stress in the repaired Y-bolt was approximately 35.3 ksi, occurring at roughly the same elevation as the top of the concrete slab (6.6 in. below the top of the bolt). The maximum von Mises stress occurred on the front and back of the bolt (approximately 0 and 180 deg from the direction of loading). This indicates that the bolt was stressed in flexure. There was also a stress hot spot near the top of the grout pad. The corresponding displacement at the top of the bolt head was 0.043 in. Figure 16 shows the von Mises equivalent stress, σ_{vm} ,

in the repaired anchor bolt. For purposes of visualization, deformations are scaled by a factor of 50. All areas with $\sigma_{vm} < 100$ psi are colored dark gray. The lowest point where $\sigma_{vm} > 100$ psi is 14.8 in. below the top of the bolt (8.2 in. below the surface of the concrete).

Figure 16. Von Mises equivalent stress (pounds per square inch) in the repaired Y-bolt anchor (deformations scaled 50×).

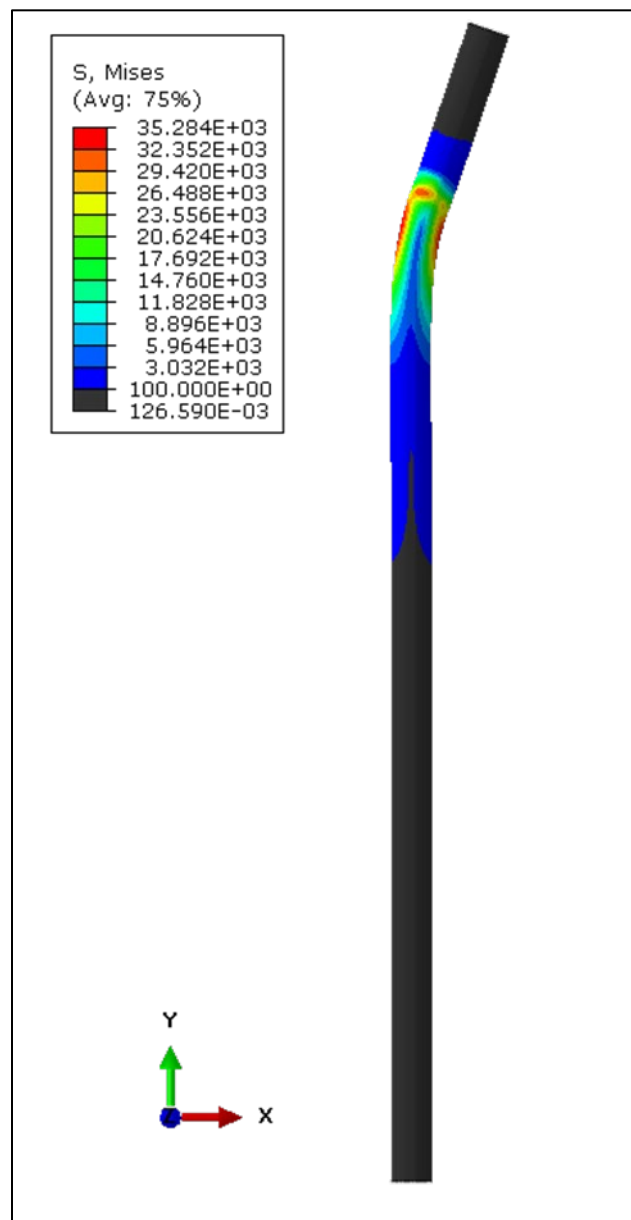


Figure 17 is a plot of von Mises stress along a path running down the rear ($-x$) face of the bolt. Note that stress is plotted on a logarithmic scale to better show the decay of stress to low levels in most of the bolt.

Figure 17. Von Mises stress along a repaired Y-bolt anchor (logarithmic scale for stress axis).

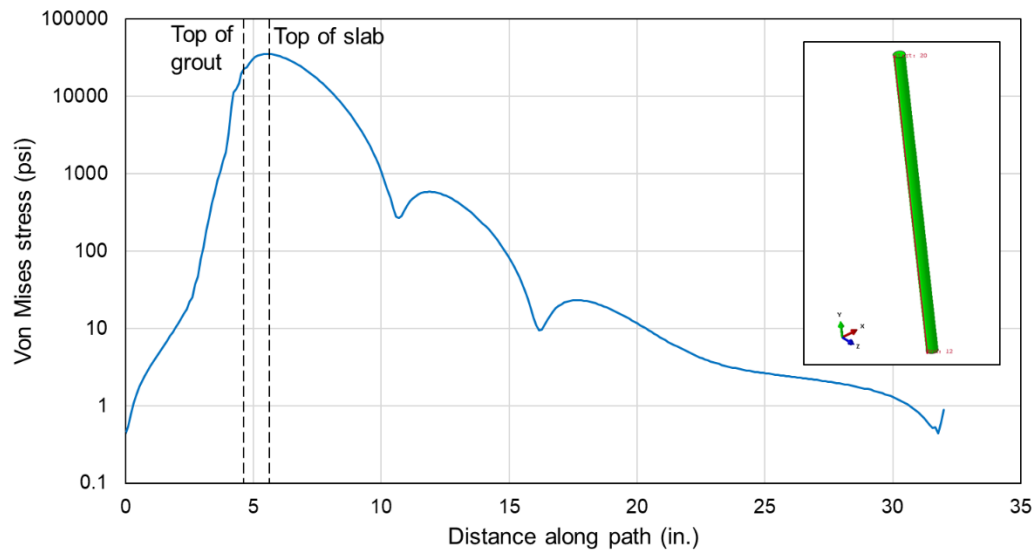
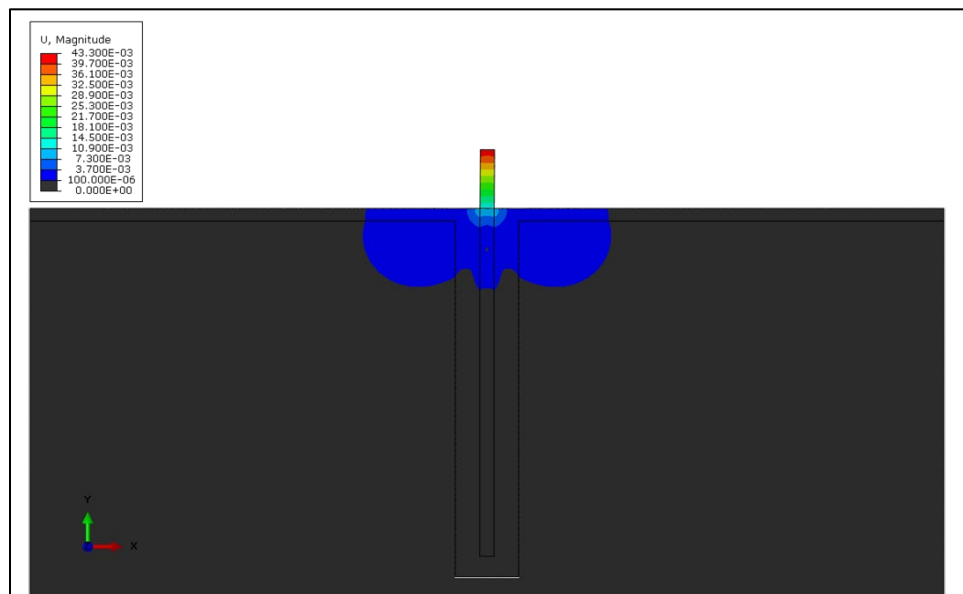


Figure 18 is a cross section through the model showing displacement magnitude. Any area with displacement magnitude less than 0.0001 in. is colored dark gray.

Figure 18. Displacement magnitude (inches) at a cross section of the repaired Y-bolt anchor model.



A range of epoxy grouts may be used on repaired anchor installations. To assess the effect of the epoxy grout's stiffness on results, simulations were conducted in which the epoxy grout's modulus of elasticity was changed by -25% and +25%, respectively. Results in Table 4 show that decreasing the

epoxy grout stiffness decreases the stiffness of the entire assembly. This results in greater displacements and higher stresses in the bolt since the bolt is bent to a larger curvature.

Table 4. Effect of epoxy grout stiffness on repaired Y-bolt anchor results.

Epoxy Grout Modulus of Elasticity (ksi)	Displacement at Top Center Node, δ (in.)	Maximum von Mises Stress in Bolt (ksi)
300	0.05124	38.60
400	0.04312	35.28
500	0.03771	33.06

3 Petrographic Analysis

This chapter provides an overview of the test methods and results of a petrographic analysis of the concrete surrounding the Y-bolt anchors from Luke AFB. The intent of the analysis was to investigate the condition of the concrete surrounding the anchor assembly for the four intact cores available for analysis.

3.1 Description of Test Methods

3.1.1 Petrographic Analysis, ASTM C856

First, visual examinations assessed modes of distress, such as physical distress and dimensional stability, of the as-received cores. Second, the polished cores were subjected to petrographic analysis according to American Society for Testing and Materials (ASTM) C856, *Standard Practice for Petrographic Examination of Hardened Concrete* (2020a). The cores were prepared for the petrographic analysis by bisection longitudinally through the length of the core, which extended above the galvanized pipe sleeve. The top 4 in. section was polished using diamond encrusted polishing pads for petrographic analysis. An overall image was obtained for the sample at low magnification by using a flat-bed scanner, and at least three selected sites were also imaged at higher magnification with a stereomicroscope. The top section of the bisected cores was analyzed by using a Zeiss Stereo Discovery V20 microscope at magnifications of 5× to 50×, and specific focus was given to microcracking, air void structure, aggregate deterioration, and any other possible modes of concrete deterioration. Due to the fragility of the cores, other than normal core preparation was required; therefore, analyses and figures are not consistent across all cores.

3.1.2 Carbonation Depth

Carbonation of concrete by chemical reaction with atmospheric CO₂ is a concern. It can result in a reduction in pH of the concrete and subsequent corrosion initiation. Rapid carbonation is also a good indicator of near-surface concrete quality. Knowing this, depth of carbonation was determined by using a phenolphthalein pH indicator at the surface of the concrete. This indicator exhibits a bright pink color when exposed to alkaline concrete and remains clear when concrete exhibits carbonation (pH below ~10). Freshly fractured or cut faces of the provided concrete cores were photographed after the solution was applied.

3.1.3 X-Ray Diffraction (XRD) Analysis, ASTM C1365

X-ray diffraction (XRD) analysis was performed to identify the mineralogy of each component present in the concrete according to ASTM C1365, *Standard Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-ray Powder Diffraction Analysis* (2018). Although this method focuses on Portland cement analysis, the preparation and analysis procedures are readily applicable to other materials, including the forensic analysis described herein. Once the desired sample was isolated from the concrete, it was crushed and ground until at least 90% of the material passed a #325 sieve (44 μm). The ground specimen was prepared into random powder pack sample holders for XRD measurements. Diffraction patterns to be used for qualitative phase identification were obtained by using a Panalytical X'Pert Pro materials research diffractometer equipped with a Co-K α x-ray source operated at 45 kV and 40 mA. Diffraction patterns were obtained over a period of 2 hr from 2° to 70° with a step size of 0.020. Phase identification was performed using MDI Jade 2010 powder diffraction file reference databases.

3.2 Results

This results section is divided into four parts, one for each of the four received cores.

3.2.1 Core 210043-1

The as-received core 210043-1 is shown in Figure 19, and the bisected core 210043-1 is shown in Figure 20. The length of the core was 37 in., and the diameter was approximately 5 in. Based on total core length and diameter of the threaded anchor rod, this core contained a Z-bolt anchor.

Additional photographs of the core are provided in Appendix B. The following subsections provide a synopsis of the physical and durability related considerations discovered during petrographic analysis of the core.

Figure 19. Core 210043-1.

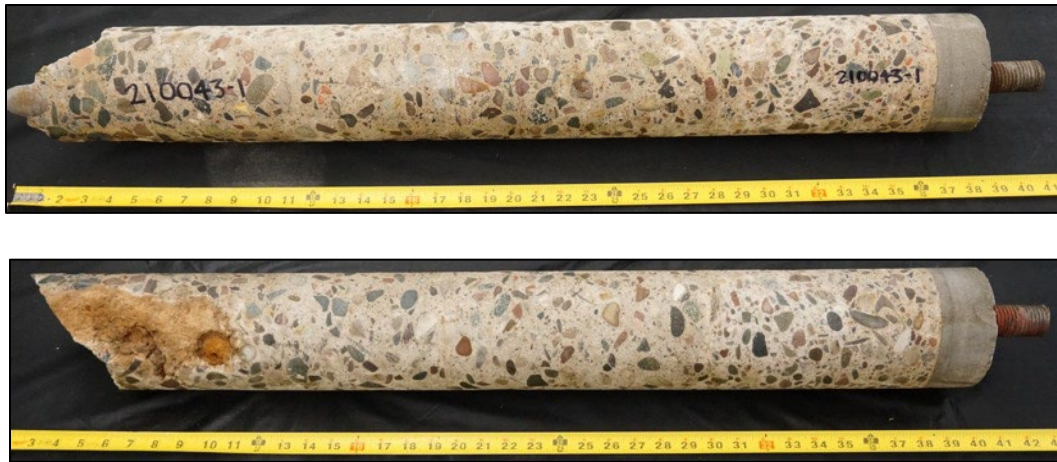


Figure 20. Bisected core 210043-1.



3.2.1.1 Petrographic Analysis

Visual inspection images of core 210043-1 are provided in Figure 21, and detailed photomicrographs of the core's microstructure are shown in Figure 22. Cracking was seen in the concrete, running a depth of about 2 in. and extending through the mortar cap. Friable concrete in the bottom third of the core was seen along with discoloration from corrosion. The coarse aggregate had a nominal size of 1.5 in. (3.8 cm). Silicate phases dominated the coarse aggregate fraction and were sub-round to round, indicative of a natural stone. The coarse aggregate made up approximately 30% of the concrete volume and was uniformly dispersed within the concrete. The paste was discolored in multiple areas from bolt corrosion. At

the top of the core, the corrosion was more pronounced at 2 to 3 in. measured from below the mortar cap. The concrete was friable in multiple locations, most notably at a depth of 30 in. from the surface. Corrosion of the pipe sleeve was noted extending 6.5 in.

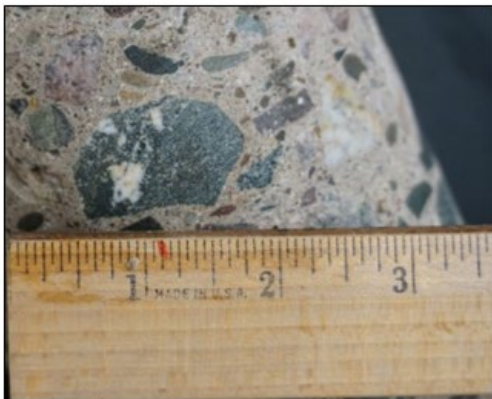
Figure 21. Visual examination of as-received core 210043-1.



(a) Corrosions and deterioration of concrete



(b) Corrosion of pipe sleeve

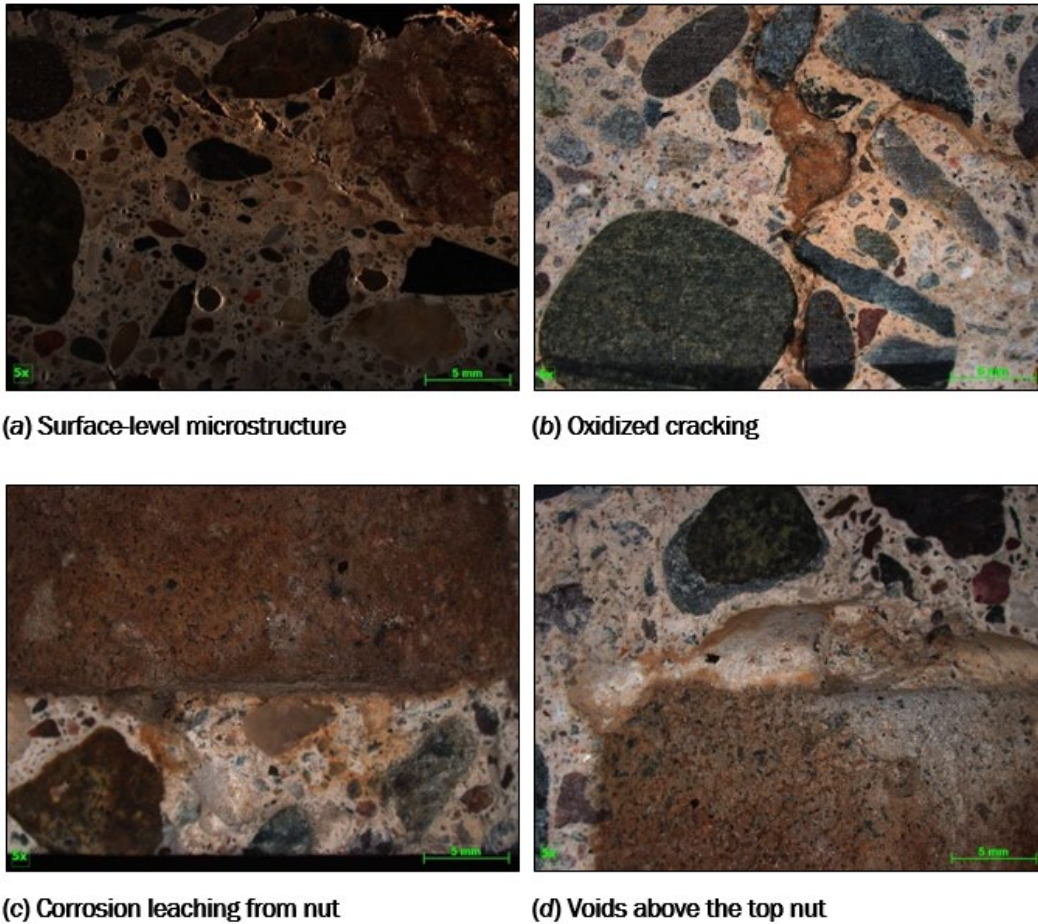


(c) Aggregate near 1.5 in. in diameter.



(d) Corrosion penetrating the lower core concrete

Figure 22. Photomicrographs of 210043-1 at 5× magnification.



3.2.1.2 Carbonation Depth

Figure 23 provides a photo of a freshly broken sample from 210043-1 with phenolphthalein applied to ascertain the degree of carbonation that occurred. Purple coloring indicates a pH of 10 and above. If the cement is uncolored, the sample tests for carbonation and the pH is below 10. The sample shows significant carbonation up to 15 mm (depth indicated by arrow).

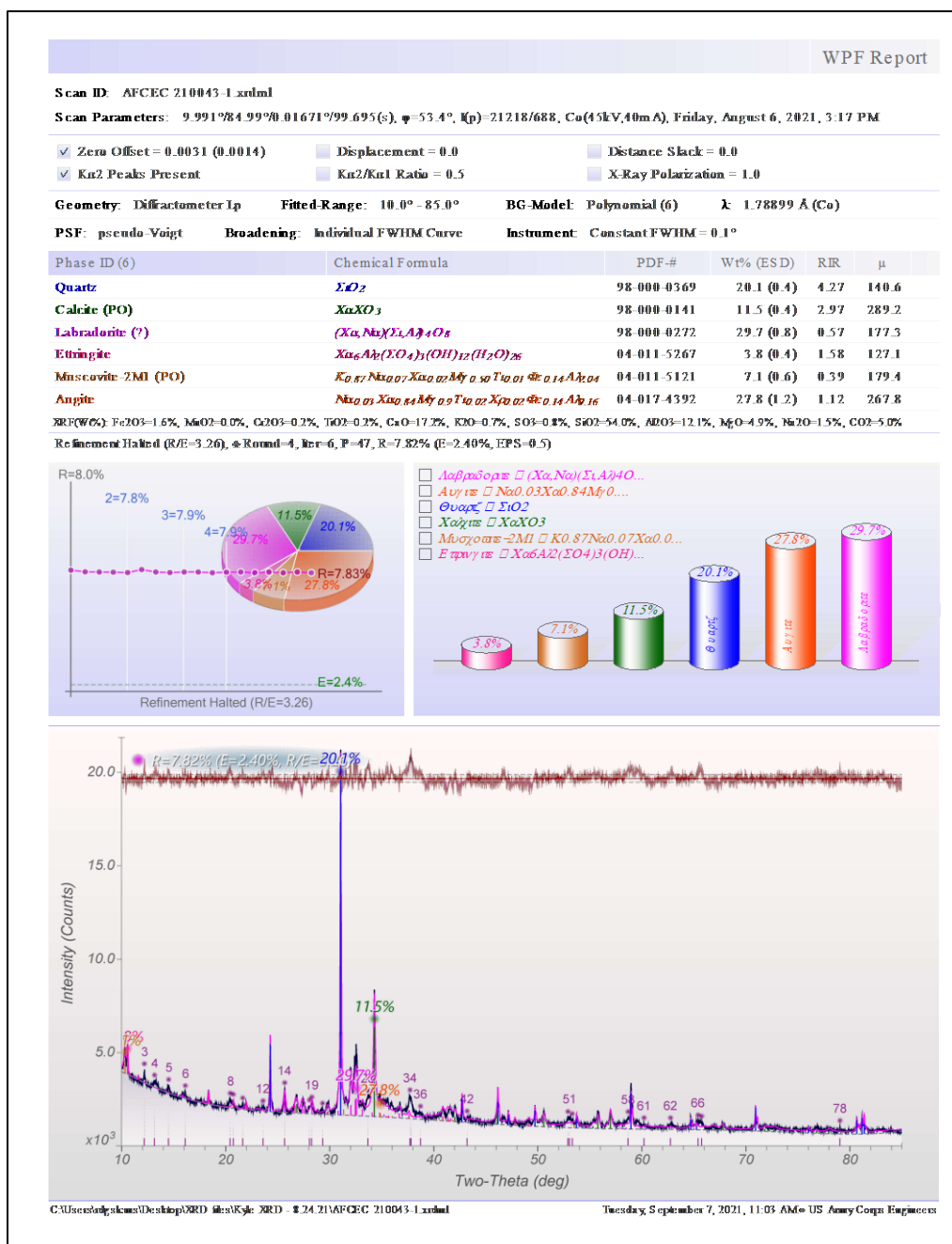
Figure 23. Phenolphthalein application for sample 210043-1.



3.2.1.3 XRD

Figure 24 provides mineralogy of the aggregate fraction of 210043-1 as determined by XRD. The aggregate composition indicates silicate-dominated lithologies, including granites and sandstones with minor calcite (11.5%). Muscovite, a clay phase, was identified, as well as ettringite, a common alteration phase associated with cementitious materials.

Figure 24. Diffraction pattern for 210043-1 with phase identifications, whole pattern fit, and calculated weight percentages.



3.2.2 Core 210043-2

The as-received core 210043-2 is shown in Figure 25, and the bisected core 210043-2 is shown in Figure 26. The core had a length of 27.5 in. a diameter of approximately 5 in.

Additional photographs of the core are provided in Appendix B. The following subsections provide a synopsis of the physical and durability related considerations discovered during petrographic analysis of the core.

Figure 25. Core 210043-2.

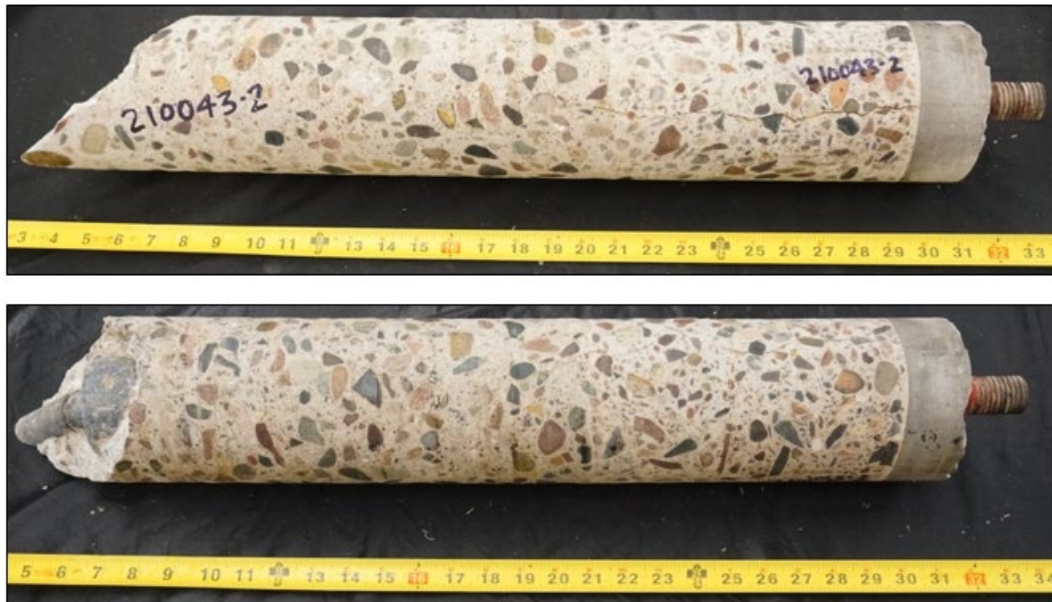


Figure 26. Bisected core 210043-2.



3.2.2.1 Petrographic Analysis

Visual inspection images for core 210043-2 are provided in Figure 27, and detailed photomicrographs of the core's microstructure are shown in Figure 28. Under the 2 in. mortar cap, cracking was seen in the concrete, running a depth of about 9 in. and terminating in the mortar cap. Corrosion

was seen only in the observable cracks, but after bisection the top 6 in. had corrosion close to the bolt. The coarse aggregate had a nominal size of 1.75 in. (4.45 cm). Silicate phases dominated the coarse aggregate fraction and were sub-round to round, indicative of a natural stone. The coarse aggregate made up approximately 30% of the concrete volume and was uniformly dispersed within the concrete. The paste was discolored in multiple areas from bolt corrosion and friable in multiple locations. Large voids above the top nut of the Y-bolt were observed.

Figure 27. Visual examination of core 210043-2.

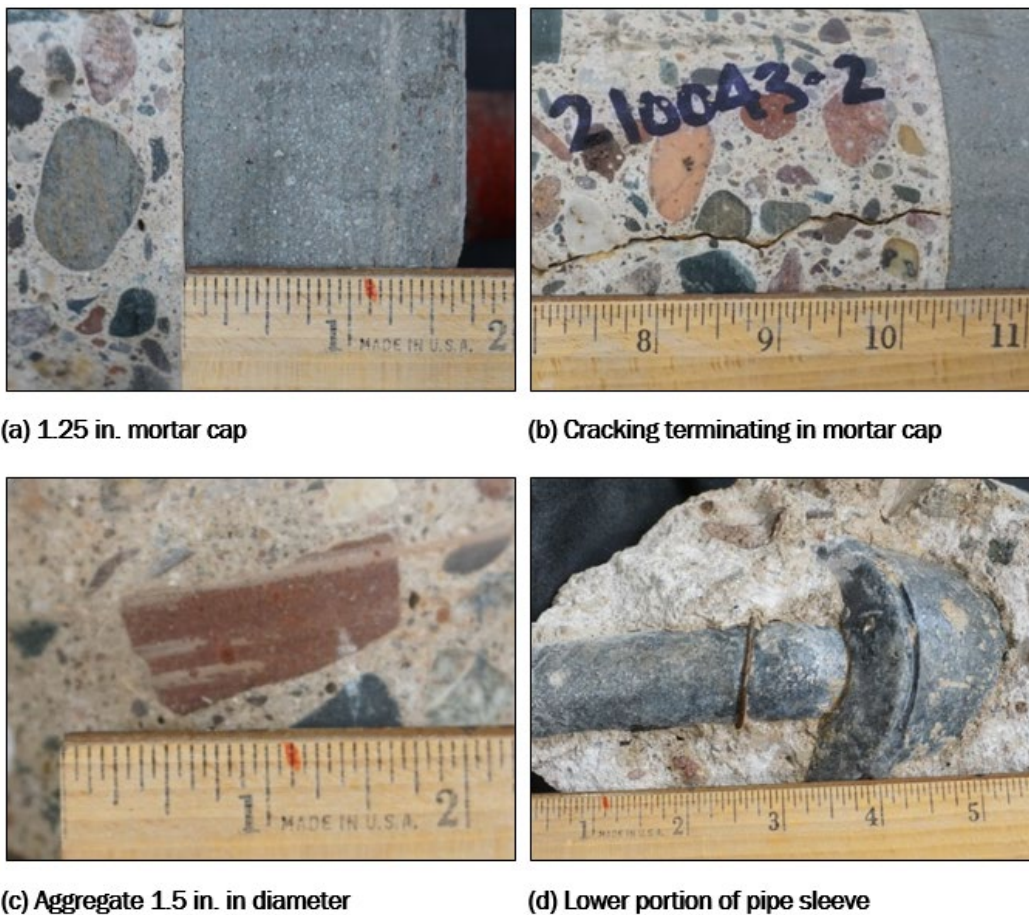
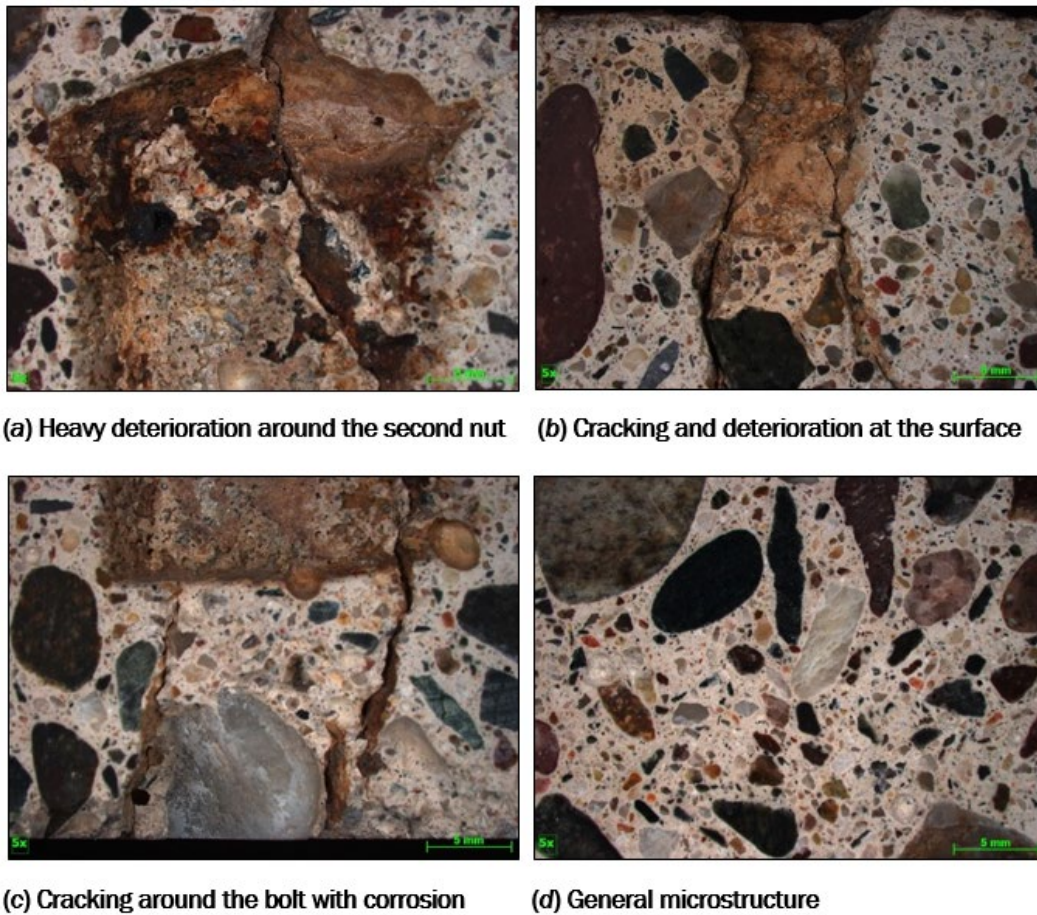


Figure 28. Photomicrographs of 210043-2 at $5\times$ magnification.



3.2.2.2 Carbonation Depth

Figure 29 shows a freshly broken sample from 210043-2 with phenolphthalein applied to ascertain the degree of carbonation that occurred. Purple coloring indicates a pH of 10 and above. If the cement is uncolored, the sample tests for carbonation and the pH is below 10. The sample shows carbonation up to 17 mm (depth indicated by arrows).

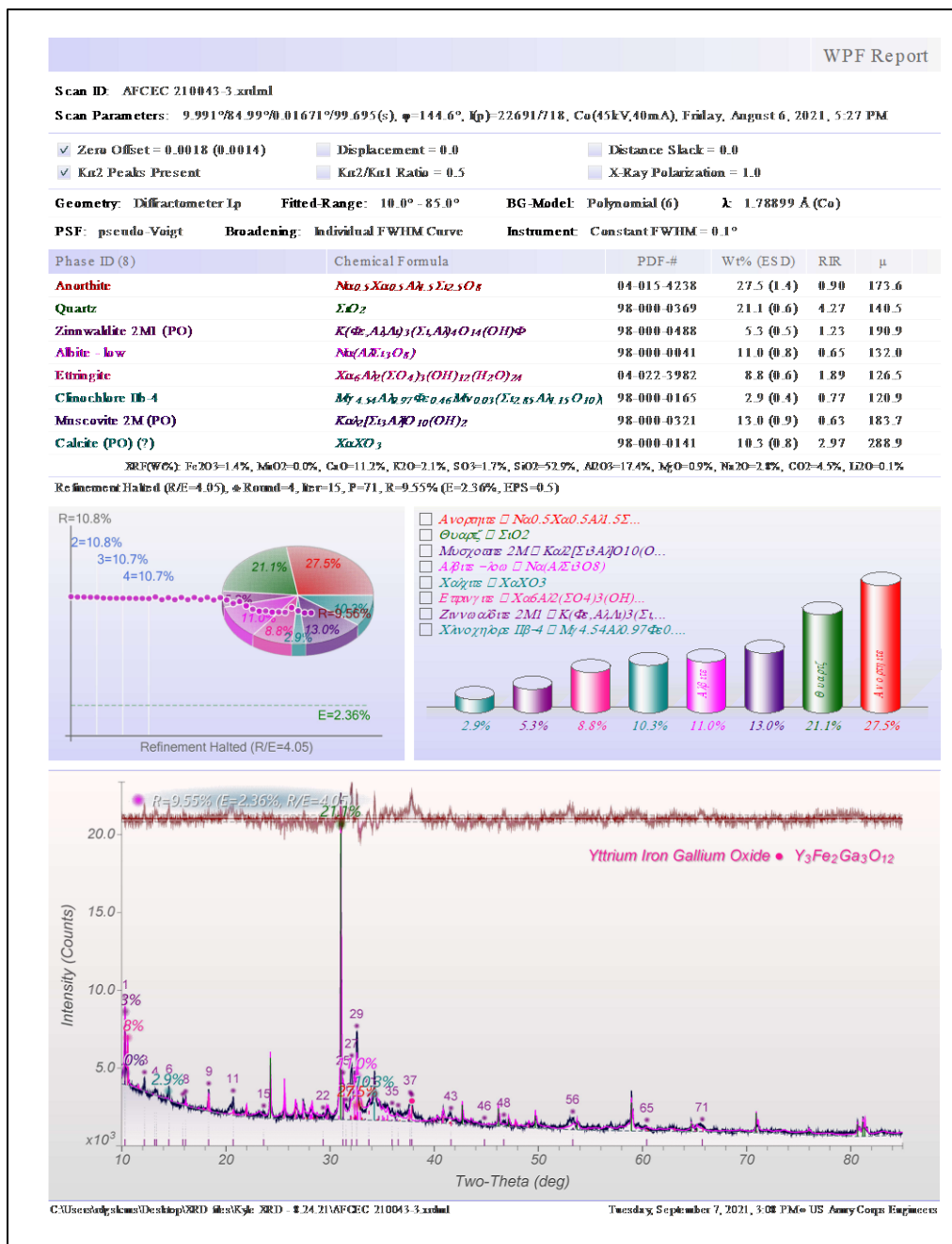
Figure 29. Phenolphthalein applied to sample 210043-2.



3.2.2.3 XRD

Figure 30 provides the mineralogy of the aggregate fraction of core 210043-2 determined by XRD. The aggregate composition indicates silicate-dominated lithologies, including granites and sandstones with minor calcite (10.3%). Clay phases zinnwaldite, clinocllore, and muscovite were detected, amounting to 21.2% of total minerals detected.

Figure 30. Diffraction pattern for 210043-2 with phase identifications, whole pattern fit, and calculated weight percentages.



3.2.3 Core 210043-3

The as-received core 210043-3 is shown in Figure 31. Images of the visual inspection and bisection of core 210043-3 are shown in Figure 32. The core had a length of 27.5 in. and diameter of approximately 5 in.

Additional photographs of the core are provided in Appendix B. The following subsections provide a synopsis of the physical and durability related considerations discovered during petrographic analysis of the core.

Figure 31. Core 210043-3.

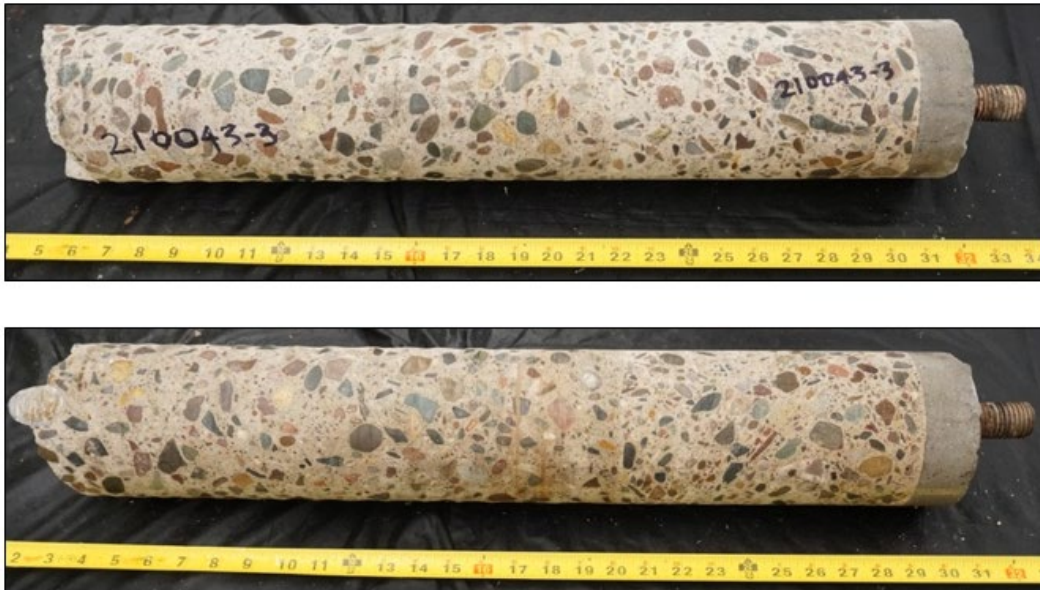


Figure 32. Visual inspection and bisection of 210043-3.



(a) Heavy deterioration around the second nut



(b) Cracking and deterioration at the surface



(c) Cracking around the bolt with corrosion



(d) General microstructure



(e) Concrete after extraction of pipe sleeve showing discoloration at the top

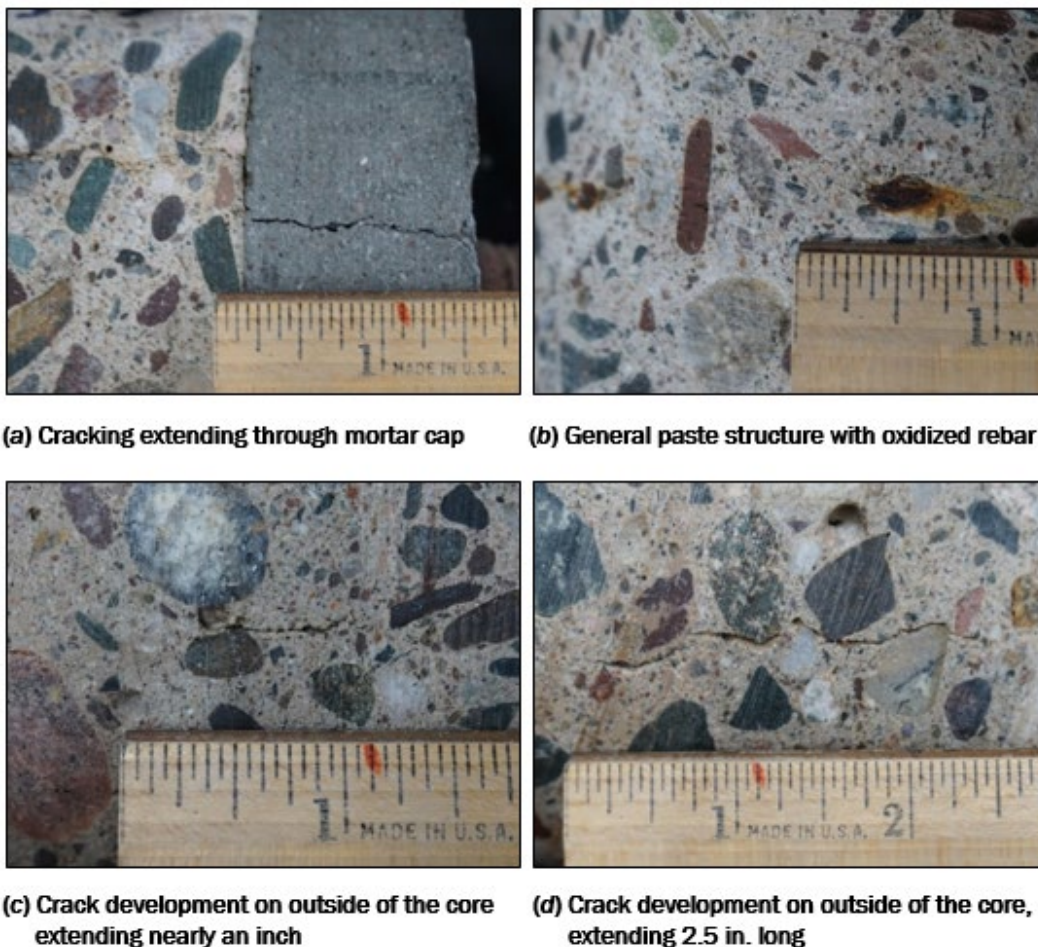


(f) Top of the pipe sleeve with discoloration

3.2.3.1 Petrographic Analysis

Visual inspection images for core 210043-3 are provided in Figure 33. Note that the top of the core was degraded during bisection and preparation; thus, optical petrography was not performed. Observations indicated that the paste was friable in multiple locations and discolored in multiple areas from bolt corrosion. Large air voids above the top of the nut of the Y-bolt were observed. Cracking was developing on the sides of the core, extending 1 in. to 2.5 in. long in two locations. The coarse aggregate had a nominal size of 1 in. Silicate phases dominated the coarse aggregate fraction and were sub-round to round, indicative of a natural stone.

Figure 33. Visual examination of as-received core 210043-3.



3.2.3.2 Carbonation Depth

Figure 34 provides a photo of a freshly broken sample from section A1 with phenolphthalein applied to ascertain the degree of carbonation that occurred. Purple coloring indicates a pH of 10 and above. If the cement is

uncolored, the sample tests for carbonation and the pH is below 10. The sample shows carbonation up to 10 mm (depth indicated by arrows). Note that the top of the core was destroyed in preparation, and phenolphthalein testing was not performed on the top of the core.

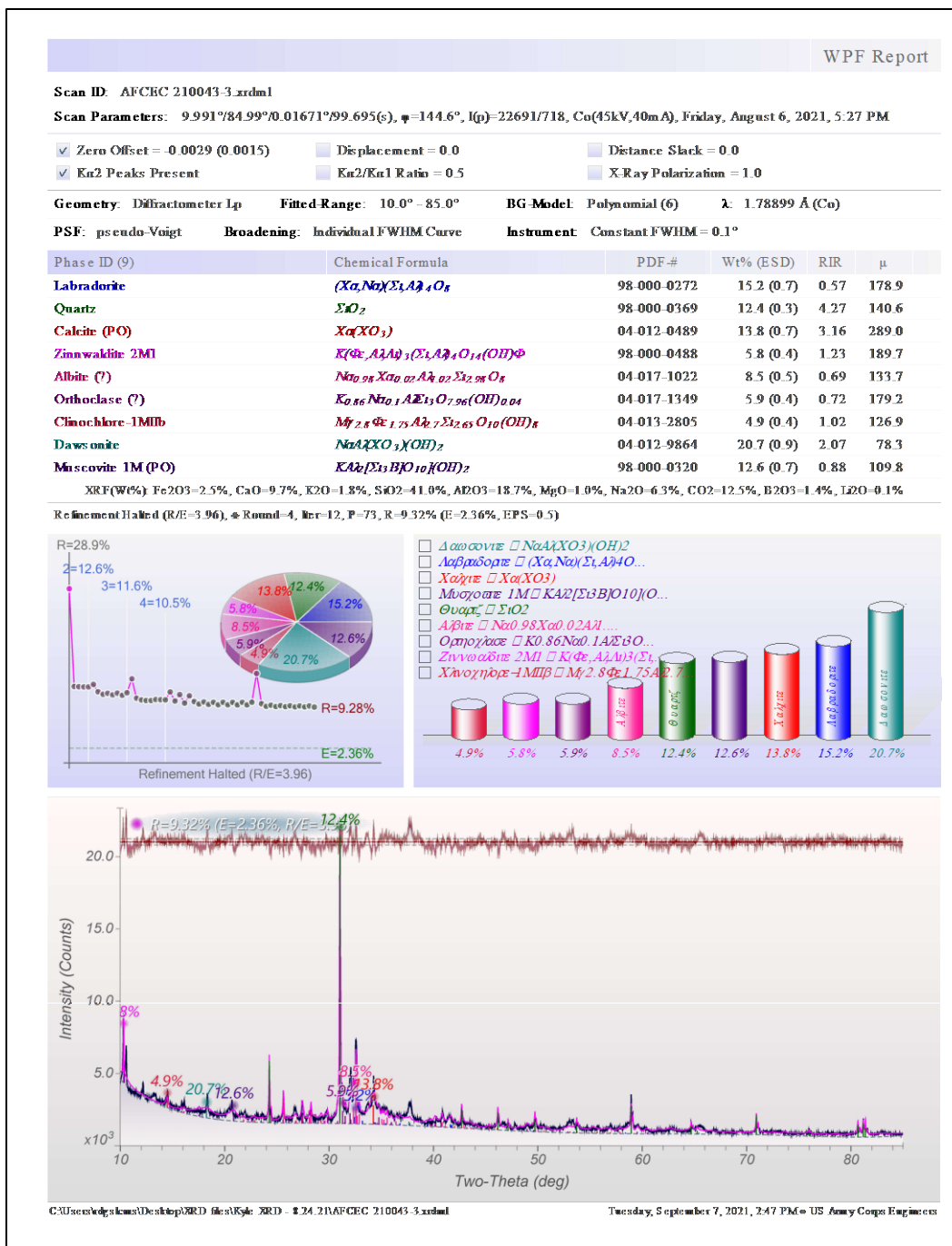
Figure 34. Phenolphthalein applied to sample 210043-3.



3.2.3.3 XRD

Figure 35 provides the mineralogy of the aggregate fraction determined by XRD. The aggregate composition indicates silicate dominated lithologies, including granites and sandstones with minor calcite (13.8%). Clay phases zinnwaldite, muscovite, and clinocllore were detected, amounting to 23.3% of total minerals.

Figure 35. Diffraction pattern for 210043-3 with phase identifications, whole pattern fit, and calculated weight percentages.



3.2.4 Core 210043-4

The as-received core 210043-4 is shown in Figure 36, and the bisected core 210043-4 is shown in Figure 37. The core had a length of 26 in. and a depth of approximately 5 in.

Additional photographs of the core are provided in Appendix B. The following subsections provide a synopsis of the physical and durability related considerations discovered during petrographic analysis of the core.

Figure 36. Core 210043-4.

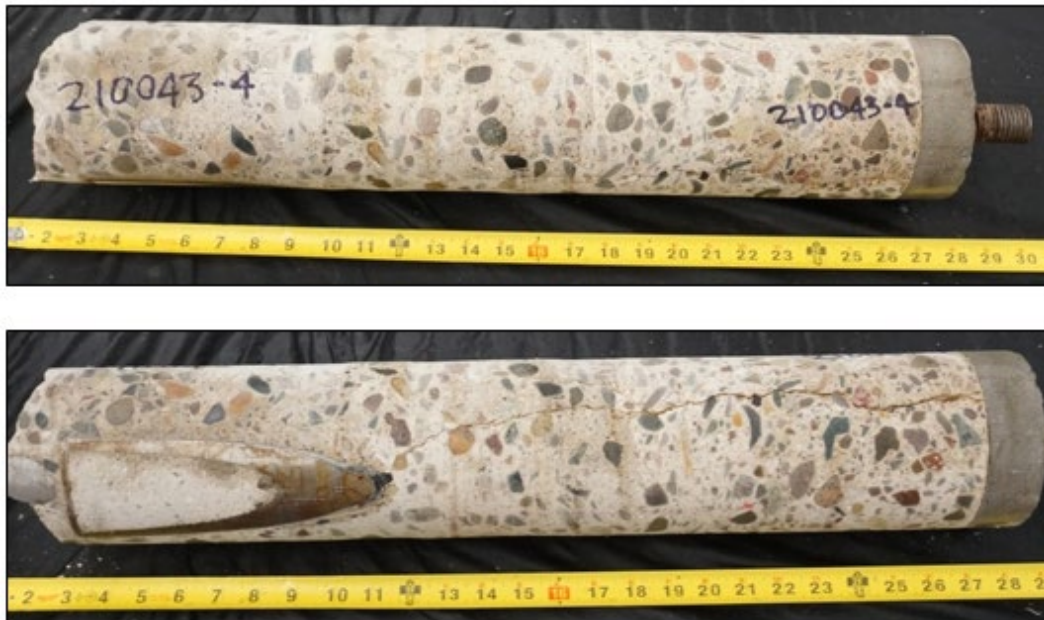


Figure 37. Bisected core 210043-4.



3.2.4.1 Petrographic Analysis

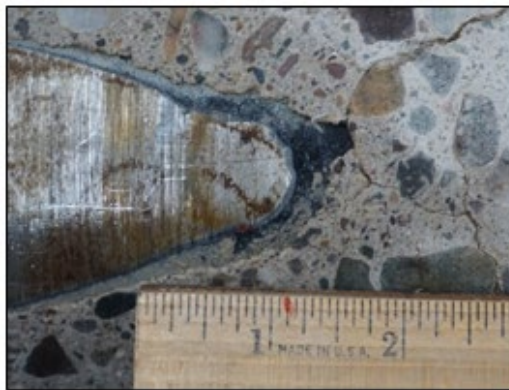
Visual inspection images for core 210043-4 are provided in Figure 38, and detailed photomicrographs of the core's microstructure are shown in Figure 39. Cracking had developed in the concrete, extending throughout the

core as well as through the 2 in. mortar cap. Corrosion was seen only in the observable cracks, but after bisection, the top 6 in. had corrosion close to the bolt and extended into voids and paste proximate to the cracking. The coarse aggregate had a nominal size of 0.75 in. and a maximum entrapped air size of 0.5 in. Silicate phases dominated the coarse aggregate fraction and were sub-round to round, indicative of a natural stone.

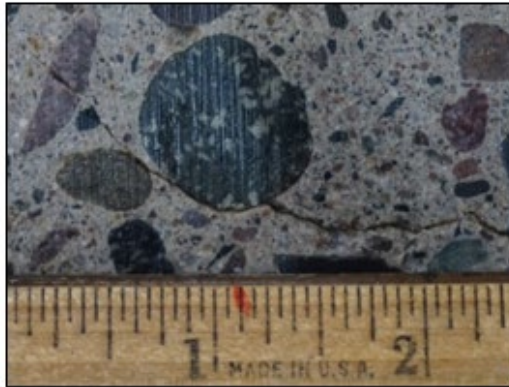
Figure 38. Visual examination of 210043-4.



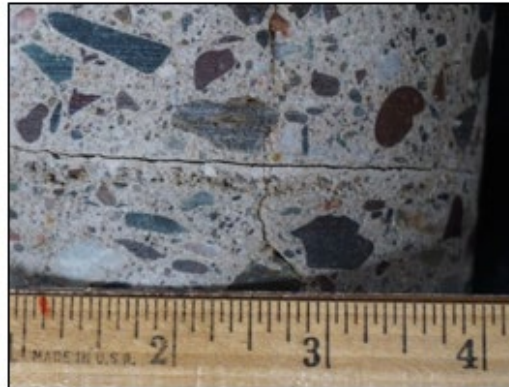
(a) Cracking terminating in cap



(b) Cracking terminating in lower pipe sleeve

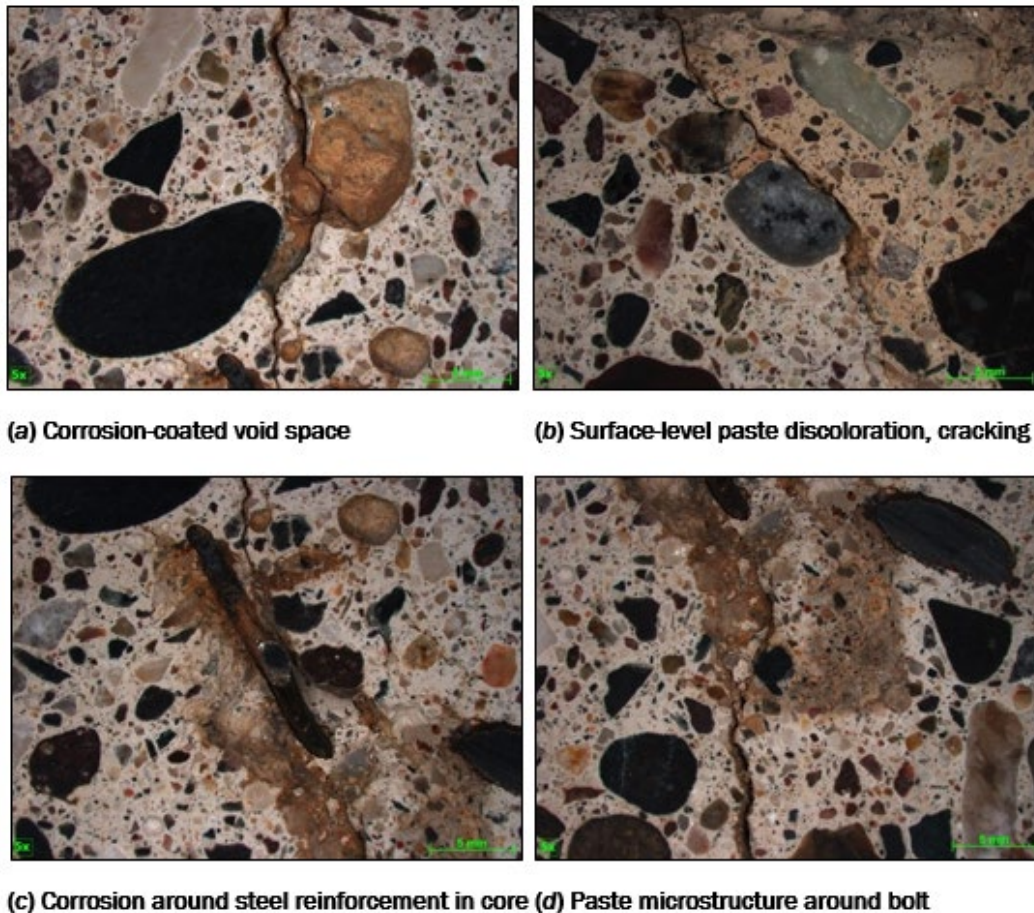


(c) Cracking around large aggregate



(d) Lateral cracking

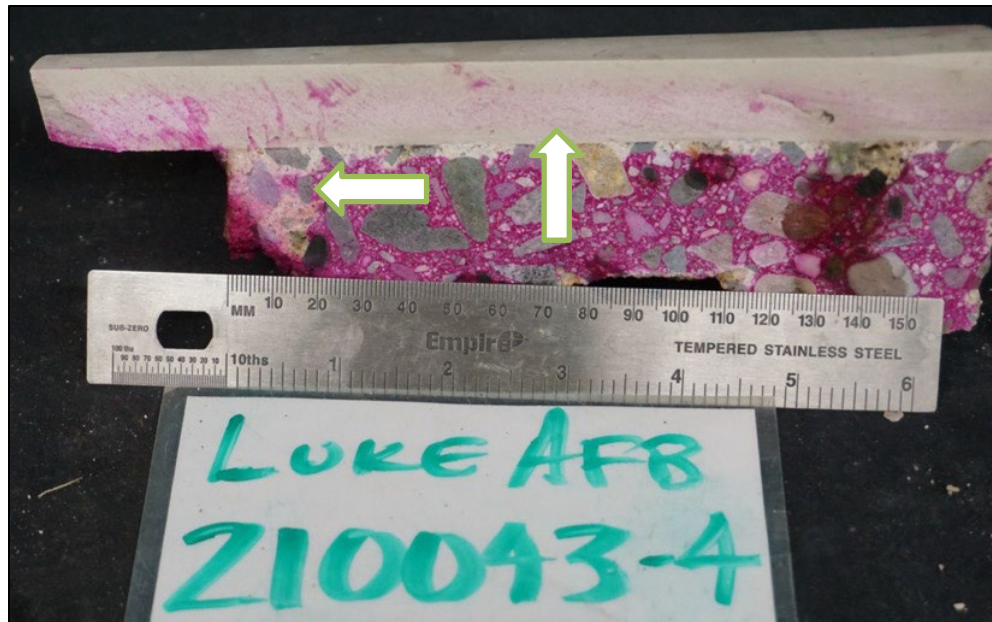
Figure 39. Photomicrographs of 210043-4 at 5× magnification.



3.2.4.2 Carbonation Depth

Figure 40 provides a photo of a freshly broken sample from Section A1 with phenolphthalein applied to ascertain the degree of carbonation that occurred. Purple coloring indicates a pH of 10 and above. If the cement is uncolored, the sample tests for carbonation and the pH is below 10. The sample shows carbonation up to 20 mm (depth indicated by arrows).

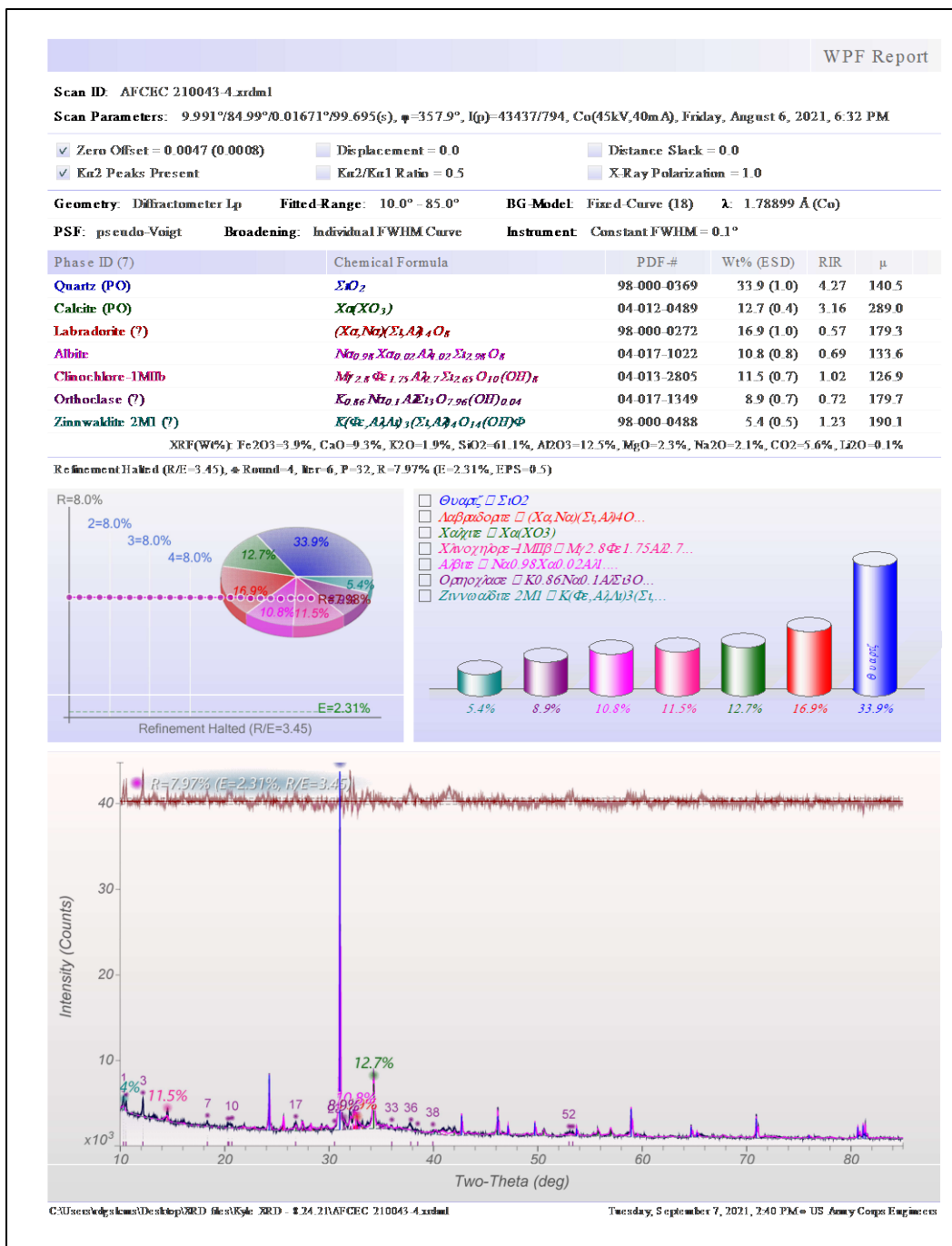
Figure 40. Phenolphthalein applied to sample 210043-4.



3.2.4.3 XRD

The mineralogy of the aggregate fraction as determined by XRD of the concrete is provided in Figure 41. The aggregate composition indicates silicate dominated lithologies, including granites and sandstones with minor calcite (12.7%). Clay phases clinocllore and zinnwaldite were detected, amounting to 16.9% of total minerals.

Figure 41. Diffraction pattern for 210043-4 with phase identifications, whole pattern fit, and calculated weight percentages.



4 Mechanical Analysis

This chapter provides an overview of specimen sampling, a description of the applicable test method, and the results for the mechanical analysis of the specimen taken from the field-cored anchor rods from Luke AFB. The intent of this analysis was to investigate the strength and yield properties of the anchor bolt for comparison to the specified required properties of anchor rod material.

4.1 Overview of Specimen Sampling and Preparation

All dogbone specimens were extracted from the centerline of the upper section of each anchor bolt above the top of the galvanized pipe sleeves. Specimen positions designated by the letter “W” were taken from near the exposed tops; specimen positions designated by the letter “E” were taken from the middle of the exposed anchor rod; and specimen positions designated by the letter “T” were taken from the base of the exposed rods above the galvanized pipe sleeve. The threaded sections were turned down on a computer numerically controlled (CNC) lathe to the specimen 3 geometry as denoted within ASTM E8 (2022) for round tension testing with gauge lengths four times the diameter.

4.2 Metallic Tension Testing by ASTM E8

Tensile testing was performed on an Instron 3300 Series Screw Driven Universal Testing Machine outfitted with a 150 kN reversible load cell and Instron Model 2663-822 Advanced Video Extensometer. Tension testing was conducted according to ASTM E8, *Tensile Testing of Metallic Materials* (2022b) with a crosshead speed of 0.06 in./min. Yield strength (YS), ultimate tensile strength (UTS), and percent elongation at failure were recorded.

4.3 Results

Twelve tensile tests in total were performed on the specimens extracted from the field-cored fairlead beam anchor rods: three tests per core with one for each of the W, E, and T specimen positions described in Section 4.1. Stress versus strain plots for cores 210043-1, 210043-2, 210043-3, and 210043-4 are provided in Figure 42, Figure 43, Figure 44, and Figure 45, respectively. Tabulated test results for the tensile testing are presented in Table 5. Issues with the test fixture prevented the completion of testing for

specimen 210043-1 T, so percent elongation at failure could not be determined.

Figure 42. Stress versus strain plot for core 210043-1.

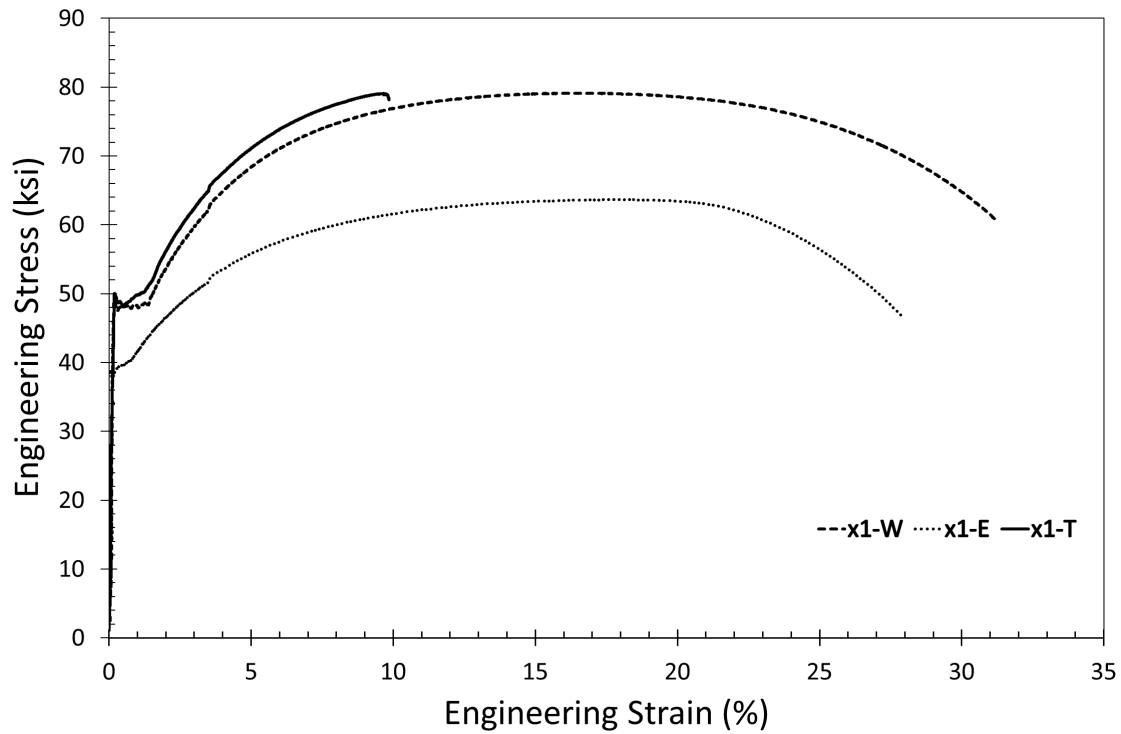


Figure 43. Stress versus strain plot for core 210043-2.

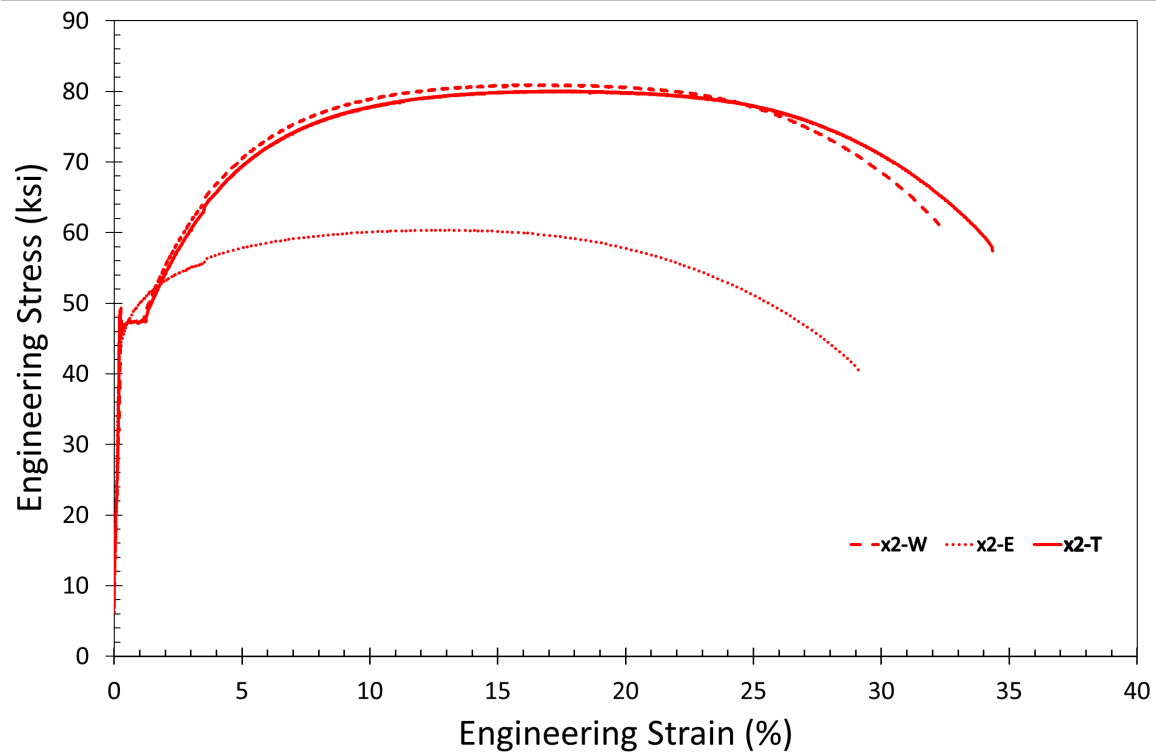


Figure 44. Stress versus strain plot for core 210043-3.

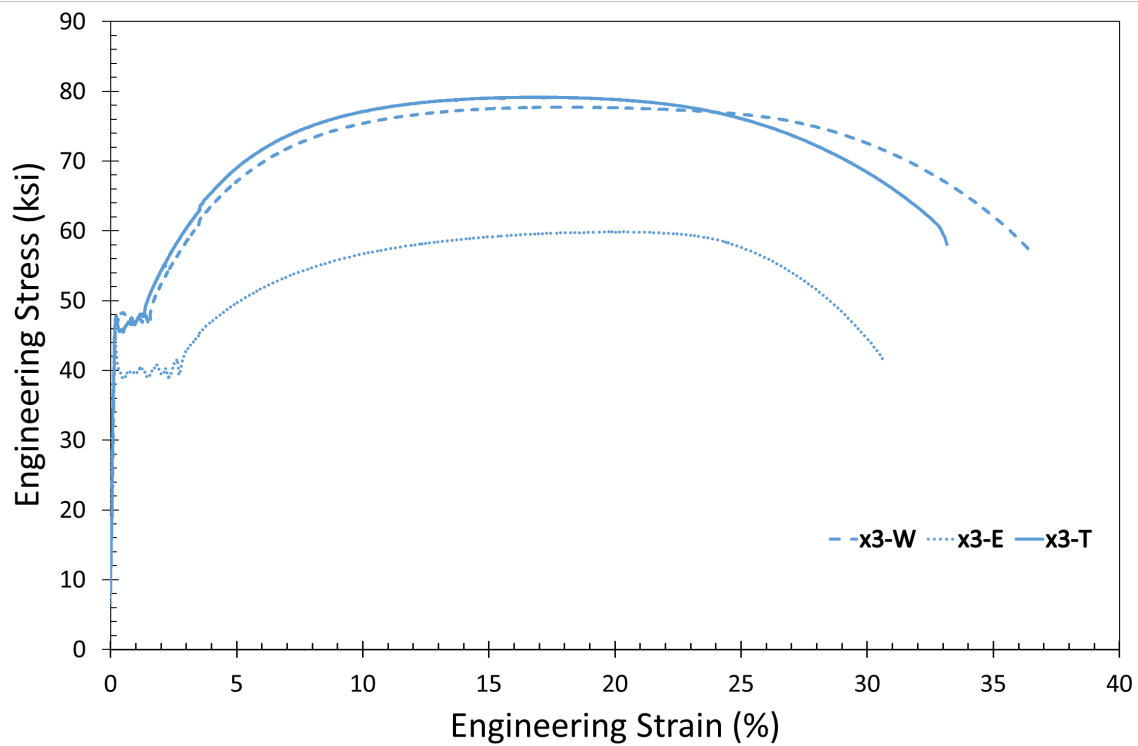


Figure 45. Stress versus strain plot for core 210043-4.

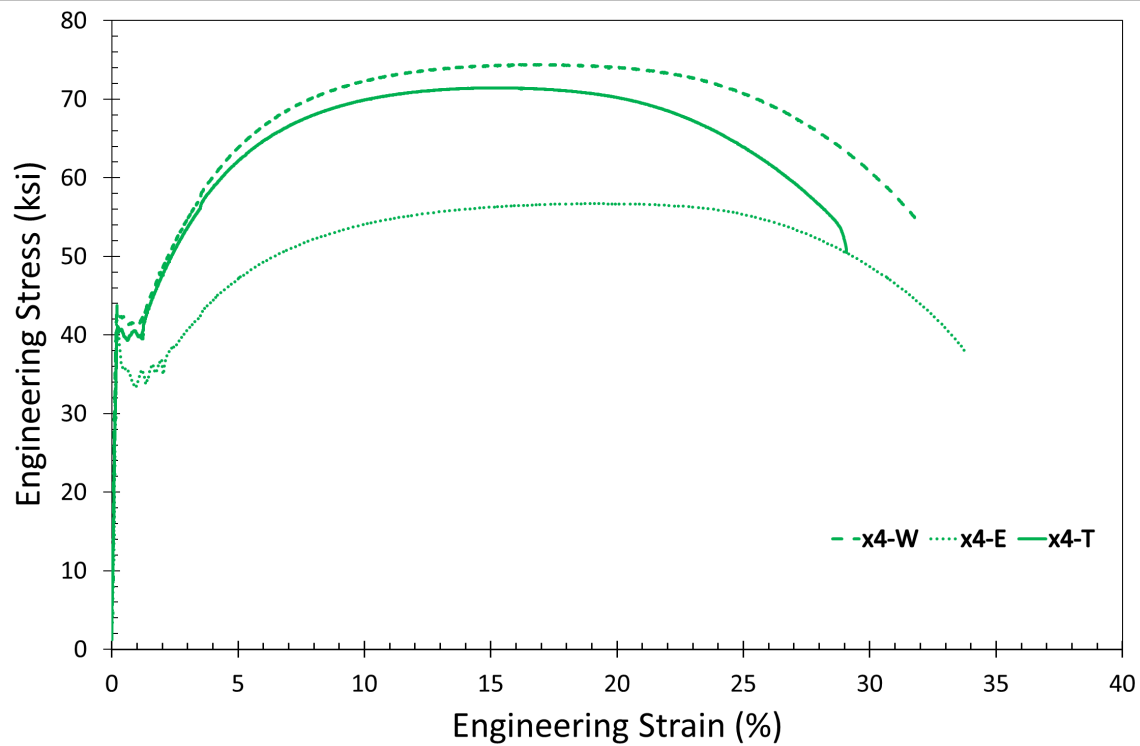


Table 5. Tensile testing results.

Core ID	Specimen Position	YS (ksi)	UTS (ksi)	Elongation at Failure (%)
210043-1	W	47.79	79.11	31.4
210043-1	E	42.21	63.67	27.9
210043-1	T	48.76	79.04	—
210043-2	W	47.38	80.82	32.4
210043-2	E	46.18	60.35	29.1
210043-2	T	47.03	80.04	34.3
210043-3	W	47.97	77.74	36.5
210043-3	E	40.54	59.84	30.6
210043-3	T	45.65	79.12	33.1
210043-4	W	42.29	74.39	32.0
210043-4	E	36.39	56.69	33.8
210043-4	T	40.69	71.41	29.1

5 Discussion

This section provides discussion of results for each of the three analyses performed as well as discussion related to observed anchor assembly deviations from design intent. These discussions serve as the basis for the conclusions and recommendations provided later in this report.

5.1 Finite Element Analysis

5.1.1 Standard Y-Bolt Analysis

Although the exact loading on the bolts is unknown, the 11-kip load corresponds to the maximum breaking load of the tape (110 kips) equally distributed among the 10 Y-bolts. This is typical design practice for horizontal shear loading. Under an 11-kip load, the maximum von Mises stress in the bolt was roughly 31.7 ksi, occurring at 0.1 in. above the top of the grout pad (or 4.5 in. below the top of the bolt). Any cracks in the Y-bolt caused by loading would be expected to occur near the top of the grout pad.

The Y-bolt material is specified as ASTM A325 (2014; withdrawn and replaced by ASTM F3125 [2022a]) or ASTM A449 (2020b). Both specifications have a minimum YS of 81 ksi and minimum UTS of 105 ksi (for 1-1/8 in. diameter). The computed results indicate that a Y-bolt should not yield under a horizontal load of 11 kips. At these low stress levels, however, fatigue may be a concern if the bolt is loaded repeatedly for many thousands of cycles.

ASTM A325 and A449 specify requirements in terms of mechanical performance, and both documents list multiple steel types that can be used at the manufacturer's discretion. Thus, it was difficult to select an equivalent AISI/SAE steel to find an S-N fatigue diagram. However, the fatigue endurance limit for ferrous alloys is typically 0.35–0.6 times the tensile strength (Hertzberg et al. 2013). In the present case, this conservatively results in $\sigma_{\text{fat}} = 0.35 \times 105 = 36.75$ ksi. Thus, the stress in the bolt is close to the worst-case estimate of the endurance limit (typically associated with $\geq 10^6$ cycles), so the bolt would be expected to have a finite fatigue life. It should be pointed out, however, that the number of loading cycles on a typical fairlead beam is far fewer than that required for high-cycle fatigue. Conversations with AFCEC subject matter experts indicated that over a 5-year lifespan, a fairlead beam might see on the order of 80 engagements. Even allowing for multiple load cycles per engagement due to vibration or

other factors, this is still a very low number of load cycles, and it is unlikely that the Y-bolt would exhibit failure due solely to fatigue.

5.1.2 Repaired Y-Bolt Analysis

As noted previously, the exact loading on the bolts is unknown, so the maximum breaking load of the tape (110 kips) was equally distributed among the 10 Y-bolts. This is typical design practice for horizontal shear loading. Under an 11-kip load, the maximum von Mises stress in the repaired Y-bolt was roughly 35.3 ksi, occurring at roughly the same elevation as the top of the concrete slab (6.6 in. below the top of the bolt). Any cracks in the repaired Y-bolt caused by loading would be expected to occur near the bottom of the grout pad.

Similar to the analysis presented in Section 5.1.1, a comparison of the repaired Y-bolt's calculated von Mises stress of 35.3 ksi to the σ_{fat} of 36.75 ksi indicates that the stress in the bolt is close to the worst-case estimate of the fatigue endurance limit (typically associated with $\geq 10^6$ cycles), so the repaired Y-bolt would be expected to have a finite fatigue life. However, the expected number of loading cycles of a fairlead beam in service is far less than 10^6 cycles, so it is unlikely that the repaired Y-bolt would exhibit failure due solely to fatigue.

5.1.3 Comparative Analysis

Table 6 compares results for displacement and peak von Mises stress for the two anchor models. The peak von Mises stresses in each design are nearly identical, with the repaired anchor having a slightly lower maximum von Mises stress. The repaired anchor does displace more under a given load; displacement is five times greater than that of the original Y-bolt. Stress results indicate that the repaired anchor design stresses the bolt primarily in flexure, whereas the original design stresses the bolt primarily in shear. This difference in response is likely due to the difference in stiffness of the grout surrounding the anchor. In the original design, the relatively small void is filled with a 10 ksi nonshrink machinery grout with an assumed modulus of elasticity of 5,700 ksi. In the repaired anchor design, there is a comparatively larger-cored void, which is filled with an epoxy grout having a lower stiffness (elastic modulus of roughly 400 ksi). Thus, the stiffness of the grout has an influence on the mechanical response of the anchor. However, we note that the results in this report are preliminary calculations using assumed material properties and loadings.

Table 6. Comparison of results between original Y-bolt and repaired Y-bolt models.

Anchor	Displacement at Top Center Node, δ (in.)	Maximum von Mises Stress in Bolt (ksi)
Original Y-bolt anchor	0.00860	31.65
Repaired Y-bolt anchor (400 ksi epoxy grout modulus)	0.04312	35.28

Note that the finite element models presented herein have not been validated against experimental data. Results are predictions based on the input data that were used. A number of factors could affect model outputs, including the following:

- Different material properties from those used here
- Different boundary conditions or loading imposed on the anchor bolt
- Cracking in either the grout or the concrete
- Imperfect bonding between the anchor bolt, grout, epoxy, pipe sleeve, or concrete

5.2 Petrographic Analysis

Petrographic analysis was performed on four concrete cores from Luke AFB. The assessment used petrographic analysis to evaluate the cored anchor rods for potential modes of concrete deterioration including corrosion, carbonation, and any other forms of deterioration.

Core 210043-1 showed cracking in the upper 5 in. of both concrete and mortar cap. Carbonation was observed up to a depth of 15 mm. Heavy corrosion was observed at a depth of 30 in. from the top surface. Friable concrete was found with resulting discoloration cascading down the core. Upon bisection of the core, more friable concrete was identified with corresponding corrosion along the pipe sleeve.

Core 210043-2 showed cracking in the upper 9 in. of the concrete, terminating in the mortar cap, with no cracking observed through the mortar cap. Carbonation was observed up to a depth of 17 mm. Corrosion was observed after the core was bisected and was limited to the area around the bolt.

Core 210043-3 showed cracking in the upper 8 in. of the concrete, terminating in the mortar cap, with no cracking observed through the mortar cap. Corrosion was observed after the core was bisected and was limited to

the area around the bolt. Possible linear stress cracking was present in the middle of the core, not extending to the surface and measuring 1 to 1.5 in. long.

Core 210043-4 showed cracking extending throughout the entire concrete core and through the mortar cap. Carbonation was observed up to a depth of 20 mm. Corrosion was observed within the heavy cracks and throughout the top 10 in. of the Y-bolt.

All cores displayed deterioration of the concrete from corrosion and stress-related cracking. Corrosion was noticeably leeching away from the bolt, creating subsequent deterioration of the concrete proximate to crack propagation paths. Corrosive cracking was mainly seen at the bolt/concrete interface and was much more prominent in the top 10 in. of each core near each nut. The highest level of deterioration was seen in core 210043-1 (which was a Z-bolt). The core was noticeably friable before and after sample preparation. Stress cracking extending through the mortar cap was prominent in all cores. Uncharacteristically high carbonation was observed in all cores except 240043-3, where carbonation testing was not performed. It is fair to estimate that the corrosion was accelerated by exposure to weathering by way of stress-related cracking.

Also found were undesirable clay deposits, which can lead to shrinking and swelling of the concrete and can also create weak points and reduce strength. Furthermore, clays can create a coating between aggregates and paste, resulting in reduced flexural and tensile strength. These clay deposits could indicate poor aggregate handling at the concrete production facility, or they could indicate that the anchor assemblies were not cleaned properly before placement of the concrete mixture in the fairlead beam foundation pad, which could affect bonding between the anchor rod or pipe sleeve and the concrete mixture while also providing locations for accelerated corrosive degradation.

5.3 Mechanical Analysis

As previously noted, the anchor rod material is required to exhibit a minimum YS of 81 ksi and a minimum UTS of 105 ksi alongside 14% elongation at failure. The overall average YS, UTS, and elongation at failure across all test specimens was 44.41 ksi, 71.85 ksi, and 31.7%, respectively. Table 7 provides average test result values for the grouping of specimens taken

from each core. Test result strengths for specimens taken from cores 210043-1, 210043-2, and 210043-3 were generally comparable, while test result strengths for specimens taken from core 210043-4 were noticeably lower than those of the other three cores. Comparison of the overall average values and the per-core average values reported in Table 7 to the minimum required values shows that none of the values for YS or UTS meet the minimum requirement. Percent elongation at failure greatly exceeded the target of 14%, which is undesirable given the fact that the strength values were not sufficient.

Table 7. Average mechanical test results per core.

Core ID	Average YS (ksi)	Average UTS (ksi)	Average Elongation at Failure (%)
210043-1	46.25	73.94	29.7
210043-2	46.86	73.74	31.9
210043-3	44.72	72.23	33.4
210043-4	39.79	67.50	31.6

To investigate general trends and variability based on specimen location within the tested areas of the anchor rods, strength data were tabulated based on specimen location in Table 8. Interestingly, both the YS and the UTS test results for those specimens taken from the E-designated areas of the anchor rods were noticeably lower than those taken from the W- and T-designated areas.

Table 8. Mechanical strength test data by specimen location.

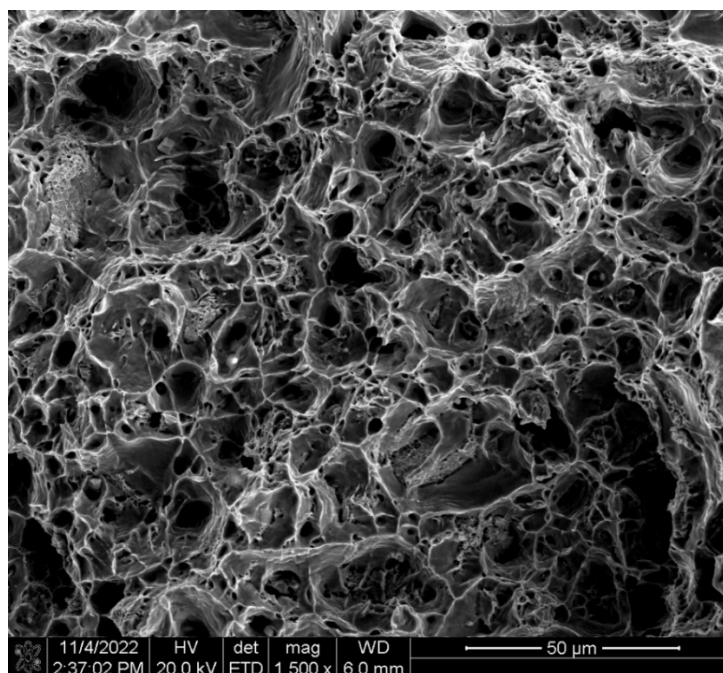
Core ID	W YS (ksi)	W UTS (ksi)	E YS (ksi)	E UTS (ksi)	T YS (ksi)	T UTS (ksi)
210043-1	47.79	79.11	42.21	63.67	48.76	79.04
210043-2	47.38	80.82	46.18	60.35	47.03	80.04
210043-3	47.97	77.74	40.54	59.84	45.65	79.12
210043-4	42.29	74.39	36.39	56.69	40.69	71.41
Average	46.36	78.02	41.33	60.14	45.53	77.40
COV*	0.06	0.03	0.10	0.05	0.08	0.05

*COV = coefficient of variation

A brief investigation into the failure mode of the cylindrical dogbone test specimens was undertaken by examining the fracture surface of tensile specimen 210043-3E. Figure 46 provides a micrographic view of the failure surface of specimen 210043-3E. Inspection of tensile test specimens

after failure showed apparent shear lips and necking. Additionally, the dimples observable in the micrograph further reinforced a ductile failure mode.

Figure 46. Micrograph of 210043-3E fracture surface.



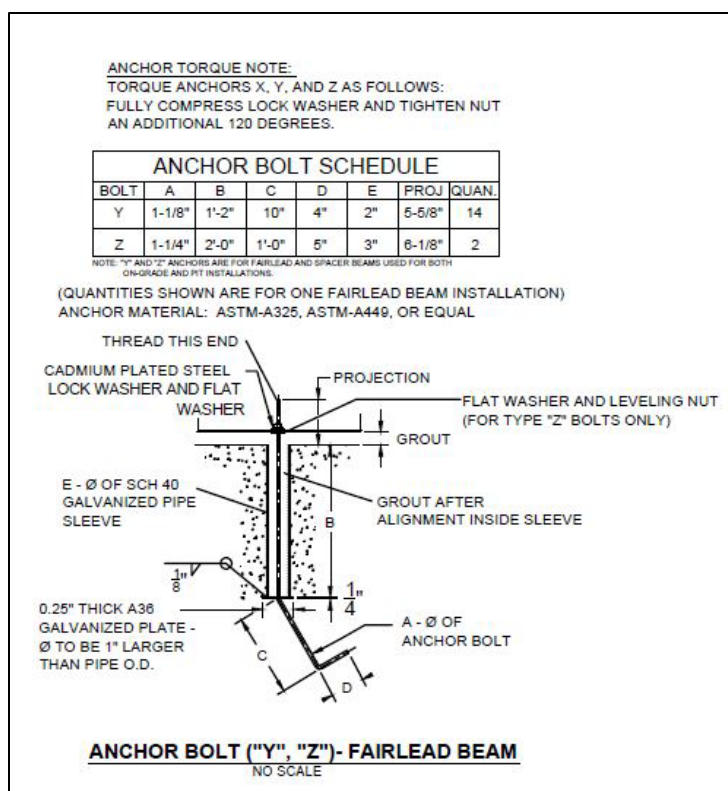
Oxidation and discoloration on the bolt surface were apparent by inspection prior to sample processing on the CNC machine. Additionally, based on the service length and relatively low corrosive environment expected to be present at Luke AFB, it is not likely that corrosive degradation occurred near the centerline of the anchor rods. This is further reinforced by the ductile failure mode discussed previously in conjunction with the low variability within the data set since corrosively degraded test specimens would have been expected to exhibit a more brittle failure mode. Based on these factors, it is highly likely that the anchor bolts were fabricated with an inferior grade of steel.

5.4 Observed Deviations from Design Intent

As described in Section 1, the design intent for the fairlead beam Y- and Z-anchor assemblies is that the top of the galvanized pipe sleeve should sit flush with the PCC placed for the fairlead beam foundation pad. Then, the galvanized pipe sleeve should be filled with grout at the time of placement of the grout leveling layer, coinciding with the time of placement of the

fairlead beam itself. The anchor drawing detail is reproduced in Figure 47 for convenience.

Figure 47. Fairlead beam anchor detail.



Upon bisection of the upper portion of the four received PCC cores with the fairlead beam anchor rods, the team observed that the galvanized pipe sleeves did not extend to flush with the surface of the concrete placed for the fairlead beam foundation pad (see Figure 20, Figure 26, Figure 32, and Figure 37), which deviates from the design intention of Drawing Number 67F2013A. Additionally, voids in the concrete mixture were observed around the galvanized pipe sleeve, indicating inadequate or inconsistent consolidation of the concrete mixture around the anchor assemblies. Furthermore, the removal of the grout layer and PCC above the top of the galvanized pipe sleeve revealed that concrete mixture—and not grout—had been placed inside the pipe sleeve. Figure 48 shows an end-on view of the top of the galvanized pipe sleeve of core 210043-1 with the grout layer and PCC removed. It appears that the same concrete mixture used to place the fairlead beam foundation pad was crudely placed into the pipe sleeves. Similar observations were made across the other three field-cored anchor rods. The presence of voids and coarse aggregate within the pipe sleeves would be expected to negatively affect the mechanical performance of the

anchor assembly while also affording sites for accelerated oxidation and corrosion of the anchor rods. These voids and corresponding corrosion would have an unknown impact on nondestructive inspections of the fair-lead beam anchor bolts.

Figure 48. Core 210043-1 pipe sleeve end-on view.



6 Conclusions and Recommendations

The objective of this effort was to conduct a finite element analysis of the loading condition of the fairlead beam Y-bolt anchor, perform a visual inspection and petrographic analysis of the concrete of the field-cored fairlead beam anchor rods from Luke AFB, and complete a mechanical analysis of specimens taken from the steel anchor rods within the concrete cores. The following conclusions and recommendations are provided.

6.1 Conclusions

- Finite element model results indicate that a standard fairlead beam Y-bolt should not yield under a horizontal load of 11 kips and should be able to withstand many thousands of loading cycles prior to experiencing failure related to the fatigue life of the anchor bolt.
- Finite element model results indicate that a standard fairlead beam Y-bolt is loaded primarily in shear, and any load-related cracking of the anchor bolt would be expected to occur near the top of or within the leveling layer of grout.
- Finite element model results indicate that a repaired fairlead beam Y-bolt should not yield under a horizontal load of 11 kips and should be able to withstand many thousands of loading cycles prior to experiencing failure related to the fatigue life of the anchor bolt.
- Finite element model results indicate that a repaired fairlead beam Y-bolt is loaded primarily in flexure, and any load related cracking of the anchor bolt would be expected to occur near the bottom of the leveling layer of grout or near the top of the concrete foundation pad itself.
- All cores received from Luke AFB displayed concrete material degradation around the anchor bolt and galvanized pipe sleeve from corrosion and stress cracking.
- All cores evaluated for depth of concrete carbonation displayed a high carbonation depth.
- Undesirable clay contents were determined via XRD for all received cores.
- All tensile test specimens extracted from the fairlead beam anchor rods within the concrete cores failed to meet minimum YS and UTS requirements.
- The high percent elongation at failure in conjunction with the low strength values is indicative of an inverse tradeoff of mechanical properties. Therefore, it is highly likely that an inferior grade of steel was

- used to fabricate the anchor bolts within the foundation pads for the AAS on the north end of Runway 03R-21L at Luke AFB.
- The galvanized pipe sleeves within the cores did not meet the design intention of being placed such that their open tops were flush with the fairlead beam foundation pad.
 - The infill material within the galvanized pipe sleeves was determined to be a concrete mixture rather than a machinery grout, and the team hypothesized that this was the same mixture that was used to place the foundation pad itself. The concrete mixture was crudely placed into the pipe sleeves with large voids visible once the material above the sleeves was removed.

6.2 Recommendations

- A baseline nondestructive inspection should be performed on all fairlead beam anchors as soon as practical after the galvanized pipe sleeves are filled with grout and set. This would provide a reference for comparison of obtained nondestructive inspection results during AAS overhauls.
- State-of-the-art inspection methods for evaluating in-place fairlead beam anchors should be investigated to determine whether a more appropriate inspection method currently exists.
- A modern design review of the anchor assembly for the fairlead beam Y- and Z-anchors should be conducted with a focus on material compatibility and corrosion mitigation.
- Design drawings should be reviewed to determine whether a more prescriptive and detailed method for installing the fairlead beam Y- and Z-anchors is appropriate.
- Design drawings or construction contractual language should require that the anchor assemblies be thoroughly cleaned prior to placement of the concrete mixture in the fairlead beam foundation pad to promote a good bond between the anchor assembly and the concrete mixture and to reduce contamination.
- Material certifications for fairlead beam anchor materials should be obtained and verified prior to acceptance of the anchors.

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Appendix A: Core Logs

Figure A-1. Core log for 210043-1.

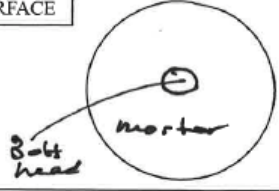
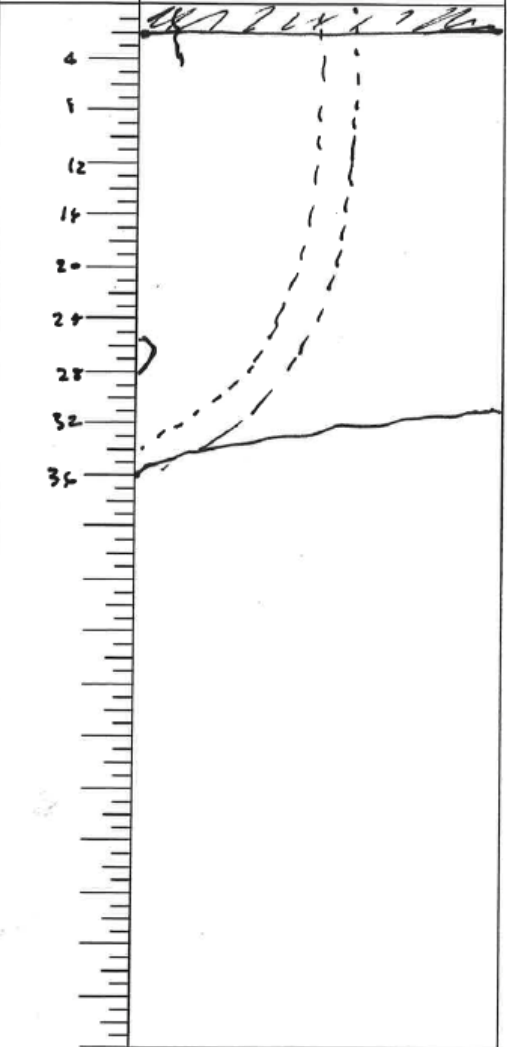
Location: Core Name: 210043-1 Investigator: Klaus Date: 6-22-20		CORE SURFACE 
Core Length: 37" Bit Diameter: 5"		
DEPTH (in)	LEGEND	REMARKS/COMMENTS
4 8 12 16 20 24 28 32 36		Max. aggregate size - 1.5" Aggregate type - Max. entrapped air size - 1.5" Cracks visible? yes Top 2" mortar
		TESTS

Figure A-2. Core log for 210043-2.

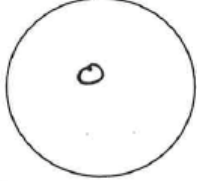
Location: Core Name: 210043-2 Investigator: Klaus Date: 6-22-21		CORE SURFACE 
Core Length: 27.5" Bit Diameter: 5"		
DEPTH ()	LEGEND	REMARKS/COMMENTS
		Max. aggregate size – 1.75" Aggregate type – Max. entrapped air size – 1" Cracks visible? yes Top 2" mortar
		TESTS

Figure A-3. Core log for 210043-3.

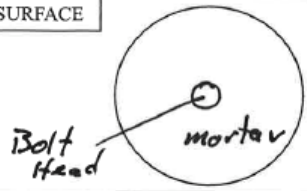
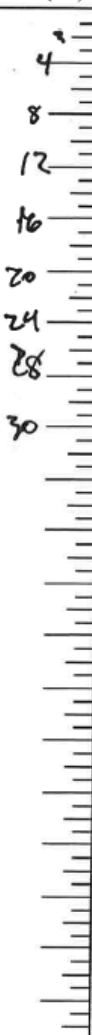
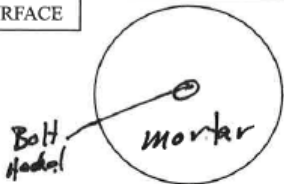
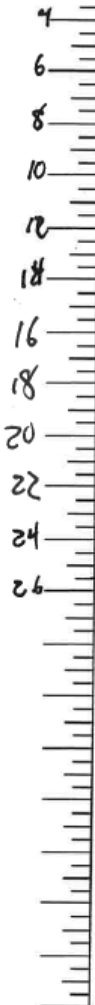
Location: Core Name: 210043-3 Investigator: Klaus Date: 6-22-21		CORE SURFACE 
Core Length: 27 3/4" Bit Diameter: 5"		REMARKS/COMMENTS Max. aggregate size – 1" Aggregate type – Max. entrapped air size – 1/2" Cracks visible? Y
DEPTH () 	LEGEND 	
		TESTS

Figure A-4. Core log for 210043-4.

Location: 210043-4 Core Name: 210043-4 Investigator: E. Klags Date: 6-22-21		CORE SURFACE 
Core Length: 26" Bit Diameter: 5"		
DEPTH ()	LEGEND	REMARKS/COMMENTS
		Max. aggregate size - .75" Aggregate type - ~~AS~~ Max. entrapped air size - .5" Cracks visible? Y
		TESTS

Appendix B: Supplemental Photographs

Figure B-1. Supplemental photographs of core 210043-1.

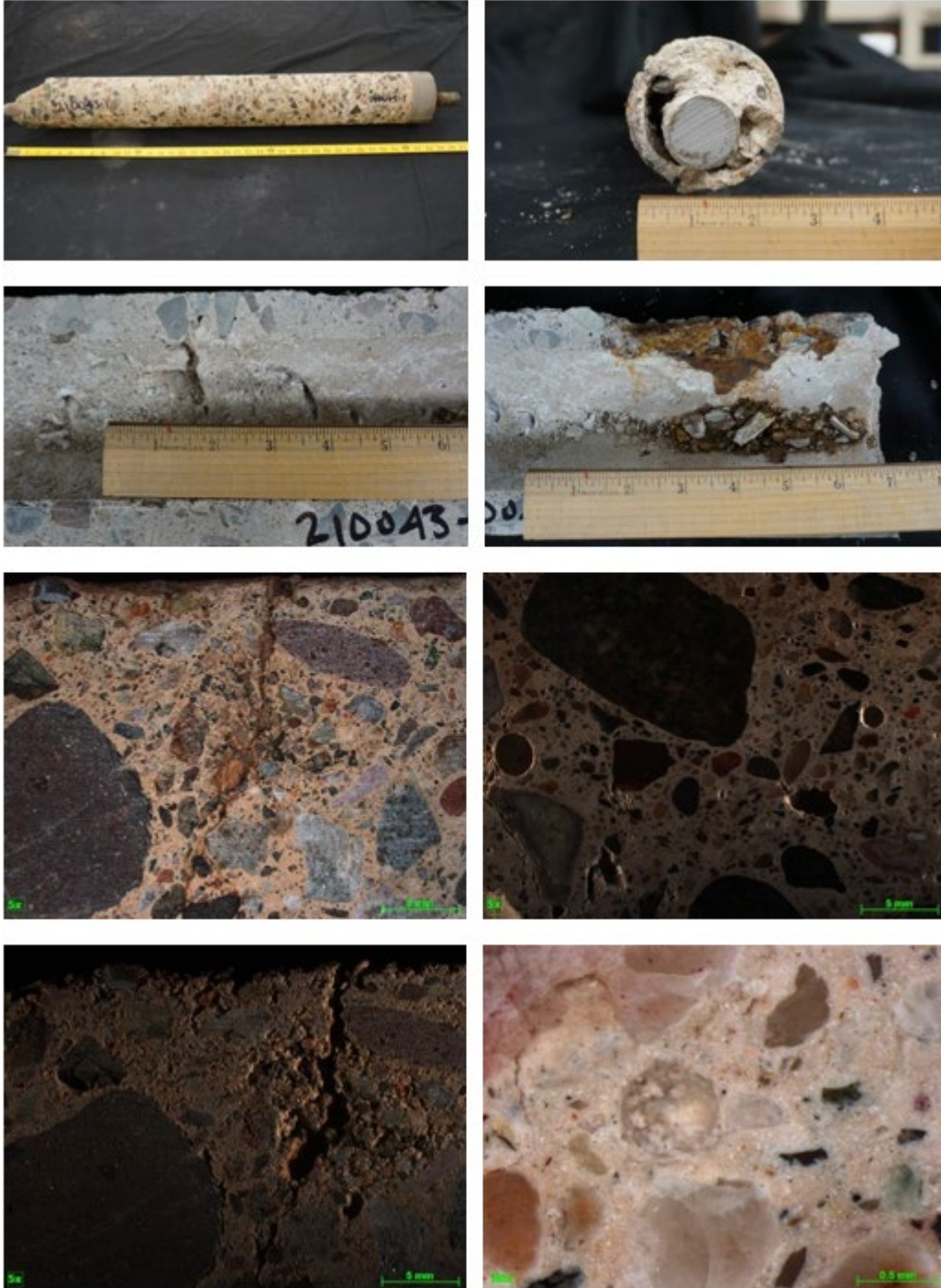


Figure B-2. Supplemental photographs of core 210043-2.

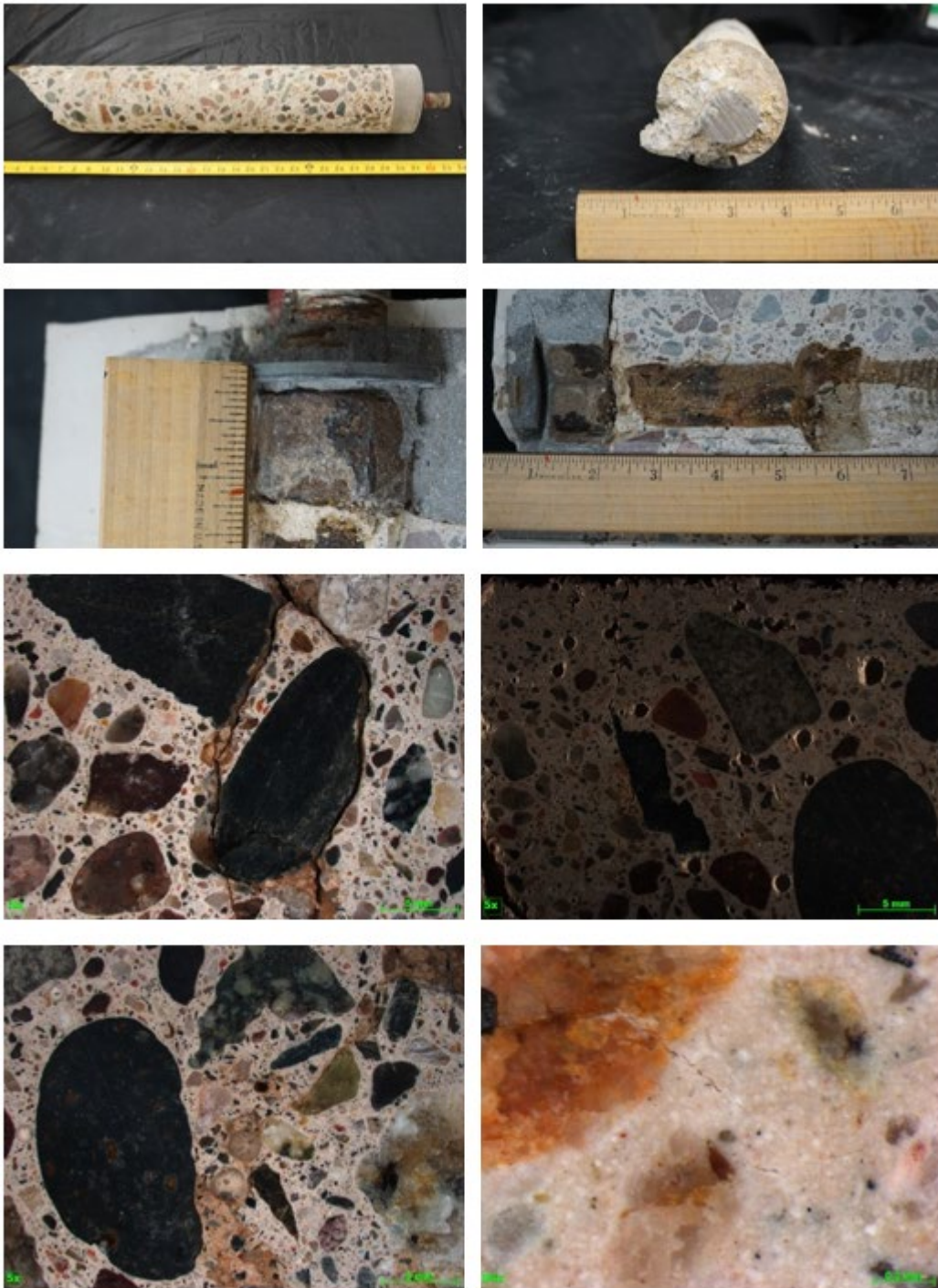
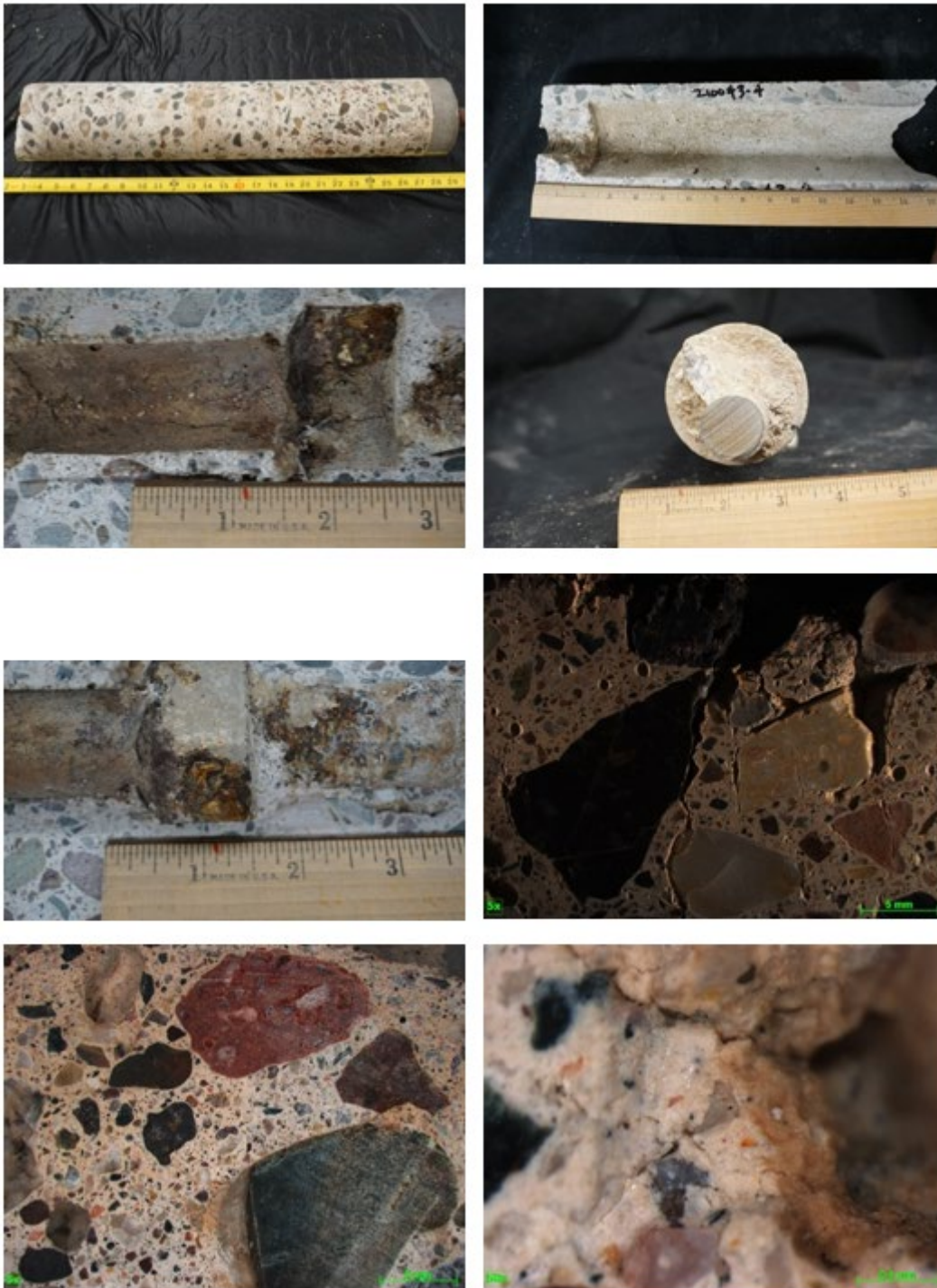


Figure B-3. Supplemental photographs of core 210043-3.



Figure B-4. Supplemental photographs of core 210043-4.



Abbreviations

AAS	Aircraft arresting system
AFB	Air Force Base
AFCEC	Air Force Civil Engineer Center
ASTM	American Society for Testing and Materials
BAK-12	Barrier Arresting Kit 12
CAE	Computer-aided engineering
CNC	Computer numerically controlled
DOF	Degree of freedom
ERDC	Engineer Research and Development Center
GSL	Geotechnical and Structures Laboratory
PCC	Portland cement concrete
USAF	US Air Force
UTS	Ultimate tensile strength
XRD	X-ray diffraction
YS	Yield strength

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14. ABSTRACT The fairlead beam is used to accomplish installation of the Barrier Arresting Kit 12 energy absorber for setback aircraft arresting system (AAS) installations at permanent operating facilities. Typical fairlead beams are affixed to a Portland cement concrete (PCC) foundation pad by a series of anchor assemblies made up of steel anchor rods set in grout inside galvanized pipe sleeves. US Air Force Civil Engineering Center (AFCEC) subject matter experts have identified a pattern of premature failures in these steel anchor assemblies when they are nondestructively inspected during AAS overhauls. The US Army Engineer Research and Development Center was tasked by AFCEC to investigate potential reasons for these premature failures. This report outlines methods and results of a finite element analysis of the anchorage, a visual and petrographic analysis of field-cored PCC anchor rods from Luke Air Force Base, and a mechanical analysis of specimens taken from the anchor rods within the PCC cores. Multiple modes of PCC distress were observed, and corrosion was evident in and around the anchor assemblies. Mechanical testing of specimens from the anchor rods indicated that an inferior grade of steel was used to fabricate these particular assemblies. Finally, observed deviations from design intention are discussed.					
15. SUBJECT TERMS Anchorage (Structural engineering)--Testing; Arrest of aircraft; Cables; Concrete; Finite element method; Pavements; Portland cement; Runways (Aeronautics)					
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