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**Innovations Deserving  
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## **Rapid Detection of Fatigue Cracking in Steel Anchor Rods Using the Impulse Response Method**

Final Report for  
NCHRP IDEA Project 175

Prepared by:  
Wesley Keller, Ph.D., P.E.  
Rachel Cohen  
Shamim Pakzad, Ph.D.  
Stephen Pessiki, Ph.D.  
Lehigh University

*June 2017*

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**IDEA Program Final Report**

**NCHRP-175**

Prepared for the IDEA Program  
Transportation Research Board  
The National Academies

*Wesley Keller, Ph.D., P.E.*

*Rachel Cohen*

*Shamim Pakzad, Ph.D.*

*Stephen Pessiki, Ph.D.*

*Department of Civil and Environmental Engineering  
Lehigh University*

*2 June 2017*

## **ACKNOWLEDGMENTS**

This research was supported through a grant from the National Cooperative Highway Research Program. The authors express their sincere appreciation to Dr. Inam Jawed and Dr. Monica Starnes for their input and assistance in the conduct of the work. Appreciation is also extended to Mr. Barry A. Benton, P.E., and Mr. Joseph A. Bracken III, P.E. for their contributions. The findings and conclusions are the views of the authors and may not represent the views of the sponsor or the individuals acknowledged above.

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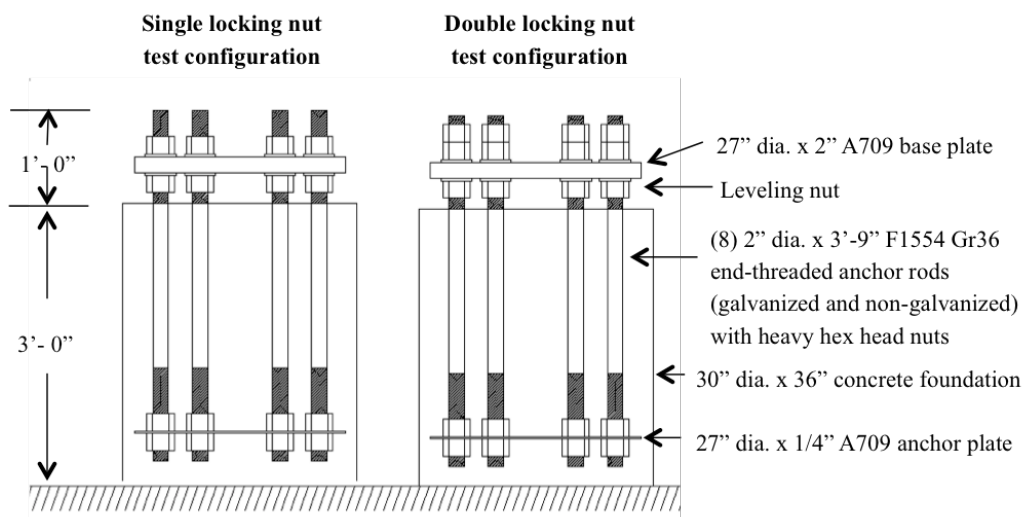
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## EXECUTIVE SUMMARY

Fatigue cracking in anchor rods for sign, signal, and luminaire structures due to wind-induced vibration is an ongoing problem that threatens public safety and impacts structural maintenance and repair expenditures. Experience has shown that fatigue cracking in auxiliary highway structure anchor rods generally occurs at either the first thread engagement near the base of the locking nut or below the leveling nut under the base plate of the structure (see figure below). These locations are difficult or impossible to inspect with visual inspection method alone. Ultrasonic testing (UT) can be used for crack detection in steel anchor rods, but many state DOT's and highway agencies do not incorporate UT in routine inspection programs due to the associated cost. Instead, UT is reserved for special inspections where a potential crack has first been identified through visual assessment.

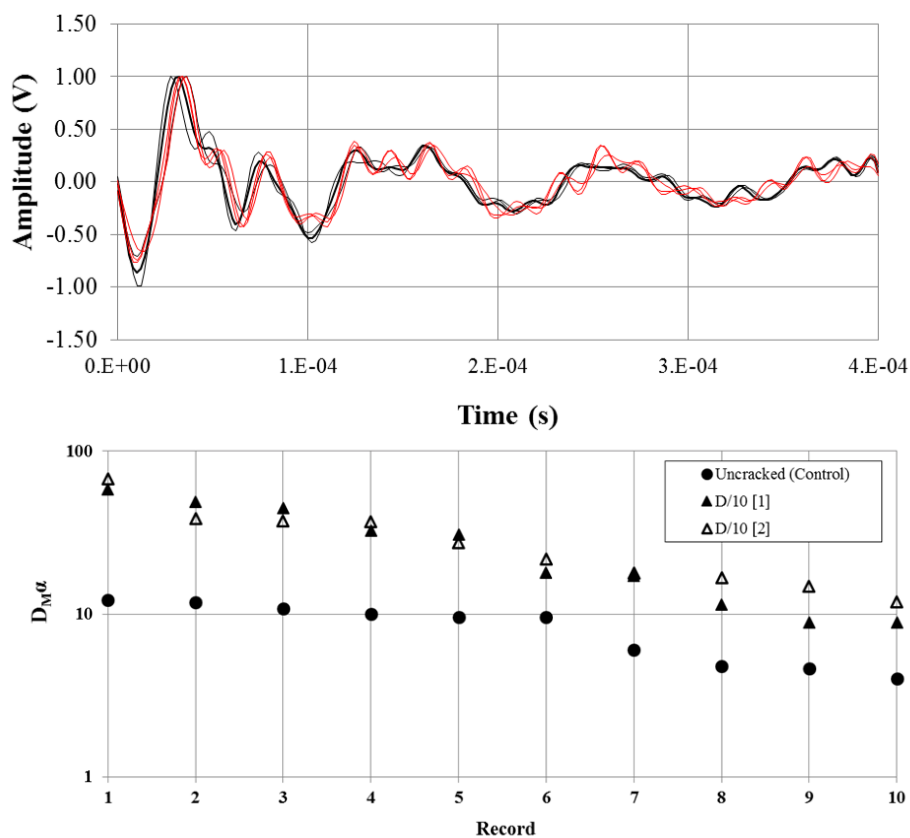
The objective of the research described in this report was to develop a rapid screening nondestructive test procedure utilizing stress wave interrogation for detection of fatigue cracks in steel anchor rods. The method sought by the research would be able to detect the presence of a fatigue crack with greater reliability than visual inspection. The proposed method is similar to the impulse response method used for integrity testing of concrete piles, wherein a stress pulse is imparted at the top surface of a pile by an instrumented hammer, and a velocity transducer is used to record surface motion due to the arrival of reflected stress waves from pile boundaries and internal defects. To interpret a test, a mobility plot is created by dividing the Fourier transform of the surface velocity history by the Fourier transform of the impact force-time function. The series of peaks in the mobility plot correspond to the fundamental and higher modes of vibration, and the difference between adjacent peaks is equal to the fundamental longitudinal frequency. With knowledge of the stress wave velocity, the distance to the reflecting surface (far end of the pile or an internal defect) can be calculated. In this research, an analogy is drawn between a steel anchor rod partially embedded in a concrete foundation and a concrete pile partially embedded in soil. The anchor rod assembly represents a much smaller length scale with a higher degree of geometric complexity (anchorage hardware including nuts, washers, baseplate, anchor plate) as compared to a concrete pile. The additional geometric complexities of anchorage systems complicate signal processing and data interpretation. This requires additional signal interpretation methods as used in this research.



The main focus of the research was an experimental evaluation of the proposed method for fatigue crack detection. A full-scale structure-foundation anchorage assembly was constructed for this purpose (see figure above). To perform a test, an accelerometer is coupled to the top surface of an anchor rod, and the surface is struck with an instrumented hammer. Typical surface acceleration records are shown below for an uncracked rod (black) and for a rod with a crack at the base of the leveling nut (red) that extends for 1/10 of the rod diameter.

In order to identify indicators of fatigue cracking, several damage-sensitive features extracted from univariate and multivariate regression models were evaluated, including alpha-based regression coefficients, angle coefficients, cosh spectral distances, and regression residuals. Of the investigated features, alpha-based regression coefficients was found to be the most reliable indicator of anchor rod cracking. Evaluation of impulse response data for the purpose of damage identification involves measuring the variation in the response signal from a known baseline (healthy or uncracked condition). Since the recorded data is a collection of discrete points, regression models are employed to develop best-fit functions for statistical

comparison. Autoregressive models (AR) are a particular classification of regression models that relate the current value of a predicted time series to past values of the same series. In this research, the AR models were used to fit accelerometer recordings normalized by the applied impulse. The figure below shows Mahalanobis distance for regression models fitting the surface acceleration response during the 2P reflection for an uncracked rod, and for two tests of the rod with a crack extending to 1/10 of the rod diameter D. The presence of the crack is evident in the result.



From the experimental program it was found that by establishing a baseline measurement for an uncracked rod, and evaluating the change in Mahalanobis distance between the alpha coefficients of regression models fitting the test data, the test method was able to identify artificial cracks at the base of the leveling nut (a region known to be susceptible to fatigue cracking), extending 1/4 and 1/2 of the rod diameter in depth, with at least 95% confidence.

## CHAPTER 1 – INTRODUCTION

### 1.1 PROBLEM DESCRIPTION

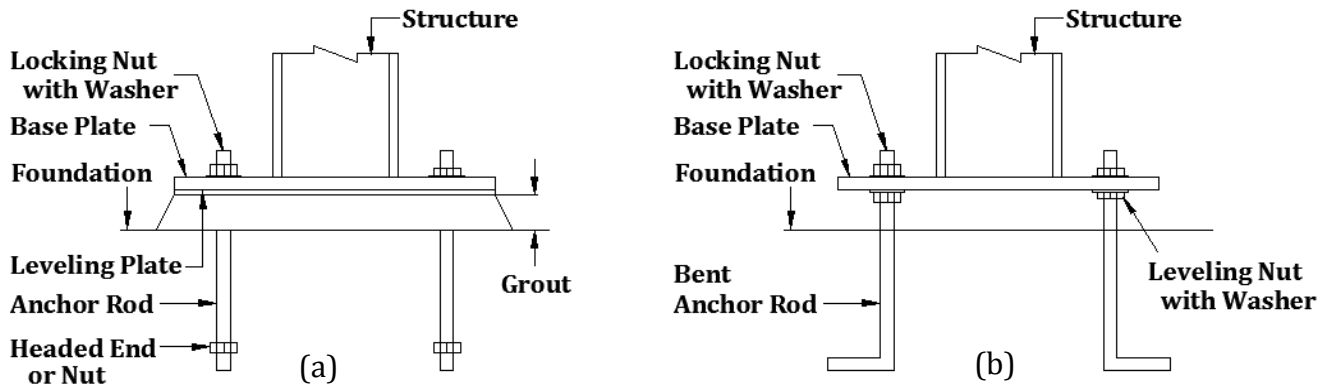
Fatigue cracking in sign, signal, and luminaire structures due to wind-induced vibration is a widespread problem that threatens public safety and impacts structural maintenance and repair expenditures. While research in this area has helped to mitigate the problem by improving design and detailing guidelines (1-5), the large inventory of auxiliary highway structures with deficient designs, coupled with the uncertainty in site-specific wind exposure and the complexity of wind-induced vibration phenomena, suggest that ongoing issues with fatigue cracking in auxiliary highway structures should be anticipated. In recent sign structure failures in New Hampshire in 2010 (6) and Virginia in 2012 (Figure 1) (7), structural collapse was triggered by fatigue failure of the steel anchor rods tying the structure to its foundation. As an illustration of the pervasiveness of fatigue cracking in auxiliary sign structure anchor rods, the Virginia Department of Transportation (VDOT) identified two cracked anchor rods in a second cantilevered sign structure along Interstate 95 within the first 25 inspections following the 2012 collapse (8). The structure was promptly removed from service.



**FIGURE 1 Sign structure collapse due to fatigue-induced anchor rod failure, Fairfax, VA (2012) (7).**

#### 1.1.1 Fatigue Failure of Steel Anchor Rods

Typical structure-foundation connection details for self-supporting auxiliary highway structures are presented in Figure 2. Research and field experience has shown that the steel anchor rods utilized in these details are susceptible to fatigue failure during wind-induced vibration. High-cycle cyclic loading, inherent stress concentrations, and environmental degradation contribute to crack initiation and propagation.



**FIGURE 2 Typical anchorage details for auxiliary highway structures: (a) threaded-shear-and-uplift connection with headed anchor rods (grouted), (b) double-nut-moment connection with bent anchor rods (ungrouted).**

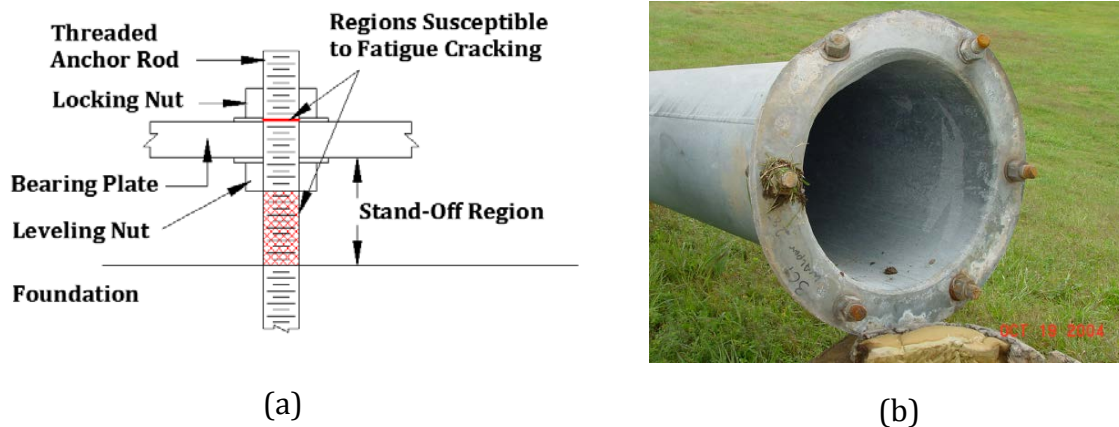
Experience has shown that fatigue cracking in auxiliary highway structure anchor rods generally occurs at either the first thread engagement near the base of the locking nut or below the leveling nut in the stand-off region, as illustrated in Figure 3(a). The growth rate of a fatigue crack is a function of crack geometry and environmental exposure. Anchor rod failure can trigger progressive collapse of the structure if the subsequent redistribution of load cannot be accommodated. Figure 3(b) shows a collapsed sign structure with evidence of anchor rod fatigue failure (9).

### 1.1.2 Deficiencies in Current Practice for Crack Detection in Steel Anchor Rods

Routine inspection of steel anchor rods is critical to ensuring structural integrity and public safety. The detection of fatigue cracks, however, is complicated by the fact that crack growth rate increases exponentially with crack length. Fatigue cracks, therefore, can spend long periods of time as a small fraction of the anchor rod diameter (not readily detectible during a visual inspection) and then rapidly propagate to failure. Early detection during routine inspection is essential for corrective intervention, particularly considering the extended period of time between site visits in a typical inspection cycle.

Ultrasonic testing (UT) has proven to be an effective tool for crack detection in steel anchor rods (10). Unfortunately, many state DOT's and highway agencies have been reluctant to incorporate UT in routine inspection programs due to the associated cost. The Pennsylvania Department of Transportation (PennDOT), for example, reserves UT for special inspections where a potential crack has first been identified through visual assessment (11).

The current practice of crack detection in steel anchor rods is therefore overly reliant on visual assessment, which is largely ineffective because the regions susceptible to fatigue cracking are generally obscured from view (Figure 3). Anchor rod inspection would benefit greatly from a cost effective and reliable nondestructive test method that can be readily incorporated in a routine inspection program.



**FIGURE 3** Fatigue failure of auxiliary highway structure anchor rods: (a) fatigue susceptible locations, (b) photograph of fractured anchor rods where fatigue cracking initiated in the stand-off region (9).

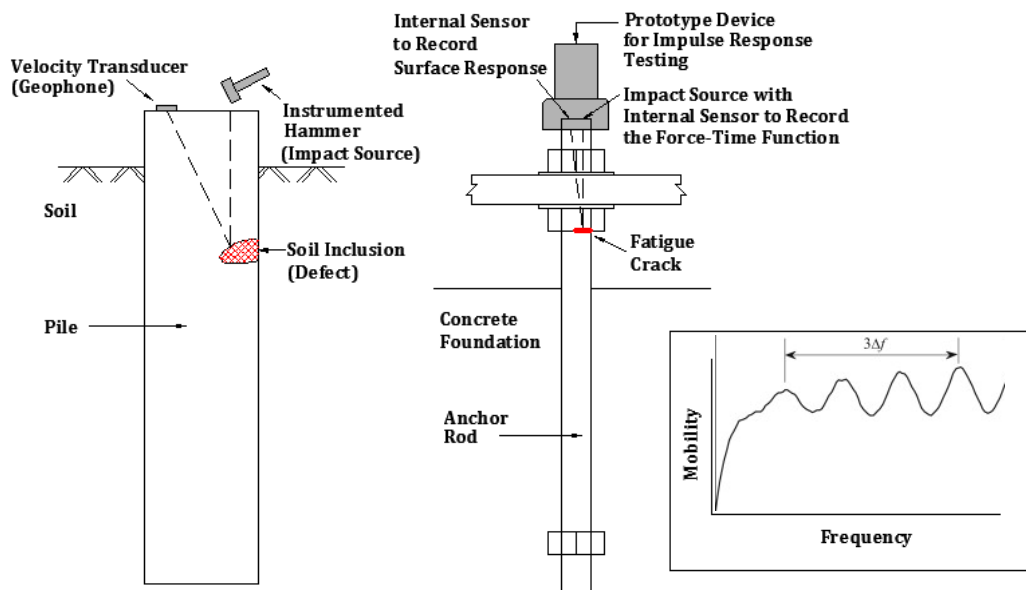
### 1.1.3 IDEA Topic - Application of the Impulse Response Method to Crack Detection in Steel Anchor Rods

The impulse response method is a nondestructive stress wave interrogation-based approach that has found use in pile integrity testing for the detection of voids, inclusions, necking, and other defects (12). A schematic illustration of the procedure is presented in Figure 4. In the evaluation of piles, a stress pulse is generated by an instrumented hammer and a velocity transducer (geophone) is used to record surface motion due to the arrival of reflected stress waves, including stress waves reflected off of internal defects. A mobility plot (i.e., Transfer Function) is generated by dividing the Fourier transform of the response waveform (surface velocity history) by the Fourier transform of the forcing function (impact force-time function). The series of peaks in the mobility plot correspond to the fundamental and higher modes of vibration, and the difference between adjacent peaks,  $\Delta f$ , is equal to the fundamental longitudinal frequency. With knowledge of the material sound speed, the distance to the reflecting surface can be calculated. If a defect is present, the length associated with the dominant frequency from the mobility plot will be the length to the defect, since the stress waves will reflect off of the defect before reaching the base of the pile.

#### *Proposed Application of the Impulse Response Method to Steel Anchor Rods*

As illustrated in Figure 4, an analogy can be drawn between a steel anchor rod partially embedded in a concrete foundation and a concrete pile partially embedded in soil. The basic approach of impulse response testing of steel anchor rods is therefore comparable to its current use in pile integrity testing, but at a smaller length scale and with a higher degree of geometric complexity. In terms of scale and due to the smaller dimensions, the impact source for anchor rod testing must contain higher frequency content than what is generated in pile integrity testing. This can be accomplished by reducing the contact time (duration) of the impact. The additional geometric complexities of anchorage systems (i.e. additional reflective surfaces) complicate signal processing and data interpretation.

In the proposal for this project, it was noted that while the application of impulse response testing to anchor rods does present additional challenges, the signal processing and data interpretation methodologies can be substantially simplified by considering that crack detection (as opposed to identifying crack location and length) is the primary objective during a routine inspection.



**FIGURE 4 Comparison of impulse response testing of piles and anchor rods.**

**1.2 RESEARCH OBJECTIVE**

The objective of the research described in this report was to develop a nondestructive test procedure utilizing stress wave interrogation for detection of fatigue cracks in steel anchor rods. The research objective addresses the research need identified in the NCHRP IDEA Highway Program announcement for *advanced diagnostic technologies to enhance early detection of deterioration*, listed under the *Maintenance and Renewal of Service Life* research category. The project also identifies potential barriers for practical implementation, and develops recommendations that will allow this technology to move more easily into practice as part of routine inspection programs.

**1.3 SUMMARY OF RESEARCH APPROACH**

The research approach is described as a series of research tasks in the following sections.

**1.3.1 Research Task 1: Survey of State DOTs and Highway Agencies**

Research Task 1 involved a survey of state DOT’s and highway agencies to collect information regarding experience with anchor rod cracking and current anchor rod inspection procedures (methods utilized and inspection frequency). The objective of this task was to identify fatigue prone anchorage details and structure types, to provide information regarding current anchor rod inspection practices, and to identify potential end users for the developed technology.

### **1.3.2 Research Task 2: Experimental Evaluation of Stress Wave Interrogation for Crack Detection**

Research Task 2 experimentally evaluated stress wave interrogation for crack detection in steel anchor rods. This task included: (1) design and construction of a large-scale structure-foundation anchorage assembly; (2) baseline tests of isolated anchor rods and anchor rods partially embedded in a concrete foundation to characterize stress wave response; (3) baseline testing of uncracked rods in the structure-foundation anchorage assembly; and (4) tests of rods in the structure-foundation anchorage assembly with cracks at fatigue susceptible locations.

### **1.3.3 Research Task 3: Field Trials**

Research Task 3 was to include a series of field trials to validate the test procedure under actual service conditions. This task was folded into Research Task 2 since that laboratory work included testing of a full-scale structure-foundation anchorage assembly with the same hardware used in actual field installations, but with known crack characteristics.

## **1.4 OUTLINE OF REPORT**

The remainder of this report is organized as follows. Chapter 2 presents the results of the Research Task 1 DOT survey. Chapter 3 describes the experimental program conducted in Research Task 2. The work described in this chapter constitutes the main thrust of the research program. Chapter 4 describes a numerical study on stress wave propagation in steel anchor rods. While this work was not emphasized in the original research plan, modeling and simulation was explored as a possible tool for conducting parametric studies to refine the test approach. Chapter 5 presents conclusions from the research. Finally, Chapter 6 discusses future research needed for the development and implementation of the proposed test method.

## CHAPTER 2 - DOT SURVEY

### 2.1 INTRODUCTION

In order to obtain information regarding DOT experience with anchor rod cracking, and to identify potential end users for the developed technology, a concise, one page questionnaire was prepared and distributed to all state and the District of Columbia DOT agencies. The objective of the survey was to identify fatigue prone anchorage details and structure types, to provide information regarding current anchor rod inspection practices, as well as to identify potential end users for the developed technology.

### 2.2 SURVEY DETAILS AND RESULTS

Details of the survey are given in the Appendix. Appendix Figure A.1 and Table A.1 present the survey details. Figure A.1 is the survey that was distributed via email to each of the contacts listed in Table A.1. The survey was sent via email to a total of 51 contacts, and a total of 27 responses were received.

Table 1 presents the results of the survey. The survey found that 18 of the 27 responding agencies have anchor rod inspection programs. UT and visual inspection are two common inspection methods. Of the 18 responding agencies that have anchor rod inspection programs, 10 of them have found anchor rod cracking and / or failure. Thus anchor rod cracking has been found by about half of the agencies that inspect for cracking. Unfortunately, the survey did not capture whether the observed instances of anchor rod cracking and / or failure were considered to be isolated events, or found to be more widespread.

TABLE 2 Results of state DOT and Highway agencies survey.

State	Responded to Survey 0 = No, 1 = Yes	Experience with Anchor Rod Cracking 0 = No, 1 = Yes	Inspect for Anchor Rod Cracking 0 = No, 1 = Yes	Visual/Sounding Only 0 = No, 1 = Yes	UT Used in Some Form (Regular or Special Inspection) 0 = No, 1 = Yes	UT Regular 0 = No, 1 = Yes	Notes
AK	1	0	0	X	X	X	no inspection
AZ	1	0	0	X	X	X	no inspection
AR	1	0	1	1	1	0	UT if problem detected
CO	1	0	1	1	0	0	visual only
DE	1	1	1	0	1	1	UT regular
FL	1	0	1	1	0	0	visual only
GA	1	1	1	1	1	1	visual + UT
IL	1	0	1	1	0	0	visual only
IA	1	1	1	1	1	1	visual + UT
LA	1	0	0	X	X	X	no inspection
MI	1	1	1	1	1	1	visual + UT
MN	1	1	1	0	1	1	UT regular
MS	1	0	0	X	X	X	no inspection
MO	1	0	0	X	X	X	no inspection
MT	1	0	0	X	X	X	no inspection
NE	1	1	1	0	1	1	UT regular
NV	1	0	0	X	X	X	no inspection
NJ	1	1	1	0	1	1	UT regular
NM	1	0	1	1	1	1	visual + UT
NY	1	1	1	1	1	0	UT if problem detected
ND	1	0	1	1	0	0	visual only
OH	1	0	0	X	X	X	no inspection
SD	1	0	1	1	0	0	visual only
UT	1	0	0	X	X	X	No inspection
VA	1	1	1	0	1	1	UT regular
WA	1	1	1	1	1	1	visual + UT
WY	1	0	1	1	0	0	visual only
TOTALS	27	10	18	13	12	10	



## **CHAPTER 3 - EXPERIMENTAL PROGRAM**

### **3.1 INTRODUCTION**

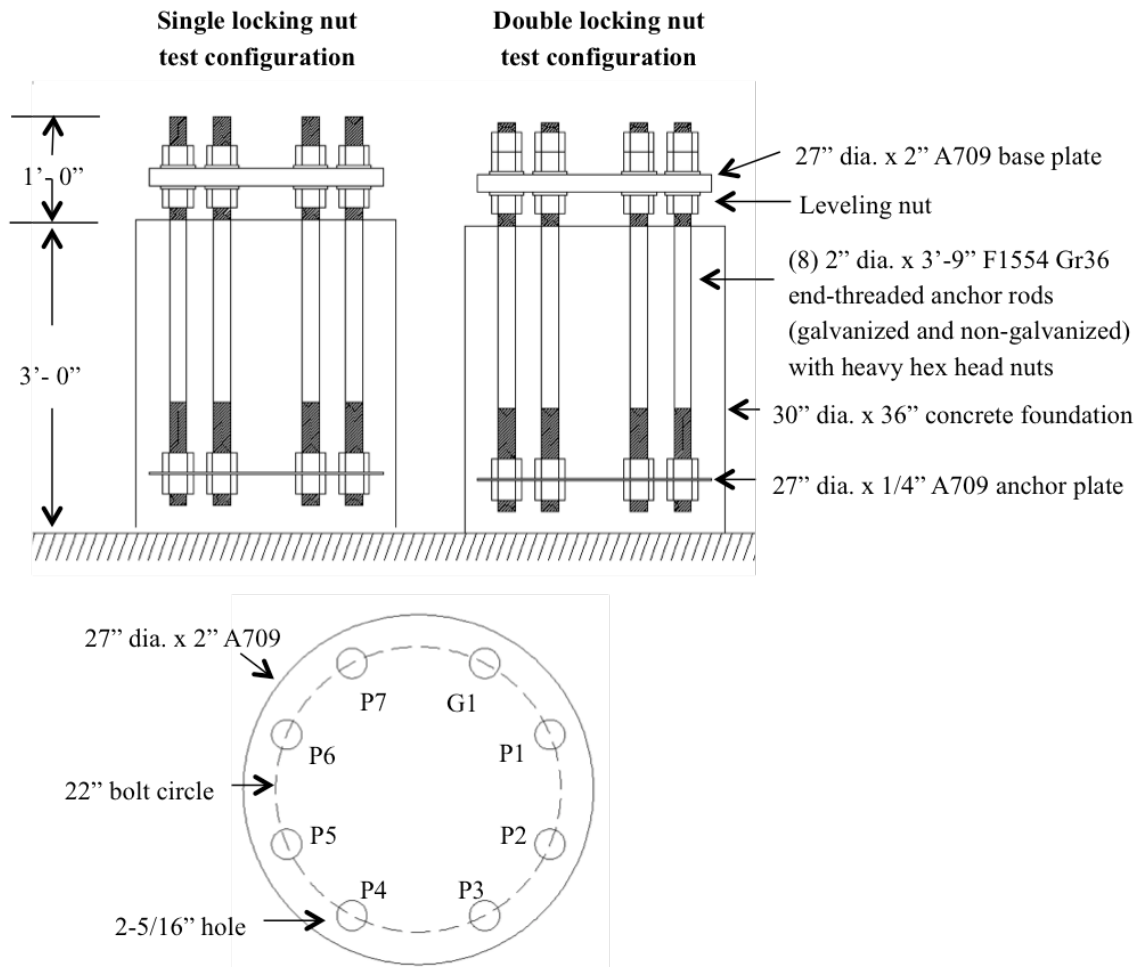
This chapter outlines the experimental program conducted in Research Task 2 to evaluate stress wave interrogation for crack detection in steel anchor rods. Section 3.2 describes the full-scale structure-foundation anchorage assembly that was used as the test specimen for the study. The assembly is representative of an anchorage system for sign and luminaire structures. Section 3.3 describes testing to evaluate experimental parameters (equipment and procedures) that impact the ability to generate reliable and repeatable measurements. Section 3.4 describes baseline tests of isolated anchor rods and anchor rods partially encased in concrete without anchorage hardware. These baseline tests were conducted to identify geometric features and material interfaces attributed with stress wave reflections, to evaluate frequency content for stress wave interrogation, and to characterize signals for uncracked rods without anchorage hardware. Section 3.5 describes baseline tests performed on the structure-foundation anchorage assembly. These baseline tests were conducted to characterize impulse response measurements for uncracked anchor rods and to evaluate the effect of anchorage construction (specifically, side contact between the anchor rods and base plate) on crack detection. Finally, Section 3.6 describes tests performed on the structure-foundation anchorage assembly that included artificial cracks in the anchor rods at locations known to be susceptible to fatigue. These tests provide data for the evaluation of damage-sensitive features for crack detection.

### **3.2 FULL-SCALE STRUCTURE-FOUNDATION ANCHORAGE ASSEMBLY**

Figure 5 shows dimensioned drawings of the full-scale structure-foundation anchorage assembly constructed for the experiments. The assembly is composed of a 30 in dia. x 36 in deep concrete foundation with eight 2 in dia. x 3 ft-9 in F1554 Gr36 steel anchor rods. The base plate for the assembly is a 27 in dia. x 2 in A709 steel section with a 22 in bolt circle and 2-5/16 in dia. holes. The offset dimension between the bottom of the base plate and the top of the concrete foundation is 4.25 in. The assembly also includes an embedded 27 in dia. x 1/4 in A709 steel anchor plate that is located 7 in from the base of the foundation. The heavy hex nuts used in the assembly are 3.5 in (width across flats) x 2-13/64 in thick. The anchor rod-to-base plate connection uses 4 in dia. x 1/4 in washers, while the anchor rod-to-anchor plate connection excludes washers. In this report, the anchor rod nuts located below the base plate are designated as the ‘leveling nuts’, while the nuts located above the base plate are designated as ‘locking nuts’. The assembly was configured to study both single locking nut and double locking nut construction.

Designations for the plain (non-galvanized) and galvanized anchor rods are shown in Figure 6, noting that the ‘P’ designation denotes a non-galvanized rod and the ‘G’ designation denotes a galvanized rod. Both galvanized and non-galvanized rods and anchorage hardware were considered in order to investigate the influence of galvanization on stress wave propagation characteristics, particularly in terms of the influence on thread engagement. All of the anchor rods investigated in the study were partially threaded at both ends with a 12 in threaded length and a thread pitch conforming to the ANSI/ASME B1.1 Unified Coarse Thread Series (4.5 threads/in). Figures 6 and 7, respectively, show the anchor rods prior to assembly and the completed structure-foundation anchorage assembly (single locking nut configuration).

The small tab welded to the center of the base plate was used for handling the base plate in the laboratory with an overhead crane.



**FIGURE 5 Structure-foundation anchorage assembly showing both single locking nut and double locking nut test configurations. Anchor rod designations are galvanized (G1) and non-galvanized (P1-P7) end-threaded F1554 Gr36 anchor rods with heavy hex head nuts and washers.**



**FIGURE 6** Photograph of anchor rods, nuts and washers.



**FIGURE 7** Photograph of the completed structure-foundation test specimen.

### 3.3 EVALUATION OF TEST PARAMETERS

Early experimental work focused on the development of test parameters (equipment and procedures) that impact the ability to generate reliable and repeatable measurements. The test parameters included impact source, signal duration and filtering, transducer coupling, and impact-measurement location. From this development work, the following general test parameters were determined and used in the experiments described later in this chapter. The tests were conducted using the piezoelectric accelerometer and instrumented hammer shown in Figure 8. The accelerometer was a PCB Series 303A Quartz (piezoelectric) accelerometer that exhibits a flat response range ( $\pm 5\%$ ) out to 10 kHz and a resonant frequency of 70 kHz. The instrumented hammer was manufactured by PCB and was specially designed for this type of testing.



**FIGURE 8 PCB piezoelectric accelerometer (left) and instrumented hammer (right).**

#### 3.3.1 Impact Source and Location

As discussed in Chapter 1, stress wave testing of anchor rods is at a significantly smaller length scale than piles, and thus requires higher frequency content for flaw detection. This section specifically describes work performed to develop an appropriate stress wave input, since that was found to be an important parameter in the experimental program. Two different methods to input stress waves were considered: (1) impact by steel spheres dropped on to the top surface of the anchor rods; and (2) impact by an instrumented hammer. The first method, impact by steel spheres, was eliminated because of practical issues associated with accurately striking the small target area (the top end of the rod) with a dropped sphere, and also because of the difficulty in determining contact time of the impact, which is needed to approximate the frequency content of the impact. Thus, work concentrated mostly on the use of an instrumented hammer.

The issue identified as most important was the repeatability of the hammer strike both in terms of location on the end of the rod and also on impact duration (which determines frequency input). Two methods of hammer strike were studied in detail: (1) hand-held hammer strike; and (2) spring-assisted hammer strike. In the hand-held hammer strike, the test operator simply attempts to strike the rod with the same force and at the same location with each repeated test. In the spring-assisted hammer strike, the hammer shaft is fitted inside a coil spring. The hammer spring assembly is fixed in location with respect to the top end of the rod. To strike the rod, the hammer is pulled back from the surface, flexing the spring, and when the hammer is released, it returns to its starting position and strikes the top of rod surface.

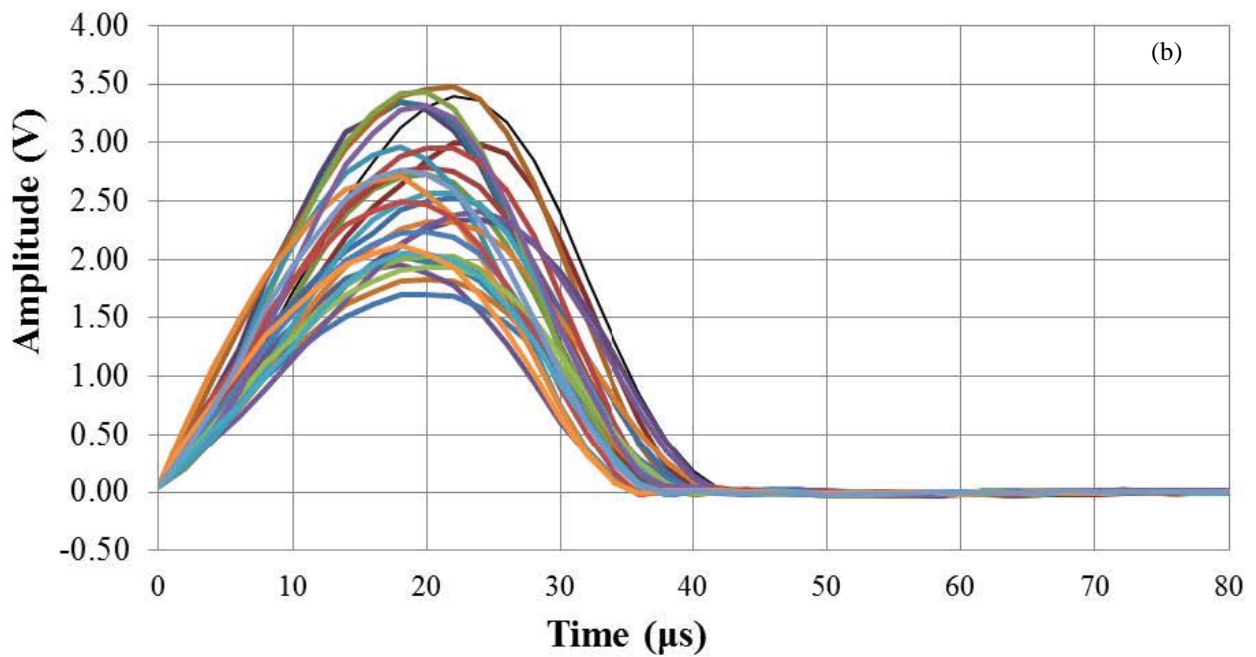
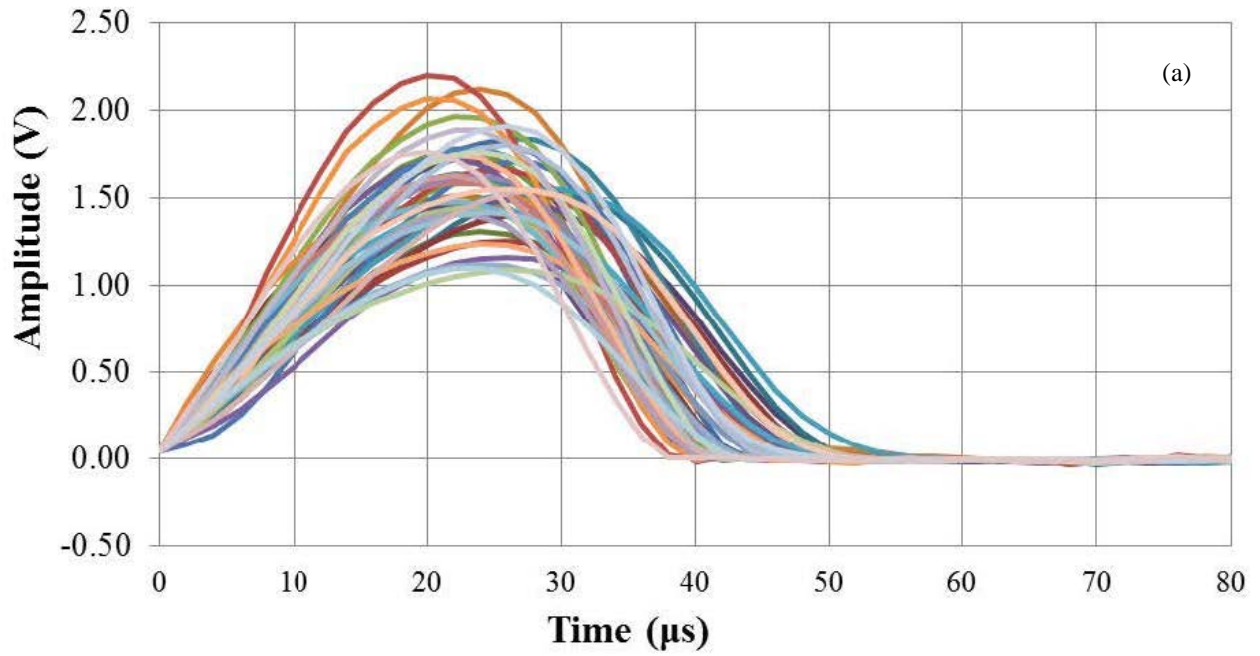
Force-time records for the hand-held and spring-assisted hammer strikes are shown in Figure 9(a). Fifty tests were conducted for each approach. The contact time for the hand-held strikes ranged from approximately 40-50  $\mu$ s. For these contact times, the maximum frequency of useful energy imparted on the specimen is between 25-31 kHz (Sansalone and Streett, 1997), which is greater than the required crack detection frequency range of 10-20 kHz. The corresponding force-time records for the spring-assisted hammer strike approach are shown in Figure 9(b). The contact times were slightly shorter (ranging from approximately 35-40  $\mu$ s) but the pulse shape and imparted frequency content were comparable with the hand-held approach. No significant advantage was therefore found with the spring-assisted device, so impact loading from the hand-held instrumented hammer was determined to provide sufficient input for this study. As discussed later in the report, an eventual integrated testing device could be made to better control impact repeatability (location, magnitude and duration).

Finally, it is noted here that work was performed to explore other impact locations in addition to the top of the anchor rod including on the side of the anchor rod, and on the locking nut. It was found that impact at locations other than the top of the rod provided no advantage or improvement, and often produced incoherent results. Impact on the top end of the anchor rod provided the most useful and consistent results.

### **3.3.2 Transducer Coupling**

The accelerometer was mounted to the top surface of the rod in one of two ways: (1) using a high vacuum grease coupling agent (Figure 10); or, (2) threaded in to a drilled and tapped hole in the top of the rod. The instrumented hammer was used to impart a stress pulse in the rod by impacting the top surface near the quarter points in the four cardinal directions (test locations are described in greater detail later in this report). Data from the instruments was acquired using a National Instruments USB-6361, X-Series DAQ system at a sampling rate of 500 kHz (sampling period 2  $\mu$ s) for a record duration of 1 ms. The analog trigger for recording was set at 50 mV, with the measured noise less than 5 mV.

Evaluation of test data for the grease coupled setup revealed significant variation in the surface acceleration response between test setups with similar conditions. This discrepancy was attributed to variability in the coupling condition between the surface-mounted accelerometer and the anchor rod, which can impact measurement sensitivity as well as the dynamic response of the accelerometer. In order to provide a more consistent coupling condition that improves crack detection sensitivity by reducing the inherent test variability, two anchor rods were drilled and tapped so that the



**FIGURE 9** Impact records: (a) hand-held hammer strikes; and, (b) spring-assisted strikes (50 records each)

accelerometer could be threaded directly into of the rod. Mechanical fastening of the accelerometer to the rod was shown to greatly improve test repeatability compared to grease-coupling (Figure 11). It is believed that a similar coupling condition can be achieved through a more practical means in the prototype testing device by spring loaded or magnetic attachment.



**FIGURE 10 Accelerometer mounted on the top surface of a test rod with high vacuum grease coupling agent.**

### **3.4 BASELINE TESTING OF ISOLATED AND EMBEDDED ANCHOR RODS WITHOUT ANCHORAGE HARDWARE**

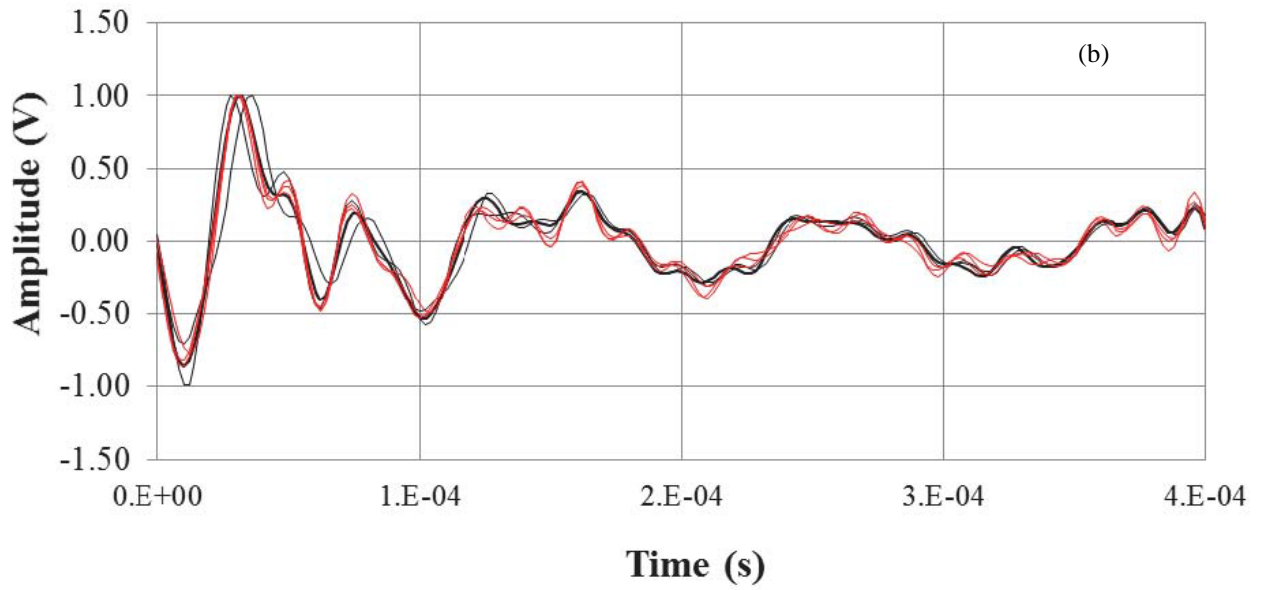
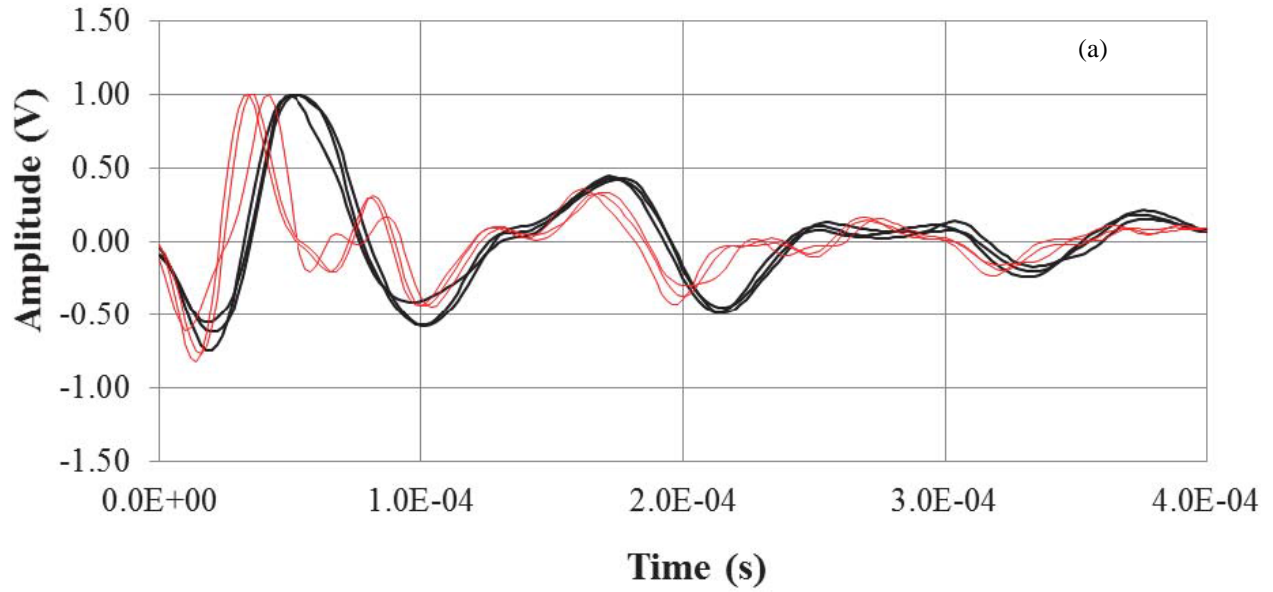
Baseline tests of isolated and embedded anchor rods without anchorage hardware were conducted in order to identify geometric features and material interfaces attributed with stress wave reflection and to characterize signals for uncracked rods.

#### **3.4.1 Test Set-up**

12 shows the test setup for a single isolated rod test without the concrete foundation. Details for the rods were presented earlier. During testing, the bottom end of the rod was placed on a layer of foam padding, and the top end was wrapped in a second piece of foam, and held upright by light wood framing. The foam padding was used to acoustically separate the rods from its surroundings. Figure 13 shows the test setup for the isolated embedded rods (i.e. without the base plate, washers and nuts). The concrete foundation was supported on wood blocking during testing.

#### **3.4.2 Mobility Spectra**

The relationship between structural response and frequency content of the input is determined by dividing the Fourier transform of the response waveform (acceleration history) by the Fourier transform of the impact force-time function.



**FIGURE 11** Surface acceleration recordings for an uncracked anchor rod measured for two accelerometer installations: (a) grease-coupling; and, (b) mechanical attachment. Installation 1 shown in black and installation 2 shown in red.



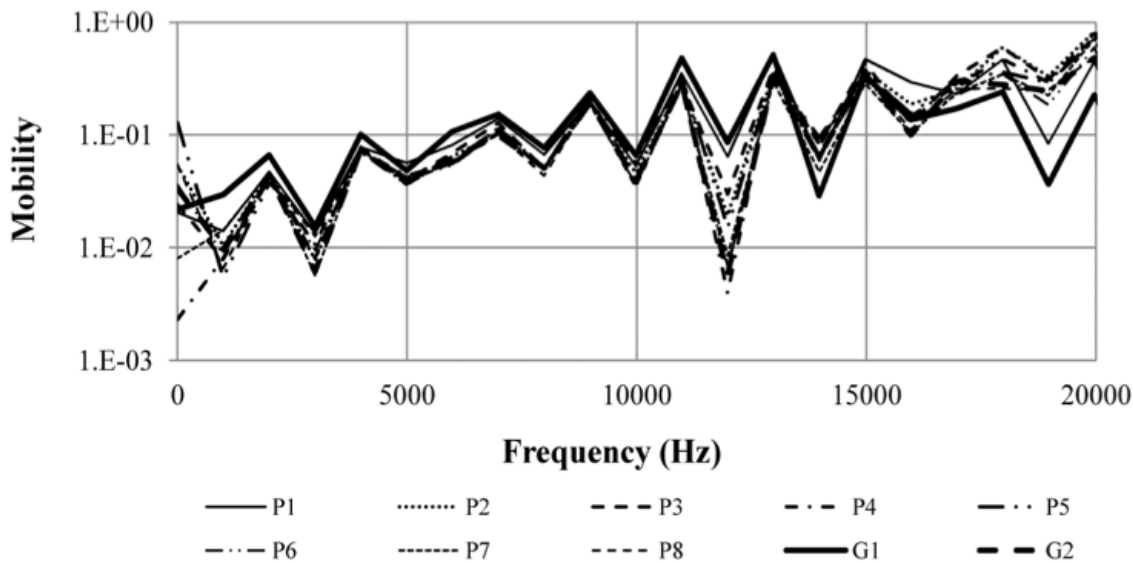


**FIGURE 12** Test set-up for a single isolated anchor rod.

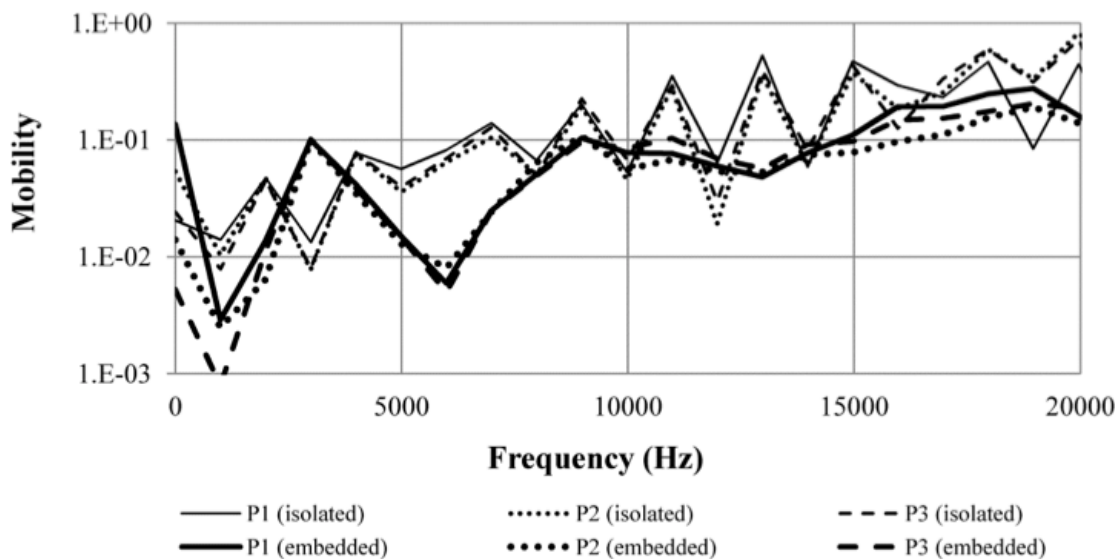


**FIGURE 13** Test set-up for embedded rods without base plate, washers and nuts.

The resultant response spectrum is the mobility spectra (system transfer function or mobility plot as described in Chapter 1). Both the isolated and embedded rod tests produced consistent mobility spectra within the frequency range of interest (2-20 kHz), where the peak at 2 kHz in the isolated test spectra is indicative of resonant stress wave reflections from the rod ends, and the 10-20 kHz range is the anticipated resonant frequency content for stress wave reflections from known fatigue crack locations in the completed assembly. In general, the mobility spectra were in good agreement between individual tests of the same rod and between tests of different rods in the assembly, as shown in Figures 14 and 15. It is noted that the mobility spectra for the embedded rod tests exhibited a smoother high frequency range due to an increase in material damping.



**FIGURE 14** Mobility spectra for tests of isolated rods P1-P8 and G1-G2.



**FIGURE 15** Mobility spectra for tests of isolated and embedded rods (without baseplate, washers and nuts) rods P1-P3.

### 3.5 BASELINE TESTING OF THE COMPLETED STRUCTURE-FOUNDATION ANCHORAGE ASSEMBLY

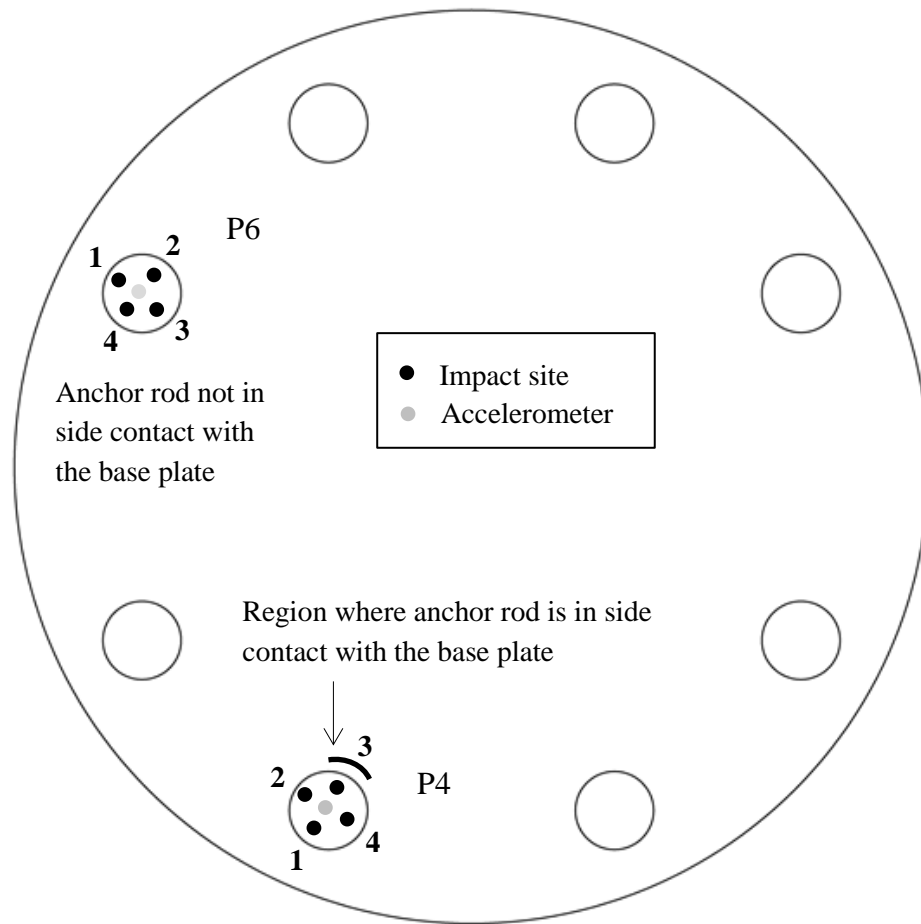
This section of the report describes baseline tests performed on the structure-foundation anchorage assembly to characterize impulse response measurements for uncracked anchor rods and to evaluate the effect of anchorage construction (specifically, side contact between the anchor rods and base plate) on crack detection. A photograph of the completed structure-foundation anchorage assembly is shown in Figure 16.



**FIGURE 16** Baseline testing of the completed structure-foundation anchorage assembly.

#### 3.5.1 Test Setup

Similar to the isolated and embedded rod tests without anchorage hardware, the accelerometer was mounted on the top surface of the rod (near the center) using a high vacuum grease coupling agent (non-tap installation), and the instrumented hammer was used to impart an impulse at four designated impact sites. The notation used to describe the impact sites is shown in Figure 17. For each rod, the impact sites are labeled 1 through 4 in a clockwise direction from the outer surface of the rod. This is illustrated for rods P4 and P6 in Figure 17.

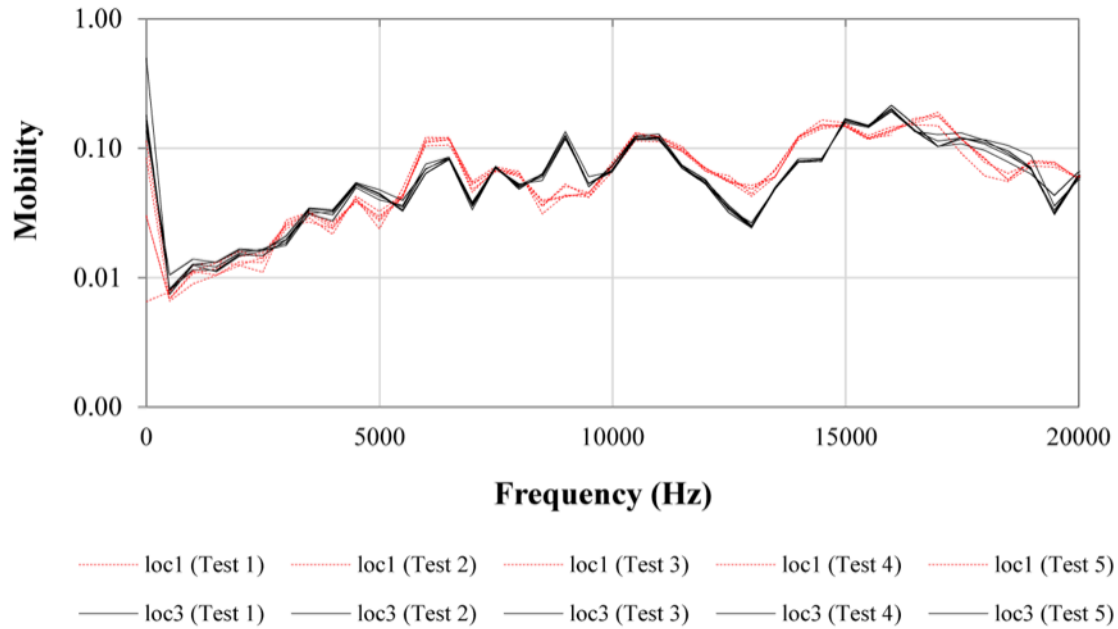


**Figure 17 Test configuration for baseline measurements of rods P4 and P6.**

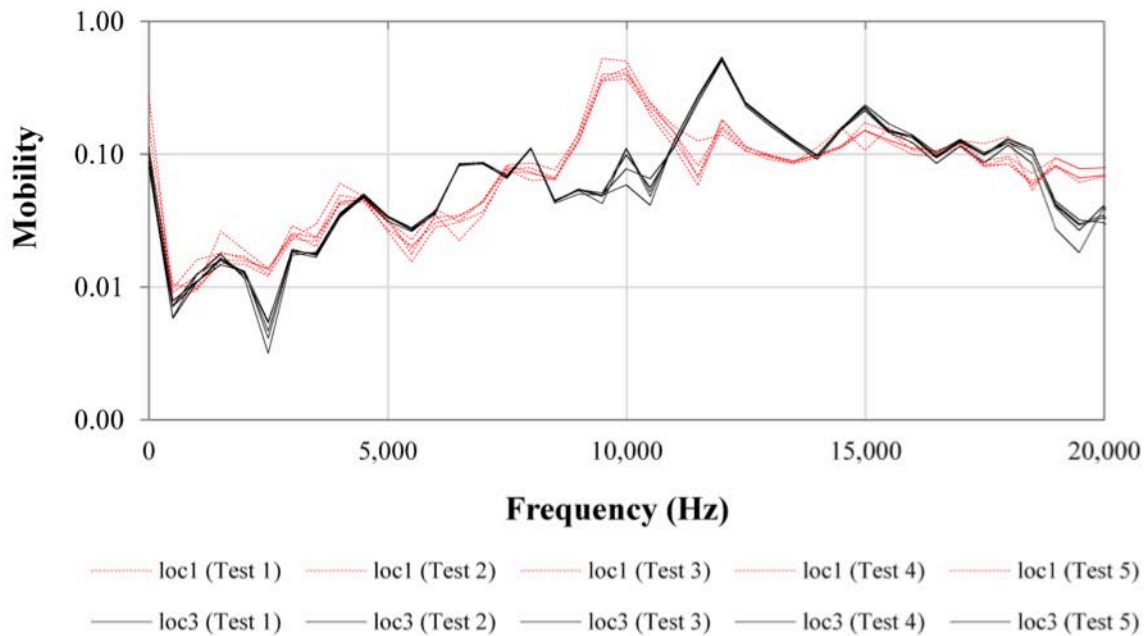
### 3.5.2 Mobility Spectra

In any given round of testing, the testing was conducted over several days in order to characterize the inherent variability in the test approach. For each day of testing, 40 baseline measurements were recorded for each rod, at each impact site. Similar to the isolated rod tests, data was acquired at a sampling rate of 500 kHz (sampling period 2  $\mu$ s) for a record duration of 2 ms, using an analog trigger of 50 mV. Measured noise was less than 5 mV.

The mobility spectra show relatively high repeatability for tests using the same transducer installation but exhibit more variability between different installations, as illustrated in Figures 18 and 19. It is noted that these tests utilized grease coupling and that, as discussed in 3.3.2, tapping can significantly improve measurement repeatability between different installations. The mobility spectra are generated for impacts at locations 1 and 3 (identified as loc1 and loc3 in the figure legends). Rod P6 passes through the base plate hole without direct contact, while rod P4 bears against the interior surface of the plate. As anticipated, side contact alters wave propagation within the rod, altering the mobility signature (as evidenced by the discrepancies in mobility between P4 and P6). Side contact also appears to exacerbate the issue with



**FIGURE 18** Baseline mobility spectra for rod P6 which passes through the baseplate hole without direct contact with the baseplate (impact at locations 1 and 3).



**FIGURE 19** Baseline mobility spectra for rod P4 which bears against the baseplate where the rod passes through the baseplate hole (impact at locations 1 and 3).

inconsistent measurements between similar transducer installations. When comparing mobility spectra, anchor rod-base plate contact will complicate signal interpretation, and therefore crack detection, for scenarios where a healthy (uncracked rod) baseline measurement is not available.

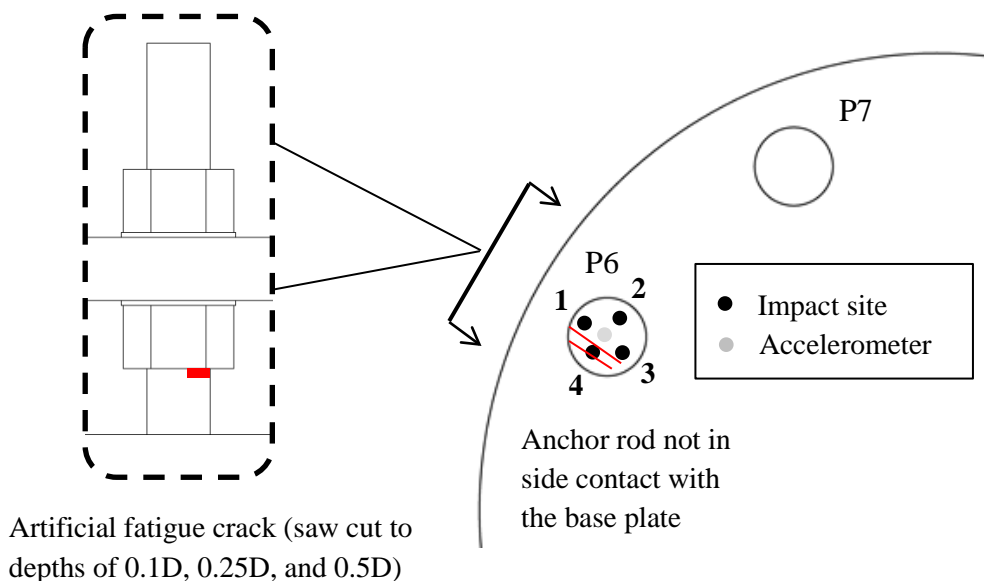
### 3.6 CRACK DETECTION STUDIES

This section of the report describes tests performed on the structure-foundation assembly that included artificial cracks in the anchor rods. These tests provided data for the evaluation of damage-sensitive features for crack detection.

#### 3.6.1 Test Setup

All crack detection tests were performed on the same structure-foundation anchorage assembly described earlier in the report. Artificial cracks were introduced by saw cutting the rod at the base of the leveling nut (Figure 20). This crack location was selected based on experimental tests by Frank (1) and Kaczinski et al. (2) on the fatigue performance of anchorage connections under cyclic loading. Crack depths of 1/10, 1/4, and 1/2 of the rod diameter (D) were investigated. Each crack was introduced near location 4 since the threading in this location allowed for the closest placement of the crack to the base of the leveling nut. Field experience and testing has shown that cracking generally initiates in a groove near the first thread engagement due to non-uniform stress distribution in the threaded connection. This places the crack near an abrupt geometric transition in the assembly (i.e. the base of the leveling nut). Since geometric transitions cause stress wave reflections in the absence of a crack, this crack location is problematic from a detection standpoint because the inherent geometric reflections can mask the resonant crack reflections.

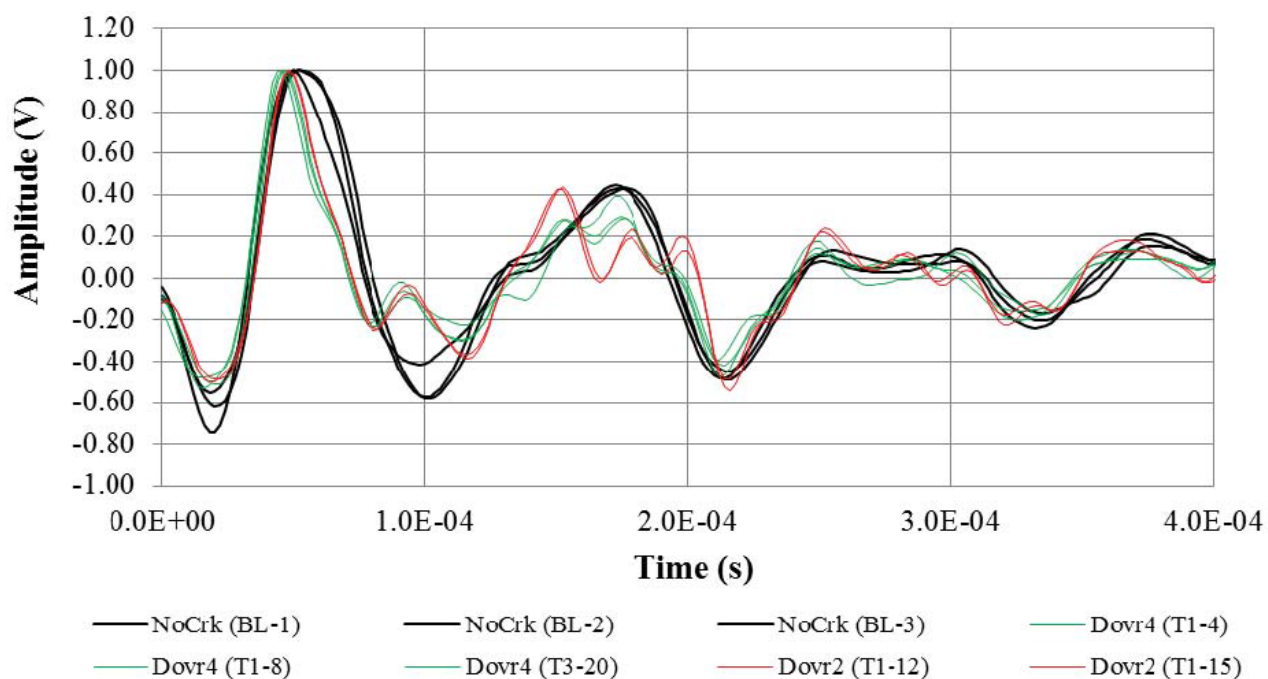
Testing was carried out in a similar manner to the baseline testing outlined in the previous section. For each target crack depth, a minimum of 20 tests were performed at each impact site.



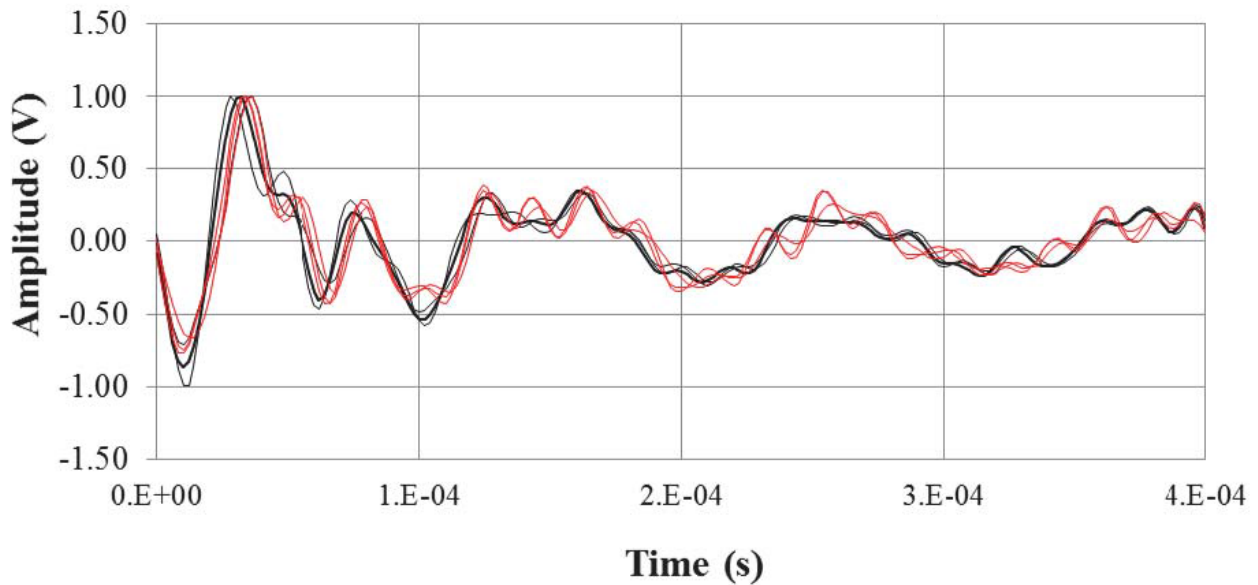
**FIGURE 20** Test configuration for the crack detection studies.

### 3.6.2 Comparison of Recorded Waveforms for Cracked and Uncracked Anchor Rods

Figure 21 presents surface acceleration recordings for anchor rod P5 (single locking nut configuration) in the uncracked condition and with D/4 (1/4 of the effective diameter) and D/2 (1/2 of effective diameter) cracks at the base of the leveling nut, where D is the diameter of the rod. The data in Figure 21 was generated for an impact load applied in the quadrant over the crack surface. The presence of a crack at the base of the leveling nut appears to alter the tension wave that is reflected back to the rod surface from the base of the leveling nut, designed as the 2P reflection. This reflection in the uncracked condition is due to the abrupt change in geometry and results in the downward motion of the rod surface around 0.1 ms. Attenuation of the reflected tension wave could be attributed with crack alternation of the reflective boundary. The effect of the crack appears to damp out relatively quickly and is notably absent from the 4P reflection. Similar results were obtained for anchor rod P2 (double locking nut configuration). Figure 22 presents surface acceleration recordings for the uncracked condition and with a D/10 crack (1/10 of the effective diameter) located at the base of the leveling nut. Similar to the single nut configuration, the peak associated with the 2P reflection is lessened when a crack is present.



**FIGURE 21** Surface acceleration recordings for rod P5 (single locking nut configuration): uncracked condition (black); D/4 crack (green); and D/2 crack (red)



**FIGURE 22 Surface acceleration recordings for an anchor rod P2 (double locking nut configuration): uncracked condition (black) and with a D/10 crack at the base of the leveling nut (red)**

### 3.6.2 Signal Processing for Damage Detection

The effect of cracks on the recorded waveform provides a feature that can be utilized for crack detection. Signal processing can then be employed to automate the detection process and evaluate statistical significance. The signal processing and data interpretation algorithms studied in this research sought a relatively high level of sensitivity for crack detection, considering that fatigue cracks spend long periods of time as a small fraction of the anchor rod diameter.

#### *Regression Models and Damage-Sensitive Features*

In order to identify indicators of fatigue cracking in impulse response data, several damage-sensitive features extracted from univariate and multivariate regression models were considered, including alpha-based regression coefficients, angle coefficients, cosh spectral distances, and regression residuals. Of the investigated features, alpha-based regression coefficients was found to be the most reliable indicator of anchor rod cracking, and are discussed in this report. The reader is referred to Yao and Pakzad (13-15) and Shahidi et al. (16) for additional details.

Evaluation of impulse response data for the purpose of damage identification involves measuring the variation in the response signal from a known baseline (healthy or uncracked condition). Since the recorded data is a collection of discrete points, regression models are employed to develop best-fit functions for statistical comparison. Autoregressive models (AR) are a particular classification of regression model that relate the current value of a predicted time series to past values of the same series. In the present application, the AR models are used to fit accelerometer recordings



normalized by the applied impulse. The AR model (Eqn 1) can be expanded to include information about the system from past and present time points:

$$y_j(n) = \sum_{p=1}^P \alpha_p y_j(n-p) + \varepsilon(n) \quad (\text{Eqn 1})$$

where  $y_j$  is the output at location  $j$ ,  $\alpha_p$ 's are alpha-based AR coefficients,  $\varepsilon(n)$  represents the residuals,  $n$  is the time index, and  $P$  is the order of the AR model.

When the driving (or exogenous) input is considered, the modeling approach is referred to as autoregressive with exogenous input (ARX), where the predicted time series is not only a function of its own history, but also the present and past values of the exogenous series (Eqn 2).

$$y_j(n) + \sum_{p=1}^P \alpha_{jp} y_j(n-p) = \sum_{q=0}^Q \beta_{iq} y_i(n-p) + \varepsilon(n) \quad (\text{Eqn 2})$$

where the subscripts  $i$  and  $j$  designate unique locations, and  $P$  and  $Q$  are the order of the AR and exogenous parts, respectively.

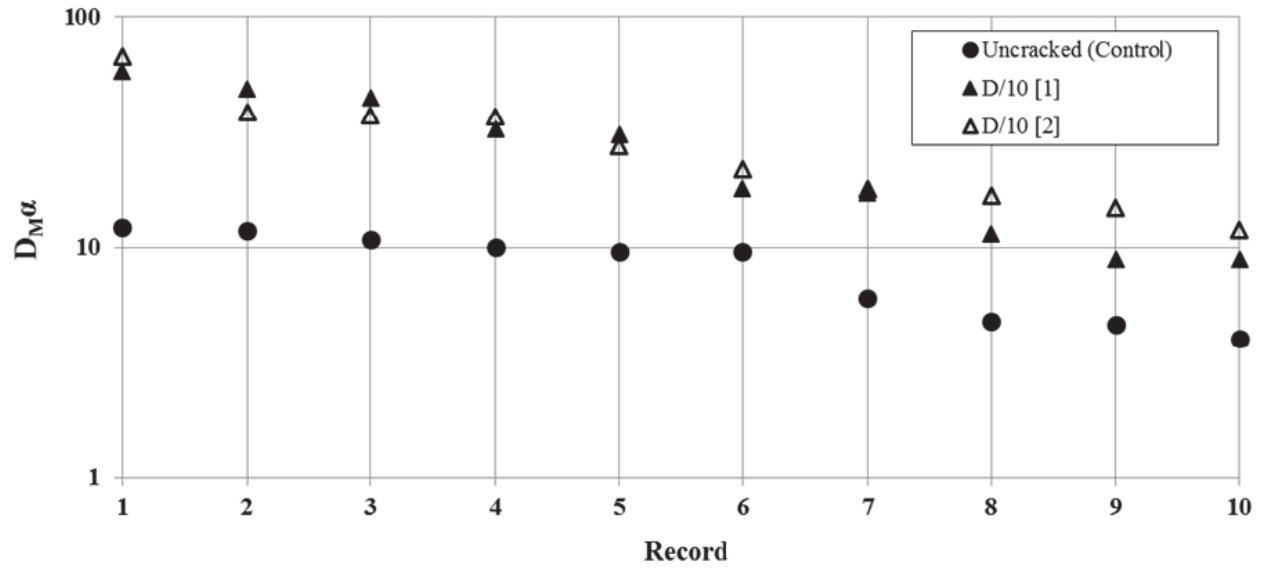
For alpha-based regression coefficients, Mahalanobis distance (Eqn 3) can be used to form a scalar representation of the regression coefficients for direct comparison (17).

$$D_m(x) = \sqrt{(x - \mu)^T S^{-1} (x - \mu)} \quad (\text{Eqn 3})$$

where  $\mu$  is the mean of the baseline regression coefficient matrix and  $S$  is its covariance matrix.

#### *Damage Feature Extraction and Crack Detection*

Damage feature calculations from the test measurements were performed using the DIT (Damage Identification Toolsuite) software developed by Pakzad et al. (18). By fitting a regression model to window the 2P region of the waveforms in Figure 22, the presence of the D/10 crack can be clearly and consistently detected by evaluating the regression coefficients through the single, scalar Mahalanobis distance parameter ( $DM\alpha$ ). As illustrated in Figure 23, the distance parameter is consistently larger for the cracked condition compared with control data for the uncracked condition (> 95% confidence in crack detection).



**FIGURE 23** Mahalanobis distance for regression models fitting the surface acceleration response during the 2P reflection

## CHAPTER 4 - NUMERICAL MODELING

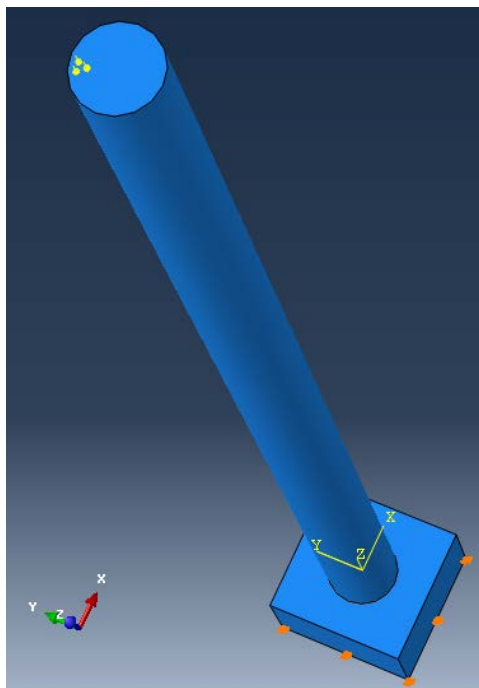
### 4.1 INTRODUCTION

This chapter describes a numerical study on stress wave propagation in steel anchor rods. A modeling and simulation approach was explored as a potential tool for conducting parametric studies to refine the test approach. The model development increased in complexity, beginning with plain isolated rods, and extending to rods embedded in concrete and including hardware such as the nuts and the anchor plate as well as the surrounding concrete. The finite element (FE) analysis software Abaqus (19) was used for the analyses.

### 4.2 FINITE ELEMENT MODELS

#### 4.2.1 Isolated Rod Simulations

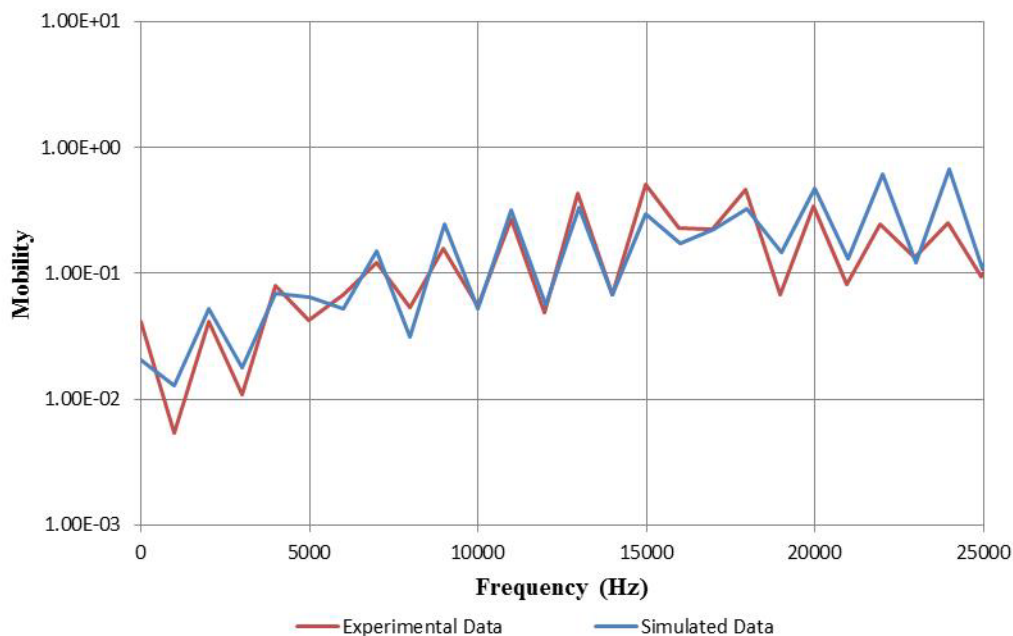
The initial modeling effort focused on impulse response tests of an isolated rod. A solid, 45 in long, 2 in diameter unthreaded rod was modeled to match the overall dimensions of the actual rod specimens. Similar to the physical experiment, the rod was supported on a flexible foam base (Figure 24). The support material was modeled as a 4 in x 4 in x 3 in block of polystyrene, and it served as a tunable flexible foundation to control numerical noise at the boundary conditions due to the artificial concentration of reaction forces. A tie constraint was used to merge the bottom surface of the rod and the top surface of the polystyrene base.



**FIGURE 24** Finite element model of an isolated rod.

Mesh discretization was based on recommendations from previous finite element studies of impact echo testing (20). The simulations were run using an explicit Lagrangian scheme with a mesh resolution of 0.08 in and a constant time step of

0.1  $\mu$ s to satisfy the CFL stability criterion. The impact force was distributed to nine adjacent nodes located on the surface of the rod. Time-history records of surface displacement, velocity, and acceleration were produced and converted to mobility spectra for comparison with the experimental tests. Figure 25 presents the experimental and simulated mobility spectra for an isolated rod test. In general, excellent agreement was found within the frequency range of interest.

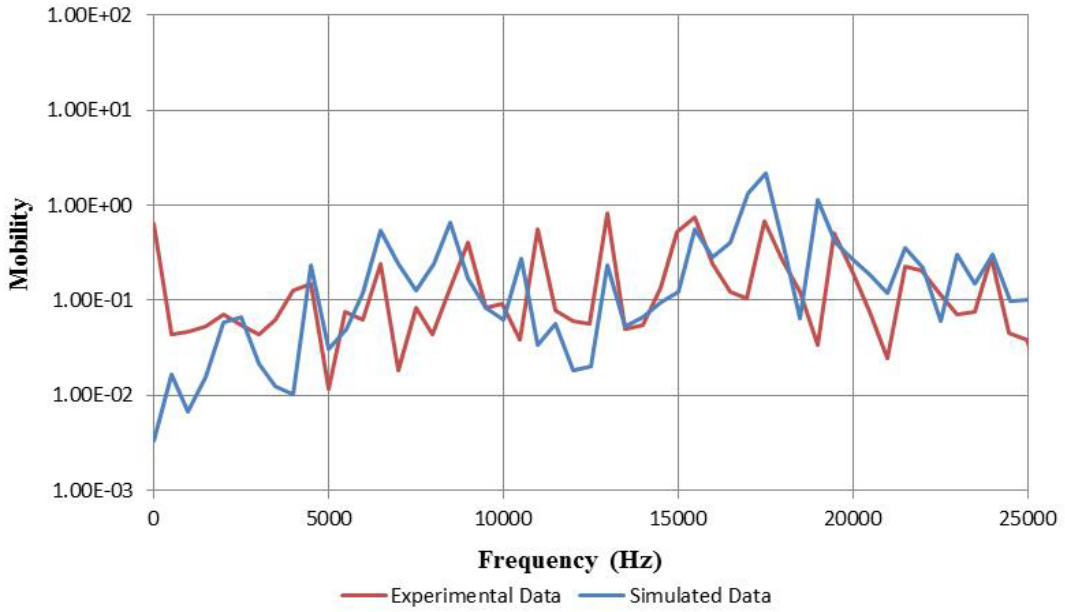


**FIGURE 25 Experimental and simulated mobility spectra for an isolated rod.**

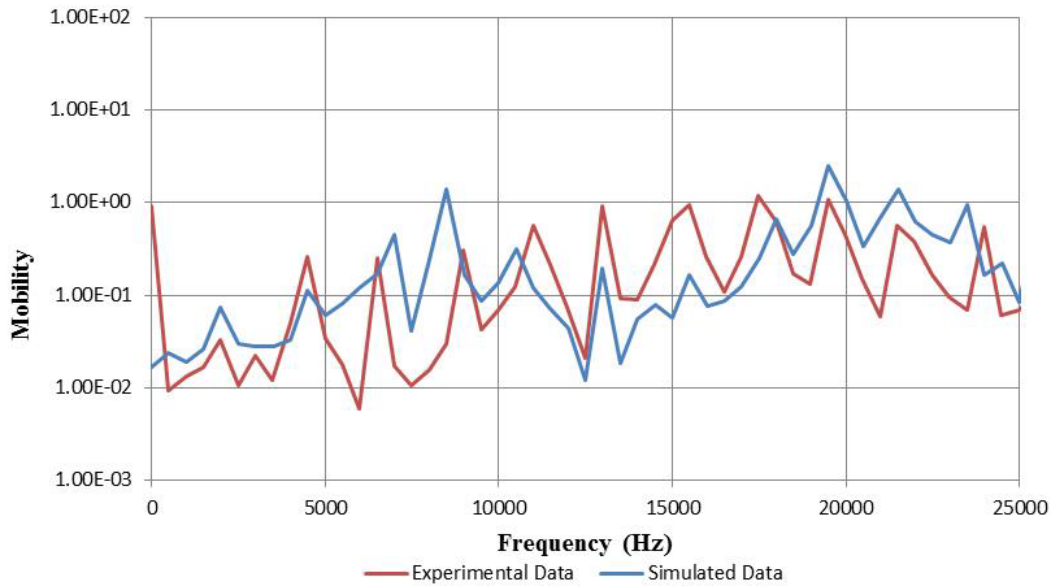
#### 4.2.2 Isolated Rod Model with Single/Double Nuts and Cracks

The isolated rod model was then extended to include single/double nuts and cracks. These simulations and companion laboratory tests were used to evaluate the ability of the finite element model to reproduce stress wave reflections from the geometric features of the assembly. The investigated cases included: (1) rod with a single nut located 8.5 in from the top of the rod; (2) rod with two nuts (tightened against each other) located at 8.5 in from the top of the rod; (3) rod with a single nut and a 0.5D crack at the base of the nut; and, (4) rod with a single nut and a 0.75D crack at the base of the nut. For simplicity, threads were excluded from the models and the nuts were fully constrained to the rods. An additional simulation was run with only the top half of the nut constrained to the rod in order to investigate the effect of partial contact.

Figures 26 and 27 compare experimental and simulated mobility spectra for models considering a single loose fitting nut and two nuts tightened against each other, respectively. In general, the use of an idealized perfectly constrained boundary along the rod-nut interface in the model poorly approximates the thread engagement in the physical connection. As



**FIGURE 26** Experimental and simulated mobility spectra for an isolated rod with a loose fitting nut.

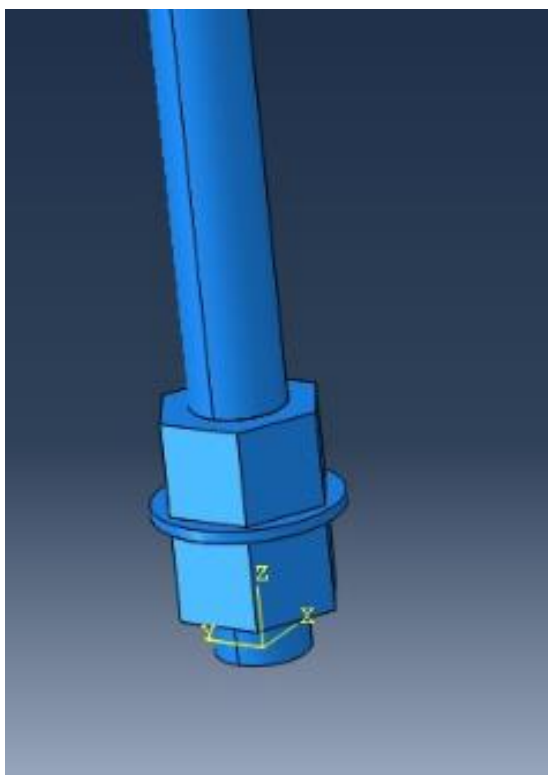


**FIGURE 27** Experimental and simulated mobility spectra for an isolated rod with two nuts tightened against each other.

expected, the modeling approach provides marginally better results for the case with two nuts tightened against each other since the threads are subject to greater contact forces.

### 4.2.3 Embedded Rod Model

An embedded rod model was developed to study the influence of the concrete encasement. This model included an embedded anchorage detail with two heavy hex nuts and a partial model of the embedded anchorage plate (Figure 28), dimensioned to match the structure-foundation anchorage assembly described in Chapter 3. The concrete encasement was modeled with a cylindrical region, which was tied to the outer surface of the anchor rod (Figure 29). A comparison of experimental and simulated mobility spectra is provided in Figure 30. The model effectively captures the diffusive damping of the composite system (smoother distribution) and reasonably replicates the frequency content.



**FIGURE 28** Anchorage detail of embedded rod with nuts for the embedded rod model (concrete omitted from the image).



FIGURE 29 Finite element model of the embedded rod assembly.

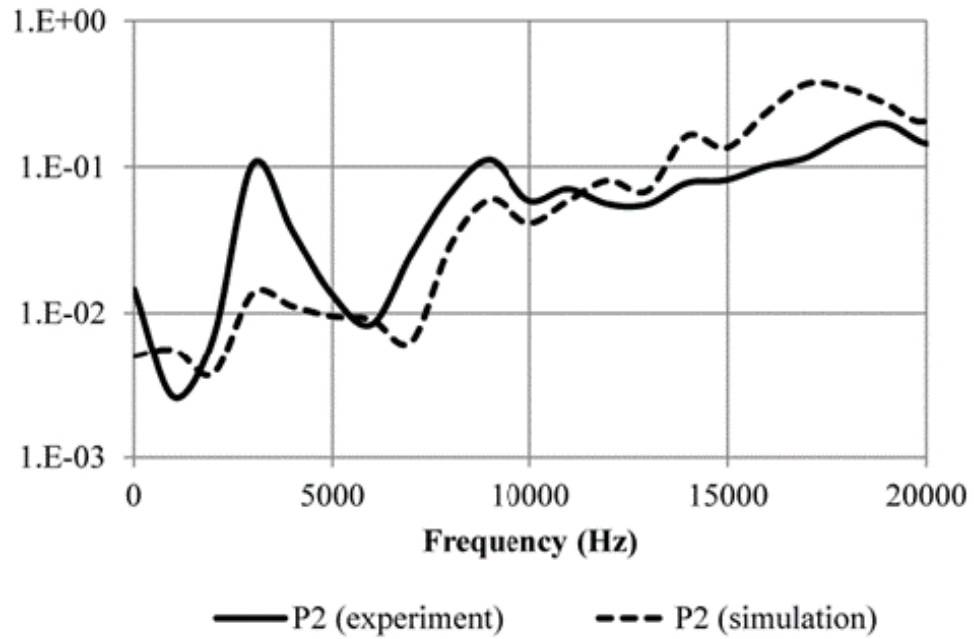


FIGURE 30 Experimental and simulated mobility spectra for an embedded rod

## CHAPTER 5 – SUMMARY AND CONCLUSIONS

### 5.1 SUMMARY

The objective of the research described in this report was to develop a nondestructive test procedure for detection of fatigue cracks in steel anchor rods. The objective addresses the research need identified in the NCHRP IDEA Highway Program announcement for *advanced diagnostic technologies to enhance early detection of deterioration*, listed under the *Maintenance and Renewal of Service Life* research category.

A large-scale structure-foundation anchorage assembly was constructed as a test specimen for the study. Stress wave interrogation measurements were taken for uncracked rods and rods with artificial fatigue cracks. Additional tests were performed on isolated rods with and without anchorage hardware. Experimental data sets from these laboratory tests were used to identify potential damage features for crack identification, and to evaluate the repeatability and reliability of the proposed test approach. The testing also provided insight into the effect of construction conditions, e.g. anchor rod-base plate contact, on stress wave propagation.

The experimental program also provided benchmark data for validating numerical finite element simulations of anchor rod impulse response testing. These numerical models were explored as a means to expand the scope of the experimental study to evaluate a wider range of construction details and crack conditions. While simulations of isolated rods showed good agreement with experimental results, accurately capturing reflections near the threaded nut-rod interface will require further improvement.

Finally, as a part of this research, a survey was distributed to state DOT agencies in order to obtain information regarding nationwide experience with anchor rod fatigue cracking, and to identify potential end users for the developed technology. Feedback received to date from the survey indicates that anchor rod cracking is a pervasive issue, with over half of the reporting agencies that conduct anchor rod inspection indicating previous experience or ongoing issues with anchor rod cracking/failure.

### 5.2 CONCLUSIONS

The following conclusions are made from this study:

1. From the experimental program it was found that by establishing a baseline measurement for an uncracked rod, and evaluating the change in Mahalanobis distance between the alpha coefficients of regression models fitting the test data, the test method was able to identify artificial cracks at the base of the leveling nut (a region known to be susceptible to fatigue cracking), extending 1/4 and 1/2 of the rod diameter in depth, with at least 95% confidence.



2. Repeatability of the test approach was influenced by inconsistent transducer-to-rod coupling conditions. Mechanical fastening of the accelerometer to the rod was shown to greatly improve test repeatability compared to grease-coupling. It is believed that a similar coupling condition can be achieved through a more practical means in the prototype testing device by spring loaded or magnetic attachment.
3. Repeatability of the test approach was also influenced by inconsistent stress wave input from impact. Use of an instrumented impact source allowed for verification of the impact signal during testing.
4. The final simulation model for the isolated rod configuration was successful in reliably producing simulation results that agree with experimental data. However, there remained a fair amount of discrepancy between experimental and simulation results for the embedded rod model.

## **CHAPTER 6 - FUTURE WORK**

### **6.1 INTRODUCTION**

This chapter describes future work. This includes the identification of potential barriers / research needs for practical implementation of the proposed method that may allow this technology to move more easily into practice as part of routine inspection programs.

### **6.2 POTENTIAL BARRIERS / RESEARCH NEEDS**

Potential barriers for implementation of the proposed method, and research needs to be addressed to overcome those barriers, are discussed below.

1. As noted earlier, it was found that the method developed in this report was able to identify artificial cracks at the base of the leveling nut extending  $1/4$  and  $1/2$  of the rod diameter in depth, with at least 95% confidence. The artificial cracks were created using a saw cut, and are likely larger in gap dimension than a real fatigue crack. Further, in field applications, the anchor rod is exposed to environmental conditions that may promote the accumulation of moisture, debris and / or corrosion on the cracked surface. These field conditions may impact the strength of the reflected signal from the crack. Additional research is needed to explore the impact of such environmental factors on the ability to make successful measurements on real fatigue cracks.
2. Also as noted earlier, the influence of inconsistent transducer-to-rod coupling was found to be the most important factor impacting the repeatability of results. Transducer coupling may be further complicated in actual field conditions due to corrosion and debris, though simple cleaning with a wire brush will likely adequately prepare the top surface of the test rod. It is thought that an improved coupling condition can be achieved through a more practical means in a prototype device by spring loaded or magnetic attachment. Additional research is needed to further develop a repeatable and reliable method of transducer coupling in actual field conditions.
3. Repeatability of the test approach was also influenced by inconsistent stress wave input from impact. Again, actual field conditions such as corrosion and debris may further complicate the ability to generate reliable impact in actual field conditions. Future work to develop a prototype instrument should consider the use of a more inherently repeatable impact source such as an instrumented spring-loaded impactor similar to those used for hardness testing of metals.
4. Once an integrated prototype test device is constructed, presumably with improved reliability in both impact source and transducer coupling, additional testing should be performed to seek improved crack detection (e.g. crack sizes smaller than  $0.25D$ ). This may be particularly useful since, as noted earlier, fatigue cracks can spend long periods of time as a small fraction of the anchor rod diameter and then rapidly propagate to failure.

### 6.3 VISION FOR PRACTICAL IMPLEMENTATION

The objective of this study was to investigate stress wave interrogation for fatigue crack detection in steel anchor rods in order to develop an efficient and reliable test method that would improve routine inspection of auxiliary highway structure anchorages. Similar to the experimental tests presented in this report, the method would be implemented by measuring the variation in response features from a known baseline (uncracked) condition. It is important to note that the objective of the test, as it is envisioned for routine inspection, would be crack detection and not crack location or measurement. This greatly simplifies signal processing and data interpretation, and therefore relaxes operator skill level requirements for successful implementation. Once an indication of a crack is obtained, the decision can be made to follow up with a more detailed UT inspection, which could provide additional information about crack depth and positioning.

The envisioned prototype instrument would integrate impact and receiver functionality into a single device. This compact design would be essential given that the area accessible at the top of a rod for testing is relatively small, and would greatly improve test efficiency compared to setups involving multiple impact – receiver installations. The impact can likely be implemented with high repeatability using a spring-loaded device, but solenoid driven impactors should also be investigated. The ability to perform multiple tests during a single installation with varied impact locations would greatly improve crack detection capability, especially for cracks that are a small fraction of the rod diameter.

As noted in this report, one of the biggest challenges during laboratory testing was transducer coupling. Mechanically fastening the accelerometer to the rod by drilling and tapping holes in the rod surface greatly improved test repeatability compared to grease coupling, but this approach is impractical for field testing. However, a similar coupling condition can be achieved through other means, e.g. spring loading or magnetic attachment. Examples exist in practice for the successful coupling of receiving transducers in other commercially available nondestructive test equipment (e.g. impact-echo). The prototype instrument should incorporate on-board data processing and storage, and wireless data transmission would greatly improve the portability of the setup. The on-board data processing would include the ability to compare results with a database of baseline measurements to look for crack indications while still in the field.

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## APPENDIX

**ATLSS Research Center**  
Lehigh University  
www.atlss.lehigh.edu

**National Cooperative Highway Research Program (NCHRP)**  
**Highway IDEA Project 175**

**DOT QUESTIONNAIRE**

(Please email the completed form to [wjk207@lehigh.edu](mailto:wjk207@lehigh.edu))

1. Has your agency experienced issues with anchor rod cracking in auxiliary highway structures?

YES \_\_\_\_

NO \_\_\_\_

If NO, please skip to Question 2. If YES,

1.1 What was the structure type?

overhead sign support structure \_\_\_\_

cantilevered sign support structure \_\_\_\_

signal structure \_\_\_\_

luminaire structure \_\_\_\_

1.2 If possible, please identify an individual or office that we could contact to obtain additional information.

1.3 Would your agency consider allowing us to try a field-deployment of the test method?

2. Does your agency inspect for anchor rod cracking in sign, signal or luminaire structures as part of regularly-scheduled inspection activities?

YES \_\_\_\_

NO \_\_\_\_

If YES,

2.1 What is the frequency of inspection?

2.2 What inspection method(s) are used (e.g. visual inspection, ultrasonic testing, other)?

1 of 1

**FIGURE A.1 Survey of state DOTs and Highway agencies.**

TABLE A.1 Contact list for state DOT and Highway agencies survey.

Alabama Department of Transportation (ALDOT) Mr. John Black, State Bridge Engineer	Nebraska Department of Roads (NDR) Mr. Mark Traynowicz, Division Manager, Bridge Division
Alaska Department of Transportation (AKDOT) Mr. Richard Pratt, Chief Bridge Engineer	Nevada Department of Transportation (NDOT) Mr. Mark EliceGUI, Chief Structures Engineer
Arizona Department of Transportation (ADOT) Dr. Jean Nehme, State Bridge Engineer	New Hampshire Department of Transportation (NHDOT) Mr. Mark Richardson, Administrator, Bureau of Bridge Design
Arkansas State Highway and Transportation Department (AHTD) Mr. Carl Fuselier, Division Head, Bridge Division	New Jersey Department of Transportation (NJDOT) Mr. Nagnath Kasbekar, Director, Bridge Engr & Infrastructure Management
California Department of Transportation (Caltrans) Mr. Barton Newton, State Bridge Engineer Deputy Division Chief	New Mexico Department of Transportation (NMDOT) Mr. Raymond Trujillo, Bureau Chief, Bridge Design Bureau
Colorado Department of Transportation (CDOT) Mr. Joshua Lipply, State Bridge Engineer	New York State Department of Transportation (NYSDOT) Mr. Richard Marchione, Deputy Chief Engineer, Structures
Connecticut Department of Transportation (ConnDOT) Mr. Scott Hill, Manager of Bridges and Facilities	North Carolina Department of Transportation (NCDOT) Mr. Gregory Peretti, State Bridge Design Engineer
Delaware Department of Transportation (DelDOT) Mr. Barry Benton, Supervising Bridge Engineer	North Dakota Department of Transportation (NDDOT) Mr. Terrence Udland, State Bridge Engineer
Florida Department of Transportation (FDOT) Mr. Sam Fallaha, Assistant Sate Structures Design Engineer	Ohio Department of Transportation (ODOT) Mr. Timothy Keller, State Bridge Engineer
Georgia Department of Transportation (GDOT) Mr. Paul Liles, Assistant Director of Bridges and Structures	Oklahoma Department of Transportation (ODOT) Mr. Robert Rusch, State Bridge Engineer
Hawaii Department of Transportation (HDOT) Mr. Paul Santo, Engineer, Materials Testing and Research Branch	Oregon Department of Transportation (ODOT) Mr. Bruce Johnson, State Bridge Engineer
Idaho Transportation Department (ITD) Mr. Matthew Farrar, State Bridge Engineer	Pennsylvania Department of Transportation (PennDOT) Mr. Thomas Macioce, Division Chief, Bridge Design and Technology Division
Illinois Department of Transportation (IDOT) Mr. Carl Puzey, Bureau Chief, Bridges and Structures	Rhode Island Department of Transportation (RIDOT) Mr. David Fish, Managing Engineer, Bridge Design
Indiana Department of Transportation (INDOT) Ms. Anne Rearick, Director of Bridges	South Carolina Department of Transportation (SCDOT) Mr. Barry Bowers, Structures Division
Iowa Department of Transportation (Iowa DOT) Mr. Norman McDonald, Bridge Engineer	South Dakota Department of Transportation (SDDOT) Mr. Kevin Goeden, Chief Bridge Engineer
Kansas Department of Transportation (KDOT) Mr. Loren Risch, Bureau Chief, Bureau of Structures and Geotechnical Services	Tennessee Department of Transportation (TDOT) Mr. Wayne Seger, Director of Structures Division
Kentucky Transportation Cabinet (KYTC) Mr. Marvin Wolfe, Transportation Engineer Specialist, Division of Structural Design	Texas Department of Transportation (TxDOT) Mr. Greg Freeby, Bridge Division Director
Louisiana Department of Transportation & Development (LaDOTD) Mr. Paul Fossier, Assistant Bridge Design Administrator	Utah Department of Transportation (UDOT) Ms. Carmen Swanwick, Chief Structural Engineer
Maine Department of Transportation (MaineDOT) Mr. Wayne Frankhauser, Assistant Bridge Program Manager	Vermont Agency of Transportation (VTrans) Mr. Wayne Symonds, Structures Design Engineer
Maryland Department of Transportation State Highway Administration (SHA) Mr. Earle Freedman, Director, Office of Structures	Virginia Department of Transportation (VDOT) Mr. Kendal Walus, State Structure and Bridge Engineer
Massachusetts Department of Transportation (MassDOT) Mr. Alexander Bardow, Director of Bridges and Structures	Washington State Department of Transportation (WSDOT) Mr. Thomas Baker, State Materials Engineer
Michigan Department of Transportation (MDOT) Mr. Matthew Chynoweth, Engineer of Bridge Field Services	West Virginia Department of Transportation (WVDOT) Mr. Gregory Bailey, Director, Engineering Division
Minnesota Department of Transportation (MnDOT) Ms. Nancy Daubenberger, State Bridge Engineer	Wisconsin Department of Transportation (WisDOT) Mr. Scot Becker, State Bridge Engineer
Mississippi Department of Transportation (MDOT) Mr. Nick Altobelli, Director of Structures, State Bridge Engineer	Wyoming Department of Transportation (WYDOT) Mr. Gregg Fredrick, Assistant Chief Engineer of Engineering and Planning
Missouri Department of Transportation (MoDOT) Mr. Dennis Heckman, State Bridge Engineer	District of Columbia Department of Transportation (DDOT) Mr. Ronaldo Nicholson, Deputy Director/Chief Engineer
Montana Department of Transportation (MDT) Mr. Kent Barnes, Bureau Chief, Bridge Engineering Division	