University Transportation Research Center - Region 2

Final Report

Corrosion Damage Assessment of Post-Tensioned Concrete Structures

Performing Organization: University at Buffalo/SUNY

March 2013

Sponsor:
University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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16. Abstract

Detecting corrosion in the tendons of post-tensioned (PT) concrete structures is technically challenging. The general inaccessibility of the tendons makes evaluation difficult, costly and often inconclusive.

This study had two objectives. The first objective was to design, implement and validate the use of an innovative monitoring system based on embedded arrays of low profile piezoelectric transducers to generate and receive guided ultrasonic waves (GUW) over the length of a pre-stressing tendon. The second objective was to develop a new signal processing technique based on fractal theory, to enable the monitoring of the corrosion progression. To accomplish the objectives of the study, accelerated corrosion tests were carried out on two seven wire steel strands embedded in two concrete blocks.

Signal generation and data acquisition were achieved with a National Instruments (NI), modular PXI unit. This unit included an arbitrary waveform generator card and one, multi-channel digitizers. In addition, a high voltage amplifier was used to amplify the excitation to the ultrasonic transmitters. Toneburst signals, consisting of 3.5 cycles, were excited by sweeping the generation frequency from 50 kHz to 400 kHz. LabVIEW software developed at the University at Buffalo (UB) was used to control the sensors, acquire and process the data. A box counting algorithm was used to calculate the fractal dimension (FD) of the GUW signals. The changes in FD as a function of time at the anchorages and inside the beam were analyzed. The following corrosion stages were observed at the anchorages: 1) an initial stage in which the FD shown no significant change in values; 2) a second stage characterized by sharp drops, indicated that a significant change in the signal shape occurred due to the initiation of the corrosion in the strand (as corrosion progress scattering, multiple reflections and mode conversion are expected). Inside the beam two corrosion-induced damage mechanisms were observed: 1) loss of bond between strand and grout that caused an increasing FD and 2) deterioration of the strand which resulted in a decreasing FD. In addition, an outlier detection algorithm based on the fractal dimension of GUWs was developed to automatically identify the initiation of the corrosion.

Finally, the proposed approach may play an important role in decision-making processes by providing a relatively “early warning” of the corrosion process and allow the authorities for the planning and implementation of corrosion control strategies at a point where it is less expensive and invasive than when visible surface signs of corrosion have been observed. However, more theoretical investigations and formal tests need to be carried out to verify the robustness of the approach. In addition, large scale specimens should be examined.

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1. INTRODUCTION

During the last three decades, post-tensioning has progressively become the predominant choice for pre-stressed concrete construction ranging from commercial and residential buildings, bridges, parking structures to pressure vessels, tanks and containment vessels for nuclear power plants. Corrosion of the steel strands has become a concern for designers, owners and regulators. Many of these structures [1], some only ten years old, have suffered the failure of tendons due to corrosion. Extensive inspection and maintenance/repair programs have been established, with attendant direct costs and significant indirect costs due to business interruption. Detecting corrosion in the tendons of PT structures is technically challenging. The general inaccessibility of the tendons makes evaluation difficult, costly and often inconclusive [2]. Visual inspection may reveal corrosion, by cracking or spalling of concrete caused by tendon failure. However there may be no outward signs that the tendon has broken. In addition, the location at which the tendon or wire has erupted out of the structure is usually some distance away from the location of actual failure. Exploratory concrete removals combined with the removal of the broken tendon will be required to identify the location, nature, and the possible causes of the failure. Several nondestructive evaluation (NDE) techniques for evaluating the condition of PT tendons have been developed to address these issues in the past few years. Remanent magnetism and magnetic flux method has met success in detecting corrosion in prestressing steel strands ([3], [4], [5]). However, both methods have limitations for potential use in internal tendons due to difficulties with disturbing magnetic signals generated from non-prestressed reinforcement. Radiography has been effective at detecting corrosion in PT tendons but radiation safety concerns and expense have limited its use ([6], [7], [8]). Acoustic emission has been used in some cases to report the time and location of tendon rupture by detecting the sound emanating from the rupture ([9], [10], [11]). This is achieved with an array of acoustic sensors attached to the structure and connected to an on-site data-acquisition system. Although this technique can be effective, it requires continuous monitoring of the structure to provide useful information and cannot be used to identify pre-existing broken tendons. Importantly, it can only provide information on the final stage of the corrosion process (i.e., strand failure). However, it is desirable to be able to identify corrosion process at early stages to allow for the planning and implementation of control strategies at a point where it is less expensive and invasive than when visible surface signs of corrosion have been observed ([12], [13]).

Techniques based on sparse arrays of sensors, which have the capability of transmitting and receiving guided ultrasonic waves (GUWs) are among the most promising candidates for corrosion detection. As opposed to the waves used in traditional impact-echo (IE), that propagate in 3-D within the PT structure, GUWs propagate along the tendon itself by exploiting its waveguide geometry. The advantages of this technique over those mentioned above include: (1) the use of transducers permanently attached to the tendon to perform real-time structural monitoring and routine inspection with the same sensing system, and (2) the capability to detect both active and pre-existing cracks by toggling between the modes of “passive” acoustic emission testing and “active” ultrasonic testing. The ability of GUWs to locate cracks and notches has been demonstrated in several laboratory works ([14], [15], [16], [17], [18]). In this research a new approach based on fractal analysis of GUWs is presented for monitoring the corrosion evolutionary path in post-tensioned systems. Fractal analysis is a new scientific paradigm that has been used successfully in many fields including biological and physical sciences ([19], [20], [21], [22], [23], [24], [25], [26], [27], [28]) but the use of this method in GUW-based SHM systems has not been fully investigated [28].

2. FRACTAL DIMENSION

2.1. Background

The term “Fractal” was first introduced by Mandelbrot [29] to indicate objects whose complex geometry cannot be characterized by an integer dimension. A classical example to illustrate this technique is the ‘‘length” of a coastline [30]. When measured at a given spatial scale *d*, the total length of a crooked coastline *L*(*d*) is estimated as a set of *N* straight line segments of length *d*. Because small details of the coastline not recognized at lower spatial resolutions become apparent at higher spatial resolutions, the measured length *L*(*d*) increases as the scale of measurement d increases. Therefore, in fractal geometry the Euclidean concept of “length” becomes a process rather than an event, and this process is controlled by a constant parameter called fractal dimension (FD). The FD can be a non-integer number varying depending on the complexity of an object. For example, the FD for a curve will lie between 1 and 2, depending on how much area it fills [31]. Similarly, the FD of surfaces lies between 2 and 3 depending on the roughness of surface [32]. The complexity of two curves or two surfaces can then be easily compared, as the values of FD are not anymore restricted to the topological dimensions of 1 and 2. Several algorithms have been proposed for the calculation of the FD, including the box-counting algorithm, Hurst R/S analysis, fractional Brownian motion, and the power spectrum method ([33], [34], [35]). Among them, the box-counting algorithm is the most popular [28].

2.2. Box-counting algorithm

The box counting method is motivated by the approach of considering the space filling properties of the curve as an indication of its complexity. In general in the box counting method, a data set (e.g., a curve) is covered with a collection of equal-sized boxes, and the number of elements of a given size *r* is counted to see how many of them are necessary to completely cover the curve. As the size of the area element approaches zero, the total area covered by the area elements will converge to the measure of the fractal dimension ([36], [37], [32], [38], [39], [40]). This can be expressed mathematically as:

$$D = \lim_{r \to 0} \left(\frac{\log N(r)}{\log(1/r)} \right) \tag{1}$$

where $N(r)$ is the number of boxes of size *r* required to completely cover the curve and *D* is the fractal dimension of the curve. In practice, *D* is estimated by fitting a straight line to the log-log plot of *N*(*r*) versus 1/*r* over a range of box sizes. This can be expressed as:

$$\log(N(r)) = D \log\left(1/r\right) + C \tag{2}$$

where *C* is a constant. The slope of the least square fit line is taken as an estimator of the fractal dimension (*D*) of the curve. Figure 1 illustrates a typical structure of a graph of $\log\left(N\left(r\right)\right)$ vs. $\log\left(1/r\right)$ for the fractal analysis of a 2D object.

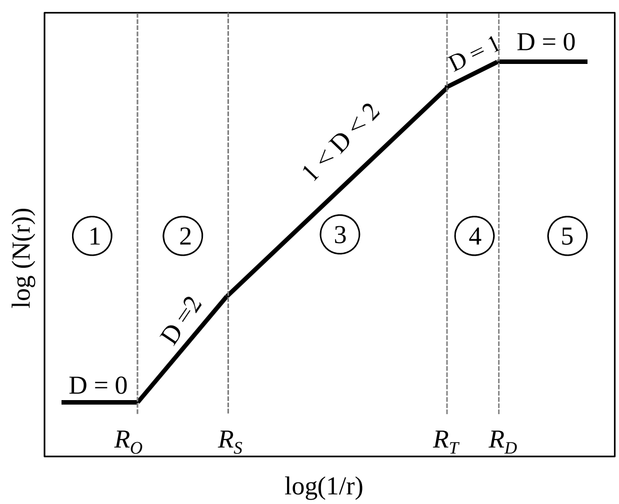


Figure 1. Variation of FD versus box sizes

Five regions can be identified: (1) if *r* is much larger than the size of the object, R_O, (i.e., the box always cover the object so *N*(*r*) =1) then *D*=0; (2) if *r* is larger than the size of structure in the object, R_S, (e.g., if *r* is large that it covers the whole area enclosed by the signal, then the boxes required to cover the signal will fill the whole surface) thus D=2 as for an area; region (3) is the region from which the box sizes should be selected to give the best estimation of fractal dimension; (4) in this region the transition from the Fractal to Euclidean regime occurs; (5) finally if *r* is smaller than the discretization size, R_D (e.g., sampling frequency) *D*=0 because it will be measuring the dimension of a point.

2.3. Fractal Dimension of Guided Ultrasonic Waves

In general, the ''boxes'' used to cover the data set are often squares to cover 2-D data sets, or cubes to cover 3-D data sets. However, time signals, including GUWs exist in the affine space where the axes have incompatible units, and there is no natural scaling between them; as a result distance along the time axis cannot be compared with distance along the amplitude axis and the classical box counting method with square boxes will lead to a fractal dimension of zero (i.e., the dimension of a point) [28]. To overcome this limitation, different solutions have been proposed in the past ([39], [40]). In this research, a box-counting method based on rectangular boxes has been used. In general, a grid of rectangular boxes is superimposed over a signal (e.g., GUW). Next the number of boxes that intersect the signal, *N*(*r*), is counted. The method is repeated with a denser and denser grid to define the number of boxes as a function of the grid spacing, *r*. Therefore, the estimated *D* is the slope of least square fit line in the log-log plot of *N(r)* versus *1/r*. This procedure is illustrated in Figure 2. The width (t_i) and height (h_i) of the rectangular boxes can be defined as follows:

$$t_i = \frac{t_{\max}}{N_i} \quad (3)$$

$$A_i = \frac{A_{\max,b} - A_{\min,b}}{N_i} \quad (4)$$

where, $t_{\max}$ is the duration of the signal, $A_{\max,b}$ and $A_{\min,b}$ are the maximum and minimum amplitude of the signal, respectively and N_i is a set of integers. The box sizes are determined so that the smallest size is not less than the sampling rate. The same number of divisions is used for both time and amplitude axes for the ease of computation by maintaining an integer number of boxes in both directions.

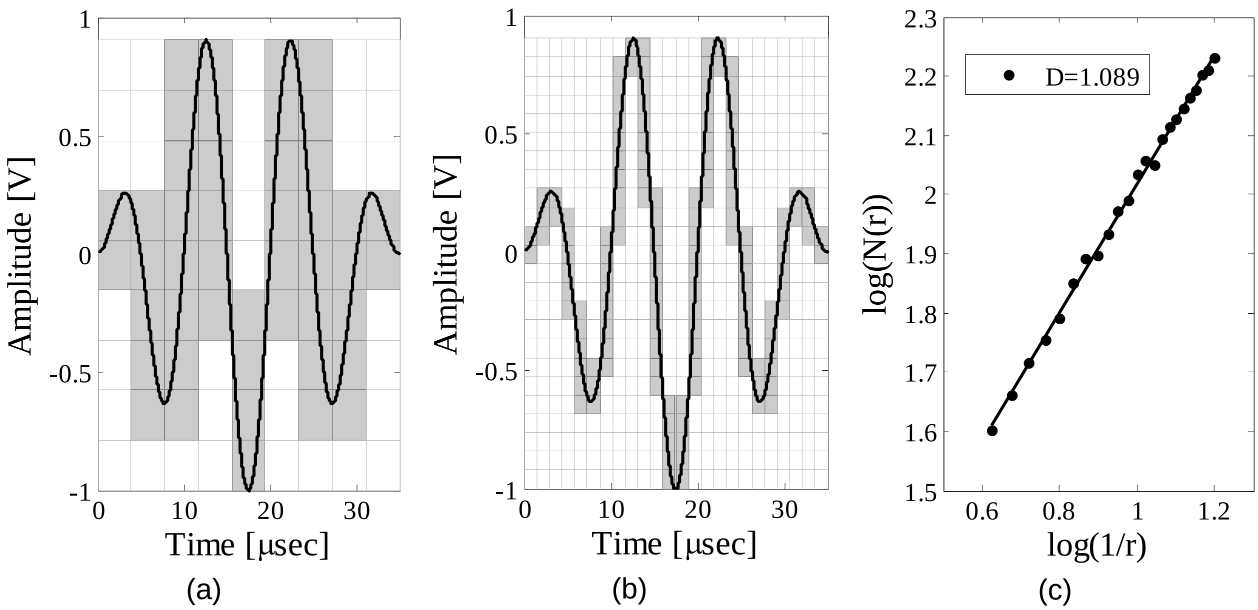


Figure 2. Fractal dimension procedure

3. EXPERIMENTAL STUDY

Experimental tests were performed on two seven wire steel strands embedded in two 152 mm (6 in) × 152 mm (6 in) × 400 mm (15.7 in) concrete blocks (Figure 3).

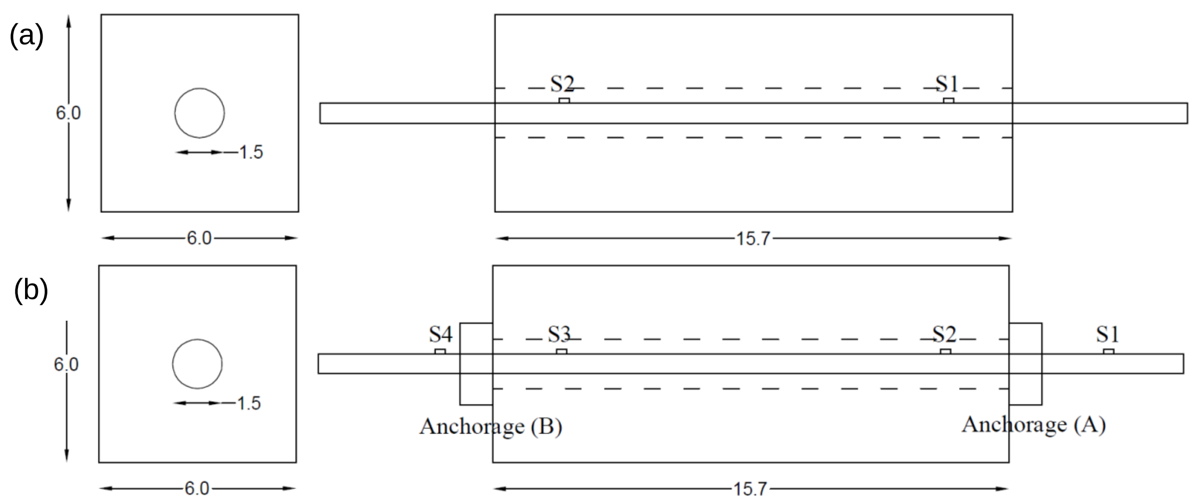


Figure 3. Sensors layout: (a) control beam, and (b) post tensioned beam

The concrete compressive strength was 35 MPa (5000 psi) after 28 days. After the concrete cured, one of the strands was post-tensioned and grout was injected into the beam. Once the grout gained strength, the strand is now bonded to the concrete block (i.e., PT beam). The second strand was left unstressed to provide a control beam (i.e., reference beam) for comparing the corrosion propagation in the post-tensioned beam. Sand was used to fill the core of the control beam for allowing the extraction and visual inspetion of the strand during the corrosion process.

3.1. Experimental setup

The control beam was instrumented with two, 10 mm x 3 mm piezoelectric (PZT) transducers (APC International), in a through-transmission configuration. The PZT transducers were placed on a peripheral wire (see Figure 3a). The PT beam was instrumented with four PZT transducers placed on the same peripheral wire; two transducers were embedded inside the beam (i.e., S2 and S3) whereas the other two were placed outside the concrete beam (i.e., S1 and S4) as shown in Figure 3b. In the PT beam, three different sensor-actuator paths were investigated: 1) S1-S2 for monitoring the corrosion at the anchorage (A), 2) S4-S3 for monitoring the corrosion at the anchorage (B) and 3) S2-S3 for monitoring the corrosion of the steel strand inside the beam. Signal generation and data acquisition were achieved with a National Instruments (NI), modular PXI 1042 unit. This unit included an arbitrary waveform generator card (PXI 5411) and one, 20GS/s 12-bit multi-channel digitizers (PXI 5105). In addition, a high voltage amplifier was used to amplify the excitation to the ultrasonic transmitters. Toneburst signals, consisting of 3.5 cycles, were excited by sweeping the generation frequency from 50 kHz to 400 kHz. LabVIEW software developed at the University at Buffalo (UB) was used to control the sensors, acquire and process the data.

3.2. Accelerated corrosion tests

Accelerated corrosion tests were carried out using the impressed current method. A direct current was applied to the strand using an integrated system incorporating a small rectifier power supply with an inbuilt ammeter to monitor the current, and a potentiometer to control the current intensity. The concrete beam suffit was immersed in a 5% sodium chloride (NaCl) solution serving as the electrolyte needed in the impressed current method and the direction of the current was arranged so that the strand served as the anode while a steel bar counter electrode was positioned in the tank to act as a cathode. This setup ensured a uniform distribution of the current along the whole length of the strand. Figure 4 shows the accelerated corrosion test setup for the PT beam. The test was kept running for 55 days, the data was recorded daily and the visual monitoring of the anchorages was performed.

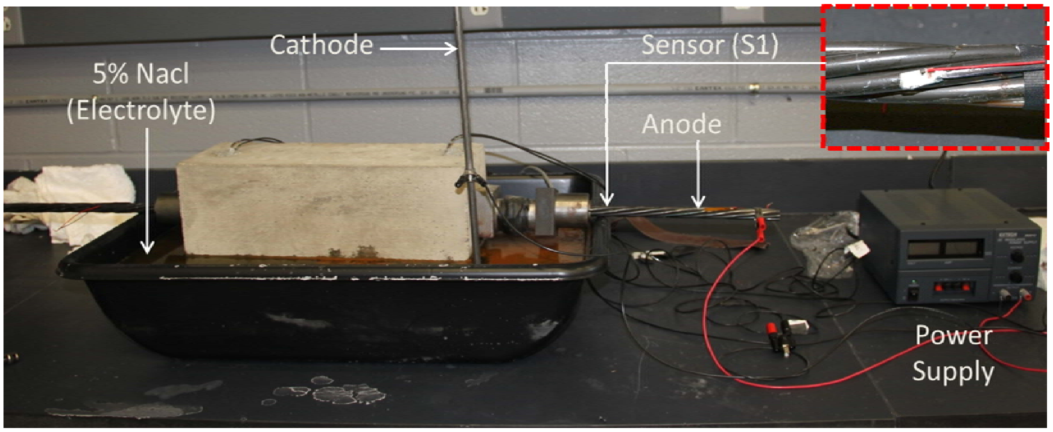


Figure 4. Accelerated corrosion test setup

4. EXPERIMENTAL RESULTS

This section presents the results of the fractal dimension of GUWs for monitoring the corrosion-induced damage in post-tensioned concrete beams. First the results obtained from the control beam are presented in order to show the FD variations for different "known" stages of corrosion. Next the results of the PT beam are presented.

4.1. Control beam results

The proposed monitor system utilizes distributed actuators/sensors permanently attached to the strand, to generate elastic waves and measure the arriving waves at sensors. When a single actuator/sensor path is considered, the corrosion monitoring is performed through the examination of the FD of the arriving waves in comparison with a "baseline" condition (i.e., healthy strand). In fact, since the FD is a measure of the complexity of the signal, it may contain fundamental information related to the corrosion process. Figure 5 shows the strand before the accelerated corrosion test (i.e., pristine condition) and for three increasing levels of corrosion. In Figure 5(d), a significant loss of strand cross-sectional area (about 50%) can be observed and is caused by localized corrosion (i.e., pitting corrosion).

Before the accelerated corrosion test the FD of the wave packet (containing only the first arrival) for the pristine condition (i.e. baseline), was calculated using the approach described in section 2. Next, the same grids of rectangular boxes used to calculate the FD of the baseline signals were used for computing the FD of GUWs recorded during the corrosion test (i.e., current signals).

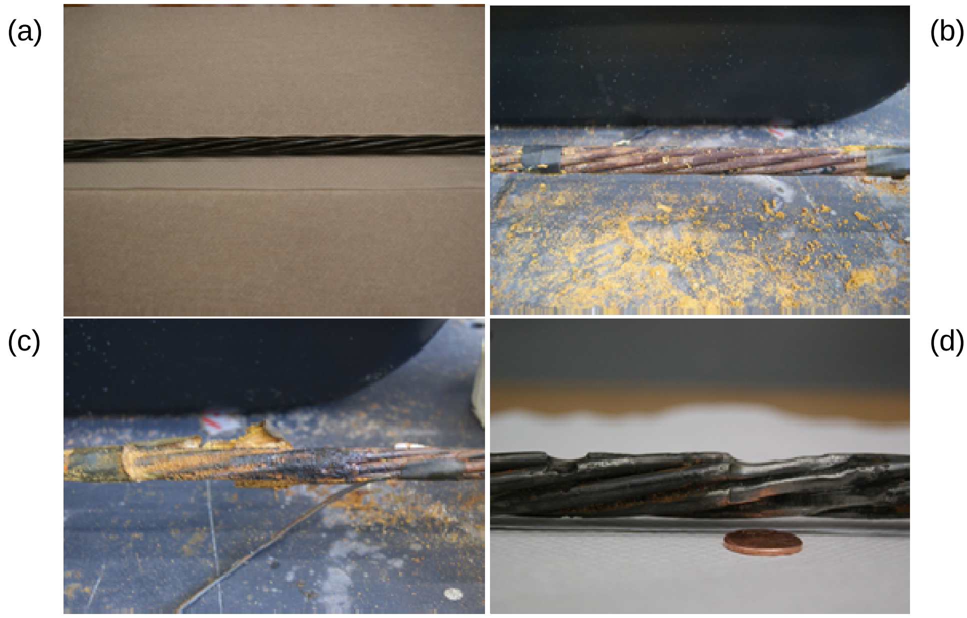


Figure 5. Corrosion stages: a) pristine case, b) corrosion stage 1, c) corrosion stage 2, and d) corrosion stage 3

Figure 6 shows the FD of signals recorded at the four corrosion stages illustrated in Figure 5. In particular, Figure 6(a) illustrates the graph of *log*(*N*(*r*)) vs. *log*(*1/r)* for each stage, and in Figure 6(b) the FD is computed as the slope of each line shown in Figure 6(a). It can be observed that FD decreased with the severity of the corrosion. As a result, one may infer that GUWs signals with relatively smaller values of FD may correspond to strands with greater losses of mass. It should be mentioned that the deterioration of the strand (i.e., local loss of material) led to attenuation of the signal. Therefore, the FD is capable to capture this information (i.e., signal attenuation).

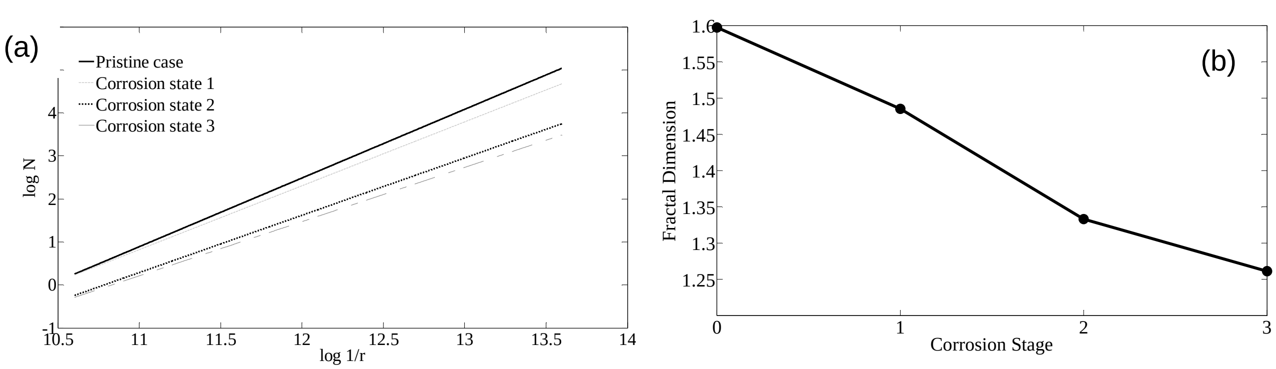
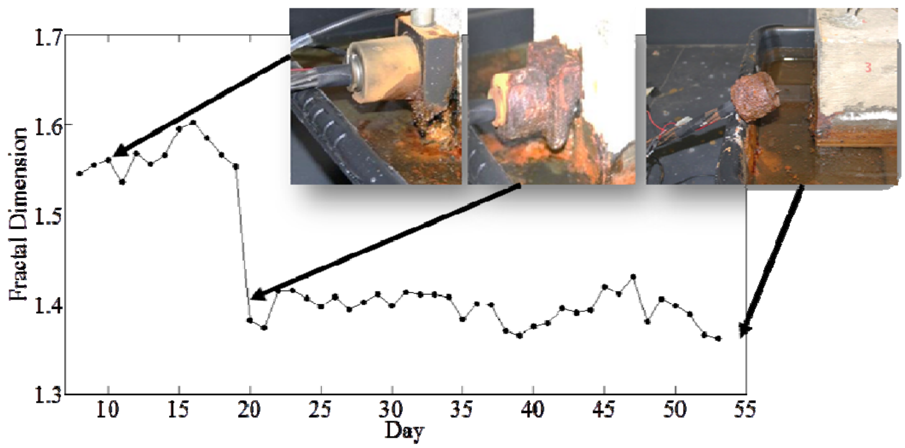


Figure 6. Results of the FD: (a) FD for the pristine and 'corroded' cases and (b) the change of FD with the corrosion stage

4.2. Post-tensioned beam results

The changes in FD as a function of time at the anchorages and inside the beam are plotted in Figure 7 and Figure 8, respectively (i.e., S1-S2 path, S4-S3 path, and S2-S3 path). The frequency of 300 kHz was selected to generate these graphs. Also in this case, the same grids of rectangular boxes used to calculate the FD of the baseline signals were used for computing the FD of the current signals (i.e., during the progression of corrosion).

(a)



(b)

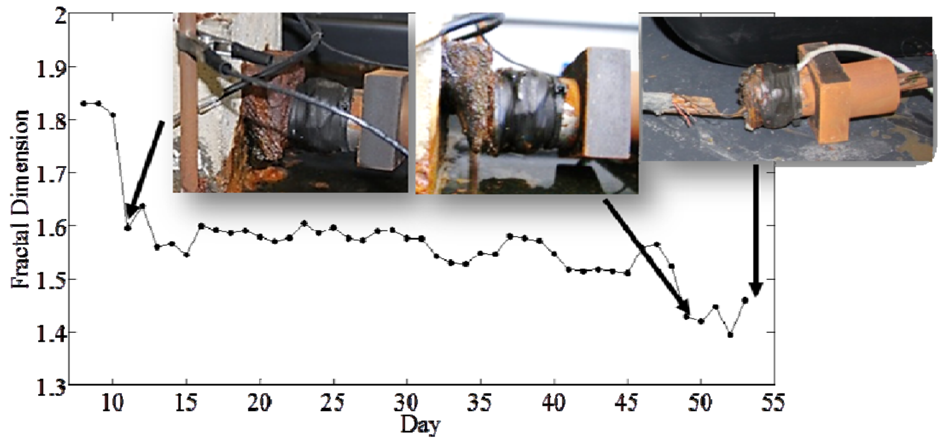


Figure 7. FD changes versus time: (a) anchorage *A*, and (b) anchorage *B*

The following observations can be made: 1) an initial stage in which the FD shows no significant change in values can be identified. The duration of this stage at the anchorage *B* was longer than at the anchorage *A*; 2) then a sudden drop occurred in day 11 for the anchorage *A* and in day 20 for the anchorage *B*; this drop mostly indicates that a significant change in the signal shape occurred due to the initiation of the corrosion in the strand (as corrosion progress scattering, multiple reflections and mode conversion are expected); this stage is characterized by a slowly decreasing trend caused by localized corrosion (i.e., pitting corrosion). Note that the corrosion rate at the anchorage *A* was higher than at the anchorage *B*; 3) next a further drop in FD occurred at the anchorage *A* in day 49 (see Figure 7a); this anchorage failed few days later (on the 53rd day).

Figure 8 shows the FD results using the actuator-sensor path "S2-S3" (i.e., embedded transducers). In general, two corrosion-induced damage mechanisms are expected inside the beam: 1) loss of bond between strand and grout as a result of corrosion products that are larger in size than the original strand and 2) deterioration of the strand (i.e., pitting corrosion) [1]. In Figure 8 it can be observed that, after an initial phase with no significant changes, the FD exhibits an increasing trend as a result of the increasing signal strength (i.e., loss of bond). After 31 days of exposure, the FD continuously dropped as a result of the decreasing signal strength (i.e., strand degradation), until the failure of the anchorages. It should be noted that corrosion rate at the anchorages is higher than inside the beam; the anchorages are part of the corrosion cell and are in direct contact with air whereas inside the beam the strand is actually protected by the high alkalinity of the surrounding grout.

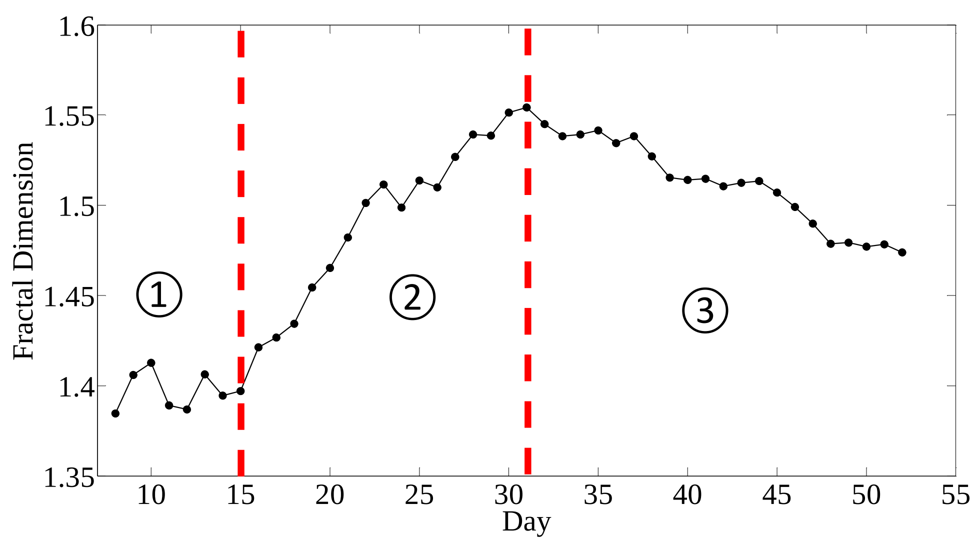


Figure 8. FD changes versus time using embedded sensors (path S2-S3)

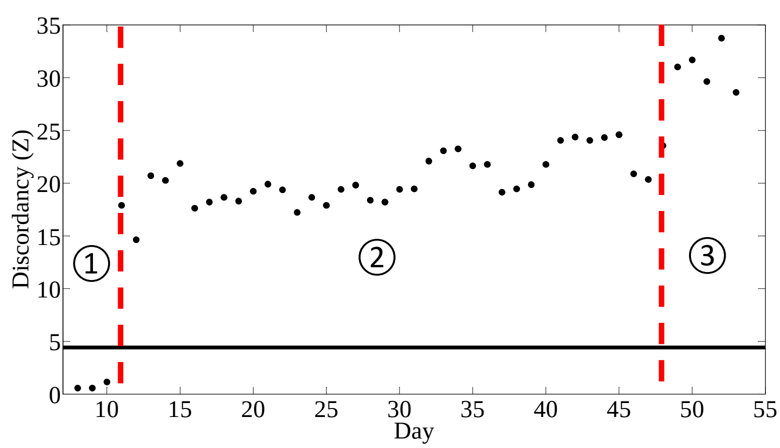
5. FRACTAL DIMENSION-BASED OUTLIER ANALYSIS

In the previous section, it was discussed that corrosion in steel strands can produce significant changes in the FD of GUWs. The next step in constructing a structural health monitoring (SHM) system is to automatically judge from measured data whether the condition of the structure has deviated from its normal operational condition, i.e., detecting the initiation of the corrosion. For this purpose, a statistical approach developed on the basis of outlier analysis is proposed. The outlier analysis has been widely used in the field of non-destructive evaluation (NDE) ([41], [42], [43], [44], [45], [46], [47], [11]). An outlier is an observation that is numerically distant from a set of baseline data. The baseline data describes the normal operating condition of the structure under investigation [11]. In the analysis of univariate data, the detection of outliers is based on the calculation of the discordancy between a single observation and the baseline statistics ([11], [40]). One of the most used discordancy tests is defined as:

$$z_{\xi} = \frac{\left| x_{\xi} - \overline{x} \right|}{s} \tag{5}$$

where x_{ξ} is the measurement corresponding to the potential outlier and $\overline{x}$ and s are the mean and standard deviation of the baseline, respectively ([11], [48]). In general, the value of z_{ζ} is compared to a defined threshold value, to determine whether x_{ζ} is an outlier (i.e., above the threshold) or not. In this work, the baseline set incorporates FD values of GUW measurements acquired at 300 *kHz* during the first week of test. For a given observation, the discordancy value z_{ζ}, calculated using Equation (5), was compared with a threshold value, in order to classify the observation as an anomaly (i.e., outlier) or normal operating conditions of the system (inlier). A Monte Carlo simulation was employed to compute the threshold. When baseline measurements are limited, a Monte Carlo simulation is an effective method for generating a large number of random data to populate the baseline distribution ([11], [49], [50]).

The results of the univariate analysis are illustrated in Figure 9. The horizontal line represents the 99% confidence threshold calculated by the Monte Carlo simulation ([49], [50]). It can be seen that all observations associated to the initiation of the corrosion are successfully classified as outliers.



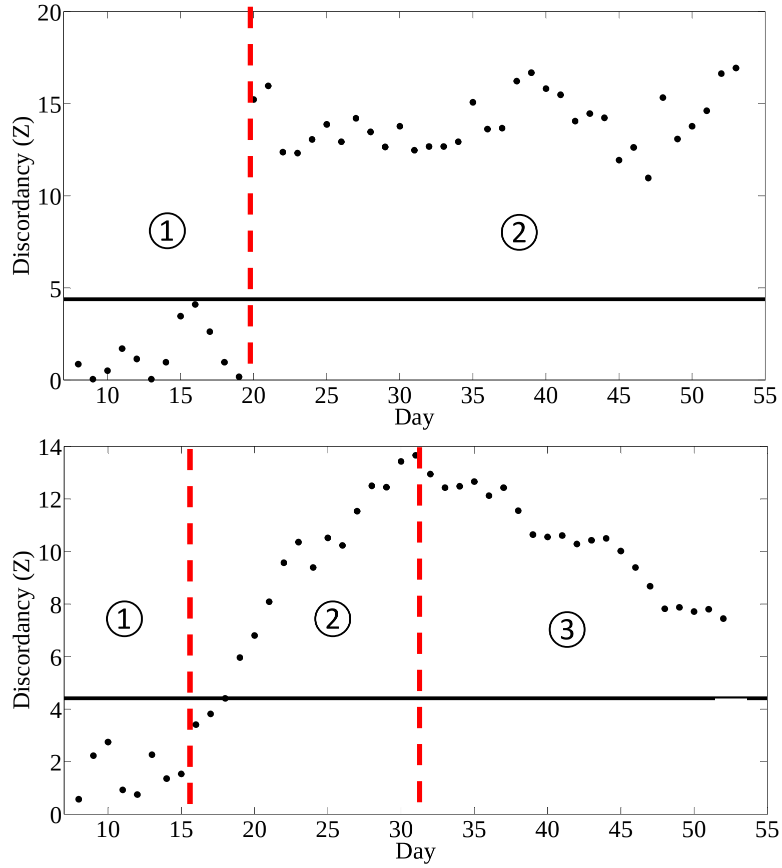


Figure 9. Univariate analysis results: (a) anchorage A, (b) anchorage B, and (c) embedded transducers

6. CONCLUSIONS

A new approach based on the fractal dimension (FD) of GUWs was proposed for monitoring the corrosion evolutionary path in complex structural systems such as post-tensioned systems. The system utilizes distributed actuators/sensors permanently attached to the strand, to generate elastic waves and measure the arriving waves at sensors. When a single actuator/sensor path is considered, the corrosion monitoring is performed through the examination of the FD of the arriving waves in comparison with a “baseline” condition (i.e., healthy strand). In fact, since the FD is a measure of the complexity of the signal, it may contain fundamental information related to the corrosion process. Accelerated corrosion tests were carried on two seven wire steel strands embedded in two concrete blocks, to validate the proposed algorithms. It was shown that the FD is capable to monitor the progression of the corrosion-induced damage in the strand. In particular a decreasing trend of the FD was observed in the anchorages as a result of the strand degradation. Inside the beam two corrosion-induced damage mechanisms were observed: 1) loss of bond between strand and grout that caused an increasing FD and 2) deterioration of the strand which resulted in a FD decreases. Moreover an outlier detection algorithm based on the fractal dimension of GUWs that was able to successfully classified as outliers all observations associated to the initiation of the corrosion was presented.

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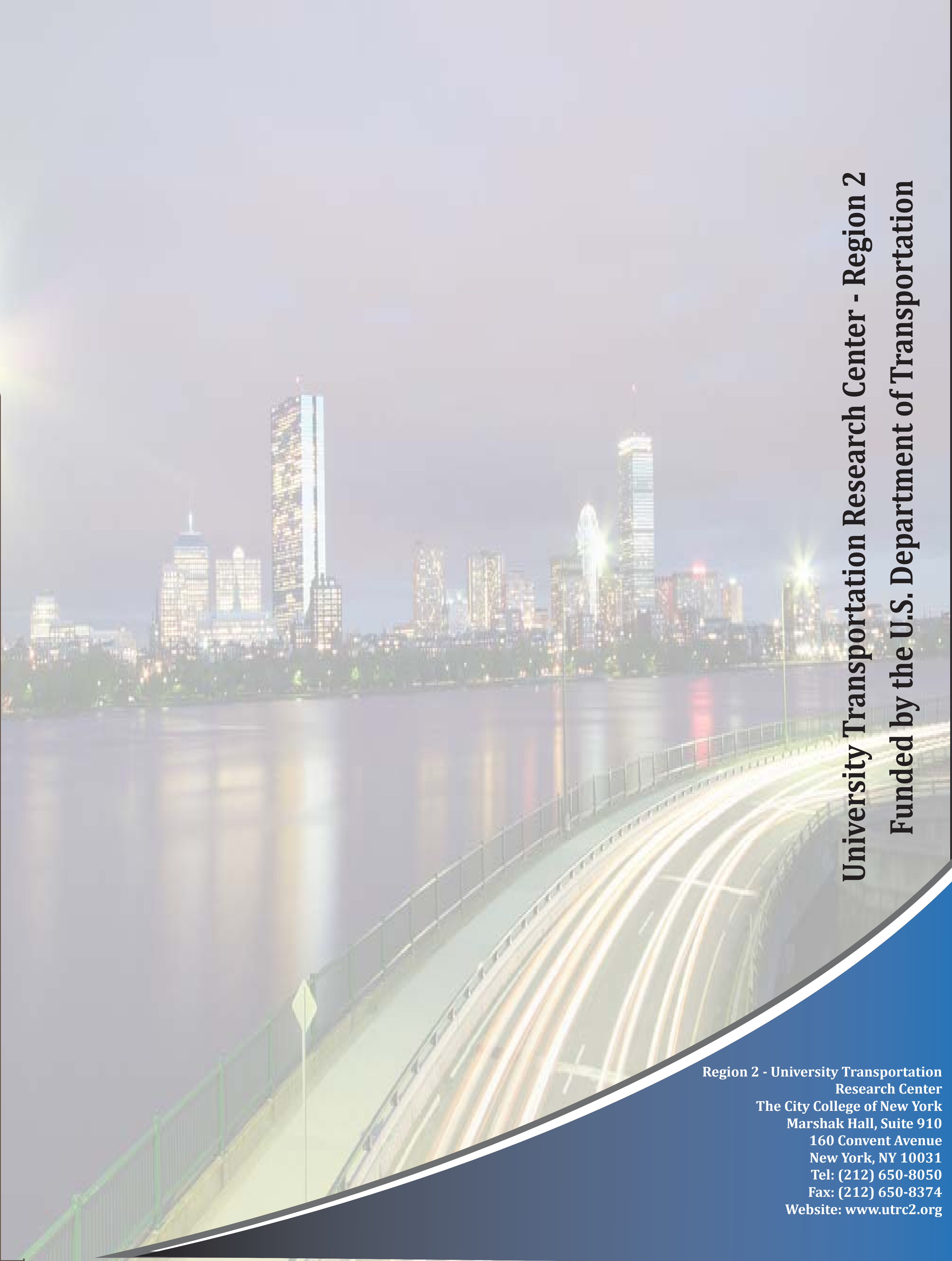

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