

Spatial Variation Analysis of Localized Corrosion of Steel Bar with Spectral Analysis Technique

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ABSTRACT

This study aims to statistically analyze the distribution characteristics of localized corrosion along the length of corroded steel bars with spectral analysis techniques. Steel bars were embedded in a concrete prism and subjected to accelerated corrosion to levels ranging from 5.0 wt.% to 30.0 wt.% mass loss. After the corrosion test, the corroded steel bars were taken out of the concrete and cleaned with a sand blaster, and then scanned with a 3D laser scanner. The scanned point clouds were processed with an image processing software to determine the residual cross-sectional area distribution. Empirical mode decomposition (EMD) was performed by considering the area distribution of the steel bars as a nonlinear and non-stationary time series and the length as time. The intrinsic mode functions (IMFs) extracted from the EMD reveal the characteristics of pitting corrosion of various sizes, and the magnitude of the IMF is related to the cross-sectional area of corrosion pits. To extract the characteristic length of pitting corrosion, the fast Fourier transform (FFT) was performed on each IMF. Results show that the EMD-FFT successfully extracts the spatial distribution characteristics of corroded steel bars including surface irregularity, deformation (ribs and lugs), small corrosion pits and big corrosion pits. Presence of pitting corrosion changes the characteristic length of surface irregularity and rib spacing compared to a non-corroded bar.

Key words: Concrete, Pitting Corrosion, Spatial Distribution, Empirical Mode Decomposition, Fast Fourier Transform

INTRODUCTION

Chloride-induced corrosion of steel reinforcement in concrete structures usually experiences two stages: pitting corrosion initiation and propagation.¹⁻² Initiation of pitting corrosion occurs as the chloride

content on the surface of a steel bar exceeds a critical value (or chloride threshold) and breaks down the passive film locally.³⁻⁴ Depending on environmental factors at the steel-concrete interface, such as temperature, moisture, and availability of oxygen, pitting corrosion initiation is not stable in the very beginning and some corrosion pits may continue to develop and become stable, while others cease.⁵ These stable developed corrosion pits continue to grow and become deeper and larger, and may connect to each other over time, which corresponds to the propagation stage. The propagation of corrosion would cause concrete cover cracking, rapid diffusion of oxygen and moisture, and subsequently increased corrosion rate and further enlargement of localized pitting corrosion.⁶⁻⁷

Both the initiation and propagation of pitting corrosion are stochastic in nature, over time and in space.⁸⁻⁹ Therefore, some statistical methods or stochastic models have been proposed to simulate the two processes. Valor et al.¹⁰ developed stochastic models to simulate both pitting initiation and propagation. The generation of pitting corrosion is modeled as a nonhomogeneous Poisson process, while the pit growth is simulated by using a homogeneous Markov process. The models are capable to simulate pitting corrosion progress of different materials in different corrosive environments. Different from pitting corrosion occurred on alloys or stainless steel in liquid solution as mentioned above, the initiation of pitting corrosion on reinforcement steel in concrete structures is usually controlled by the penetration process of chlorides and, therefore, the modeling is mainly focused on this.¹¹⁻¹² As for the pitting corrosion propagation, a hemispherical corrosion pit has been proposed for the simplicity of calculation.¹³⁻¹⁶ However in most cases, the shape of pitting corrosion is irregular, and thus it is not reasonable to use the hemispherical shape. Two more general indices of pitting corrosion have also been proposed by researchers: the pitting factor and the cross-sectional area spatial heterogeneity factor.¹⁷⁻¹⁹ These two indices are directly associated with the maximum corrosion pit, and extreme statistics and Gumbel extreme value distribution have been used to model their distribution. The two indices can also be extended to increased length or large surface area of steel bars by modifying the Gumbel parameters.

These statistical or probabilistic models to simulate pitting corrosion of a steel bar in concrete mainly focus on the time domain, i.e. pitting initiation and propagation. Less work has been done to model or investigate the spatial distribution of pitting corrosion or the pattern of corrosion pits along the length of a steel bar. A previous study²⁰ shows that small corrosion pits are randomly distributed along the length of a steel bar in the beginning of corrosion, and these small corrosion pits become greater and deeper and start to connect with each other with an increase of time. From the perspective of electrochemical corrosion, there are two main types of corrosion for steel bar in concrete: microcell corrosion and macro-cell corrosion.²¹ Microcell corrosion causes general corrosion, while macro-cell corrosion results in localized corrosion.

Spectral analysis is one of several statistical techniques to characterize and analyze sequenced data, and in most cases it refers to the decomposition of sequenced data into oscillations of different lengths or scales.²² The decomposed data in the data domain (usually time domain) is converted into the spectral domain. The underlying characteristics in the system can be extracted from the spectral analysis. If the length of a corroded steel bar is treated as the time and the residual cross-sectional area is considered to be the magnitude of the time series, then the characteristics of spatial distribution of pitting corrosion along the length of a steel bar could be extracted.

The purpose of this study is to statistically analyze the distribution characteristics of pitting corrosion on the surface of steel bars with spectral analysis. The outline of this study is as follows: first, the basic theories of empirical mode decomposition (EMD) and fast Fourier Transform (FFT) are introduced, and they are used to analyze the cross-sectional area distribution of a steel bar without corrosion; second, experiments are designed and carried out to accelerate corrosion of steel bars embedded in a concrete prism to different levels, and the morphology of corroded steel bars is scanned with a 3D laser scanner after the corrosion test. Finally, the spatial distribution characteristics of corroded steel bars are analyzed with both EMD and FFT.

EMPIRICAL MODE DECOMPOSITION AND FAST FOURIER TRANSFORM

Empirical Mode Decomposition

EMD, which was originally proposed by N.E. Huang et al. in 1998,²³ is a method to analyze nonlinear and non-stationary time series or signals. By adaptively and locally decomposing any time series or signal into a sum of intrinsic mode functions (IMFs), the physical properties contained in the system can be extracted. It is widely used in research areas such as signal/image processing, system identification, ocean engineering, chemical engineering and seismic studies.²⁴⁻²⁷

The IMFs are obtained from the sifting process of the original data series, and each IMF has a simple oscillatory component extracted from the original data. The IMF satisfies two conditions: (i) the number of IMF extrema (the sum of the maxima and minima) and the number of zero-crossings must either be equal or differ at most by one; (ii) at any point of an IMF the mean value of the envelope defined by the local maxima and the envelope defined by the local minima shall be zero. The sifting procedure for the distribution of the residual cross-sectional area of a corroded steel bar along its length $A(x)$ is as follows:

- (1) Calculate the mean value $\bar{A}(x)$ of $A(x)$, then obtain the modified distribution $A_r(x) = A(x) - \bar{A}(x)$,
- (2) Identify all the local extrema for $A_r(x)$,
- (3) Connect all the maximum points by cubic spline approximation to form an upper envelope $u(x)$,
- (4) Connect all the minimum points by cubic spline approximation to form a lower envelope $l(x)$,
- (5) Calculate the mean envelope of the upper and lower envelope by using the equation $m(x) = [u(x) + l(x)]/2$,
- (6) Compute the difference between $A_r(x)$ and $m(x)$, which is the first component of the IMF and is given as $h_1(x) = A_r(x) - m(x)$. It is an IMF if it satisfies the two conditions as mentioned above, otherwise $h_1(x)$ is treated as the input to the second sifting process. The second component is the difference between the $h_1(x)$ and the mean $m_1(x)$ that is $h_2(x) = h_1(x) - m_1(x)$. The sifting process is repeated until $h_k(x) = h_{k-1}(x) - m_{k-1}(x)$ is an IMF.

By performing EMD analysis, the original cross-sectional area distribution of a steel bar can be expressed as:

$$A(x) = \sum_{i=1}^k h_i(x) + r(x) \quad (1)$$

where $h_k(x)$ are the IMFs obtained from the sifting process and $r(x)$ is the remainder which is a non-mean slowly varying function with only a few extrema.

Fast Fourier Transform

An FFT is commonly used to convert a signal from the time domain to the frequency domain, from which the frequency characteristics of the system can be extracted.²⁸ The IMFs of the residual area distribution of a steel bar reveal the spatial distribution of certain types of surface roughness or irregularity induced by localized corrosion. An FFT of the IMFs of the residual area distribution reveals the spatial frequency of certain types of surface irregularity caused by localized corrosion. Therefore, FFT was performed on the IMFs by using:

$$H(\omega) = \int_{-\infty}^{\infty} h(x) e^{-i\omega x} dx \quad (2)$$

where $H(\omega)$ is the spatial frequency function of the $h(x)$ of IMF and $i = \sqrt{-1}$.

EMD-FFT of a Non-corroded Reinforcing Steel Bar

Figure 1a shows the scanned surface morphology of a non-corroded steel bar with a diameter of 19.1 mm. The ribs can be seen clearly. The distribution of the cross-sectional area along the length is shown in Figure 1b, and it can be observed that a wave line is present due to the presence of ribs.

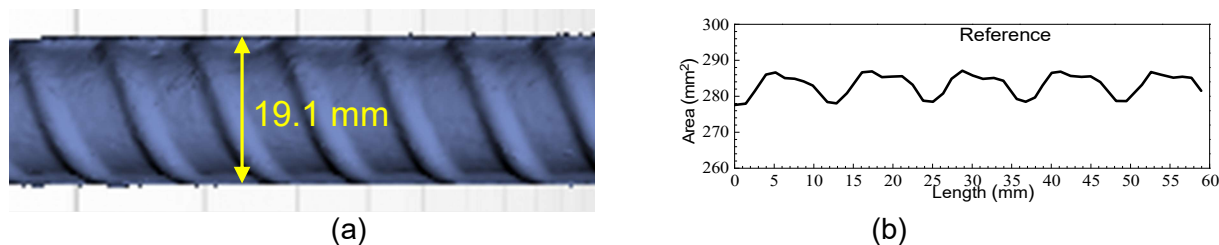


Figure 1: (a) Scanned image of a non-corroded steel bar (with a scale bar), and (b) distribution of cross-sectional area.

EMD is performed on the distribution of the cross-sectional area along its length, and the results are shown in Figure 2a. A total of four IMFs are decomposed. IMF1 reflects the slight variation of the cross-sectional area, mainly from the irregular shape of the rib along the length. An FFT is also performed as shown in the frequency plot of IMF1 in Figure 2b. The peak in the frequency plot indicates the spatial pattern of the corresponding IMF. One peak is present and the corresponding frequency is 0.169 mm^{-1} , which corresponds to a repeated length pattern of 5.88 mm. The magnitude of IMF1 is around 2.79 mm^2 . IMF2 typically reflects the main variation of ribs along the length of the steel bar, and the spatial frequency 0.078 mm^{-1} corresponds to a repeated pattern of 12.82 mm, which is the spacing of ribs on the surface. Regarding IMF3 and IMF4, there is no physical meaning associated with them.

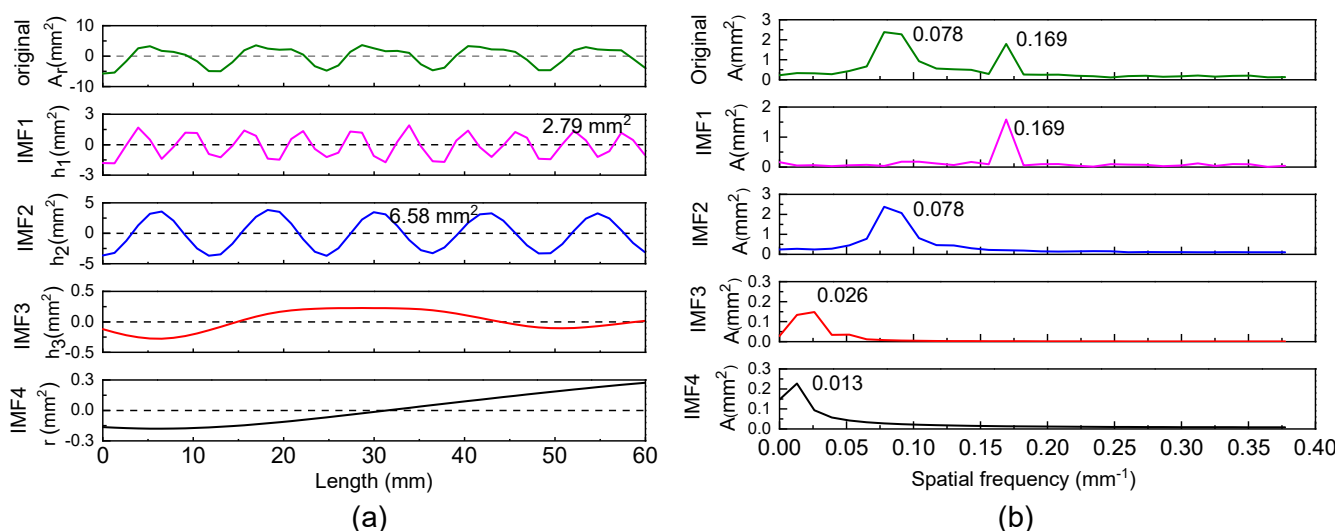


Figure 2: (a) The IMFs of cross-sectional area distribution of a non-corroded steel bar, and (b) the corresponding FFT.

Table 1 summarizes the parameters extracted from each IMF and their corresponding physical meanings. It can be observed that the first two IMFs are related to the surface morphology of a deformed steel bar. IMF1 reflects the spatial characteristics of surface irregularity due to rib shape and IMF2 reveals the distribution pattern of steel bar deformation (mainly ribs and lugs).