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On-site transient analysis for the corrosion assessment of reinforced concrete

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ABSTRACT

A range of methods exist to assess the condition of steel reinforcement in concrete. The analysis of the transient response to a small perturbation has been employed successfully in laboratories to assess corrosion. This work examines a simplified method for the application of transient analysis to in situ reinforced concrete structures. The complex analysis has been simplified and undertaken with the use of common spreadsheet packages. The results illustrate that transient response analysis is a viable technique for use on site and appears to provide a more accurate representation of steel corrosion current densities at very low values than polarisation resistance.

1. Introduction

The study outlines a trial of transient response analysis on full-scale motorway bridge structures to obtain information concerning the steel–concrete interface and is part of a larger study to assess the long-term sustained benefits offered by Impressed Current Cathodic Protection (ICCP) after the interruption of the protective current [1]. These structures had previously been protected for 5–16 years by an ICCP system prior to the start of the study. The protective current was interrupted, in order to assess the long-term benefits provided by ICCP after it has been turned off. This paper develops and examines a simplified approach for the on-site use of transient response analysis and discusses the potential advantages of the technique as a tool for the assessment of the corrosion condition of steel in reinforced concrete structures.

1.1. Theoretical background

Impedance has been used previously to obtain corrosion information regarding the steel–concrete interface [2,3]. To obtain this information, data is required at very low frequencies (mHz–μHz) [2–5]. The conventional method of obtaining impedance is to subject the specimen to a cyclic perturbation at the frequency of interest and analyse the response [2,6]. However, at very low frequencies it is preferable to subject the specimen to a perturbation and analyse its response resulting from the perturbation [7–10].

The steel–concrete system can be described in the form of an electrical circuit. A common and simple approach is the use of the Randle's circuit (Fig. 1a). This analysis characterises the steel–concrete interface with a polarisation resistance (R_p), interfacial capacitance (C) and electrolyte resistance (R_e). R_p can be directly associated with the steel corrosion current density (I_{corr}) [11,12]. The validity of the simple Randle's circuit to adequately represent the steel–concrete interface is still subject to debate. Impedance data may appear to produce a distorted or flattened semi-circle and at high frequencies a second semi-circle may appear [7].

A number of alternative electrical circuits have also been proposed incorporating additional components in order to obtain a better fitting of the experimental data, as shown in Fig. 1b, c and d [13–16]. These additional components improve the fit of the data because each component represents an additional variable that may be adjusted to improve the fit.

Impedance data may be presented in a Bode plot of the response function of a linear-time invariant system versus frequency or a Nyquist plot as a parametric plot of a transfer function, with the latter most commonly used [17]. The shape of the impedance plane on a Nyquist plot gives an indication regarding the accuracy of the model. A near perfect semi-circle will indicate that the impedance response corresponds to a single activation-controlled process (Fig. 1a), a depressed semi-circle will indicate a need for parallel components (Figs. 1b and c) model and multiple semi-circles in general indicates a series of components (Fig. 1d) [17].

In this work the simplified Randle's circuit has been applied due to its simplicity for data analysis [7,15]. This approach provides an estimate of the corrosion condition in critical sections of the

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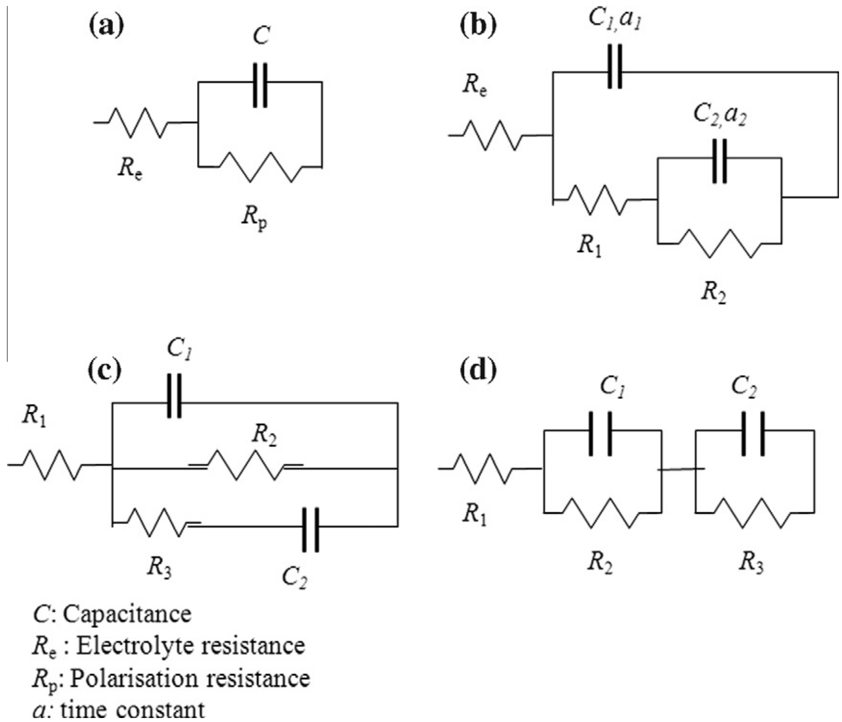

Fig. 1. Various electrical circuits to simulate the steel concrete interface, (a) Randle's circuit, (b) modified Randle's circuit holding two time constants [14], (c) model proposed by Feliu et al. [15], (d) model proposed by John et al. [16].

structure and is particularly suitable for use on full-scale site structures due to its simplicity. Feliu et al. [18] also support the use of a simplified abstract representation of the system in order to interpret its fundamental properties as opposed to a more accurate but significantly more complex circuit model.

Transient response analysis is used to overcome the complexity of the frequency response analysis and simplified for use on site. Transient analysis is the analysis of the response of an electrode after the application of a short pulse over a period of time.

2. Transient data analysis

Laplace transformation is used to convert data on the time domain to data on the frequency domain. This transformation may be expressed as [19]:

$$\overline{Z} = \frac{\overline{V}}{\overline{I}} \tag{1}$$

The Laplace transformations of $\overline{V}$ and $\overline{I}$ can be written as [3]:

$$\overline{V} = \mathrm{a} + \mathrm{jb} = \int_0^\infty \Delta E(t)\cos(\omega t)dt - \mathrm{j}\int_0^\infty \Delta E(t)\sin(\omega t)dt \tag{2}$$

$$\overline{I} = \mathrm{a} + \mathrm{jb} = \int_0^\infty I(t)\cos(\omega t)dt - \mathrm{j}\int_0^\infty I(t)\sin(\omega t)dt \tag{3}$$

where ΔE is the difference in potential, I is the current, t is the time and ω is the range of angular frequencies of interest.

When the highest frequency of interest has a period which is much greater than the period of the pulse ($\frac{1}{\omega'} >> T$) and for times less than the period of pulse ($I(t) \neq 0$) then $\sin(\omega t) \cong 0$, $\cos(\omega t) \cong 1$ and Eq. (3) becomes:

$$\overline{I} = \int_0^\infty I(t)dt = Q \tag{4}$$

where ω' is the highest frequency of interest, T is the period of the pulse and Q is the charge.

Under these conditions the Laplace transformation of the current perturbation will be the charge.

Eqs. (2) and (3) can be solved using standard spreadsheet packages and is illustrated as follows:

i. ΔE and I are measured from the transient data obtained on site. A typical representation is given by Fig. 2a. The data is a set of discrete points.
ii. The voltage transformation from Eq. (2) is a function of the angular frequency (ω), in the range of frequencies of interest. Fig. 2b illustrates a typical example of the contents of the real integral of Eq. (2) at a selected value of ω = 0.04 Hz.
iii. Fig. 2c illustrates a typical example of the contents of the imaginary integral of Eq. (2) at a selected value of ω = 0.04 Hz.
iv. The real and imaginary integrals can be calculated simply by the respective areas under the curves in Figs. 2b and c. For equally spaced points, it is calculated as the sum of the points multiplied by the spacing (seconds) between the points.
v. The real and imaginary parts of Eq. (2) can then be divided individually by the charge to obtain the impedance for this particular angular frequency.
vi. This gives a point on the Nyquist plot at a selected value ω = 0.04 Hz. The real integral divided by the charge provides the x-axis value and the imaginary integral divided by the charge provides the y-axis value.
vii. The above procedure can be repeated at different angular frequencies (ω_x) in order to obtain the impedance spectrum. The procedure provides a suitably simplified analysis process for use with site data.

For very low frequencies where $\omega \cong 0$ Eq. (2) may be simplified further as follows:

$$\overline{V} = \int_0^\infty \Delta E(t)dt \tag{5}$$