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Statistical characterization of surfaces of corroded steel plates

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ABSTRACT: The statistical characteristics of corroded steel plate surfaces exposed to marine environments are of interest for assessing longer-term structural safety and integrity using probabilistic methods. This requires information about the variability of corrosion loss and pitting over surfaces. The present paper reports on the observed statistical character of the surfaces of 10 large (1.2 m x 0.8 m x 3mm thick) steel plates exposed in temperate climate marine immersion, tidal and splash zones for 2.5 years. For the analysis the plates were cut into smaller segments that were mechanically scanned to obtain digitised surface topographies. These were then analysed to estimate the correlation structure and the standard deviation of the surface topography. Considerable differences were found for these and for the mean corrosion loss between different exposure zones. For any one segment the surface topography was found to be highly statistically dependent, implying that smaller coupon sizes can provide adequate estimates of corrosion loss. From this it may be inferred that the deepest pits are not statistically independent as commonly assumed in extreme value statistical representations.

Keywords: Marine, corrosion, steel, plates, statistics.

1 INTRODUCTION

Marine infrastructure, including sheet-piling, bridges, jetties, pipelines, off-shore structures and ships as well as nuclear containment systems exposed to saline ground waters, makes very extensive use of structural grade steels. Usually the exposed steel surfaces are protected using one or more of protective coatings (paints), sacrificial coatings (galvanizing) and impressed current or

sacrificial cathodic protection. However, there is widespread evidence that such systems are not always effective, particularly over long-term exposures, under less than perfect maintenance regimes and under severe exposure conditions. For this reason it is common practice in the design of steel structures particularly those operating in the marine environment to make some (sacrificial) allowance for future corrosion. Three questions arise from this for engineers (i) for an existing structure how much corrosion can be expected in the future, (ii) for new designs what is a reasonable corrosion allowance, and (iii) what interpretation can be placed on reported corrosion loss results since these invariably have been obtained for small-scale corrosion coupons when in practice much larger constructions are of interest?

There is an extensive corrosion literature but it does not always provide information the type of information required by structural engineers concerned with major physical infrastructure. The corrosion science literature that deals with fundamental understanding of the corrosion process for a variety of metals (and other materials) typically exposed in the laboratory for short-term durations (seconds, hours, sometimes days) under a range of artificial exposure conditions and often under anodic polarization to artificially accelerate the corrosion process. Care must be exercised in translating the results obtained to field conditions.

The second category of corrosion information deals with empirical field exposure studies, with the results often quoted as corrosion rates, giving the misleading impression that corrosion is a linear process in time. For atmospheric corrosion in particular the empirical research literature provides relatively simple nonlinear models often based on curve-fitting to data with little reference back to corrosion science fundamentals. This situation is changing, particularly for corrosion of steels in the immersion, tidal and costal zones [1]. An intensive research program currently is addressing questions (i) and (ii) above for a variety of exposure conditions (immersion, tidal, marine atmospheric) in terms useful for structural engineers. The question of central interest in the present paper is the third – namely the relationship between corrosion loss results and pit depth characteristics for larger steel surfaces compared with results typical for small-scale coupons in conventional empirical corrosion trials.

Only mild or structural steel exposed to marine immersion, tidal and splash conditions is considered in this paper. Field testing is used rather than laboratory experimentation, despite the much better control that can be achieved in the laboratory. The main reason for this is the difficulty in replicating bacterial, biological and marine growth characteristics of real seawater [2]. Increasingly, these are recognized as key components in the corrosion behaviour of steels (and other metals) in seawater.

The next section describes previous relevant investigations of the variation of surface profile of steel strips and plates in the marine immersion and tidal environments. This is followed by a description of the test program on steel plates, the analysis of their surfaces after recovery at various times and the mathematical and statistical characterization of these surfaces. Conclusions about variability of plate surface corrosion are then given. These results are compared to earlier results obtained for small coupons.

2 PREVIOUS INVESTIGATIONS

Estimates of the rate of 'uniform' corrosion may be obtained most directly from differences in mass-loss measurements, usually converted to a rate of material loss expressed in mm/year or equivalent. For practical applications the mass-loss measurements are obtained for small coupons of steel exposed in-situ, generally over a period of at least one year and sometimes (much) longer, with periodic coupon recoveries for the longer term programs. Size of coupon employed varies widely, from 300 mm square down to 50 x 100 mm with metal thickness kept small to reduce errors due to high surface energies and hence higher corrosion at the edges. Larger coupons are preferable for greater accuracy in mass loss determinations but practicalities favour smaller coupons. This is particularly the case for coupon recovery of racks of coupons when there is much biofouling since lifting such racks can be a major logistic issue. On the other hand, where water or exposure conditions change quickly smaller coupons may be preferred to capture variability. Conversely, for structures straddling more than one exposure zone only larger coupons or test pieces can capture the corrosion effect of differential aeration such as caused by differences in wetting and oxygen access in the tidal zone [3]. Conventionally only 2 or 3

coupons are exposed for any given time period, although for variability studies multiple coupons must be used. There are international and national Standards describing the processes involved in surface preparation, cleaning, exposure, recovery and cleaning and weighing coupons, including the use of blanks. The conventional wisdom is that data from coupons are essentially the same as that which would be expected from larger steel surfaces. This has been investigated previously for coupons in the immersion zone varying in size from 50 x 100 mm to 100 x 200 mm and 50 x 400 mm and for coupons of different geometries including circles, squares and rectangles [4]. Only negligible differences were found for the effect of shape and of surface area.

For strips of mild steel and for continuous steel sheet piling it has been found that there are distinct vertical corrosion profiles related to the various exposure zones. These are similar to those for electrically connected coupons but all are distinctly different from the results obtained for electrically isolated coupons [5,6,7,8] and for shorter isolated strips [9]. These results show that the importance of differential aeration for exposure straddling different corrosion zones. This effect appears not to have been investigated for larger steel surfaces.

The mathematical or statistical analysis of corroded surfaces has had relatively little attention. Yamamoto et al. [10] used a Fast Fourier Transform (FFT) approach to characterize the surfaces of mild steel plates 100 x 100 mm exposed for one year in various marine environments. They found that for these relatively small plates the autocorrelation function, estimated from the FFT results, suggested the average distance between the cathodic and anodic regions. However they made no conclusions about the effect of coupon size. Sumi and Rahbar-Ranji [11] used a two-dimensional discrete spectrum to analyze the effect of the form of the corroded surface on the stress analysis of a steel plate. They applied techniques derived from modelling of surface roughness and contact mechanics [12,13]. These are applied also in the analysis below. A similar approach was used in preliminary results for small steel plates recovered from shipyards [14].

3 EXPERIMENTAL METHODS

Commercial low carbon mild steel plates 1200 mm x 600 mm x 3mm thick were exposed in two locations at the NSW Fisheries complex at Taylors Beach, a protected inlet that is part of Nelson Bay on the east coast of Australia about 200 km north of Sydney. The waters at this location are closely similar to Pacific Ocean coastal seawater. Table 1 summarizes the water quality at the site. Five plates were suspended with nylon ropes from a piled rig located mid-estuary at a site previously used for corrosion testing and exposed sufficiently deep to ensure immersion conditions throughout the year. Another 5 plates were suspended vertically under a local timber jetty (Figure 1). Two holes were drilled in each to enable suspension. Practicalities dictated that all plates were exposed in the ‘as received’ condition.

Table 1 Water quality at Taylors Beach

Figure 1 Steel plates immediately after being suspended under jetty at Taylors Beach.

Plates were recovered at 6, 12, 18, 24 and 30 months from first immersion. Figure 2 shows three of the plates suspended from the jetty, at low tide and immediately before recovery after 6 months exposure. Evidently, the rusts at this time give a uniform pattern over the corroded surface. Figure 3 shows one of the fully immersed plates immediately after recovery at 12 months exposure. Evidently this plate had tilted from the horizontal as evident from the black area (lower right) corresponding to where the plate had buried into the mud. All plates were washed to remove marine growth and loose rusts before the plates were taken back to the laboratory. Figure 4 shows the plate in Figure 3 after washing with a high-pressure hose. This revealed that the majority of the surfaces had a rather regular undulating surface texture. For the plates that were exposed for more than one year, some areas of bright steel surface that began to tarnish almost immediately upon exposure to air were noted.

Figure 2 Corroded surfaces of steel plates under jetty after 6 months splash and tidal zone exposure showing uniform nature of external rust layer.

Figure 3 Plate recovered from mid-estuary at 12 months exposure, showing that it inclined into the mud (at lower right). Note the distinctly different external rusts.

Figure 4 The same plate as in Figure 3 immediately after washing with high pressure water. Note the appearance of some bright metal in the region of the transition zones between mud and tidal and splash zones.

In the laboratory the plates were cleaned initially by electrolysis in a dedicated tank. They were then dried and guillotined into 3 equal strips along the length and into 4 equal pieces along each strip. This gave twelve 300 x 200 mm pieces that could be handled for final cleaning using standard chemical techniques (ASTM G3) [15]. The plates were then weighed. They were stored in a dessicator while awaiting digitization of each side of each plate. Digitization was done using a mechanical 3D scanner (Picza PIX-30) set to a 2mm square sampling grid. The scanning process was slow (but relatively inexpensive) and it took many months to process all the plate pieces. The digitised scan results were then transferred to a computer for further processing. Figure 6 shows a typical result with expanded vertical scale (z-axis). A contour map of the same piece of plate with 0.5 mm (relative) contours is shown in Figure 6. In neither case was it possible to fix an absolute origin vertically since the plates had to be propped in the scanner. This also means that the slope of the plate pieces in the x and y directions as shown in Figures 5 and 6 is arbitrary.

Figure 5 Wire frame map of the surface geometry of part of plate A, exposed in the splash zone for 6 months. The sample shown was at the top left corner of the plate. Note the fixing hole at top left.

Figure 6 Relative contours at 0.5 mm interval of the surface shown in Figure 5. Note the fixing hole at top left.

Because of the difficulty in orienting the plate pieces in an absolute orientation for digitization, the loss of plate thickness and hence an estimate for ‘uniform’ corrosion loss, was obtained by

weighing each plate piece and subtracting from this the initial mass estimated from the original plate size and original thickness and steel density. The results, grouped into the splash, tidal and immersion zones, are shown in Figure 7.

Figure 7 Average uniform corrosion loss as a function of exposure period for plate pieces exposed in the splash, tidal and immersion zone.

4 ANALYSIS OF CORROSION VARIABILITY

4.1 Spectral analysis

Figure 7 provides information about the average corrosion loss and its change with continued exposure period. To consider the effect of plate size on corrosion, and for structural reliability procedures [16], estimates are needed also of the variability of the corrosion loss. This can be done simply by estimating the standard deviation of the amount of corrosion over a small area and comparing it with similar estimates at other locations or for other plates or coupons. A more complex but more informative analysis considers the (auto-)correlation structure of a plate surface or, equivalently, its relative frequency distribution, determined through what is known as a spectral analysis to produce a so-called power spectrum [17]. It will be helpful to review the basics of this analysis applied to two-dimensional surfaces before presenting the results.

Although the profile of a corroded surface is a function of two orthogonal distances, it can be represented as function of frequency using a Fourier transformation. The result is a spectrum of the surface profile, that is, it is re-interpreted as the set of frequency components contained within the profile of the original surface. Thus a power spectrum represents the randomness of the surface in the frequency domain. In particular it is a measure of the frequency distribution of the mean squared value of the corrosion depths (or ‘power’) at different frequencies.

Let the corrosion depth be defined as $z(k_x, k_y)$ measured at the grid point (k_x, k_y) of a two-dimensional grid defining the surface region (x, y) of interest. Here k_x is the grid number in the x direction and k_y is the grid number in the y direction. Let the spacing of the grid points in the x -direction be denoted Δ_x and the spacing in the y -direction be Δ_y . Thus

$$z(k_x, k_y) \equiv z(l_x, l_y) \quad (1)$$

where l_x and l_y are respectively the x and y co-ordinates of the grid point (k_x, k_y) . The relationships between (k_x, k_y) and (l_x, l_y) are given by

$$l_x = k_x \cdot \Delta_x \quad k_x = 0, 1, 2, \dots, N_x - 1 \quad (2a)$$

$$l_y = k_y \cdot \Delta_y \quad k_y = 0, 1, 2, \dots, N_y - 1 \quad (2b)$$

where N_x and N_y are respectively the total number of grid points in the x and y directions.

The mean value of the $z(k_x, k_y)$ over the area defined by (l_x, l_y) is given by

$$\bar{z} = \frac{\sum_{k_y=0}^{N_y-1} \sum_{k_x=0}^{N_x-1} z(k_x, k_y)}{N_x N_y} \quad (3)$$

Evidently, there will exist a surface with exactly corresponding characteristics but with a zero mean value. It is given by

$$h(k_x, k_y) = z(k_x, k_y) - \bar{z} \quad (4)$$

This now allows the corresponding two-dimensional discrete spectrum to be defined as [11,12]:

$$\begin{aligned}
S(f_1, f_2) &= \frac{4\Delta_x\Delta_y}{N_x \cdot N_y} \cdot \left[\sum_{k_y=0}^{N_y-1} \sum_{k_x=0}^{N_x-1} h(k_x, k_y) \cdot \exp\left(\frac{i2\pi \cdot k_x \cdot n_1}{N_x}\right) \exp\left(\frac{i2\pi \cdot k_y \cdot n_2}{N_y}\right) \right]^2 \\
&= \frac{4\Delta_x\Delta_y}{N_x \cdot N_y} \cdot \left[\sum_{k_y=0}^{N_y-1} \sum_{k_x=0}^{N_x-1} h(k_x, k_y) \cdot \exp\left\{i\left(\frac{2\pi \cdot k_x \cdot n_1}{N_x} + \frac{2\pi \cdot k_y \cdot n_2}{N_y}\right)\right\} \right]^2
\end{aligned} \tag{5}$$

where, the variations of n_1 and n_2 are given by

$$n_1 = 0, 1, 2, \dots, N_x / 2 \tag{6a}$$

$$n_2 = 0, 1, 2, \dots, N_y / 2 \tag{6b}$$

and the cyclic frequencies f_1 and f_2 are defined by

$$f_1 = \frac{n_1}{N_x \Delta_x} \tag{7a}$$

$$f_2 = \frac{n_2}{N_y \Delta_y} \tag{7b}$$

If the corrosion depths $h(k_x, k_y)$ exhibit some (perhaps just approximate) repetition on frequencies (f_1, f_2) the spectrum at or near (f_1, f_2) would show a local peak. This local peak indicates an elevated relative occurrence of the frequencies (i.e. the surface characteristics) involved.

Theoretically the upper values of the frequencies f_1 and f_2 are restricted to $1/(2\Delta_x)$ and $1/(2\Delta_y)$, respectively, because no valuable information regarding the spectrum $S(f_1, f_2)$ is obtained for frequencies higher than these values. These cut-off frequencies are known as Nyquist frequencies [17]. Evidently, it is better, if possible, to choose a sufficiently small grid spacing (Δ_x and Δ_y) so as to reduce this effect, which can cause some distortion of results in the

frequency domain. It might be noted that another way to estimate the spectrum is via auto-correlation. In this case, the auto-correlations of the corrosion depths for two points separated by a constant distance are evaluated. This process is repeated and the spectrum is calculated from the Fourier transform of the derived auto-correlations. This procedure was not employed herein.

Figures 8-10 show examples of the power spectra for the splash zone, tidal zone and immersion zones as obtained using Eqns 3 and 4 after the data was normalized in each case to zero means. In each case it is clear that the frequency content is very restricted, with in each case the frequencies (along the two horizontal axes f_1 and f_2) highly localized around 0.1 cycles/mm, with only minor effects elsewhere. This means that in each case there is a high degree of uniformity or regularity in the profile of the surface, with the power spectra, and hence the surface displays a high degree of regularity, concentrated in the lower frequencies. There is little high frequency variation in the form of the corroded surfaces. Since this was the case for all pieces of plate exposed to uniform (or near-uniform) exposure conditions, this means that there is negligible or at worst very little effect of surface area in the characteristic pattern of the corroded surface. This was found to be the case throughout the complete exposure period of 2.5 years. It means that for any exposure condition small areas or (relatively) small samples can be taken as representative of the form of the corroded surface and hence of its variability.

Figure 8 Power spectrum for sample plate piece A1(side 1) exposed in the splash zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

Figure 9 Power spectrum for sample plate piece A7(side 1) exposed in the tidal zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

Figure 10 Power spectrum for sample plate piece B1(side 1) exposed in the immersion zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

4.2 Variability

As a result of the above observations, it is sufficient for representation of the variability of a corroded surface at different exposure periods to consider simply the standard deviation or the coefficient of variation rather than the complete power spectrum or the auto-correlation function. This can be done using only a relatively small area – sufficiently large, however, to capture the statistical characteristics of the surface. An estimate of the minimum size is as follows. From Figures 8-10 the number of cycles per millimetre is around 0.2 for those most commonly occurring in the plate surface. This means that to capture at least one complete cycle requires at least 5 mm. This would be the smallest possible size, although in practice it would be desirable to have considerably more. An alternative approach is to note that for random sampling it is common to assume that at least 30 independent samples are required. With sampling at 0.5 mm spacing, this means 15 mm sample size at least. But at this spacing of surface sampling the samples are not completely independent owing to the regularity of corroded surfaces [18]. A bound based on the notion of asymptotic independence can be made as follows. If it is assumed that the main surface characteristic is represented by 0.2 cycles/mm (Figures 8-10), then the data points within this range can be considered a cluster [19]. It is then reasonable to assume that, asymptotically, one independent sample is given within a spacing of one cycle (5 mm). In this case the minimum required size is around $30 \times 5 = 150$ mm. Considering the assumption of clustering and of independence between clusters, this is a conservative estimate.

The estimation of standard deviations usually is based on the assumption that the underlying distribution can be taken as Normal, at least in the limit for large numbers of (independent) observations. To estimate the standard deviations, small sections 30 mm x 20 mm were selected for each plate surface such that they could be considered to be representative of the topography of each surface. Profile measurements were made at 0.5 mm spacing in both directions. From these the means μ_z and the standard deviations σ_z were calculated using the standard formulae:

$$\mu_z = \frac{1}{n} \cdot \sum_{i=1}^n z_i \quad (8a)$$

$$\sigma_z^2 = \frac{1}{n} \cdot \sum_{i=1}^n (z_i - \mu_z)^2 \quad (8b)$$

where n is the total number of samples. The results are summarized in Figure 11. The coefficients of variation (COV) defined as μ_z/σ_z are shown in Figure 12.

Figure 11 Standard deviation estimates for corrosion profiles as a function of exposure period for each of the three exposure zones.

Figure 12 Coefficients of Variation as a function of exposure period for each of the three exposure zones.

5 DISCUSSION

The plots for the average corrosion loss as a function of period of exposure (Figure 8) are in general agreement with those found earlier for much smaller coupons, with a change in trend evident after an early period during which the rate of corrosion gradually decreases. For the immersion curve there is a distinct change soon after one year of exposure, consistent with the results for small coupons at this site [20]. The change in trend occurs less obviously and later in time for the tidal and the splash zones, again consistent with results for tidal and atmospheric corrosion [21].

The standard deviations (SD) estimated according to Eqn 8 are plotted in Figure 11. They all show an increase in standard deviation but the rate of increase declines after about one year exposure, significantly so for the splash zone and less so for the tidal zone. Interpretation of these results is not straight-forward but could be related to differences in the rate of corrosion on various parts of the overall plates, captured in the segments that were cut off. It is unlikely to be the result of errors with the digitizing as this would have been detected during the processing of the results. Previously the increase in standard deviation for the immersion zone after about one year exposure has been attributed to the effect of microbiological influences on corrosion since

this is known to be related to the highly variable settlement and growth of marine biological agents [22]. From an engineering perspective the most important results are those for the Coefficients of Variation (COV), shown in Figure 12. These show a gradual decline in COV for the splash and the tidal zone, reflecting the increasing mean corrosion levels to year 2.5. Importantly, the COV estimated from the present experiments is much lower than estimates made from spot thickness measurements of ship corrosion [23] that show COV values exceeding unity in some cases, even for parts that are not continually immersed. Similarly it is of interest that while the COV for the immersed plates was initially quite high, reflecting the low early corrosion loss and higher standard deviation, the eventual COV is roughly similar to the COV values in the splash and tidal zones.

The values for the standard deviations and the coefficients of variation are rather different from those reported earlier as estimated for small coupons [24]. The reason for the difference lies in the way the measurements were made and what was actually considered. In the present case the form of the corroded surface is considered in the estimates for SD and COV. In the earlier work the mass losses for the individual coupons were used instead, and actually represent the SD and COV of the average corrosion loss as derived from mass losses. Since the mass losses are for each coupon, they represent average values and thus the SD and COV derived from them also are averages in this sense. In contrast, the present results refer to the variation of the surface profile and are therefore a measure of the surface undulation. They should not be applied where the average properties are of interest, for example for a steel member in tension.

The spectra of each of the individual plate segments, such as typical examples shown in Figures 8-10, all show that the frequency content of the corroded surfaces is closely bounded and of a wavelength much smaller than the plate segments. As argued above, this shows that coupons of considerably smaller size than the present plates or their segments can be used to obtain the characteristic features of the corroded surface, including the mean mass loss and the standard deviation of mass loss. Intuitively this observation should not be surprising. Fundamental ideas in corrosion mechanics supports the notion that for wet corrosion the anodic and cathodic regions are closely spaced and that therefore the corrosion current is not much influenced by the

conductivity of the immediate surrounding environment [25]. In fact, once some degree of corrosion products have built up on the corroding metal surface for each of the splash, tidal and immersion zone exposures, conditions immediately adjacent to the metal are highly likely to be continuously or semi-continuously wet, permitting both the development of closely spaced anodes and cathodes and high corrosion currents. As is well-known, in these wet conditions the rate limiting step in the corrosion process is the diffusion of oxygen to the cathode, not limitations on corrosion currents. The net result, that relatively small coupons can be used to characterize the corrosion process in the splash, tidal and immersion corrosion zones is of practical importance for corrosion testing. Whether this argument can be extended to the corrosion of steel in the atmosphere remains a matter for investigation.

Some tentative lower bounds were given above for the minimum size of coupon for the splash, tidal and immersion corrosion zones. As noted, these were based on different assumptions, primarily as to the degree of independence between adjacent observations of corrosion loss measured on a surface. The bounds can be sharpened a little by proceeding from the assumption that uniform or near uniform corroded surfaces are partially if not wholly the result of multiple pits. Although a rather high degree of correlation appears to be the case for the depth of adjacent pits in the early period of exposure, the correlation appears to reduce with increased exposure. This can be seen informally through microscope observations of pitted surfaces over one or more years exposure [18]. The implication is that relative to pit size larger surface areas may be necessary for short term exposures. But since pits grow in surface area (as well as depth) with increased exposure time, the net effect is likely to be that the actual coupon size can be similar for both early and longer term exposure. On this basis the assumption used above to obtain the larger (150 mm) bounds can now be seen to be rather conservative. The smaller bounds of 15 mm are more likely to be appropriate.

6 CONCLUSION

The following conclusions may be drawn from the observations reported herein:

1. The corroded surfaces of plates exposed in the splash, tidal and immersion corrosion zones all exhibit a highly regular corroded surface within the one zone. This is evident from visual observations of the corroded surface of large plates and from the spectra extracted from the digitized surfaces of component plates.
2. These observations were found by experiment to be valid for exposures up to 2.5 years. However, the data trends suggest that these observations are likely to remain valid for much longer periods of exposure.
3. As a result it corrosion tests within each of the splash, tidal and immersion corrosion zones can employ relatively small corrosion coupons to capture the essential characteristics of the form of the corroded surfaces, including mass loss and pitting.
4. For the corrosion environment investigated herein, it was estimated that the minimum coupon size should be no less than about 15 mm square or closely similar. A conservative estimate suggests that minimum coupon size of around 150 mm.

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Figures

Figure 1 Steel plates immediately after being suspended under jetty at Taylors Beach.

Figure 2 Corroded surfaces of steel plates under jetty after 6 months splash and tidal zone exposure showing uniform nature of external rust layer.

Figure 3 Plate recovered from mid-estuary at 12 months exposure, showing that it inclined into the mud (at lower right). Note the distinctly different external rusts.

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Figure 7 Average uniform corrosion loss as a function of exposure period for plate pieces exposed in the splash, tidal and immersion zone.

Figure 8 Power spectrum for sample plate piece A1(side 1) exposed in the splash zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

Figure 9 Power spectrum for sample plate piece A7(side 1) exposed in the tidal zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

Figure 10 Power spectrum for sample plate piece B1(side 1) exposed in the immersion zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $\text{mm}^4/\text{cycle}^2$.

Figure 11 Standard deviation estimates for corrosion profiles as a function of exposure period for each of the three exposure zones.

Figure 12 Coefficients of Variation as a function of exposure period for each of the three exposure zones.

Table 1 Typical water quality at Taylors Beach

Parameter	Units	Typical value
Ammonia	ppm	0.017 – 0.080
Nitrate	ppm	0.017 – 0.050
Nitrite	ppm	< 0.003 – 0.011
Sulphate	ppm	1600 – 2750
Total P	ppm	0.003 – 0.07
Ca	ppm	374 – 392
Cl	ppm	21,000
Alkalinity	ppm CaCO ₃	409-419
Salinity	ppt	25.7-31.3
pH		8.1
DO	%	90
Water temperature (annual mean)	°C	20