REPRESENTATIVENESS OF SMALL COUPONS FOR CORROSION OF LARGE PLATES

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SUMMARY: Earlier work (Melchers and Jeffrey 2002) showed that coupon size and shape was not a major contributor to the variability in corrosion loss estimates. However these conclusions were based on the relatively small coupons used typically in corrosion field studies. In order to estimate whether such small coupons produced realistic results for much larger plates, mild steel plates 1.2 m x 0.8 m x 3mm thick were exposed for up to 2.5 years in immersion, tidal and splash zone conditions at Taylors Beach, NSW. The plates were recovered at 6, 12, 18, 24 and 30 months. At each stage the plates recovered were cleaned, dried and guillotined into 12 equal rectangles suitable for fitting into a mechanical 3D scanner. The digitised scan results show a high degree of similarity of corrosion across a surface, and a similar pattern of corrosion loss with time of exposure. Estimates for variability of corrosion loss were made from the digitized data. Differences between immersion, tidal and splash zone corrosion were observed. The results validate the use of smaller coupons for field studies and loss and variability estimates.

Keywords: Steel, Plates, Seawater, Tests, Variability.

1. INTRODUCTION

Extensive use of structural grade steels is made in various marine infrastructure applications, including sheet-piling, bridges, jetties, pipelines, off-shore structures and ships. It also has been proposed as the principal containment system for the ultimate disposal of nuclear wastes in stable rock formations. This means the containments may be exposed to saline ground waters (King 2007). For most infrastructure applications exposed steel surfaces are protected using one or more of protective coatings (paints), sacrificial coatings (galvanizing) and impressed current or sacrificial cathodic protection. Such systems can provide excellent protection provided they are maintained. There is sufficient evidence that this is not always the case, particularly under less than perfect asset management regimes and under severe exposure conditions. For this reason it is common practice in design to make some (sacrificial) allowance for future corrosion of steel structures particularly those operating in the marine environment. A good example is commercial shipping, for which a 10% corrosion allowance on plate thickness is the internationally accepted standard. For ship owners an immediate question is how quickly that corrosion allowance will be used up and what factors influences this. Despite the very extensive plate remaining thickness measurements made for ships' plating by classification societies, very little of that data is in the public domain. Moreover, it is doubtful that even if it was, it would be of use in predicting future corrosion losses since the environment is seldom recorded and the observations are made at discrete locations on steel plates (Figure 1). However, the precise locations are at the discretion of the ship surveyor, and hence not repeatable. But even if the patterns was somehow defined, repeatability in real ships would be highly unlikely. For this reason information from these discrete observations can provide only very general information about the variability of plate thickness or corrosion loss over a plate (Paik et al. 2003, Gardiner and Melchers 2003). Nevertheless, good information about plate variability is necessary to be able to make reasonable estimates of the *likelihood* of plate perforation.

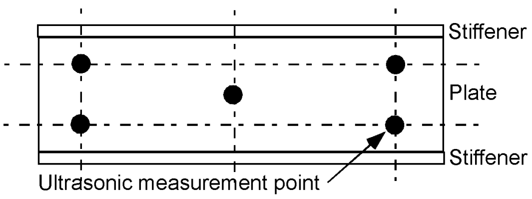

Figure 1. Typical 5 point pattern required for ultrasonic surveys of ships' plating (based on TSCF 2002).

There is extensive information about corrosion losses and pitting obtained from laboratory observations. Mostly this was obtained using electro-chemical techniques to accelerate the corrosion process. Many of the results were obtained in relatively short-term experiments that employed either sodium chloride solutions or artificial seawaters. It is well-established that results obtained using impressed current or similar techniques cannot be related, directly, to what might be expected to occur for natural corrosion situations. Also, real seawater is a 'biotic' soup not closely mimicked by saline water or artificial seawater. This means that electro-chemical laboratory measurements are unsuited to elucidating meaningful information when bacterial activity could be involved in the corrosion process (Cord-Ruwisch 2000).

A different category of information about corrosion in seawater is that derived from the corrosion of small steel coupons over extended periods of time conducted in-situ. Because 'in-situ' implies much less control over the experimental conditions compared with what can be achieved in the laboratory, there is an inevitable degree of uncertainty about the results so obtained (Lee et al. 2009). This must be accepted and included in the formulation of expected corrosion loss and maximum pit depth (Melchers 2005). The question of interest in the present paper is whether the corrosion losses and pit depths observed on small-scale coupons as used in conventional empirical corrosion trials have meaning for corrosion characteristics for larger steel surfaces.

In a previous paper the effect of coupon size, shape and aspect ratio (edge thickness vs. plate size) was considered but only for what were still relatively small plates (Jeffrey and Melchers 2002). The coupons were exposed to immersion corrosion. They varied in size from 50 x 100 mm to 100 x 200 mm and 50 x 400 mm and with different geometries including circles, squares and rectangles. Only negligible differences were found for the effect of shape and of surface area. Coupons that extend some way across different zones (immersion, tidal, splash, atmospheric) behave differently to those essentially in the one zone (Humble 1949, LaQue 1951, Larrabee 1958) and this was found also for long strips extending across several zones (Jeffrey and Melchers 2009a,b). Essentially these effects are due to differential aeration. However, none of these tests involved larger plates.

The next section describes a test program on steel plates and the results obtained from analysing the surfaces of those plates at different exposure times. The detailed mathematical and statistical characterization of the surfaces is dealt with elsewhere (Melchers et al. 2010). Observations about variability of plate surface corrosion are then given and the results compared to earlier results obtained for small coupons. Herein only mild or structural steel exposed to marine immersion, tidal and splash conditions are considered.

2. EXPERIMENTAL METHODS

Ten mild steel plates were used in the test program which was conducted 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).

Table 1. Typical water quality at Taylors Beach

Parameter	Units	Typical value	Parameter	Units	Typical value
Ammonia	ppm	0.017 – 0.080	Cl	ppm	21,000
Nitrate	ppm	0.017 – 0.050	Alkalinity	ppm $CaCO_3$	409-419
Nitrite	ppm	< 0.003 – 0.011	Salinity	ppt	25.7-31.3
Sulphate	ppm	1600 – 2750	pH		8.1
Total P	ppm	0.003 – 0.07	DO	%	90
Ca	ppm	374 – 392	Water temperature (annual mean)	^oC	20

Each plate measured 1200 mm x 600 mm x 3mm thick and was commercial quality low carbon steel from the same batch. Five of the plates were suspended with nylon ropes from a piled rig located mid-estuary at a site sufficiently deep to ensure immersion conditions throughout the year. The other five plates were suspended vertically under a local timber jetty (Figure 2). Two holes were drilled in each plate to enable suspension. Practicalities dictated that all plates were exposed in the 'as received' condition.

A plate from each set was recovered at 6, 12, 18, 24 and 30 months from first immersion. After 6 months there was already considerable corrosion in evidence, as seen in Figure 3 for three of the plates under the jetty. Figure 4 shows a plate after 12 months exposure. This plate had tilted from its originally horizontal fixing position, as evident from the black area (lower right) where the corner of the plate had buried into the mud.

Figure 2. Steel plates immediately after being suspended under jetty at Taylors Beach, at low tide, showing clean surfaces.

Figure 3. Corroded surfaces of steel plates under jetty after 6 months splash and tidal zone exposure showing the relatively uniform external rust layer.

Immediately after recovery and photography the plates were washed with a high-pressure hose to remove marine growth and loose rusts. Figure 5 shows the plate in Figure 4 after washing. Typically this revealed a rather regular undulating surface texture over most of the plate surface (Figure 6). After one year exposure most plates revealed some areas of bright steel surface that began to tarnish almost immediately upon exposure to air.

After being taken back to the laboratory the plates were given an initial cleaning using 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 to give twelve 300 x 200 mm pieces. These were given a final cleaning using standard chemical techniques (ASTM G3, 2004). The plates were weighed and then stored in a dessicator while awaiting surface analysis. This consisted of digitising each side of each plate using a (inexpensive) mechanical 3D scanner (Picza PIX–30). A 2 mm square sampling grid was used. The scanning process was slow. It took many months to process all the plate pieces.

Figure 4. Plate recovered from mid-estuary at 12 months exposure. The inclined pattern (at lower left) was caused by a failure of the suspension system such that the corner of the plate entered the local mud. The distinctly different external rusts are clearly visible.

Figure 5. The plate in Figure 4 immediately after washing with high pressure water, showing some regions of bright metal in the transition zones between mud and tidal and tidal and splash zones.

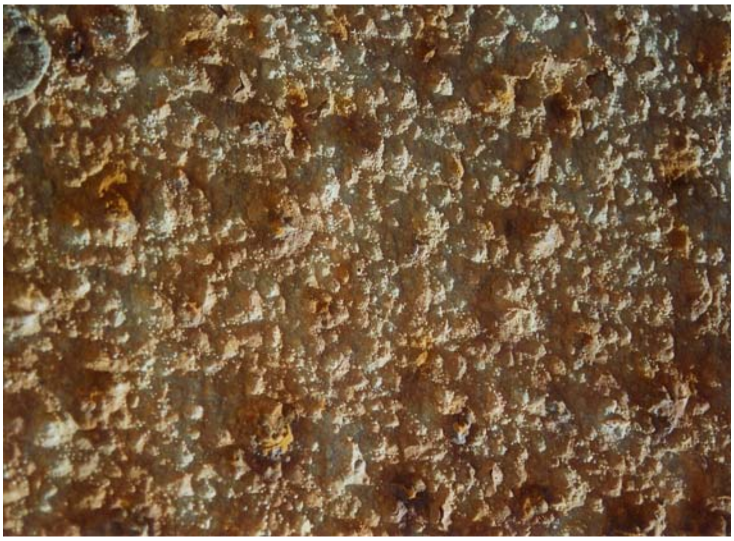

Figure 6. Close-up of corroded surface showing high degree of regularity of topography.

Each set of digitised scan data was transferred to a computer for further processing using commercial software. Figure 7 shows a typical result with expanded vertical scale (z-axis). Evidently an absolute origin vertically could not be ascertained relative to the plate surface as the plates had corroded on both sides. Since it was not possible to mount the plate pieces absolutely level in the scanner, the slope of the plates in the x and y directions in Figure 7 is arbitrary. The loss of plate thickness and an estimate for 'uniform' corrosion was obtained by comparing the mass of each plate piece after exposure with the initial mass. This was estimated from the original plate size and original thickness and steel density. The results are given in Figure 8.

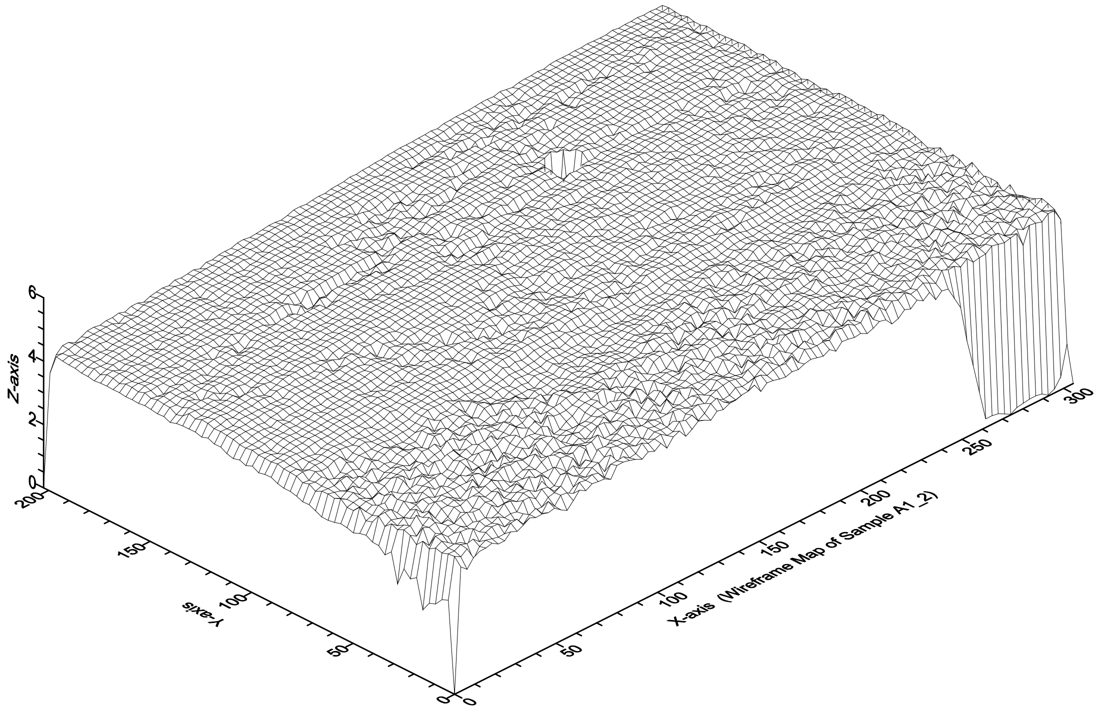

Figure 7. Wire frame map of the surface geometry of part of plate A, exposed in the splash zone for 6 months. The sample shown was at the top left corner of the plate. The vertical axis is exaggerated. Note the fixing hole at top right.

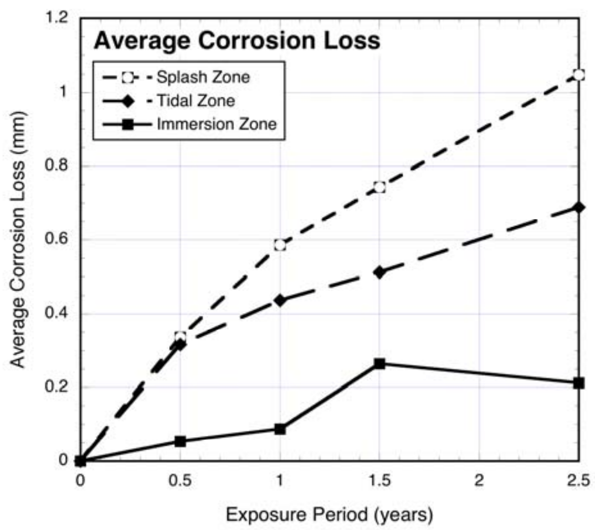

Figure 8. Average uniform corrosion loss (obtained from mass loss) as a function of exposure period for plate pieces exposed in the splash, tidal and immersion zone.

3. VARIABILITY OF CORROSION

An important parameter, particularly for structural reliability calculations, is the variability of the corroded surface. The scanned information allow this to be calculated relatively easily. It is usually sufficient to consider just the standard deviation (or the coefficient of variation) rather than the complete power spectrum (see below). An estimate of the standard deviation can be made using information from only a relatively small area of plate, but an area sufficient in size to capture the statistical characteristics of the surface. Several approaches can be used to estimate the minimum area required (Melchers at al. 2010). A useful approach arises from the notion that for statistical random sampling usually at least 30 independent samples are required. Since sampling was at 2mm spacing, this suggests that a minimum sample size would be about 60 mm. However, the regularity of corroded surfaces (Figure 7) suggests a high degree of dependence between adjacent observations and this indicates that the assumption of independence is not correct. An upper bound on the minimum sampling size can be made based on the notion of asymptotic independences. Figure 7 suggests that the main surface characteristic is repeated over a length of about 5mm. Data points within this range can be considered a cluster and it is reasonable to assume that, asymptotically, each cluster is an independent sample (Galambos 1987). This then suggests a minimum required size of around 30 x 5 = 150 mm. This is a conservative (upper bound) estimate.

The mean and standard deviation of a distribution, defined for n asymptotically independent samples z_i from a large population, are given by

$$\mu_z = \frac{1}{n} \cdot \sum_{i=1}^{n} z_i \tag{1}$$

where μ_z defines the mean and σ_z the standard deviation. The variance is given by

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

Typical coefficients of variation, defined as μ_z/σ_z for each exposure zone, are shown in Figure 9.

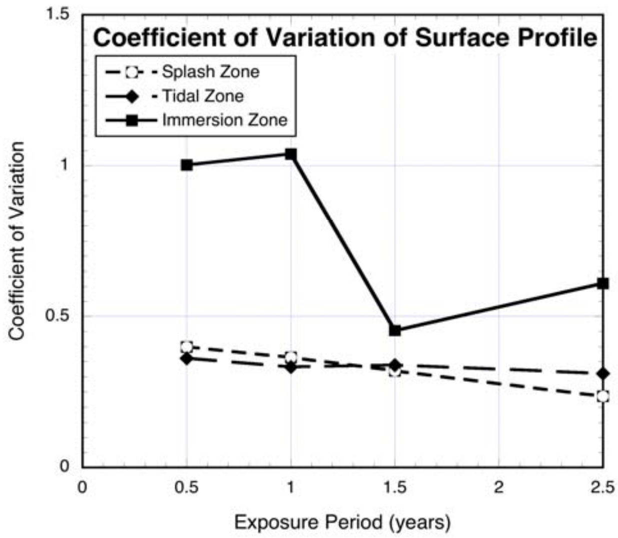

Figure 9. Typical Coefficients of Variation as functions of exposure period for each of the three exposure zones.

4. SPECTRAL ANALYSIS

A more informative but also more complex representation of the variability of the surface considers the (auto-)correlation structure of a plate surface or, equivalently, its relative frequency distribution. This can be obtained using conventional techniques of spectral analysis to produce a so-called power spectrum. The relevant theory can be found elsewhere, save to note that it relies on representing the surface topography using a set of Fourier series and then extracting the frequency content. This can be represented by a so-called 'power spectrum' that indicates the relative occurrence of the different frequencies. Physically this represents the randomness of the surface in the frequency domain, with greater 'power' for the frequencies for which the corrosion depths are greatest. Another way to estimate the spectrum is to evaluate or estimate the auto-correlation function for the corroded surface (de Silva 2000).

Figure 10 shows an example of the power spectra for the splash zone with the data normalised to zero means. In each case the frequencies with most power are very restricted. Along each of the two horizontal axes f_1 and f_2) the frequencies with the most power are those around 0.1 cycles/mm, with only minor effects elsewhere. This implies that there is a high degree of uniformity or regularity in the profile of each of the surfaces, as is indeed evident form visual inspection (Figure 6), and that irregularities are confined to the lower frequencies. The power spectra for the tidal and immersion zones were generally similar to that shown in Figure 10.

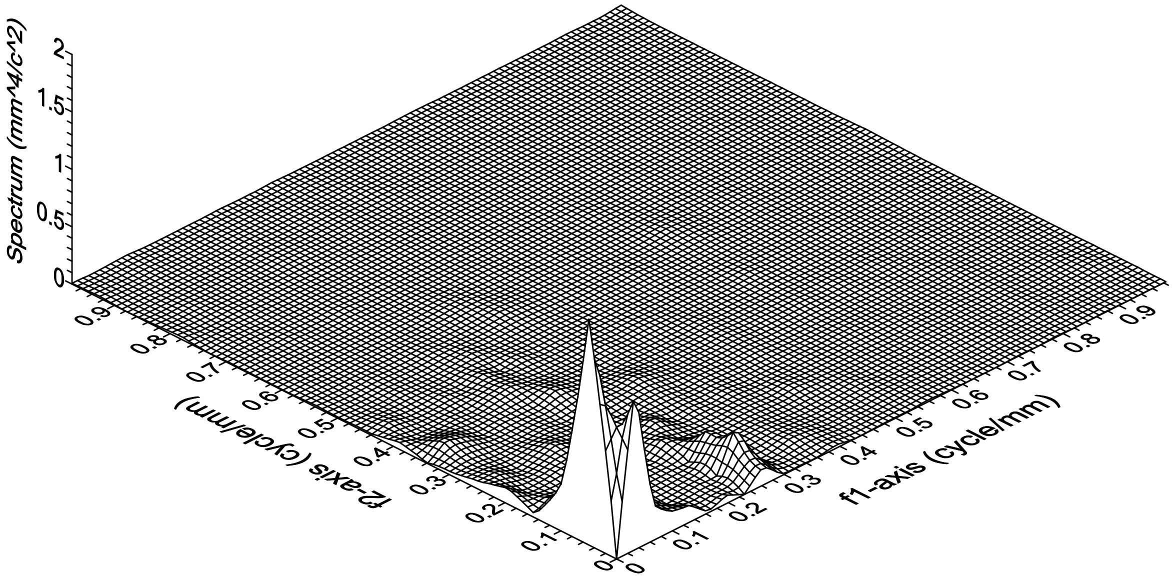

Figure 10. Power spectrum for sample plate piece exposed in the splash zone. The axis of the spectrum height, perpendicular to both frequency axes, has units of $mm^4/cycle^2$.

There is little variation in high frequency content for the form of the corroded surfaces. This was the case for all pieces of plate exposed to uniform (or near-uniform) exposure conditions. It 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 also means that for any exposure condition, relatively small coupons can be used to characterise the variability of the corroded surface.

5. DISCUSSION

The trends for the average corrosion loss as a function of exposure period (Figure 8) are in general agreement with the trends obtained earlier for small coupons, both for data reported in the literature and in our own experiments (Melchers 2003). All show an early period during which the rate of corrosion gradually decreases followed by an increase in corrosion loss which then declines with further continued exposure. This pattern is quite distinct for immersion corrosion. It is less distinct, and delayed, for the tidal and the splash zones and this is consistent with results for small coupons (Melchers 2003, 2007).

The standard deviations (SD) estimated according to (2) initially show an increase with increased exposure time but the rate declines after about one year exposure, significantly so for the splash zone and less so for the tidal zone. These results are difficult to interpret but could be related to bacterial influences, since it has been observed that the colonization and metabolic rates of bacteria can be highly erratic (Sanders and Maxwell 1983). Probably more important for engineering practice are the coefficients of variance, plotted in Figure 9. The values shown are rather lower than those reported earlier for small coupons (Melchers 2003b). The reason for this is that in the present case the estimates for SD and COV relate to the form of the corroded surface itself, that is to the variability of the profile of the surface rather than to mass loss (converted to corrosion loss) as was used for individual coupons. The latter is more relevant to estimates of uncertainty in structural strength, say.

Both the spectra, and simple inspection of the forms of the corroded surfaces of the plates show that frequency content of the corroded surfaces is closely bounded. It has a typical wavelength very much smaller than the size of the plate elements and this means that estimate means and standard deviations (variances, coefficients of variation) may be obtained, with sufficient confidence, on relatively small areas of plate, considerably smaller than those used herein. This has important implications but means that small coupons such as those used previously, can be used with a high degree of confidence for estimating variability. This conclusion should not be surprising when viewed from an electrochemical perspective. Typically, for wet corrosion, the anodic and cathodic regions are closely spaced, and after some initial period during which corrosion products build-up, these are largely protected from external influences. Thus the anodic and cathodic regions are likely to remain closely spaced. It is this spacing that has implications for corrosion variability.

6. CONCLUSION

The following conclusions may be drawn from this study:

1. Both visual observations of the corroded surface of large plates and the spectra extracted from the digitized surfaces of component plates show that the corroded surfaces of plates all exhibit a highly regular corroded surface. This applies for each of the splash, tidal and immersion corrosion zones.

2. The high degree of regularity indicates that it is sufficient to use relative small coupons to make estimates of mean corrosion loss and of the uncertainty in corrosion loss (variance, coefficient of variation).

3. The data trends given herein for exposures up to 2.5 years are likely to remain valid for much longer periods of exposure.

7. ACKNOWLEDGMENTS

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