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Long-Term Quantification of Structural Weld Capacity Loss due to Localised Corrosion

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Abstract: Severe localised corrosion has long been considered the main cause for structural integrity loss of steel assets exposed to aggressive marine environments, particularly as caused by pitting corrosion on or around weld zones. The weld heat affected zones for welds in steel structures are known for their higher rate of localized corrosion. The effects on corrosion losses on the structural reliability of welded mild steel, as commonly used within the offshore industry world-wide, are considered for quantifying the long-term loss of structural capacity. Apart from the expected reduction of capacity due to cross-section loss the results show that structural reliability is sensitive to likely nutrient pollution and macro-galvanic effects within the steel matrix. The possibility of localized corrosion being the result of thermal microstructural gradients produced during the welding process is discussed.

Keywords: Pitting corrosion, long-term, mild steel, weld, structural capacity, reliability.

1. INTRODUCTION

For many highly developed industrial societies, such as Australia, there are intense economic activities close to or on the seaboard. Naturally, there has been a steadily growing demand for larger, stronger, more efficient and safer infrastructure in practically every heavy industry sector. For the offshore and onshore coastal industry this becomes even more of a challenge as aggressive marine environment jeopardises reliability due to natural material deterioration. The transport of primary energy sources such as oil and gas through subsea pipelines is an example where larger diameters and higher operating pressures are desired alongside corrosion resistance [1]. Particularly for aggressive environments, alloyed steel is often the primary choice of material and welding the primary technique for component assembly [2].

Corrosion resistant alloys can reduce asset deterioration but at the expense of high material costs. However, passively protected corrosion resistant alloys (*i.e.* stainless steels) are prone to localised or pitting corrosion [3] and this may be severe at or near heat affected zones (HAZ) of welds [4]. Despite their low corrosion resistance, carbon steel and low-alloy steel are often an economical choice of material since corrosion mitigation techniques (*e.g.* cathodic protection) are readily available. Under less than adequate maintenance regimes, however, these steels

Usually, structural engineers design solutions for decades and not hours. It follows that the long-term quantification of structural weld capacity loss due to localised corrosion is a critical issue for the engineering design of marine facilities, including estimating the expected lifetime [6,7]. Given that the probability of failure for a given corrosion risk can be estimated on the basis of the severity and the extent of corrosion damage expected to occur on a component, this paper focuses on quantifying the long-term remaining structural reliability of weld capacity subjected to localised corrosion. Results may assist asset management, often determining the protective measures required or the sacrificial amount of steel to be used. It also may have major implications for determining appropriate maintenance regimes. The economic and safety implications are obvious [8].

2. LONG-TERM MARINE CORROSION

Information and data for the long-term corrosion of steel in marine conditions largely is confined in the literature to exposures much less than 10 years [6]. The few data for up to 16 years exposure indicate that the long-term maximum pit depth tends to follow a linear trend as a function of time t that can be described, for exposure periods greater than about 5 years by Eqn. 1:

$$c(t) = c_s + r_s \cdot t \quad (1)$$

where c_s is the 'y-intercept' at time $t = 0$ and r_s is the slope of the long-term trend. For the present study data from parent metal, weld and heat affected zones of mild steel welds exposed to Newcastle Harbour Australian Pacific waters [5,9] were used for the long-term quantification of maximum pit depth. This harbour is known to have relatively low levels of water pollution owing to high tidal flushing [10]. Moreover, 'bright-orange' localized corrosion was observed just below

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also may suffer heavy corrosion damage at weld and heat affected zones [5].

low water level and within the lower half of the tidal zone. These showed high cross-section losses or even complete wall perforations. At the time both microbiologically induced corrosion (MIC) and Accelerated Low Water Corrosion (ALWC) were suspected as contributing to the high corrosion losses observed [9,11] and this has since been shown to be consistent with observations elsewhere [10,12]. Port Corporation records showed that the piles were around 33 years old and had not been given protective coatings when first installed. Replacement of the affected piles permitted measurement of their corrosion losses to obtain estimates of the parameters c_s and r_s (Eqn. 1) for long-term maximum pit depth, [9].

The paper's methodology is describe by the following sections, where statistics for long-term localised corrosion loses are quantified along with best fit analysis in order to predict long-term weld capacity estimations. Effect of nutrient pollution and possible influence of microstructure are considered.

3. STATISTICS OF CORROSION LOSSES

The original wall thickness was nominally 16mm [13]. This was verified by careful examination of the samples for regions that appeared not to have corroded or to have corroded very little. Nevertheless, some uncertainty remains about the original wall thickness and its possible variation between the samples and over each sample surface.

The resulting wall thickness losses were then analysed using standard statistical techniques to obtain the statistics for each zone as shown in Table 1. It is immediately evident that the mean depth for the Heat Affected Zone (HAZ) is much greater than the mean depths for the other zones despite having similar standard deviations. Similar results have been reported for comparable exposure conditions [10]. Best fit analysis for maximum pit depth at time (t) = 33 years for each of the zones are presented in Table 2. Notice that a Frechet distribution would be the function of choice for reliable predictions.

The statistical results at 33 years exposure can be used in Eqn. 1 to determine the parameters c_s and r_s and the linear trend representing long-term corrosion. The estimated corrosion loss values are shown in Fig. 1 for corrosion in the HAZ and in the PMZ. Also, information about c_s was taken from [12] to give values of expected losses at close to time t = 0. From these the means were used to estimate the trends for the HAZ and the PMZ. Trends for the Weld Zone are similar but are not show ($c_s=0.301$ mm; $r_s=0.109$ mm/y). Also shown for illustration is the effect on the trends as a result of a 0.6 mgN/L increase in average dissolved inorganic nitrogen (DIN) concentration. The rationale for such a change is considered in the next section.

Table 1. Descriptive statistics for 33 year exposed steel weld zones maximum pitting corrosion loss (mm).

Region	PMZ	HAZ	WZ
Sample size	30	30	30
Range	2.991	4.372	2.617
Mean	3.204	4.692	3.691
Std. Dev.	1.004	0.933	0.704
COV	0.313	0.199	0.191
Min	1.839	2.895	2.557
Max	4.830	7.267	5.173

PM: Parent Metal Zone; HAZ: Heat Affected Zone; WZ: Weld Zone

Table 2. Best fit analysis for each zone data set at (t) = 33 years.

	PMZ	HAZ	WZ
Distribution	Frechet	Frechet	Frechet
Parameters	α : 3.424 β : 2.568	α : 5.794 β : 4.131	α : 6.286 β : 3.292
KS test	0.12	0.11	0.12

PM: Parent Metal Zone; HAZ: Heat Affected Zone; WZ: Weld Zone

Figure 1. Interpreted long-term maximum pit depth trends for the HAZ and the PMZ, based on the results shown in Tables 1 and 2 and in Ref [12]. Also shown are the effects of of a 0.6 mgN/L increase in average DIN concentration.

4. EFFECT OF NUTRIENT POLLUTION

Directly proportional to nutrient availability, microbiological influenced corrosion (MIC) may contribute to localised corrosion in natural seawaters. This involves energy intake and energy release [14, 15]. For some bacteria, energy changes result in measurable electric currents, potentially creating favourable for electrochemical reactions to take place and thus to contribute to corrosion. One mechanism is the changing resistance of surface film with metabolic products such as sulphuric or organic acids [14, 15]. In other cases, slime deposits may form at selective areas, including those promoted by surface roughness, so that they

become anaerobic [16]. As welding is known to cause changes to the microstructure and surface roughness, it is reasonable to assume that preferential microbiological attack is a possibility.

The long-term trends for the corrosion of steels in seawater have been shown to be a function of water quality and in particular the concentration of dissolved inorganic nitrogen (DIN) [12], a critical nutrient for microbiological activity. The severity of MIC also has been correlated with DIN [10]. To obtain some estimate of potential rises in DIN over a longer period of time, reported nutrient levels for the North Sea [17] may be considered indicative. These show that average DIN concentrations of 0.2-0.6 mgN/L have been reported for surface waters for winter and summer conditions [17]. It appears that regardless of seasonal effect, increases in land based sources account for the majority (65-80%) of total nitrogen inputs [17]. The effect of corrosion is that the introduction of large quantities of nutrients can lead to a considerable increase in bacterial and algal biomass. This can lead to localized anaerobic conditions and unfavourable corrosion conditions [18] as also seen in empirical in-situ studies [10,12].

5. EFFECT OF MICROSTRUCTURE

Because weldments exhibit special microstructural features they must be given careful attention in order to predict acceptable corrosion service life of welded structures [19]. The role of macro-compositional and micro-compositional variations common to weldments is emphasized in the literature, with empirical studies showing these to be the main culprits of highly localised corrosion and pitting [9,15,16,20,21,22,23,24]. Despite many reports considering these matters for passively protected corrosion resistant alloys (i.e. stainless steels) [19,25,26], empirical data for mild steel weldment corrosion is scarce [5,9]. Hence, controversy remains about specific role of microstructure on localised corrosion of mild-steel weldments.

In the early 1970's Butler and his colleagues [27] reported pitting measurements for pure iron and for chromium and copper ferrous alloys in neutral chloride solutions. Results showed that for pure iron the pits were generally polygonal in shape, while with chromium-iron alloys the shape is less regular and attack is confined to grain boundaries. If preferential grain boundaries attack is caused by micro-alloying elements, it would then be reasonable to assume that within heat affected weld areas, where crystal sizes are reduced, the higher concentration of grain boundaries followed by micro-segregation of elements could lead to preferential localised attack. Subsequently Jeffrey and Melchers [28] showed that primary pitting occurs at a few discrete points, followed by secondary pitting at a large number of points, eventually leading to wide, shallow pitting.

A somewhat different view is given by Matsushima who reports that, unlike pitting of passive

metals where formation of passive-active cells of large potential difference coupled with local breakdown of passivity leads to deeper pits, localized corrosion of iron and steel tends to be shallow in most cases, and this is claimed to be the result of the potential difference of various macro-galvanic cells being not as large [22,23]. A study where welded mild steel sheet piling heat affected area coupons were subjected to open circuit potential tests [9] showed that the parent metal is slightly more noble compared to the heat affected or weld areas. It was suggested that, even in small scale, different constituents in the banded weld structure could form galvanic couples. The macro-galvanic cells that frequently cause localized corrosion in steel in service are commonly formed by bimetallic contact, and inhomogeneous steel matrix. This is typical at weld joints. Matsushima [23] argues that in welded joints, the weld metal and/or HAZ corrodes selectively if it is less noble than the parent metal, which is commonly much larger in surface area than the weld metal and HAZ. This shift in potential is believed to be a result of the thermal cycle during welding operations.

Due to proximity to the fusion boundary, a wide range of heat affected zone (HAZ) microstructures can be produced [29]. The HAZ transformation to austenite on heating will be followed on cooling by transformation to give either a ferrite-carbide microstructure or martensite, depending on the material composition, peak temperature and cooling rate. Preferential HAZ corrosion cases in a range of aqueous environments has been reported [5,15,16,20, 21,22,23,24] however there is still some controversy regarding the specific mechanism involved. It has been suggested, based on theoretical considerations, that the presence of low-temperature transformation products such as martensite, lower bainite or retained austenite result in preferential corrosion sites [19]. If this is correct, steel compositions favouring increased hardenability (e.g. increased manganese content) may lead to localised corrosion, but micro-alloyed steels would be less susceptible. In practice this issue can be minimized by achieving the same alloying additions for the filler metal that are used to strengthen welds [30] or by making use of autogenous welding techniques when suitable [31,32].

6. EXPERIMENTAL METALLOGRAPHY

In an attempt to throw some light on the issues raised in the previous section an investigation was conducted on the potential influence that the microstructure of five (5) separate grades of steel has on corrosion [33]. Test coupons for five grades were available - the American Bureau of Shipping (ABS) certified grades A, B, D, AH, and DH [34]. The test coupons were not welded.

The experimental methodology adopted for the present work allowed for the development of representative micrographs for the five (5) steel grades

tested [33]. Three (3) replicate coupons (approx. 150 x 150 mm) of each grade of steel were retrieved at three (3) month and nine (9) month periods of exposure. Certified tensile testing information and chemical composition was obtained from the South Korean steel supplier. The grades of steel were chosen as the more common grades required across the broader shipping industry [34] which include ordinary strength grades A, B, D with average yield points at 281MPa, 329MPa and 394MPa respectively and higher strength grades AH and DH, with average yield points at 419MPa and 399MPa respectively. Table 3 summarises the chemical composition of the steel grades.

Table 3. Chemical composition of steel coupons (%wt)

Grade	A	B	D	AH	DH
C	0.15	0.14	0.15	0.16	0.16
Si	0.01	0.19	0.24	0.37	0.39
Mn	0.88	0.90	0.89	1.45	1.43
P	0.015	0.019	0.018	0.016	0.016
S	0.007	0.010	0.012	0.004	0.002
Cr	0.02	0.02	0.02	0.01	0.01
Ni	0.01	0.02	0.02	0.02	0.02
Cu	0.02	0.02	0.05	0.01	0.01
Al	-	0.05	0.04	0.03	0.03

* All grades: Traces of Mo, Ti, Nb, V

The coupons were exposed at the NSW Port Stephens Fisheries Research Institute, at Taylors Beach NSW. The site has temperate waters with low pollution and low water velocities. Taylor's Beach has been utilised as a corrosion exposure testing site previously [10]. It is well documented and allows results of the present project to be compared with previous results.

In accordance with the standardised recommendations [35] the coupons were marked with a unique designation prior to exposure testing. Fig. 2 (a) shows a coupon upon recovery and (b) cleaned coupon identification markings. Coupon cleaning consisted of mechanical brushing using nylon brush under tap water followed by chemical cleaning according to designation C3.5-Table A1.1 of the ASTM standard [35]. Once removed from the chemical solution, coupons were rinsed under tap water, oven dried and weighed for mass loss evaluation. Smaller 15 x 15 mm corner offcuts were taken from each grade for metallographic analysis. A slow rotation wet drop-saw was used. Care was taken to ensure negligible damage to the microstructure of the coupons. The coupons were then cold mounted into epoxy resin (Struers Specifix-20) according to product recommendation of mixing weight ratio of seven (7) parts of resin and one (1) part curing agent. Industry standard of grinding and polishing steel coupons was followed and automated abrasion used [36]. Polished surface were etched (2% NITAL) and micrographs taken (Zeiss AXIO Imager A1 – 20x objective).

Figure 2. (a) Representative coupon upon recovery depicting marine growth and darker under deposit rust product, (b) cleaned coupon identification marks.

Figure 3. Graphed calculated thickness loss and corrosion rate as per table 4 for each grade of steel.

Table 4. Average corrosion loss (mm) for each grade of steel tested per each exposure period.

Grades	Time of Exposure			
	0.25 year	0.5 year	0.75 year	1 year
A	0.041	0.056	0.088	0.155
B	0.051	0.054	0.084	0.119
D	0.014	0.045	0.146	0.157
AH	0.069	0.082	0.106	0.114
DH	0.047	0.069	0.095	0.123

Figure 4. Representative coupon micrograph (grade DH) after 0.75 year exposure.

7. LONG-TERM CAPACITY ESTIMATION

It has been demonstrated how severe localised corrosion can be considered in design to produce a sufficiently safe asset with a more reliable long-term service life [5,7,9]. The associated probabilistic approaches have been demonstrated by a number of investigators. This also suggests that it is appropriate to use probabilistic approaches rather than a deterministic approach for the study of asset life assessment.

As an example, consider a welded commercial AU25 sheet profile which is 14.5 mm thick [37]. Let it be assumed, as is reasonable in practice, that the welded profile is unprotected, having no protective paint coatings or cathodic protection. Let it be assumed that failure, as defined as the completed wall perforation, will halt strength and serviceability requirements tied to the welded profile. Once complete wall perforation has occurred it shall be considered that the profile cross-section has reached critical stress state for structural failure and thus is at the onset of yield. For the purpose of the welded profile analysis, and for the reliability analysis it will be reasonable, if not slightly conservative, to assume reaching of the failure condition for a single point in the weld is equivalent to failure of the whole system. After all, single wall perforation for containment structures can result in catastrophic consequences [7].

To estimate the probability of failure P_f of the welded profile, let the limit state function be defined as usual as:

$$P_f = P[G(t) < 0] \quad (2)$$

where $G(t)$ is the time dependent limit state function, defined as the difference between the steel pile yield stress capacity (f_y) and maximum stress on the critical pile cross-section (σ_{max}) which is inversely proportional to available cross-sectional area due to corrosion as respectively per:

$$G(t) = d_o - c(t) \quad (3)$$

As usual, $G(t) > 0$ indicates the safe region, $G(t) = 0$ indicates the failure surface and $G(t) < 0$ indicates the failure region. As the cross-sectional capacity is inversely proportional to remaining cross sectional area, the limit state for the profile weld is given by:

$$G(t) = d_o - (c_s + r_s \cdot t) \quad (4)$$

where c_s and r_s are the intercept and slope parameters of the long-term pit depth loss and d_o is the initial thickness of the profile.

The random variables and their means and coefficients of variation (COV) adopted for the present example are summarised in Table 5.

Table 5. Basic design random variables and statistical properties assumed.

Symbol	Unit	Type	Mean	COV
d_o	mm	Gaussian	14.5	0.05
c_s (HAZ)	mm	Gaussian	0.502	0.07
c_s (PMZ)	mm	Gaussian	0.105	0.05
c_s (WZ)	mm	Gaussian	0.301	0.05
r_s (HAZ)	mm/y	Frechet	0.127	0.19
r_s (HAZ) nutri adj.	mm/y	Frechet	0.182	0.19
r_s (PMZ)	mm/y	Frechet	0.094	0.31
r_s (PMZ) nutri adj.	mm/y	Frechet	0.121	0.31
r_s (WZ)	mm/y	Frechet	0.109	0.19
r_s (WZ) nutri adj.	mm/y	Frechet	0.143	0.19

c_s is maintained for all adjusted linear extrapolations as recalibration differences are negligible.

The uncertainty associated with the parameters c_s and r_s for the corrosion losses (Eqn. 1) is an important factor in the reliability analysis. Parameter c_s mean and COV were obtained based on previous work [12] as a function of DIN of Newcastle Harbour. Parameter r_s mean was obtained from Eqn. 1 by considering the slope intercept (c_s) and average corrosion loss given from the each data set.

The reliability analysis was performed using the Monte Carlo reliability method [38]. For the effect of nutrient concentration increase, the numerical analysis was performed by considering the rise as a series of constant step increases, allowing a simple readjustment with time of the average values of slope gradient r_s . The results obtained (Fig. 5) are discussed in the next section.

Figure 5. Welded profile probability of failure for given example and estimations considering effects of elevated DIN nutrients for each of the weld zones.

8. DISCUSSION

8.1 Structural reliability analysis

By considering an independent annual probability of failure and an acceptable reliability index of 2.3 ($P_f = 1.0\%$) [39] we obtain for the HAZ data probability of failure reaches the probability limit of acceptable design risk (collapse) after only 35 years of exposure. The welded profile parent metal zone would reach this threshold after 50 years of service while the weld zone would reach the threshold after 42 years of service. Using the nutrient adjusted data sets, the structural reliability estimates show that there is a difference in asset life serviceability estimations, with the estimated probability of failure reaching the threshold after 24 years for HAZ nutrient adjusted data; 39 years for PMZ nutrient adjusted data; and 32 years for WZ nutrient adjusted data.

Overall, these results are consistent with practical failure reports, which show that some piling infrastructure is deemed unsafe 10 to 20 years earlier than its design life [13]. Note the rapid increase in the probability of failure as a function of time for all data sets. This is somewhat expected for accelerated corrosion rates as illustrated in Fig. 5 only after a few years into exposure. This can be explained by reference to the influence of microbiological corrosion [12,18] in which microbiological growth tends to occur exponentially under elevated nutrient conditions. This means that it could be expected that risk levels would increase rapidly with time. However, what is perhaps alarming is the difference in the rate of increase in probability of failure for the HAZ data and compared with the rate for the PMZ. Indirectly this also shows the importance of correct interpretation of the phenomena that influence corrosion processes. A good understanding of the factors in corrosion mechanics is important for accurate estimation and prediction. Usually predictive capability is limited by quality and quantity of statistical input [38].

Overall, the trends for the probability of failure with nutrient increase (Fig. 5) are similar to the uncalibrated trends. The most noticeable difference is that risk levels increase at an earlier stage. As expected, a slow increase of nutrient availability with time would produce a somewhat constant effect on corrosion loss slope gradient. As noted, Fig. 5 shows that the probability of failure increases with increasing service life t , as would be expected.

A sensitivity analysis was carried out to access the relative contributions (α_2) and the associated probabilities of failure (P_f) as a function of service life, t (exposure period in years) of the model parameters for the example pile described above. This was done by changing the mean of each random variable by 10% and observing the effect of such change in the overall welded profile probability of failure. This is a well-established technique [38]. The relative contribution of random variable initial thickness (d_o) is very low and this continues to be the case over the total service life. This indicates that this random variable do not contribute much to the overall failure probability. Intercept parameters (c_s) was found to have a small influence on the overall reliability estimates. However, their contributions were found to increase gradually with increased service life. The relative contribution of the slope gradient (r_s) is noticeable and clearly the variable that has strongest effect on reliability estimations.

The statistics given in Table 2 are for steel that has been exposed for 33 years to seawater. This means that the corrosion loss process was well into the long-term corrosion range. As has been shown by extensive data analysis and model studies [7,11,12,40] this means the corrosion processes and hence the corrosion behaviour can be considered to be in a different phase to the corrosion processes that apply much earlier. It follows that, as represented by the bi-modal model for the progression of corrosion [12], the population from which data might be extracted, changes with the progression of time. Until recently a lack of suitable long-term data followed by insufficient understanding of the changes in the corrosion processes and the related fundamentals involved often led to the erroneous assumption that all data for corrosion, no matter how long the exposure period, arise from a single population of measurements [35,41]. It follows that for the prediction of long-term corrosion and associated probabilities of occurrence, statistics for long-term corrosion are of interest. These are shown in Table 2.

Table 6. Reliability and Sensitivities as a function of service life (t) in years.

Symbol	Relative contributions (%) or (α_2)					
	$t=1$	$t=10$	$t=20$	$t=30$	$t=40$	$t=60$
d_o	0.01	0.01	0.01	0.01	0.01	0.01
c_s (HAZ)	0.01	0.01	0.03	0.03	0.07	0.09

c_s (PMZ)	0.01	0.01	0.02	0.02	0.03	0.04
c_s (WZ)	0.01	0.01	0.02	0.03	0.04	0.05
r_s (HAZ)	99.8	99.8	99.6	99.6	99.2	99.0
r_s (PMZ)	99.8	99.8	99.7	99.7	99.6	99.5
r_s (WZ)	99.8	99.8	99.7	99.6	99.5	99.4

Overall the above results and observations are consistent across all three data sets analysed: HAZ, PMZ and WZ. They confirm the expectation that long term corrosion parameter r_s plays an important role in the reliability of marine infrastructure such as steel piling that typically have relatively long service lives. This expectation is reflected also in the sensitivity analysis, where r_s is shown to have a much stronger influence than the other parameters. It is considered the reason for the sudden increase in failure probability seen in Figs. 5 after a certain period of exposure (20 or more years). However, the outstanding difference between the results is the difference in the probability of failure estimated using the HAZ data compared with the PMZ data for the uncertainty related to cross sectional loss (i.e. it is the form of corrosion that mostly likely leads to failure). This is clearly illustrated by the trends in Fig. 5.

As noted, MIC is a function both of annual mean seawater temperature and microbiologically influenced corrosion [12,18]. The latter also is influenced by seawater temperature. High corrosion losses of steel piling due to MIC have been reported [10,13,18]. In addition, environmental changes such as a long term increase in seawater temperature can have an effect on the amount of nutrients available for bacterial metabolism, largely because of land-based changes causing greater nutrient run-off [17]. This has a direct effect since both c_s and r_s are positively correlated with annual average concentration of dissolved inorganic nitrogen (DIN) in local bulk seawater [12]. If it is assumed as an example, and conservatively where no pre-emptive mitigation action was taken, that there is a seawater temperature rise, it is likely that the increase in water temperature will have a slow but very considerable effect on marine fauna and flora. In turn this likely to have a major influence on corrosion through microbiological effects since, apart from most bacteria, not all species are likely to survive such changes and dead organic material constituents a source for bacterial metabolism [42].

8.2 Metallographic analysis

As can be seen in Figs. 4, typically low carbon steel ferrite (white) and pearlite (black) microstructure is present. What is interesting to note is the change in crystal concentration and distribution which is consistent for the different steel grades.

Comparatively, the micrographs of the coupons without hardening (A, B, D) show the presence of nearly 80% of ferrite-rich areas while highly clustered ferrite crystals can be observed in steel coupons that

went through hardening (AH, DH). It should be clear that a more homogeneous and finer distribution of ferrite and pearlite is associated with a longer total length of grain boundaries. As described previously, both conditions, grain boundary length and micro-segregation of elements, are considered to be linked to elevated severity of localised corrosion attack [27]. Usually leading to more numerous and deeper pits.

From the microstructures of the coupons investigated in the present series, it appears that the layout of lamellar cementite (pearlite) and ferrite regions has an influence on the corrosion rates. As shown in Figure 3, experimental mass loss of steel grade AH was the highest for the three (3) month exposure and coupon D for the (9) month exposure period. Based on the mechanistic theory of preferential grain boundary attack and influence of micro-alloying elements previously discussed [27] the higher mass losses are believed to be attributable to a higher rate of localised corrosion across the entire surface, with areas of localized corrosion then amalgamating into what is perceived as a general corrosion. This assumed mechanism becomes plausible when taken into consideration the reported experimental observations of numerous shallow secondary pitting following localised pitting [28].

The presence of non-metallic inclusions, such as manganese sulphides, could also be responsible for the observed differences in mass losses (Fig. 3) since they are known to increase pitting [43]. Steel grades AH and DH contain almost double the amount of manganese compared to grades A, B and D (Table 3). As noted above, experimental evidence has shown that steel compositions favouring increased hardenability (i.e. as a result of increased manganese content) are more prone to localised corrosion [19]. Both for passively protected alloys and for steels, manganese sulphide inclusions are known to initiate galvanic cells and to promote further damage through cracking [43,44,45]. As manganese sulphide inclusions have a tendency to occur at grain boundaries due to the manganese lowering the solubility of sulphur [43], the development of the corrosion pits is likely to initiate within the anodic zone of ferrite, thus developing the pits from an atomic scale to a visible scale.

The influence of steel microstructure on the corrosion process has been widely studied [19,25] but there is still no general agreement on the matter. However, various microstructural components within steels have been shown to influence not only the mechanical properties, but also its corrosion resistance [46,47,48]. Thus, by adopting steel preparation and treatment methods that allow for homogenous microstructures a recognisable increase in corrosion resistance of steels should be observed. Further, it is noted that in addition to the influences described above, the microstructure of steel may contribute to corrosion rates in other ways, such as through affecting inhibitor performance [49].

9. CONCLUSION

Localised corrosion of welded steel infrastructure is known to be a function of the local concentration of nutrients necessary for microbiologically influenced corrosion. A linear, long-term corrosion loss model was calibrated to data obtained from the 33 year localised corrosion of a welded mild-steel profile in Newcastle Harbour and the variability in the model parameters estimated. The reliability analysis for typical welded mild-steel profile exposed to nutrient pollution similar to that of the North Sea showed that the rate of long-term localised corrosion loss has variability about one order of magnitude greater than the variability of all other parameters. Variability of the long-term corrosion rate therefore has a major influence on the overall probability of failure estimates.

The observed results provide support for the notion that increase in hardness, characteristic of weld zones, promotes reduced crystal size and therefore increases the total length of grain boundaries. With an increased total length of grain boundaries corrosion pits are likely to initiate within the anodic area between ferrite content surrounded by collections of pearlite increasing the susceptibility of hardened steel to localised galvanic corrosion.

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