

A new approach for quantification of corrosion losses on steels exposed to an artificial seawater environment

Muntazir Abbas^{1,2*}, Nigel Simms¹, Syed Haider Mehdi Rizvi²

¹ SWEE, Cranfield University, Cranfield, Bedfordshire, United Kingdom

² National University of Science and Technology, PNEC, Karachi, Pakistan

Corresponding author's email address Muntazir.Abbas@pnec.nust.edu.pk

Abstract

The selection methodology for thickness loss measurement is very important to determine the extent of corrosion damage, as well as in formulation of corrosion prediction models and inspection/maintenance plans for offshore structures. This paper introduces a more accurate corrosion measurement technique, based on the pre-exposure dimensional metrology and post-exposure optical microscopy/image analysis on the cross-sections of steel samples. During this corrosion test, the surface grinded and uncoated steel samples were submerged vertically in an artificial seawater solution, for a duration of up to a maximum of 365 days. The corrosion damage experienced on the steel samples means that the dimensional metrology can be more accurate, and useful approach to measure both uniform and localised corrosion losses simultaneously than the conventional average mass loss method.

Keywords: artificial seawater, corrosion loss measurements, dimensional metrology, image analyser, uniform/localised corrosion

1 Introduction

Corrosion in metallic structures exposed to seawater medium takes place due to the electrochemical reactions between metallic surfaces and surrounding environment [1,2]. Typically, the corrosion phenomenon in offshore steel structures takes place by forming various kinds of corrosion deposits mainly comprised of iron oxides, hydroxides, oxy-hydroxides, and complex species rich in chlorides, sulphides, etc. [3–9]. Chemical constituents in the natural seawater bodies vary significantly in different geographical locations, and so does the variation with the seawater depths even within the same regions [10,11]. Corrosion rates in seawater submerged steels may differ significantly with change in the following seawater parameters: seawater temperature, Dissolved Oxygen (DO) concentration, pH levels, salinity levels, flow velocity, and concentrations of various forms of amalgams/pollutants including Dissolved Inorganic Nitrogenous (DINs) compounds and sulphur containing compounds [12–14].

The seawater surface temperature across various global seawater reservoirs has been reported from -2°C near poles to approximately 35°C near the equator [10,15]. As a result, there is a large difference in corrosion rates being experienced on offshore steel structures between seawaters in the colder regions and hotter regions [13,14,16–18]. Evaluation of these variations in corrosion influencing environmental factors is significant for determining the rate of corrosion damage, predicted service life, failure frequencies, and periodicity/costs of maintenance management in offshore assets [17,19,20].

Corrosion-induced damage is often measured as an average corrosion rate/loss [4,21–23], whereas in most of the ageing offshore structures exposed to corrosive environments, it is the regions of deepest corrosion damage that usually lead to a loss of integrity/containment or functional failures [24–28]. According to some of the previously conducted research studies the standard average corrosion method typically used for the quantification of average (uniform) corrosion rates may underestimate the corrosion damage [21,22,27]. Moreover, uniform corrosion loss calculated using conventional standard mass loss method is just not enough to predict risk of containment related failures occurring in offshore structures. It is the localised/pit corrosion that often lead such failures in offshore platforms. At times, the method typically used for the measurement of localised corrosion [29] become more

cumbersome, time-consuming, prone to errors and difficult to measure pit depths (manually or by optical microscopy) [21,29,30].

In recent years, some researchers have quantified metal losses and associated uncertainties logically in terms of various statistical parameters (e.g., mean, median, standard deviation, cumulative probability distribution, etc.), to track the performance of metals exposed in different corrosive conditions [27,31–33]. However, selection of suitable statistical parameters for quantification of metal losses/damages depends on the type of required information, and the measurements that have been made [34,35].

The dimensional metrology (DM) is a more accurate and a more reliable technique that has been applied in the recent years, for measuring corrosion depths on metals exposed to hot corrosion environment. It is based on pre- and post-exposure dimensional measurement for corrosion (uniform/localised) damage depths on samples, as a function of cumulative probabilities [36–38]. This paper quantifies corrosion losses on seawater exposed steel samples, using a DM technique integrated with an optical microscope and a digital image analyser. This corrosion measuring approach comprises physical dimensional metrology on the steel samples before and after their exposure in artificial seawater at 40 °C. Various statistical parameters were calculated using the data gathered that allow more interpretation of corrosion mechanism taking place in an artificial seawater solution.

2 Experiments and methodology

2.1 Experiments

Prior to the corrosion test, the composition of steel samples (S-275) was examined using the Atomic Emission Spectroscopy (Q4 Tasman) and Energy Dispersive Spectroscopy (TESCAN VEGA3). Table 1 shows elemental compositions of the steel samples.

Table 1 Elemental composition (wt. %) for steel samples used for laboratory based corrosion tests using artificial seawater

Fe	C	Mn	Si	Al	Mo
Balance	0.1	0.34	0.13	0.3	0.2

The corrosion tests were conducted in non-metallic tanks placed in a controlled laboratory environment for duration up to a maximum of 365 days. The corrosion tanks

were installed with a temperature controller, water circulation pump, filtration, and water level control system, to maintain the desired range of seawater quality, and flow velocity (as shown in Table 2). The seawater quality parameters were measured in the corrosion tank with the help of a multi-meter (HANNA–9128) throughout the duration of experiments, and desired seawater quality was maintained accordingly. Table 2 shows artificial seawater specifications maintained throughout the corrosion tests.

Table 2 Seawater quality parameters maintained during corrosion tests for an exposure duration of up to a maximum of 365 days

Parameters	Units	Values
Temperature	°C	40 ± 2
DO	mg/l	3.4 ± 0.7
pH		7.8 ± 0.2
Conductivity	mS/cm	60 ± 3
Salinity	parts per thousand (ppt)	40 ± 2.6
Velocity	m/s	~ 0.3

In this research, the mean values of seawater temperature and salinity level/conductivity in the corrosion tank were maintained at 40°C and 40 ± 2.6 ppt (conductivity of 60 ± 3 mS/cm), respectively. The seawater salinity levels (of 40 ± 2.6 ppt) were maintained in corrosion tanks by adding approximately 4 kg_s of sea salt in 100 litres of freshwater, which is equivalent to the maximum salinity levels in natural seawater of the Arabian Sea [22,39,40]. Although, similar corrosion experiments in artificial seawater medium at salinity levels of 40 ± 2.6 ppt were also conducted at different seawater temperatures, to estimate the influence of seawater temperature on the rate of uniform/localised corrosion, however, detailed deliberation of the same is beyond scope of this paper.

Table 3 shows typical composition of sea salt (Peacock Salt U.K.) used to prepare artificial seawater solution (by mixing it with freshwater in the laboratories of Cranfield University U.K).

Table 3 Composition of sea salt used in preparation of artificial seawater (at a concentration of 4 % i.e., 40 ppt)

Chemical compounds	Percentage (%)
NaCl	66.1
MgSO ₄	16.3
MgCl ₂	12.7
CaCl ₂	3.3
KCl	1.6

The experimental samples of steel were cut into 100 mm x 50 mm x 3.5 mm blocks and their surfaces were ground to a finish of 600 UK grit, followed by cleaning in the deionised water/acetone prior exposing them in the tanks containing artificial seawater. The steel samples were recovered in duplicate after every exposure duration between 90 – 365 days. The post-exposure cleaning of steel samples was carried out mechanically and chemically, as per the ASTM standard G1-03 [41]. Finally, the post-corrosion samples were washed in an ultrasonic bath using deionised water and acetone, for complete removal of corrosion deposits from the surfaces of steel samples.

2.2 Corrosion measurement approach

In this paper, a dimensional metrology (DM) based method was used for (i) measurement of pre-exposed steel sample dimensions at pre-determined thickness positions, using a digital micrometer (ii) accurate measurement of the corrosion depths on post-corrosion samples with the help of a digital image analyser; integrated with an optical microscope. Initially, the pre-exposure contact metrology of sample dimensions was carried out using a Mitutoyo-293 micrometer having round/tapered tips (resolution of 1 μm , and an accuracy of 2 μm). The surfaces of rectangular plate-shaped steel samples were marked up (as shown in Figure 1), and their pre-exposure thicknesses were taken at and around every predetermined position, prior exposing them in artificial seawater solution. After the seawater exposure, thicknesses at the predetermined positions and their immediate vicinities were measured again on steel samples, using manual micrometry (where possible), and the DM-image analyser techniques.

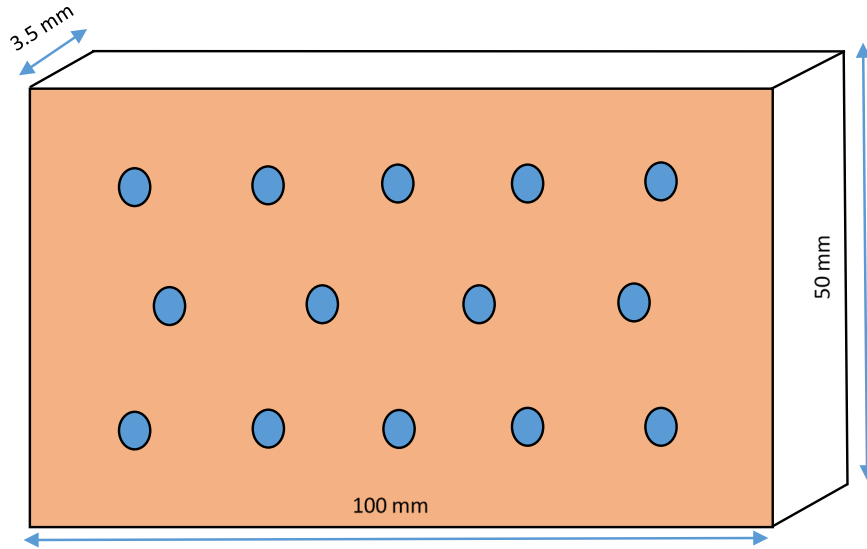


Figure 1 Schematic of the pre-exposed pattern for measuring initial thicknesses of samples and for comparing with thicknesses/dimensions of corroded samples

The DM-image analyser technique is primarily a destructive thickness loss measurement approach in which the sample cross-sections are prepared by cutting corroded samples into several parts (without missing the regions of maximum pit depths), followed by mounting them in a low shrinkage epoxy resin (ballatoni-filled), as shown in Figure 2. In this study, the cross-sections of post-exposed corroded steel samples were cut (using a precision saw fitted with a diamond cutting blade), as per the procedure given in BS ISO 26146 standard [42], and prepared cross-sections were mounted in circular flat-based jigs using epoxy resin. An abrasive cutting machine (Brilliant 220) was used for sample cutting, followed by the grinding/polishing using 240, 600 and 1200 UK grit size sand papers. Final polishing was carried out with 6-micron and 1-micron sheets, lubricated with respective diamond particle lubricants.



Figure 2 Grinding and polishing of mounts (using SAPHIR 550) to prepare cross-sections of corroded steel samples, for measurement of corrosion depths under DM- image analyser technique

A digital image analyser (integrated with an optical microscope) was used for post-exposure dimensional metrology on the prepared cross-sections, as shown in Figure 3. The software 'Axiovision' was used to acquire images around entire periphery of the mounted cross-sections. An excel spreadsheet was then used to calculate thickness loss data, from the difference in the surface position on steel samples before and after their exposure to the seawater. The digital image analyser was connected to the optical microscope via a lens (magnification 20X) and a high-resolution digital camera. The system also includes a computer-controlled motorised x-y stage with a positioning accuracy of $\pm 1 \mu\text{m}$. On the steel samples used in this research, the image analyser was set to calculate the x-y coordinates of 60 equally spaced measurement positions around the cross-sections. These measured x-y coordinates were transferred to a bespoke spreadsheet and combined with the pre-exposure dimensional measurements of the samples, to determine the metal loss in series of steps.

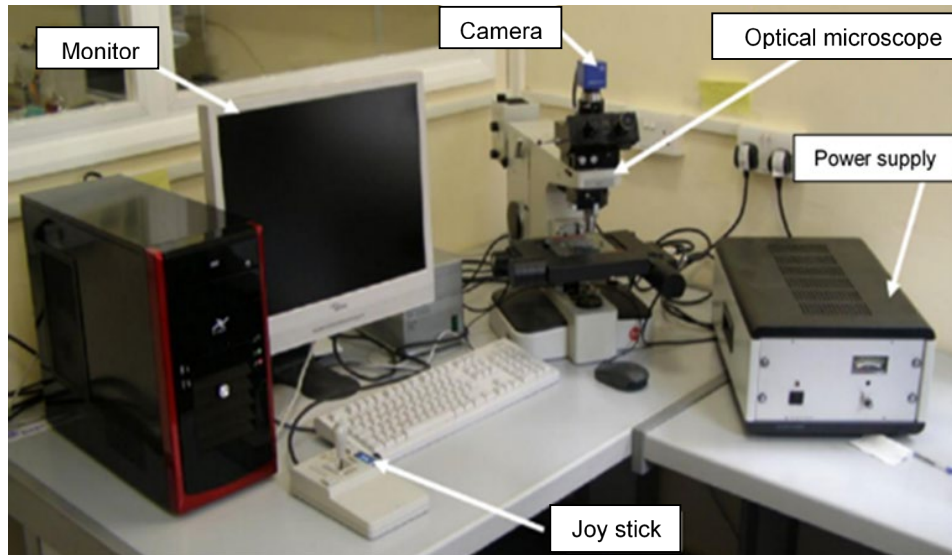


Figure 3 Digital image analyser and optical microscope arrangement used for thickness loss measurements (using DM-image analyser) at Cranfield University U.K.

Figure 4 shows a typical profile of a pre- and post-exposure steel sample using a special excel spreadsheet. The x and y coordinates of each point on post-corrosion steel samples (shown by yellow lines with triangles) indicate the dimensions of the remaining thickness profile of an originally rectangular steel sample (shown by red dotted lines). The corrosion depths experienced by steel samples are calculated by taking the differences between the two datasets using a bespoke excel spreadsheet.

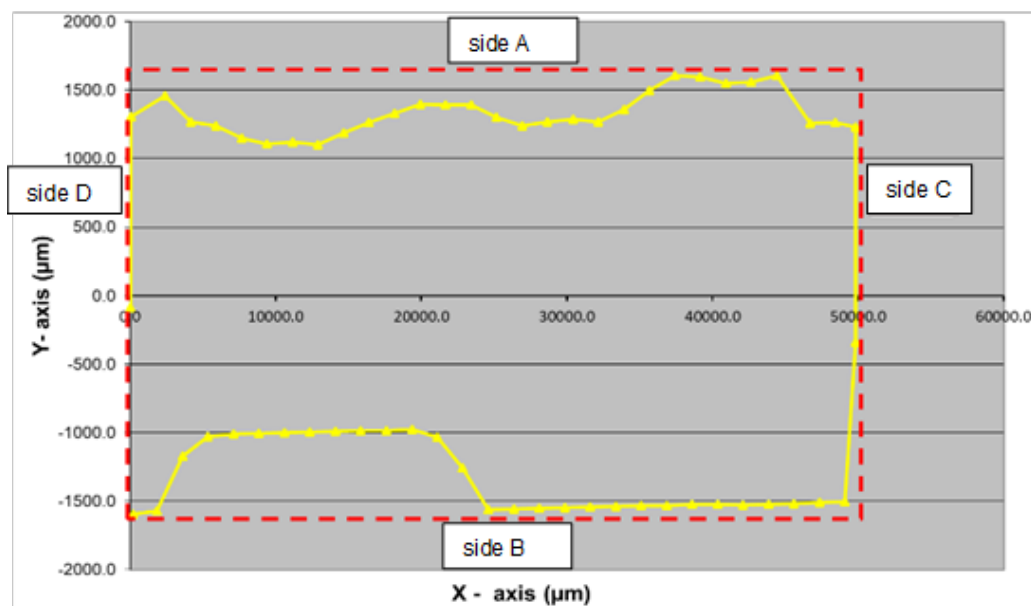


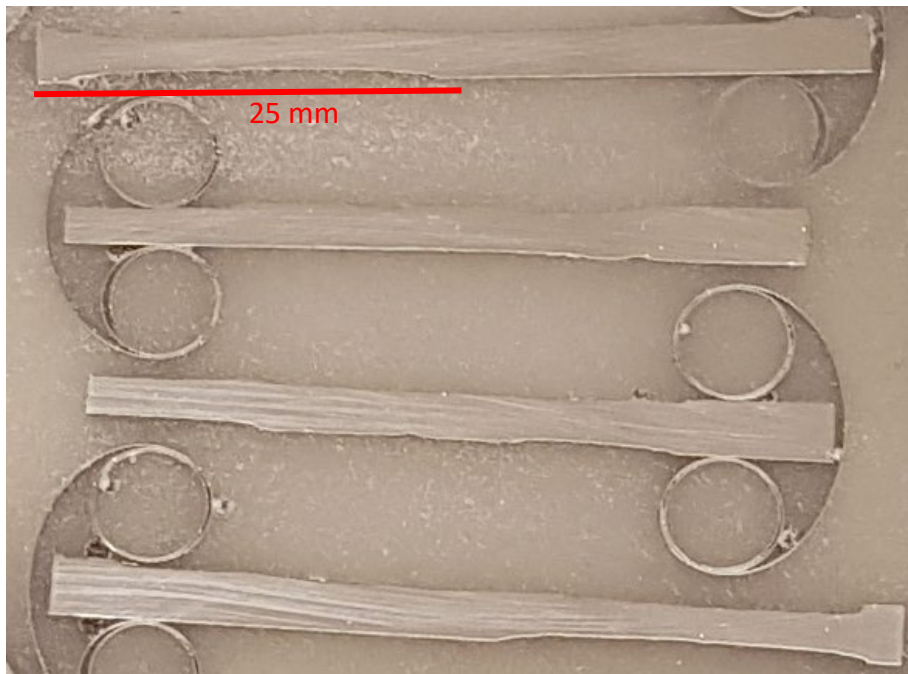
Figure 4 Typical surface positions of a pre-exposed rectangular steel sample (reference) and a corroded steel cross-section, shown on the special excel spreadsheet developed for DM-image-analyser technique

As a finite number of thickness measurements have been taken on each cross-section, the data can be presented in terms of its cumulative probability of a certain damage level being exceeded (expressed as a percentage (%)) or a standard deviation (SD). The calculated metal loss values at various positions are ranked in the order of their magnitude and then the cumulative probability is determined using following equation.

$$\text{Cumulative probability (\%)} = \frac{n}{N+1} \times 100 \quad (1)$$

Where 'n' indicates rank number and 'N' is the total number of points.

Thus, the distribution of metal losses can be calculated as a function of their cumulative probabilities. Here, the edges of steel samples may also not represent actual corrosion losses of larger faces, and they may mislead the actual corrosion loss or measurement errors. Therefore, these regions around edges and sample holding holes have been avoided during the preparation of samples, as well as during the thickness loss measurements. Figure 5 shows a pictorial view of the cross-sections of corroded steel samples, prepared in resin-filled moulds.



Post exposure cross-sections of steel samples

Figure 5 Post-corrosion steel samples prepared for corrosion thickness loss measurements using DM-image analyser approach

In addition to the DM-image analyser approach, the corrosion losses were also calculated using the typical average mass/weight loss method [21] and compared its results with those quantified using DM-image analyser approach.

Overall, the DM-image analyser technique is a more specialised/detailed corrosion measuring approach that provides more thickness loss points and enables quantification of exposed or internal corrosion depths with greater point density in a specific location. The DM-image analyser technique by virtue of the integral optical microscope (20 x lens magnification) can show a magnified view of the complex, localised corrosion defects and enables their accurate measurement.

On the other hand, the DM technique has its own limitations, as it is specialised and relatively complex method involving specialised tools and an intensive excel formulation, therefore, it requires adequate operator training to use state of the art equipment. Secondly, prepared cross-sections in the DM-image analyser technique are only a part of comparatively large corroded coupons, hence it is possible that they may not reflect the entire profile of corrosion losses when selected cross-section regions are not appropriate. Therefore, variations in measured corrosion depths and mean corrosion losses are also dependent on the qualitative selection of post-corroded coupons to be viewed and measured under optical microscope/image analyser of DM technique.

3 Results

Figure 6 and Figure 7 show corrosion depths (on either side/face of the sample plate), as a function of cumulative probability (%) and cumulative normal probability (SD) and calculated using DM-image analyser method. The datasets after long exposure durations (of up to 365 days) show significant metal losses at lower levels of probability with relatively steep gradients, whereas relatively lesser metal losses and lower gradients were observed at short exposure durations (up to initial 150 days). The higher gradients indicate localised corrosion losses and uneven distributions of damage. Here, in Figure 6 and Figure 7, [(thickness change) * (-1) = corrosion loss].

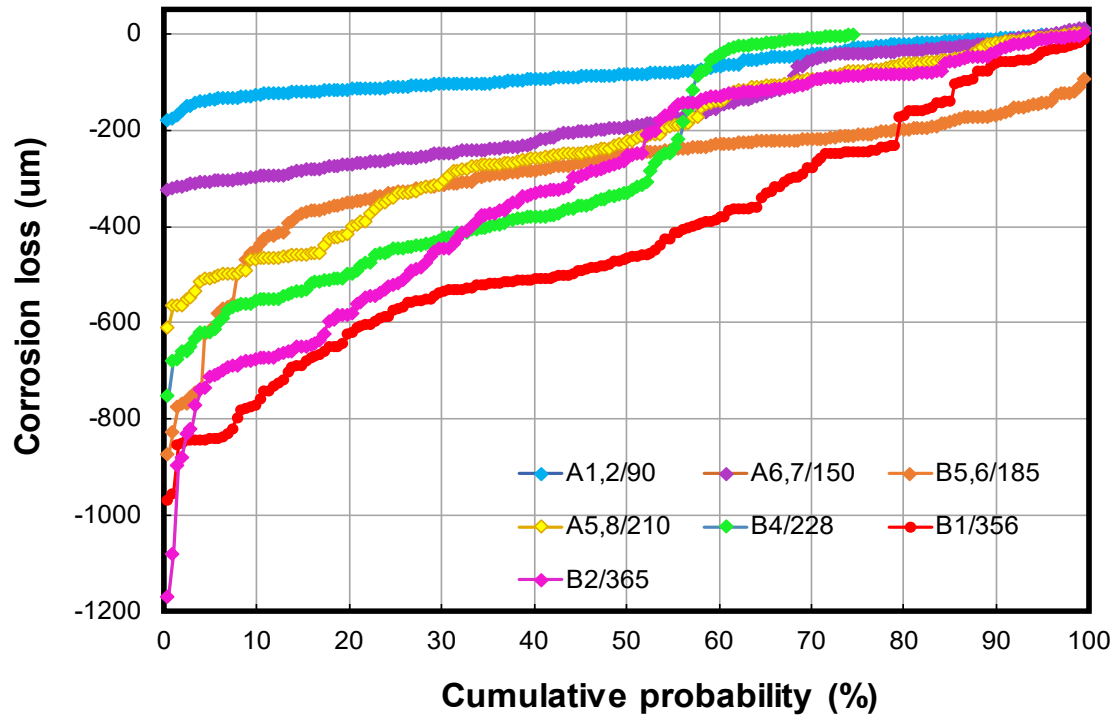


Figure 6 Cumulative probability (%) of corrosion loss data calculated for steel samples using DM-image analyser approach. The legends indicate 'sample name/exposure duration'

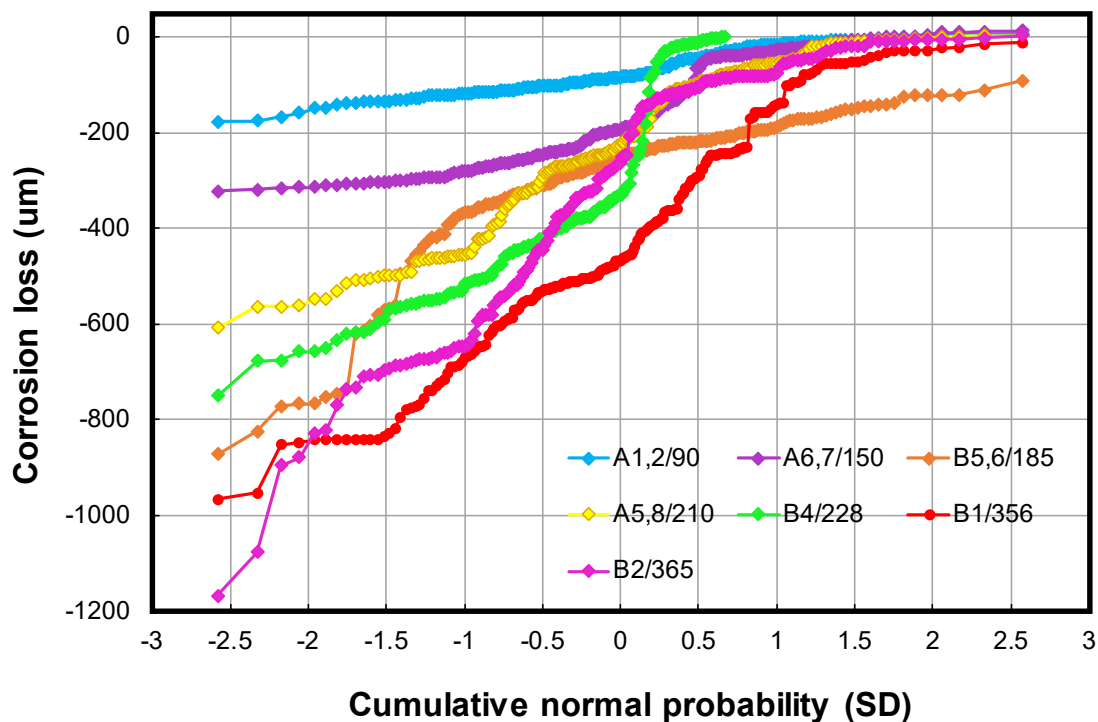


Figure 7 Cumulative normal probability (SD) of corrosion loss data calculated for steel samples using the DM-image analyser approach

These plots (in Figure 6 and Figure 7) illustrate that both the corrosion depths have increased gradually with increase in the duration of exposure. The maximum corrosion

depths between 0.9 -1.2 mm were noticed after 356 - 365 exposure days. Further, using the metal loss data in Figure 6, the statistical parameters of median, mean, and maximum corrosion depth have been compared for each exposure duration in Figure 8. These corrosion trends have shown that the mean corrosion loss values (measured using dimensional metrology) increased steadily with an increase in the exposure duration except on samples collected after 365 days, where relatively lower mean corrosion losses were observed because of smaller but deeper anodic regions.

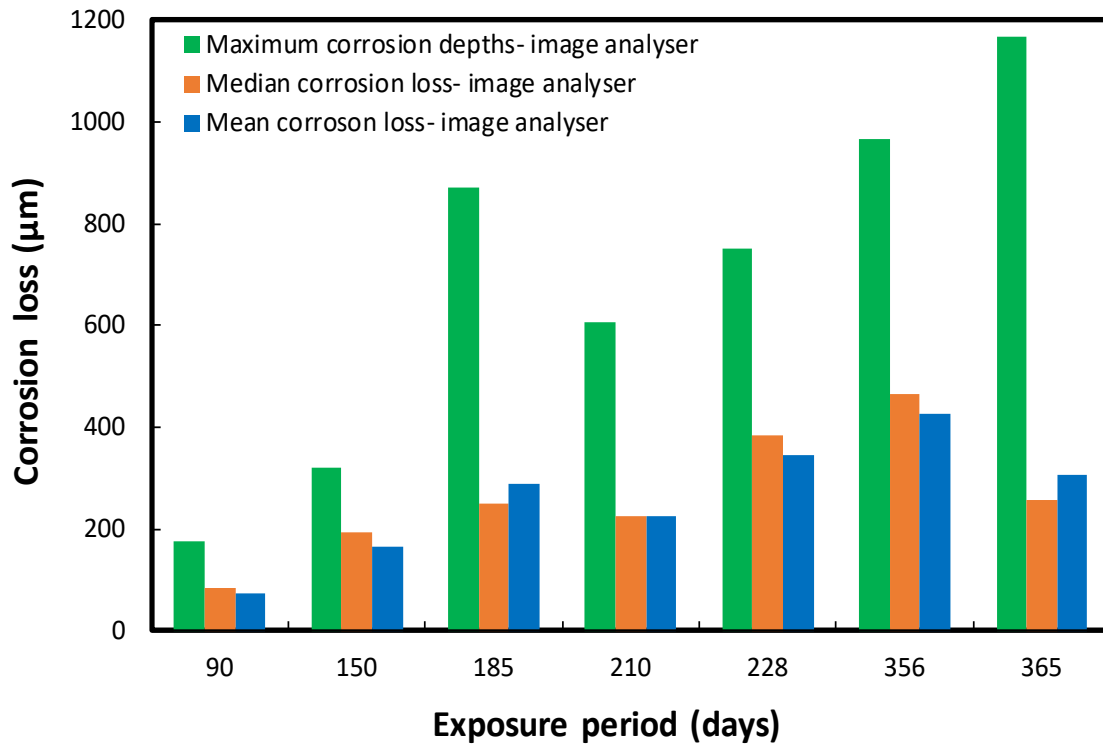


Figure 8 Maximum corrosion depths, median corrosion loss and mean corrosion loss parameters recorded on corroded steel samples, using DM-image analyser technique

Figure 9 and Figure 10 compare the total mean corrosion losses and the maximum corrosion depths calculated by adding respective corrosion depths observed on either surface of steel samples (i.e., by adding corrosion depths on side A and side B in Figure 4). Here, the mean corrosion losses were calculated using both DM-image analyser and standard mass loss methods, whereas the maximum depths (in Figure 10) have been calculated with the help of DM-image analyser and micrometry (manually) methods.

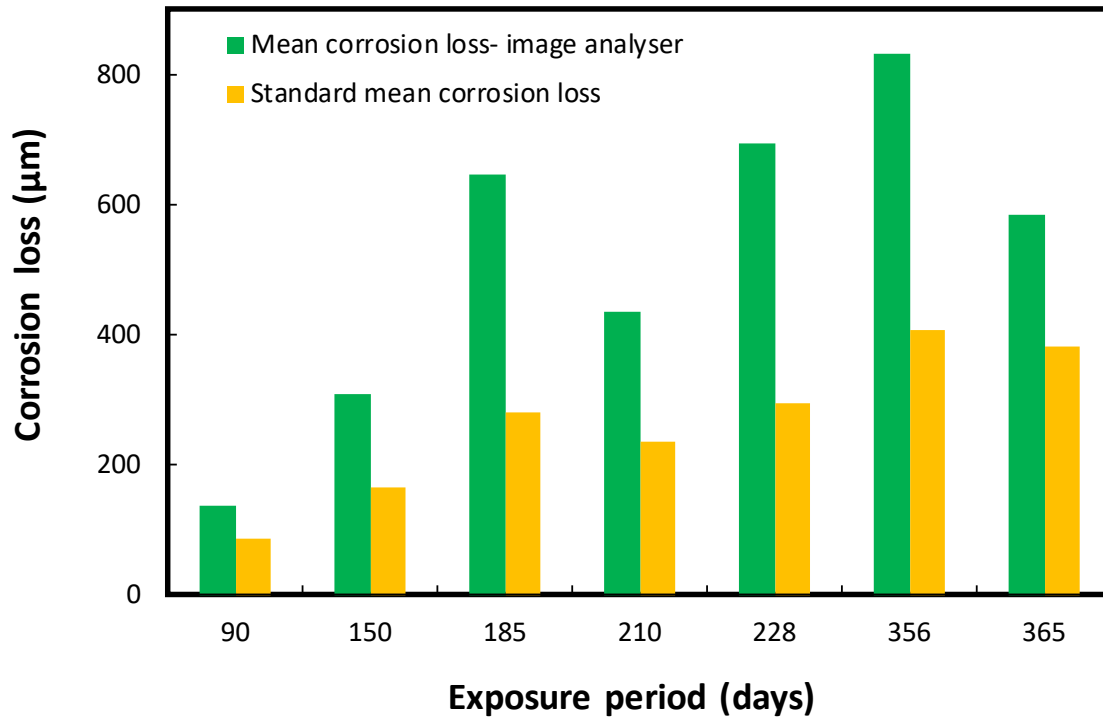


Figure 9 Comparison of total mean corrosion losses calculated using DM-image analyser and standard mass loss methods

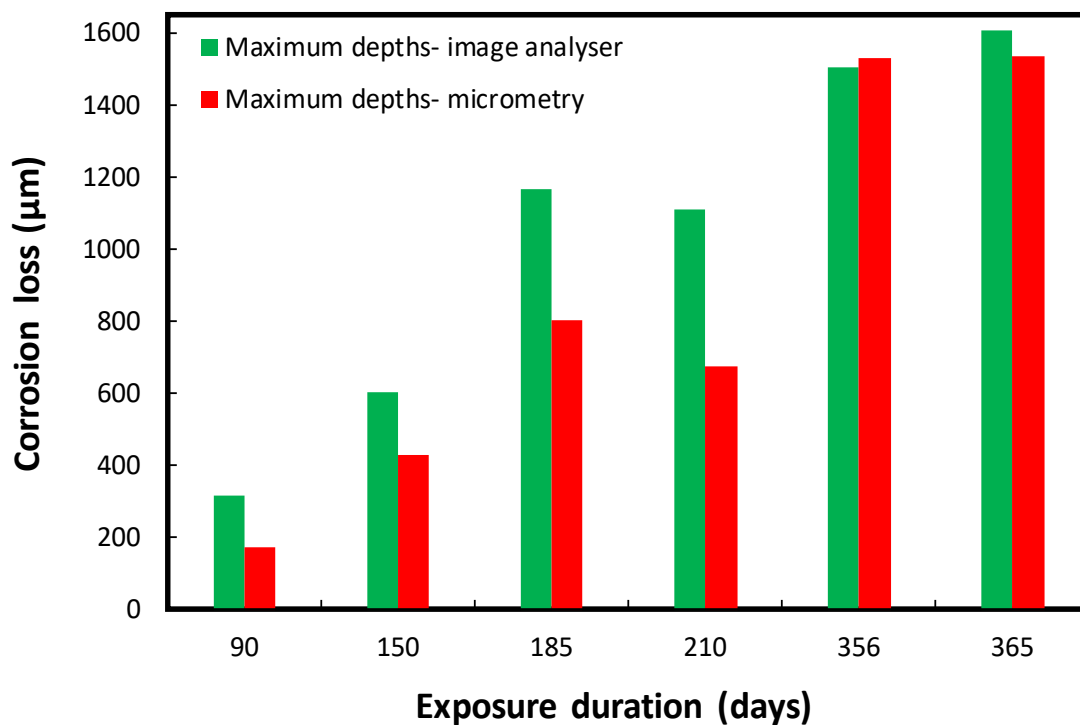


Figure 10 Comparison of maximum corrosion depths (by adding depths on corresponding surfaces of steel plates) and calculated using DM-image analyser and micrometry methods

4 Discussion

This research encompasses measurement of corrosion depths on steel samples exposed to the artificial seawater primarily by using DM-image analyser technique. This measurement technique provided more refined and quality data than was possible with the traditional standard mass loss approaches used in research studies conducted previously. Principally, the cumulative probability (%) and the cumulative normal probability (SD) graphs generated (in Figure 6 and Figure 7) using the DM-image analyser approach can be further analysed to provide several statistical parameters, as a function of total exposure period and corrosion influencing environmental factors (see Figure 8-9). These statistical parameters for corrosion loss data (uniform/ localised corrosion) can be instrumental in formulating corrosion prediction modelling, remaining useful life estimation and reliability-based inspection/maintenance plans for offshore structures.

The DM-image analyser technique comprises a detailed process that provides more points of thickness loss data on a single steel plate (against each exposure period) than the single-point average corrosion rate/loss (calculated using standard mass loss approach see Figure 8). The DM approach has enabled quantification of corrosion depths as well as greater data point density in a specific location. For the same corroded steel samples at each exposure duration, the mean (uniform) corrosion losses measured with the DM-image analyser method are significantly higher (almost double after around 200 - 365 exposure days, as shown in Figure 9) than the uniform corrosion losses calculated for similar exposure durations using the standard mass loss approach. These results imply that the mean corrosion depths quantified using DM-image analyser approach is a more logical parameter to determine the regions of localised corrosion losses on offshore steel structures; susceptible for loss of containment [22,43–45]

On the other hand, the average corrosion losses calculated (in Figure 9) using the standard mass loss method is purely based on the total weight loss as a function of exposure duration. Therefore, it does not account significantly for the risks of structural failures associated to loss of structural integrity, containment, and/or indication of the regions of highest corrosion loss, which are crucial factors for estimation of safety and reliability of the offshore platforms [46,47].

During corrosion tests, after a steady start of the corrosion process, a considerable increase in the uniform corrosion losses and maximum damage depths (as shown in Figures 6-9) was observed after around 150 - 200 days that resulted in thick corrosion layer formation in anodic regions of the steel samples. This rapid corrosion trend on offshore steels during extended durations has previously been reported by several researchers, primarily because of the active involvement of microbiological factors [13,26,48]. Overall, the mean corrosion losses recorded during this research (in Figure 9) were found to be comparable to those corrosion results recorded previously for similar steels exposed in the Arabian Sea conditions [22].

Figure 10 shows that for most of the exposure durations, the maximum corrosion depth values measured with the help of DM-image analyser method are relatively higher than those measured using the DM-micrometry. Few of the possible reasons for these variations can be (i) limitations of the digital micrometer in reaching narrow and intricate pits on the surfaces of corroded samples, which can be measured accurately with the help of DM-image analyser (ii) a total error of ± 5 microns associated with the micrometry approach.

Typically, in absence of biological factors, pollutants and nutrients in seawater, the corrosion losses in steels tend to decrease with the increase in the duration of exposure [49–52]. However, in this research where corrosion tests were conducted in an uncovered tank, it is very much possible that retention of the sterile conditions throughout these prolonged durations (up to 365 days at 40°C seawater temperature) may have been compromised possibly because of the addition of airborne/waterborne microbial aerosols in seawater from surrounding environment. Unfortunately, some waterborne microbes (*pseudomonas/legionella*) were observed in a wave tank (containing freshwater) located at 2 meters from the corrosion testing setup used in this research. Further, investigation of the corrosion deposits with the help of analytical tools, and characterisation of microbiological agents during the prolonged artificial seawater exposures is beyond the scope of this paper.

5 Conclusion

This paper investigated the corrosion behaviour of a low carbon steel exposed to artificial seawater at 40°C, for exposure duration up to a maximum of 365 days. The corrosion depths on experimental steel samples were quantified using a special DM-

image analyser technique, comprised of pre-exposure contact metrology and post-exposure metrology using image analyser/optical microscopy.

- By the end of the exposure duration of up to a maximum of 365 days, the maximum corrosion depths and mean of corrosion losses recorded on each side of the steel coupons (measured using DM-image analyser method) ranged between 0.9 – 1.2 mm and 0.3 – 0.4 mm, respectively. Likewise, the total mean corrosion losses and maximum depths measured by adding corrosion depths on both surfaces of steel samples (DM-image analyser) ranged between 0.7 – 0.8 mm and 1.5 – 1.6 mm, respectively. On the other hand, the mean corrosion losses on these steel samples when measured using the standard mass loss method ranged between 0.4 – 0.45 mm.
- The mean corrosion losses calculated using the DM-image analyser method were significantly higher than those measured using the standard mass loss method. It is mainly because of the reason that the former mean corrosion loss parameter is a direct function of maximum corrosion depths which increased significantly particularly after initial 150 exposure days.
- The cumulative probability distributions (percentage and standard deviation) for corrosion loss parameter provided highly valuable information (including mean/median and maximum depth profile), and greater insight about the corrosion process taken place on structural steel samples, as function of exposure environment, elemental compositions in steel and duration of seawater exposure.
- Overall, these corrosion losses observed within just 365 seawater exposure days are significantly high but comparable to those corrosion losses previously recorded for similar steels exposed in the Arabian Sea.
- For further research, this DM-image analyser technique and the statistical parameters used for measurement of the corrosion losses on steel samples submerged in artificial seawater medium can provide instrumental information/data for developing prediction models for corrosion (uniform/localised), estimation of service life and inspection/maintenance intervals for offshore structures.

Acknowledgements

The unfathomable assistance of Cranfield University (UK) for assisting in the design of corrosion experiments, provision of artificial sea salt, and dimensional metrology

setup (contact metrology, image analyser, and optical microscope is highly appreciated.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author's contribution

MA performed the experimental work, analytical analysis, and wrote the manuscript text. NS assisted in developing the methodology, reviewed the manuscript and made contributions to its structure, whereas SR reviewed the paper.

Funding

This research did not receive any kind of grants from funding agencies.

References

1. Melchers, R.E. Corrosion Uncertainty Modelling for Steel Structures. *J. Constr. Steel Res.* **1999**, *52*, 3–19, doi:10.1016/S0143-974X(99)00010-3.
2. Chaves, I.A.; Melchers, R.E. Extreme Value Analysis for Assessing Structural Reliability of Welded Offshore Steel Structures. *Struct. Saf.* **2014**, *50*, 9–15, doi:10.1016/j.strusafe.2014.03.007.
3. Goldman, M.; Tully, C.; Noël, J.J.; Shoesmith, D.W. The Influence of Sulphide, Bicarbonate and Carbonate on the Electrochemistry of Carbon Steel in Slightly Alkaline Solutions. *Corros. Sci.* **2020**, *169*, 108607, doi:10.1016/j.corsci.2020.108607.
4. Fontana, M.G. *Corrosion Engineering*; 3rd ed.; McGraw Hill Book Company: New York, USA, 1987; ISBN 0070214638.
5. Revie, R.W.; Uhlig, H.H. *Corrosion and Corrosion Control-An Introduction to Corrosion Science and Engineering*; 4th ed.; John Wiley and Sons: New Jersey, USA, 2008; ISBN 9780471732792.
6. Moore, J. *Long-Term Corrosion Processes of Iron and Steel Shipwrecks in the Marine Environment: A Review of Current Knowledge*; 2015; Vol. 10;.
7. Pourbaix, M. Recent Application of Electrode Potential Measurement in the Thermodynamics and Kinetics Corrosion of Metals. *Corros. Sci.* 1969, *25*, 267–281.
8. Gardiner, C.P.; Melchers, R.E. Corrosion Analysis of Bulk Carriers, Part I: Operational Parameters Influencing Corrosion Rates. *Mar. Struct.* **2003**, *16*, 547–566, doi:10.1016/S0951-8339(01)00026-0.
9. Roberge, P.R. *Corrosion Engineering-Principles and Practice*; McGraw Hill Company Limited: New York, USA, 2008; ISBN 0071482431.
10. Aromaa, J.; Forsén, O. Factors Affecting Corrosion in Gulf of Finland Brackish Water. *Int. J. Electrochem.* **2016**, *2016*, 1–9, doi:10.1155/2016/3720280.
11. Hussain, M.A.; Abbas, S.; Ansari, M.R.K. Arabian Seawater Temperature Fluctuations in the Twentieth Century. *J. Basic Appl. Sci.* **2012**, *8*, 105–109.
12. Melchers, R. Principles of Marine Corrosion. In *Ocean Engineering*; Dhanak, M., Xiros, N.I., Eds.; Springer: London, 2016; pp. 111–123 ISBN 9783319166490.
13. Phull, B.S.; Pikul, S.J.; Kain, R.M. Seawater Corrosivity around the World: Results from Five Years of Testing. In *Corrosion Testing in Natural Waters*; Kian, R.M., T.Young, W., Eds.; ASTM International: Norfolk, Virginia, USA, 1997; Vol. 2, pp. 34–73.
14. Soares, C.G.; Garbatov, Y.; Zayed, A. Effect of Environmental Factors on Steel Plate Corrosion under Marine Immersion Conditions. *Corros. Eng. Sci. Technol.* **2011**, *46*, 524–541, doi:10.1179/147842209X12559428167841.
15. Soares, C.G.; Garbatov, Y.; Zayed, A.; Wang, G. Non-Linear Corrosion Model for Immersed Steel Plates Accounting for Environmental Factors. In *Proceedings of the SNAME Maritime Convention*; OnePetro: Houston, Texas,

- USA, 2005; pp. 193–211.
16. Kovalenko, R.; Melchers, R.; Chernov, B. Long-Term Immersion Corrosion of Steel Subject to Large Annual Variations in Seawater Temperature and Nutrient Concentration. *Struct. Infrastruct. Eng.* **2017**, *13*, 978–987, doi:10.1080/15732479.2016.1229797.
 17. Melchers, R. Effect of Temperature on the Marine Immersion Corrosion of Carbon Steels. *Corros. Sci.* **2002**, *58*, 768–782, doi:10.5006/1.3277660.
 18. Melchers, R.; Chernov, B.B. Corrosion Loss of Mild Steel in High Temperature Hard Freshwater. *Corros. Sci.* **2010**, *52*, 449–454.
 19. Zayed, A.; Garbatov, Y.; Soares, C.G. Corrosion Modelling of Single Hull Crude Oil Tanker Subjected to Complex Deterioration Environment. In Proceedings of the Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering; ASME International: San Diego, California, USA, 2007; pp. OMAE2007-29741.
 20. Zakowski, K.; Narozny, M.; Szocinski, M.; Darowicki, K. Influence of Water Salinity on Corrosion Risk - The Case of the Southern Baltic Sea Coast. *Environ. Monit. Assess.* **2014**, *186*, 4871–4879, doi:10.1007/s10661-014-3744-3.
 21. ASTM G1 – 03 Standard Practice for Preparing , Cleaning , and Evaluating Corrosion Test 2017, 1–9.
 22. Abbas, M.; Simms, N.; Lao, L.; Malik, O.A.; Syed, A.U.; Ali Sarfraz, S.; Ashraf, L.; Rizvi, S.H.M. A Dimensional Metrology-Based Approach for Corrosion Measurement of Ship Grade Steels Exposed to Various Marine Environmental Conditions. *Corros. Eng. Sci. Technol.* **2021**, *0*, 1–13, doi:10.1080/1478422X.2021.1904096.
 23. de la Fuente, D.; Díaz, I.; Simancas, J.; Chico, B.; Morcillo, M. Long-Term Atmospheric Corrosion of Mild Steel. *Corros. Sci.* **2011**, *53*, 604–617, doi:10.1016/j.corsci.2010.10.007.
 24. Caleyó, F.; Velázquez, J.C.; Valor, A.; Hallen, J.M. Markov Chain Modelling of Pitting Corrosion in Underground Pipelines. *Corros. Sci.* **2009**, *51*, 2197–2207, doi:10.1016/j.corsci.2009.06.014.
 25. Li, S.X.; Akid, R. Corrosion Fatigue Life Prediction of a Steel Shaft Material in Seawater. *Eng. Fail. Anal.* **2013**, *34*, 324–334, doi:10.1016/j.engfailanal.2013.08.004.
 26. Wang, X.; Melchers, R.E. Long-Term under-Deposit Pitting Corrosion of Carbon Steel Pipes. *Ocean Eng.* **2017**, *133*, 231–243, doi:10.1016/j.oceaneng.2017.02.010.
 27. Simms, N.J.; Oakey, J.E.; Nicholls, J.R. Development and Application of a Methodology for the Measurement of Corrosion and Erosion Damage in Laboratory, Burner Rig and Plant Environments. *Mater. High Temp.* **2000**, *17*, 355–362, doi:10.1179/mht.2000.17.2.025.
 28. Melchers, R.E. Extreme Value Statistics and Long-Term Marine Pitting Corrosion of Steel. *Probabilistic Eng. Mech.* **2008**, *23*, 482–488,

- doi:10.1016/j.pro bengmech.2007.09.003.
29. ASTM-G46-94 Standard Guide for Examination and Evaluation of Pitting Corrosion 2018, 12, 1–8.
 30. NACE Standard Guide for Laboratory Immersion Corrosion Testing of Metals 2000, 1–10.
 31. Melchers, R.; Ahammed, M.; Jeffrey, R.; Simundic, G. Statistical Characterization of Surfaces of Corroded Steel Plates. *Mar. Struct.* **2010**, 23, 274–287, doi:10.1016/j.marstruc.2010.07.002.
 32. Engelhardt, G.; Macdonald, D.D. Unification of the Deterministic and Statistical Approaches for Predicting Localized Corrosion Damage. I. Theoretical Foundation. *Corros. Sci.* **2004**, 46, 2755–2780, doi:10.1016/j.corsci.2004.03.014.
 33. Melchers Statistical Characterization of Pitting Corrosion - Part 2: Probabilistic Modeling for Maximum Pit Depth. *Corrosion* **2005**, 61, 766–777, doi:10.5006/1.3278211.
 34. Syed, A. Fireside Corrosion Study of Superheater Materials in Advanced Power Plants, Cranfield University, Cranfield, Bedfordshire, U.K., 2011.
 35. Potter, A. Hot Corrosion in Industrial Gas Turbines School, Cranfield University, Cranfield, Bedfordshire, U.K., 2018.
 36. Hussain, T.; Syed, A.U.; Simms, N.J. Fireside Corrosion of Superheater Materials in Coal/Biomass Co-Fired Advanced Power Plants. *Oxid. Met.* **2013**, 80, 529–540, doi:10.1007/s11085-013-9394-y.
 37. Sumner, J.; Encinas-Oropesa, A.; Simms, N.J.; Nicholls, J.R. Type II Hot Corrosion: Kinetics Studies of CMSX-4. *Oxid. Met.* **2013**, 80, 553–563, doi:10.1007/s11085-013-9395-x.
 38. Syed, A.U.; Simms, N.J.; Oakey, J.E. Fireside Corrosion of Superheaters: Effects of Air and Oxy-Firing of Coal and Biomass. *Fuel* **2012**, 101, 62–73, doi:10.1016/j.fuel.2011.03.010.
 39. Jilani, S. Present Pollution Profile of Karachi Coastal Waters. *J. Coast. Conserv.* **2018**, 22, 325–332, doi:10.1007/s11852-017-0581-x.
 40. Nergis, Y.; Sharif, M.; Choudhry, A.F.; Hussain, A.; Butt, J.A. Impact of Industrial and Sewage Effluents on Karachi Coastal Water and Sediment Quality. *Middle-East J. Sci. Res.* **2012**, 11, 1443–1454, doi:10.5829/idosi.mejsr.2012.11.10.63209.
 41. ASTM Standard Practice for Preparing , Cleaning , and Evaluating Corrosion Test 2017, 1–9.
 42. BS ISO 26146 Corrosion of Metals and Alloys - Method for Metallographic Examination of Samples after Exposure to High Temperature Corrosive Environments 2011, 22.
 43. Bisaggio, H. da C.; Netto, T.A. Predictive Analyses of the Integrity of Corroded Pipelines Based on Concepts of Structural Reliability and Bayesian Inference.

- Mar. Struct.* **2015**, *41*, 180–199, doi:10.1016/j.marstruc.2015.02.003.
44. Thodi, P.; Khan, F.; Haddara, M. Risk Based Integrity Modeling of Offshore Process Components Suffering Stochastic Degradation. *J. Qual. Maint. Eng.* **2013**, *19*, 157–180, doi:10.1108/13552511311315968.
 45. Peng, L.; Stewart, M.G.; Melchers, R.E. Corrosion and Capacity Prediction of Marine Steel Infrastructure under a Changing Environment. *Struct. Infrastruct. Eng.* **2017**, *13*, 988–1001, doi:10.1080/15732479.2016.1229798.
 46. Melchers The Effect of Corrosion on the Structural Reliability of Steel Offshore Structures. *Corros. Sci.* **2005**, *47*, 2391–2410, doi:10.1016/j.corsci.2005.04.004.
 47. Schumacher, M. *Seawater Corrosion Handbook*; 1979; ISBN 0815507364.
 48. Melchers, R. Modelling Immersion Corrosion of Structural Steels in Natural Fresh and Brackish Waters. *Corros. Sci.* **2006**, *48*, 4174–4201, doi:10.1016/j.corsci.2006.04.012.
 49. Abbas, M.; Shafiee, M. An Overview of Maintenance Management Strategies for Corroded Steel Structures in Extreme Marine Environments. *Mar. Struct.* **2020**, *71*, 23, doi:10.1016/j.marstruc.2020.102718.
 50. Melchers, R. Influence of Seawater Nutrient Content on the Early Immersion Corrosion of Mild Steel - Part 1: Empirical Observations. *Corrosion* **2007**, *63*, 318–329, doi:10.5006/1.3278385.
 51. Melchers, R. A Review of Trends for Corrosion Loss and Pit Depth in Longer-Term Exposures. *Corros. Mater. Degrad.* **2018**, *1*, 42–58, doi:10.3390/cmd1010004.
 52. Duan, J.; Wu, S.; Zhang, X.; Huang, G.; Du, M.; Hou, B. Corrosion of Carbon Steel Influenced by Anaerobic Biofilm in Natural Seawater. *Electrochim. Acta* **2008**, *54*, 22–28, doi:10.1016/j.electacta.2008.04.085.



DSSPACE

<https://dspace.org/>

A new approach for quantification of corrosion losses on steels exposed to an artificial seawater environment

Abbas, Muntazir; Simms, Nigel J.; Rizvi, Syed Haider Mehdi

2023-06-01

Taylor & Francis

<https://doi.org/10.1080/1478422X.2023.2185987>

Abbas M, Simms N, Rizvi SH. (2023) A new approach for quantification of corrosion losses on steels exposed to an artificial seawater environment. Corrosion Engineering, Science and Technology, Volume 58, Issue 4, June 2023, pp. 355-363