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Effect of Tensile Strain on the Rate of Marine Corrosion of Steel Plates

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Abstract

It has been observed in the shipping industry that the rate of corrosion of steel plate may increase with longer duration of exposure, typically over many years. This effect has been attributed to the flexure of ships plates causing the loss of protective rust layers. The present paper describes the results of laboratory experiments in which plates with pre-existing rusts were subject to high levels of tensile strain, with and without subsequent exposure and corrosion. All rusts were obtained by exposing the steel to a natural marine environment, including the atmospheric and tidal zones. Careful observation of the rusts under tensile strain conditions showed that only strains near and beyond the elastic limit of the steel have the capacity to cause significant damage to the rust layers. Subsequent short-term exposure tests on pre-corroded and pre-strained steel coupons showed that there can be a moderate (10-15%) increase in the short-term corrosion rate.

Keywords: A. Mild steel; B. Weightloss; C. Atmospheric corrosion, Effects of strain, Rust

1. Introduction

In the shipping industry there is some information to suggest that it is possible to have increasing rates of steel corrosion with time. This has been attributed to significant flexure of a ship's plates causing the loss of protective rust layers [1]. This may be important for ship inner bottom plates subject to loading and unloading and also subject to corrosion particularly when protective coatings either are not applied (as in bulk carrier ships or older ballast tanks) or becomes ineffective owing to less than perfect maintenance.

There is much evidence in the literature that the corrosion wastage in ship structures with time is extremely scattered [2, 3], implying that a considerable number of influential parameters are likely to be involved in the initiation and progress of corrosion loss. In fact, the database of corrosion measurements in ship structures shows that the corrosion rate becomes moderate with time for some plates, but that in some cases it accelerates with time for other plates. In the latter situation, it is considered that the actions (e.g., external loads) or action effects (e.g., deformation or stress) applied to the structural components as a result of and in association with ship's hull girder actions in waves and/or during loading and unloading of cargo may play a role. That is, it is possible that these actions cause the acceleration of the corrosion rate because they damage or break the rust layer on plate surface, thereby allowing the corrosive environment to continuously or semi-continuously attack the plate. This is likely to result in a high corrosion rate, generally similar to that experienced during the initial and early corrosion of a new unprotected plate.

Studies regarding this issue appear to be lacking in the literature. In particular, there appear to be no observations about the nature of the damage done by high strain rates to the rust layer and the mechanism by which this influences corrosion. The objective of the present paper is to investigate the effect of the applied tensile strain on the progress of corrosion. The paper reports on a small number of initial field tests to investigate the effect of applied strain on the adhesion of rusts and hence the effect on short-term corrosion for common structural steel exposed to marine conditions.

The conventional model for marine corrosion of steel is that adherent rust layers inhibit the diffusion of oxygen to the corroding surface and that this diffusion becomes increasingly more difficult as the corrosion products build-up. Evidently, the permeability of the rusts is critical in this process. The question of interest thus becomes the extent to which applied strains influence the permeability of the rust layers. Experimentally this is not easy to ascertain directly. Early corrosion tests with moderate levels of applied strain indicated that the effect on the rate of corrosion, measured through weightloss, largely could be discounted [4, 5]. However, weight loss may not be fully indicative of the effect strains may have since cracking of the rusts could cause localized corrosion, with implications for pitting and for fatigue. The known non-uniform nature of the rust layers [6, 7] may contribute to localization of cracking. Evidently, the rusts of interest here are the dense, relatively impermeable adherent rusts, that tend to be tightly bound to the steel, rather than the outer generally 'non-adherent' layer adjacent to the external environment [8]. Under most exposure conditions the non-adherent rust layer is very easily knocked-off or peels off with the removal of marine growth. It tends to be flaky and offers little protection to oxygen diffusion.

The adherent rust layer has been observed to be quite variable in thickness. It is usually associated with magnetite (Fe_3O_4) [9] and tends to be brittle. This means it could be fractured by sufficiently high levels of applied strain, particularly along the rust-steel substrate interface, since the elastic moduli of the steel and the rust are not equal. Moreover, because of the variable thickness of the rust layer, cracking is likely to be random and localized. In turn this is likely to cause localized reduction in the resistance to oxygen diffusion and hence offer the potential for differential aeration, leading to aggressive localized corrosion [10, 11].

Particularly for thinner rust layers, applied strains are likely to lead to a finer but still random mesh of cracks or fractures to develop over the surface, thereby permitting more widespread but still non-uniform access of oxygen. In turn this would lead to the development of multiple localized but less intense differential aeration cells and hence essentially non-uniform but generalized surface corrosion. In the limit it may be viewed as a situation where the rusts are sufficiently fractured to expose essentially all of the

steel surface underneath to the environment, in a manner generally similar to that for bare steel. As a result, it might be expected that the steel surface will corrode at a rate similar to that for bare steel, with the adherent rusts under these highly cracked conditions offering no protection. Scully [12] recognized this possibility much earlier and postulated that the decreasing corrosion rate eventually would become approximately linear (Figure 1).

Figure 1 – Effect of periodic loss of protective rusts on overall corrosion loss as a function of exposure time (schematic). As shown, the equivalent, approximately linear, corrosion rate depends on the frequency of fracture or loss of protective rusts.

The present paper reports and experimental investigation of the loss of adherent rusts as a function of applied strain for a number of specimens of corroded steel, obtained from a range of sources. It also presents results for the effect of axial straining when steel specimens were exposed for 2 months in the tidal zone, then subject to direct (axial) tensile strain followed by further exposure in the tidal zone for another 2 months. The experimental program reported here consisted of three parts. The first is on observations of the effect on rust layers when surface axial tensile strain was applied to two different corroded steel specimens recovered from industrial environments near the coast. The second considers the effect of steel flexing on the adherence and cracking of adherent rust layers for strips of steel exposed for 1.5 years in the tidal zone at two different locations. The third part reports on the effect of axial tensile strain on the corrosion loss observed over a period of 2 months for coupons after they had been strained. This followed earlier exposure (and corrosion) for 2 months in the tidal zone.

2. Effect of axial tensile strain on adherence of rusts

Two pieces of corroded steel were sourced from a dockyard in Newcastle and also from the corrosion testing facility at a steelmaker in Wollongong. Both sites are close to the sea and the steel plates showed significant but not high levels of overall surface corrosion. The plates were 5 mm thick and were trimmed to tension specimens with a working area of 40mm x 220 long. Cutting and machining were carefully controlled so

as not to significantly raise the temperature of the steel and thus potentially change the material properties or to damage the corrosion products on the surface of the steel. A total of 10 specimens were available.

The specimens were strained axially in a universal testing machine after carefully aligning the machine grips in relation to the specimen to ensure that a uniform axial strain was achieved through the specimen. A slow loading rate was used and the behaviour of the rust layers observed. Figure 2 summarizes the observed load strain plots for 10 specimens and summarizes the strains for which different observations were made of the behaviour of the rusts. Below about the yield strain of the steel no rust damage was evident. At about yield and just beyond there were some very small specks of rust started to fall off the rusted surface. At about 0.7% strain shear bands were observed to form (Figure 3). Only at much higher tensile strains were rust flakes observed to fall away from the corroded surface.

Figure 2 – Load- (stress-) strain plots for 10 steel specimens from steel sourced from industry, showing range of strains at which various observations were made of the behaviour of the rusts.

Figure 3 – A typical specimen at about 0.7% strain showing the rust that had off the coupon and the presence of 45° shear strain bands (Luder's bands) showing through the rust layer on the steel surface.

3. Effect of flexural strain on rust adherence and rust cracking

Four pieces of structural steel 50 x 3 mm in cross-section exposed in the tidal zone for 1.5 years as part of a long strip at two locations (Queenscliff in Victoria and Port Arthur in Tasmania) were recovered from these test sites and, after removal of the marine growth and the non-adherent rust with light brushing using a soft wire brush, were tested in semi-static bending to observe the dislocation of adherent rusts with increasing flexural strain and whether cracking of the rusts occurred. The steel strip was tested under a point load over a span of 300mm and over a range of central deflections. A

board with white paper was placed about 100mm under the strip to catch and observe any dislocated rusts. The white paper was replaced at each increase in deflection (and strain). A camera was also positioned under the strip to record the condition of the rust surface at each deflection measurement. It was found that for low deflections and hence low strains no rust dislocated from the surface. At moderate strains, within the elastic limit of the steel, some very small rust specks were observed on the white board. The rust specks were barely visible and estimated to be less than 0.1mm in size. At higher surface strains some larger rust particles were observed to deposit on the white board. The larger particles appeared to be dislocated from the surface with some force rather than just appearing to fall off as was the case for the specks. This supports the notion that the rusts being examined were adherent rusts and that flaking off occurs only under considerable strain differential between the rust particle and the remaining rust or steel surface. The number of rust specks was estimated. The number of larger particles was counted. Table 1 summarizes the findings.

Table 1

Figure 4 shows the estimated number of rust specks plotted against surface strain in bending. It is clear that the specimens exposed at Port Arthur produced a much lower degree of rust loss than the specimens exposed at Queenscliff. This is likely to be due to differences in environmental conditions at the two sites. The steel strips were from the same source and nominally similar and in any case small variations in steel composition are well-known not to be a significant factor in corrosion loss and in rust formation at least while the process is controlled by oxygen diffusion [4, 13]. The annual average water temperature at Queenscliff is a little higher (16 °C) than that at Port Arthur (14 °C). However, the water quality at Queenscliff is known to have a somewhat elevated nutrient content at various times of the year [14]. This has previously been associated with increased corrosion [15] and hence greater surface rust coverage.

Figure 4 - Estimated number of rust specks as a function of applied surface strain in bending. The strained area was 50 mm wide and estimated to be 20 mm along the specimen.

Close-up photographs were taken at each load step of the tensile face of the strip. These were examined after the tests for the presence of cracking in the adherent rust surfaces. No visual evidence of such cracking was found even for the highest applied strain level, including when the surfaces were examined with a magnifying glass and after significant magnification of the photographs.

4. Short-term corrosion, applied strain and further short-term corrosion tests

The third test program considered the effect of tensile strain applied to already corroded steel followed by a further period of corrosion. This was to attempt ascertain whether the subsequent corrosion was increased by applied strain. Mild steel coupons 3mm thick and 300 x 50 mm were exposed for 2 months to Pacific Ocean waters in the mid-tide zone in secure locations at the entrance to Newcastle Harbour and at Taylors Beach [16]. All coupons were electrically insulated from the support frame.

The Newcastle Harbour test site is within about 300m of the Pacific Ocean and subject to tidal water velocities, wave action and sediment transport. The Taylors Beach site is protected from wind and wave action and has low water velocities. It is some 14 km from the Pacific Ocean but water quality measurements consistently show it to have waters closely similar in composition and other characteristics to ocean coastal waters. Table 2 gives an overview.

Table 2

After cleaning the coupon surfaces according to standard preparation protocols [17] and mass measurements, 9 coupons were exposed at each site. They were all recovered after 2months. Three coupons were set aside for detailed observation of the corrosion products. Three coupons were cleaned according to standard protocols [17] and weighed to determine mass loss. The third set of 3 coupons were placed in an Instron Universal testing machine and loaded in tension to generate axial tensile strain. Several other samples were exposed to less severe and shorter exposures to permit

experimentation for appropriate strain levels. This produced load of 35, 40 and 45 kN corresponding to strains of 1170, 1330 and 1500 microstrain. Table 3 summarizes the observations of the behaviour of the 2-month old rusts under different axial strains. Microscope photographs were taken of the rust surfaces before and after each of the coupons were strained. Figures 5 and 6 show two selected images.

Table 3

Figure 5 – Close-up view of adherent rust surface and irregular cracking Taylors Beach coupon at 1330 microstrain. Scale: the height of the side of the photo is approximately 15 mm.

Figure 6 – Close-up view of adherent rust surface, localized loss of rust and rust cracking for Newcastle Harbour coupon at 1500 microstrain. Scale: the height of the side of the photo is approximately 20 mm.

The effect of strain on the mass loss after 4 months total exposure is shown in Figure 7. Evidently, there is a slight trend for increased mass loss with higher strain levels applied at 2 months exposure, but the effect is relatively modest, considering that the applied strains were close to or exceeding the material yield strain. The results for Taylors Beach show some randomness. There are no obvious reasons for this other than the variability in the thickness and strength properties of rusts between coupons and, to a much lesser extent, variability in applied strains.

Figure 7 – Effect of applied surface strain on mass loss after 4 months total exposure with strain applied after 2 months.

A different view of the data is given in Figure 8 which shows mass loss as a function of time, assuming that in the first 4 months of exposure of steel in seawater the corrosion loss is a linear function of exposure time. This is generally consistent with other observations [18]. Assuming also that the coupons with no applied surface strains can be used as a reference, and that all coupons corrode about the same amount in the first 2

months, the effect of applied strain can be considered to be confined to the second 2 month exposure period. Figure 8 shows that the corrosion rate for this second period increased by about 10-15% for both sites relative to the rate for zero applied strain.

Figure 8 – Effect of applied surface strain on mass loss as a function of exposure time.

5. Discussion

Despite differences in the source of the steels, the degree of corrosion and the differences in application of the surface strains, the laboratory experimental results are quite consistent and show that for applied strains below the steel yield strain there is little visible evidence of significant loss of adherent rusts or of cracking of the adherent rusts. Both rust loss from the steel surface and cracking of the adherent rusts was found to produce evidence observable by visual inspection only once the surface strains exceeded the yield strain. As shown in the experiments, this tended to cause even the otherwise quite adherent rusts to flake off the steel surface.

The effect of high levels of strain on subsequent corrosion loss is shown in Figure 7. Although only short-term corrosion is involved, it is apparent that the effect of strain levels approaching and exceeding yield strain on subsequent corrosion is quite moderate. The increase in corrosion loss compared with samples that were not strained, was found to be in the range 10-15%. While the corrosion process is linear these values can be assumed to extend in time. However, it is evident that even for longer term exposures, when there is usually a non-linear trend in corrosion mass loss, the effect is likely to be generally similar in percentage terms.

In terms of the applicability of the above to ships under operational conditions, an important aspect is the relative frequency of occurrence of high levels of straining. A related factor is the potential influence of the duration of high strain events for those parts of ships that for one reason or another have no protective coatings or no or low levels of cathodic protection. As noted this is the case for the holds of bulk carrier ships and for certain ballast tanks. If ships are kept in good condition and are managed so as

to avoid overloading or high stress conditions under storm events at sea or loading/unloading conditions whilst in port, high levels of hull strain for extended periods are unlikely to occur. This means that where rust is present, any fracturing or loss of that rust also will be of short duration compared with the overall progression of corrosion. There is time, therefore, between events involving high levels of strain, for the rust to build-up in the cracks and so restore the overall protective nature of the rust layers. This means that the overall effect of sporadic high strain levels and consequent loss of protection from rusts is likely to be relatively small. Conversely, for vessels in advanced stages of corrosion, high levels of strain are likely to occur much more often, even under moderate sea-states. In this case rebuilding of rust layers to offer some measure of protection is much less likely. A similar outcome may arise for vessels repeatedly exposed to very high loading levels either at sea or during loading/unloading. The net effect is that under such conditions corrosion will continue to occur (semi-continuously) at a relatively high rate. The present experimental results show that under these conditions an increase of 10-15% in mass loss (and hence uniform corrosion loss) is the current best estimate for the effect of repeated loading on corrosion rate.

Importantly, corrosion mass loss as considered herein as an indicator of the effect of applied surface strain on subsequent corrosion may not be an adequate measure of the effect of strain. There are two potential reasons for this. Firstly, as seen in Figures 5 and 6, cracking of the rust layer is likely to be localized and may therefore have only a local corrosion effect - this clearly can not be reflected adequately in mass loss measurements. However it may be important for fatigue life estimation, particularly if localized corrosion induces locally higher fatigue stresses. This possibility was not investigated in the present work and is an issue for further investigation.

The second reason is that no account has been taken of rust layer thickness. As is well-known, marine rusts tend to consist of a strongly adherent layer underneath a rather friable outer rust layer. For a given total rust thickness the relative thickness of the two layers tends to be quite variable and this may have had an effect on the observations given herein. Moreover, the adherence of each layer also could be a factor in the degree of loss of rust under higher strains. This could be investigated using cross-sectional

microscopic analysis. These are matters the effect of which could be elucidated with more detailed further investigations, although it is considered unlikely that the overall conclusions will be changed.

The tests herein considered only flexure and tensile strains. While these are considered the most likely significant mechanisms for the break-down of the protective rust layer, in principle compressive strains also could be involved, causing the brittle rusts to flake-off through buckling action. This also is a topic for further investigation.

6. Conclusion

The present investigation shows that low levels of tensile strains applied to previously corroded steel specimens have a relatively small influence on the loss of adherent rusts from the surface of the metal and this appears to have negligible influence on steel mass loss due to marine immersion corrosion. Only high levels of strain, approaching the yield strain of the steel, produce observable losses of adherent rusts and observable cracking of the adherent rust layer. This was found, in short-terms marine immersion exposure tests, to increase the mass loss due to corrosion by some 10-15%. The effect of highly localized corrosion in conjunction with fatigue and the potential influence of compressive strains are matters for further investigation.

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Figure titles

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Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Table 1 Estimated number of rust specks and small particles falling from tensile flexural face as a function of increase in surface strain

Central deflection (mm)	Approximate flexural strain	Specimen 1 Port Arthur	Specimen 2 Port Arthur	Specimen 3 Queenscliff	Specimen 4 Queenscliff
0	0	0	0	0	0
5	0.001	0	0	0	0
10	0.002	2 s	0	0	1 s
15	0.003	6 s	1 s	25 s	2 s
20	0.004	6 s + 2 m	4 s	40 s + 5 m	> 40 s
25	0.005	0	6 s	45 s + 5 m	> 30 s

‘s’ denotes rust ‘speck’ and ‘m’ denotes a piece of rust fractured from the surface, typically 3-4mm in size. The number of rust specks was estimated. The number of rust pieces was counted. Numbers shown are incremental between applied strain.

Table 2 – Water quality characteristics at the test sites

Characteristic	Taylors Beach	Newcastle Harbour
Salinity (%)	2.01 – 2.89	2.9
Temperature (°C)	13.6 – 17.9	15.1
Velocity (max) (m/s)	0.06	0.07
Dissolved Oxygen (mg/l)	5.4 – 8.4	9.3
pH	6.5 – 7.5	7.4 – 7.6
Conductivity (mS/cm)	31.2 – 44.6	28.3 – 48.4

Table 3 – Observations of rusts under axial tensile strain

Exposure location	Tensile strain (microns)	Description of rust (with aid of magnifying glass)
Taylors Beach	1170	A few small cracks along coupon edges but otherwise minimal cracking.
	1330	Several cracks visible with naked eye. Some rust flaking.
	1500	Several small tensile cracks, flaking and larger diagonal (shear) cracking.
Newcastle Harbour	1170	Very limited very fine cracking.
	1330	Localized flaking and some tensile cracking.
	1500	Two larger cracks visible to the naked eye and considerable flaking.