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Effect of Flexure on Rusting of Ship's Steel Plating

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Abstract

Data collected from ageing ships indicates that the rate of corrosion of ship's plating may increase with long periods of exposure when combined with plate flexure. The reasons for this have not been clarified. Herein the possibility is investigated that the observed effect is due to the loss of protective rusts under high strains in the steel plating, as might be caused by high sea-states and during loading and unloading. Recent relatively short-term exposure studies of the tensile strain-induced fracture of rusts formed on structural steels during natural marine exposure show an increase in corrosion rate of some 10-15% but only when the strains are near and beyond the elastic limit of the steel. This has implications for ship management. An interpretation is given for the corrosion loss curves reported in the literature and it is shown that, qualitatively at least, they are consistent with earlier observations and models for the corrosion of steel in marine environments. It is proposed that the validity of the conclusions be tested using long-term exposures under corrosion and flexure conditions in actual ships.

Keywords: Corrosion, marine, ships, plates, strain, flexure.

1. Introduction

Particularly for ageing ships that have already lost protective coatings, and which are (perhaps locally) corroding under marine conditions, the information currently available

suggests that it is possible for rates of corrosion of some ship plating to increase with time (TSCF 2002). The data, available primarily in classification society database, also show considerable scatter (Paik et al. 2003a, 2003b). While the scatter is likely to be due to it not being possible in field observations to isolate all the important influencing variables, the increasing rates of corrosion usually are considered to arise from significant flexing of ship's plates. This can arise from actions (e.g., external loads) or action effects (e.g., deformation or stress) transferred to the structural components. In turn, these arise from hull girder response to external wave action or in response to cargo loading and unloading environments and practices. As is well-known, the stresses so generated can be very high in localized areas such as in corners and highly constrained regions where two or more plates meet. It follows that high strains, reaching yield, also are possible in these areas.

For steel exposed to marine environments without applied strains it has long been observed that the rate of corrosion decreases with increasing exposure period. There are good scientific reasons for this occurring, and is chiefly the result of the development of an increasingly protective layer of rust over the steel (Evans 1960, Jones 1996). These rust layers inhibit the diffusion of oxygen from the external environment to the corroding surface. This tends to occur more or less uniformly over the surface. The result is reduction in the rate of corrosion as the rust layers build-up. However, if the steel is subject to high levels of strain such as due to the flexing of plates, it is possible for the protective rust layer to be damaged or fractured. Should this occur, there is the potential for the oxygen diffusion to the corroding surface to increase. If the strain effect is sufficiently high, the rust layer is likely to become ineffective and permit a high level access of oxygen to the corroding steel surface, creating conditions not dissimilar from those for a steel plate when first exposed to the marine environment. In turn that can result in the observed high, perhaps increasing, corrosion rate. Evidently, this can have important implications for the remaining life of a ship and for replacement policies in areas such as bulkheads and ballast tanks.

Apart from the observations for tankers, and a recent experimental study (Melchers and Paik 2009), there appear to be no studies in the literature of the effect of high levels of strain on the corrosion of ship's plates. The present paper reviews some of the recently obtained experimental results for the effect of strain on the rust layers and on the (short-

term) corrosion rate for common structural steel exposed to marine conditions. The results are then interpreted in the light of the (admittedly limited) observations available for commercial ships. Throughout the intent is to obtain a better understanding of the effect of repeated strains on the continued corrosion of ship plates. The discussion herein is focused on general corrosion as measured for example by mass loss but localized effects also may be important, particularly in relation to a possible influence on fatigue life (Paik et al 2003a, 2003b).

2. Background

The effect of applied stress and hence strain on the rate of marine corrosion of steel has, in the corrosion literature (Evans 1960, Friend 1940), been discounted as a significant variable. One reason for this is that strain is not a chemical reaction and therefore not involved in the oxidation of steel. However, when the corrosion rate of steel becomes controlled by the rate of oxidation through the build-up of rust layers, the permeability of the rust layers is critical. The theoretical aspects of this are complex but for engineering purposes may be simplified, after some period of initialization, to a consideration of the diffusion of oxygen through the rust layers. Various authors have formulated this mathematically; Melchers (2008) has given a recent review. In these works the characteristics of the rust layers have not been given much attention. It was sufficient simply to work with a build-up of the rust layers, although Melchers (2003a) proposed to include (i) the non-uniform nature of the rust layers with thickness, (ii) the fact that not all iron is converted into rust, and (iii) that some of the exterior rust tends to be lost by erosion and wear.

The non-uniform nature of the rusts that form on structural steels under marine exposure conditions has been recognized for a long time (Pereira et al. 1993, Waseda and Suzuki 2006). They are variable spatially over the surface of the corroding surface, both in layer thickness and in specific chemical properties. Much of this variability is of little interest for engineering purposes. However, the aspect of specific interest for the present investigation is that the rusts that form on structural steels usually are considered to consist of two physically different layers even if their chemical properties have similarities – an adherent layer immediately adjacent and tightly bound to the steel and another, much looser and

flaky layer, between the adherent layer and adjacent to the external environment (Garcia et al. 2006). The adherent layer is quite variable in thickness but is dense and hence relatively impermeable. It is usually associated with magnetite - a dark-brown iron oxide (Fe_3O_4) (Oh et al. 1999). The non-adherent layer tends to be flaky and easily removed (Figure 1). Unlike the adherent layer it clearly can offer little protection to oxygen diffusion. Under most exposure conditions the non-adherent rust layer is very easily knocked-off or peels off with the removal of marine growth.

Figure 1 – (a) Non-adherent rust layers (left) removed from coupon that has adherent rusts (at right) (b) Schematic diagram showing non-uniform nature of rust layers.

The adherent rust layer tends to be brittle. This means it could be fractured by sufficiently high levels of applied strain, particularly along the rust-steel substrate interface. This is likely to cause random localized cracking of the rust layer. In turn this may cause a localized reduction in the resistance to oxygen diffusion and hence offer the potential for increased localized corrosion. It also may set up differential oxygen diffusion (Jones 1996), leading to aggressive localized corrosion. This may have an influence on the fatigue life of ship's hulls (Paik 2003b). If the fracture of the adherent rust layer is sufficient widespread increased generalized corrosion may result.

Localized corrosion generally is the result of the creation of a local anodic region, that is one where the loss of Fe ions occurs without a corresponding build-up of corrosion product that absorbs the local availability of electrons (Uhlig and Revie 1985, Jones 1996). It is usually associated with 'differential aeration', implying that a localized electrical circuit is setup between the anodic (metal loss) locations and the cathodic regions where the rust products build-up. In generalized corrosion these processes tend to be distributed widely and superficially randomly over the corroding surface. This implies smaller, more localized differential aeration cells and hence a fine mesh of cracks or fractures to permit access of oxygen. 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. In essence, the adherent rusts under these highly cracked conditions would offer no protection. This possibility has long been

recognized, it being postulated that the decreasing corrosion rate would become approximately linear (Scully 1975).

A somewhat similar idea was applied recently for the modelling of the longer-term corrosion of working steel anchor chain (Melchers et al. 2007). In this case the wear between the anchor chain links is likely to be sufficient to continually remove the build-up of rusts thereby continuously exposing new steel surfaces to the marine environment. The continued rate of corrosion is thus likely to be similar to that of unprotected steel, implying a linear corrosion rate. Since new steel is continually involved, the corrosion rate is likely to be similar to the corrosion rate for short-term corrosion field studies of new steel. Thus the corrosion rate is likely to be similar to the initial rate r_0 developed in phase 1 of the long-term corrosion model proposed earlier (Melchers 2003b). Like the model proposed by Scully (1975), the analysis for anchor chain corrosion did not indicate an acceleration of corrosion rate with time.

Data obtained largely from the surveys of Tanker Structures Cooperative Forum (TSCF 2002) suggests that corrosion rates may be very high and that after some years of reasonably steady values they may increase (Figure 2). Shipping industry sources have suggested that the reported results were for cases of advanced corrosion – levels much above what might be expected in conditions comparable with the normal operation of modern ships – and also involved very high levels of surface strains of the corroding steel. Moreover, it was considered that the reported ‘representative’ curve most likely is the result of compounding data from different ships, a matter previously noted as not necessarily valid (Gardiner and Melchers 2003).

Figure 2 – Schematic representation of increasing corrosion rate with time according to data for tankers (based on data reported in TSCF 2002).

3. Review of recent experimental results

Preliminary tests to observe the effect of applied strain on the rust layers were conducted on mild steels that had been exposed for some time to marine atmospheric conditions and up to 1.5 years to a tidal marine environment. In the latter case the steel was covered with a

substantial layer of rust and marine growth. The marine growth and loose rusts were removed prior to tensile testing. The tests showed that in contrast to the exterior rusts that were easily removed even before applying axial tensile strain, the rusts immediately adjacent to the steel were adherent and difficult to remove. This is consistent with the normal pattern for rust layers (Waseda and Suzuki 2006). The strain was applied by placing the specimens in a universal testing machine and applying controlled axial tensile loading with strains measured with a mechanical strain gauge. For the flexural strains the lateral deflection was measured and converted to tensile strain. In all cases the strain was applied at a slow rate in order not to induce dynamic effects. There was no visible loss of rust particles until strains approaching yield strain were reached, that is, at around 0.004 strain. This was the case in all specimens tested, both for applied axial strain and for tensile strain in bending (Melchers and Paik 2009).

The rust particles that were flaked off initially were barely visible specks less than about 0.1 mm in size. At higher strains, [beyond yield strain](#), the rust particles were larger flakes, some 3-4 mm in size. These appeared to be dislocated from the surface with considerably more energy than 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.

Much greater strains, well into the plastic yield zone for the steel, were required to produce cracks in the rust layer sufficiently large to be photographed (Figure 3). These results were obtained on specimens of various sizes so that it may be concluded that there was no obvious size effect. Tests were carried out at two geographical locations with different average water temperatures. There also was no evidence that this had any effect.

Figure 3 – Close-up view of adherent rust surface showing crack at about 45 degrees to strain axis under an applied tensile strain of 1500 microstrain. Scale: the height of the side of the photo is approximately 15 mm. The crack is about 0.3 mm wide.

A different test program considered the effect of rust cracking or spalling on subsequent short-term corrosion. Axially strained specimens were used (Melchers and Paik 2009). These had been exposed for a period of 2 months in the tidal zone, were then strained to

various strains (1170, 1330 and 1500 microstrain) near the yield strain of the steel and were then re-exposed in the tidal zone for 2 months prior measurement of mass loss. Two different exposure sites were used, both with Pacific seawater (Table 1). The tests were made on mild steel coupons 300 x 50 mm in size and 3mm thick.

Table 1 – Water quality characteristics at the test sites

Characteristic	Taylors Beach (Australia)	Newcastle Harbour (Australia)
Location relative to Pacific Ocean	14 km via Port Stephens estuary – protected site	300m from harbour entrance – exposed site
Salinity (%)	2.01 – 2.89	2.9 (av.)
Temperature (°C)	13.6 – 17.9	15.1 (av.)
Velocity (max) (m/s)	≈ 0.06	≈ 0.07
Dissolved Oxygen (mg/l)	5.4 – 8.4	9.3 (av.)
pH	6.5 – 7.5	7.4 – 7.6
Conductivity (mS/cm)	31.2 – 44.6	28.3 – 48.4

In analyzing the data it was assumed, reasonably, that in the first 4 months of exposure in temperate ocean waters the rate of corrosion is approximately constant with time. This is generally consistent with other observations (Melchers 2003b). Any deviation from linearity could therefore be interpreted as the result of axial straining after 2 months exposure. Figure 4 shows mass loss as a function of time, assuming 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. Evidently the corrosion rate for the second 2 month exposure period increased by about 10-15% for both sites relative to the rate for zero applied strain. Although the interpretation used for Figure 4 assumed a constant corrosion rate with time, it should be evident that in the more general case of nonlinear corrosion with time the effect is likely to be generally similar, with higher strains causing greater damage to the rust layer and hence greater subsequent corrosion loss.

Figure 4 – Effect of applied surface strain on mass loss with strain applied after 2 months.
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4. Interpretation of strain data for ship plate corrosion

In interpreting these experimental results in relation to the observations that have previously been made for ships (Figure 2), it is noted that thinning of plates due to corrosion will, for a given applied loading, cause the surface strains to increase gradually with time. As shown in the experiments, this will, in turn, increase the tendency for even the otherwise quite adherent rusts to flake off, provided the surface strain is high enough. Hence under repeated (but not necessarily continuous) straining over time, rust flaking will tend to occur at slowly decreasing stress or load levels and hence will tend to occur more often. Since the loss of adherent rusts from the steel surface will provide less overall protection against oxygen diffusion, the result is that the overall impression is of an increasing rate of corrosion. Importantly, this phenomenon will occur only under states of advanced corrosion loss, as only such losses can have a significant influence on the surface strains generated by a given level of applied load.

It is now possible to give an interpretation for the corrosion loss observations for ships, as summarized in Figure 2. Two aspects must be considered. The first is the apparent increase in corrosion rate during the first 2-3 years and the second is the increase in corrosion rate after 6-8 years exposure. The latter will be considered in more detail below. Attention will be given now to the early corrosion period. The key here is that the data shown in Figure 2 ought to be consistent with what is known about the earlier stages of corrosion of bare steel in seawater, immersed or periodically immersed (Melchers 2003b, 2007). In particular, it has been shown, for a wide range of climatic conditions and many different geographical locations, that there are essentially two sequential processes involved in marine corrosion of steel. The first is governed mainly by oxygen diffusion to the corroding surface, a process that soon becomes inhibited by the build-up of rust layers and that leads to a gradually slowing of the rate of corrosion.

Figure 5 shows the data trends of Figure 2 (except for LBL-CS6 as it has too few data points). For the first 2-3 years, a gradual reduction in corrosion rate is seen in the trends

through the data from the origin to points A and B. At about these points the oxygen flux has become sufficiently low for local anoxic (or suboxic) conditions to occur at micro-niches within the rusts. Given also adequate nutritional availability, these conditions then permit sulfate-reducing bacteria to flourish, leading to microbiologically influenced corrosion. The result in terms of corrosion loss is shown in Figure 5 as the curved trends beyond A and B, becoming nearly linear with time (Melchers 2003b). This shows that the corrosion loss data for the first 2-3 years as reported in TSCF (2002) for tankers is consistent with other observations for the marine corrosion of steel. It is also consistent with well-known observations and interpretations that ship plating after some years of exposure is subject to microbiologically induced corrosion (Campbell et al. 1987, Huang et al. 1997, OCIMF 1997).

Figure 5 – Interpretation of ship plate mass-loss data (TSCF 2002) in terms of the general corrosion-loss model proposed by Melchers (2003b, 2007).

Although the sources of the data shown in Figures 2 and 5 are not known, the interpreted trends shown are generally consistent with expectations. Thus the trend for the elevated temperature data is higher and has the transition A occurring earlier, as expected (Melchers 2003b). The time for the transitions A and B is related both to the mean temperature of the water or moisture governing the corrosion process and also to the duration of wetness. Neither of these were reported in the original data (TSCF 2002). Hence it is difficult to make conclusions. Elucidating the relationships involved and comparing with the model (Melchers 2003b) is a potential area for further research.

The increase in corrosion wastage for the period after about 6-8 years exposure (Figure 5) can now be considered in the light of the experimental observations. For typical ship plating in the range 10-15 mm, and with accepted IACS rules that corrosion wastage over 10% is sufficiently serious for plate replacement to be mandatory, it is clear that wastage of 2 or more millimetres is very serious. As seen in Figure 5, this thickness loss corresponds, for outboard transverse web frame plating, to the onset of accelerated corrosion loss. For the longitudinal stiffeners of transverse bulkhead it corresponds to a wastage of 3 mm or more. These figures might be compared to the effect of plate thinning on surface strains, assuming similar applied loadings. For example, a wastage of 4 mm for one side of a 20

mm side plate in flexure, or 3 mm for a 15 mm plate, would cause the surface tensile stress to increase by some 60% for similar applied loading. Such an increase in stress would move the plate from well within the elastic behaviour range into plastic, post-yield behaviour range. As is well-known, moving from the elastic stress range into the plastic range will produce a much greater increase in strain once yield strain is reached. This supports the contention that the increasing corrosion rates reported for uncoated tanker spaces (TSCF 2002) is applicable mainly to situations with advanced levels of corrosion.

Overall, the implication of the above observations is that modern, well-managed vessels, operating under normal conditions that attempt to minimize extreme loadings, the effect of applied strain on the loss of plate thickness in areas that are not protected by CP or protective coatings is likely to be relatively small. However, this may not apply in areas or parts of vessels that are subject to local high stress (and hence strain) concentrations. The potential effect of high local stress concentration in such areas on the local corrosion behaviour is a further area for more detailed investigation.

5. Discussions

An important aspect of understanding the importance of high levels of strain is the influence of the duration of such events. Typically vessels in good condition and managed such as to avoid overloading or high load conditions under storm or loading/unloading conditions would not be expected to undergo high strains for extended periods. This is likely to mean that any fracturing or loss of corrosion product will also 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 and hence the possibility for rebuilding of rust layers to offer some measure of protection is much reduced. 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.

Although sometimes the dynamics of flexure is noted as a possible contributor to the phenomenon seen in Figure 2, it is considered unlikely that the *dynamics* of flexing itself has an effect on the corrosion process other than through the mechanism of rust breakdown caused by surface strains. However, it should be clear from the information presented above that the *rate* of flexing can have an influence through the rate at which the rust layer is fractured or damaged. The rate of flexing is, of course, a function of the dynamic characteristics of a vessel. This is a function of the mass of the vessel and of its stiffness and both of these are influenced by corrosion loss. In this sense there is an interaction between dynamics and corrosion, since, for vessels with an advanced level of corrosion the flexing of the vessel will reduce the protectiveness of any rust layers and this will, in turn increase the rate of corrosion.

The corrosion mass loss used above as an indicator of the effect of applied surface strain on subsequent corrosion may not be an adequate measure of the effect of strain. The reason is that local cracking of the rust layer will have a (limited) local corrosion effect and this clearly is not reflected adequately in mass loss measurements. But it may be important in relation to fatigue life if localized corrosion induces locally higher fatigue stresses and so has an accumulating effect on fatigue life. This possibility was not investigated in the present paper.

It would require a more detailed investigation of localized corrosion effects. To capture the effect of localized corrosion at and near cracks in rust layers, a possible improvement to the experimental procedure could be the use of ultrasonic measurements to measure thickness loss, even though the relatively low thickness measurement resolution of standard equipment compared to the resolution required is likely to be a limitation. It would also require multiple measurements to locate localized advanced corrosion loss. An alternative would be detailed examination of corrosion pitting and in particular differentiation of pitting in the cracked zones compared to elsewhere. This is considered to be an important matter for further investigation.

The observations and conclusions reached herein are for short-term exposures. They are likely to be valid also for steels subject to much longer periods of exposure but this would need to be verified by experiments involving longer-term observations for flexing and non-flexing strips of steel in realistic marine environments. Emphasis would be placed on making observations of localized corrosion as well as mass-loss. Given the harsh conditions of marine climate exposures the use of mechanical devices to achieve specimen flexing is unlikely to prove successful for long-term experimental field testing.

One potential approach is to harness natural wave action in a suitably enclosed and protected harbour, alongside a more protected area where wave action is minimal for strips not to be subjected to flexing action. Periodic measurement of the flexing action achieved would be sufficient to characterize the flexural strain environment. Periodic removal of some of the test strips is likely to lead to increased flexural action, thereby simulating overall deterioration of the structure. It would be possible to perform laboratory experiments along the same lines but with much better control over all variables. This is advantageous for achieving improved understanding of the influence of the variables on the accelerating corrosion process.

The discussion herein was confined to [tensile](#) 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. Concluding remarks

The rusts that form on structural steels under marine corrosion conditions are predominantly of two types – loose rusts and adherent rusts. Only the adherent rusts have the potential to offer protection from oxidation and hence to inhibit the progression of the corrosion process. Tests have shown 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 but may cause localized cracking of the rusts.

The general corrosion rate was found to increase by some 15% when the strains approached the yield strain of the steel. Such high levels of strain are much higher than normally tolerated for ship plating. The effect of such strains on localized corrosion in areas of high strain and on pitting corrosion, the effect of compressive and flexural strains, the long-term corrosion behaviour under strains and comparison between model and observations all remain matters for further investigation.

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Figures

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Figure 2 – Schematic representation of increasing corrosion rate with time according to data for tanker ships (based on data reported in TSCF 2002).

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Figure 1

Figure 2

Figure 3

Figure 4 SAOSversion

Figure 5