# Validity and Quality of Deterioration Models for Structural Reliability Assessment

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There are increasing pressures to extend the service lives of existing Abstract: infrastructure and to provide optimal management of their maintenance. Structural reliability theory now provides a very comprehensive approach to assessing risks for complex infrastructure systems. It requires probabilistic models for the prediction of the long-term changes to structural capacity and resistance as may result, for example, from changes in the management or operation of the asset or from material deterioration in harsh operational environments. While empirical models may be sufficient in some cases, it is preferable for the models to be based on fundamental science and to deal with remaining uncertainty in a probabilistic manner. Herein models for the prediction of the corrosion of structural steel in marine environments are considered. The issues involved are reviewed and some of the pitfalls in model development are considered. These include (i) models based on inadequate underlying theories, (ii) use of inhomogeneous populations, (iii) use of inappropriate influencing factors, (iv) use of laboratory test results rather than field results, (v) insufficient attention to limitations and conditions, (vi) insufficient understanding of the changes in conditions with time, and (vii) invoking model simplifications too early. Drawing on material that has already been published in the literature, examples are given of each to show how these matters may provide misleading information to potential end-users.

#### 1 Introduction

Most infrastructure, particularly that in the public domain or for public access or for national purposes such as defence, etc. typically is meant to have long life, remaining 'fit-for-purpose'. Because the cost of replacement typically is high, there are increasing pressures to extend the service lives of existing items of infrastructure and to provide optimal management of their maintenance. The problem is exacerbated by the increasing average age of existing infrastructure since older items tend

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to require more resources for maintenance and thus require an increasing proportion of resources. As items of infrastructure age the risk of structural failure (and other forms of failure) increases. For major infrastructure this may have serious consequences - both in terms of loss of life and economically. Typically there is tension between the economics for the construction of new infrastructure and the costs of infrastructure maintenance. This has led to increasing pressure being placed on asset management, including the justification of its techniques. There is now gradual acceptance that proper asset management requires high quality methods and procedures, including for risk assessment. This must include both the probability of occurrence of potential modes of failure and the potential consequences that may arise.

Structural reliability theory now provides a very comprehensive approach to assessing risks for complex infrastructure systems. However, it relies on having available adequate models for loadings and for resistances and also models for changes in both these inputs. A weak link at present is the quality of the models for the prediction of the long-term changes to structural capacity and resistance resulting from material deterioration. For proper reliability analysis the deterioration models must be probabilistic models. The present paper considers models for the corrosion of structural steel in the marine environment. It notes the necessary probabilistic framework for model development and outlines the way such models should be used together with some of the pitfalls. Throughout the emphasis is on development of high-quality models for deterioration. Obviously, it is not difficult to build poor quality models but knowing how 'poor' the model is, is another matter. In contrast, 'simplified' models are those that have been obtained from systematic simplification of high quality models or theory. It follows that the degree of simplification is understood. Evidently, the development of simplified models involves the same issues as for high-quality models, even if the eventual modelling outcome does not obviously reflect them.

#### 2 Structural reliability assessment

Probabilistic methods in structural analysis and design provide a means for estimating the probability of violation of one or more so-called limit states (Melchers 1999). The limit states describe the functional conditions required to be met by the structure, including adequate load capacity and operational requirements. Typically the applied loadings and the structural capacities are not known with a high degree of accuracy. In conventional deterministic analyses, these quantities are represented by nominal numbers. However, in a probabilistic analysis they are formulated as probabilistic quantities, typically using appropriate probability distributions. These typically are derived from observed data, perhaps modified (such as by Design Code committees) to reflect professional experience. The precise processes involved (which can be of considerable mathematical complexity particularly when time-dependent aspects are included) are given in standard texts (Melchers 1999, 2005a). For deteriorating structures, the loss of material (and hence strength or capacity) can be expressed by  $c(t, \mathbf{E})$ . It is a function of time (*t*) and of environmental conditions  $\mathbf{E}$  and may be described in general terms as:

$$c(t, \mathbf{E}) = b(t, \mathbf{E}) \cdot f(t, \mathbf{E}) + \varepsilon(t, \mathbf{E})$$
(1)

where  $f(t, \mathbf{E})$  is the mean-value function describing the deterioration process as a function of t and  $\mathbf{E}$ ,  $b(t, \mathbf{E})$  is a bias function and  $\varepsilon(t, \mathbf{E})$  is a zero-mean error function. In the present paper expression Eqn (1) will be considered in relation to corrosion, that is, when  $c(t, \mathbf{E})$  represents corrosion material loss or maximum pit depth. It will be sufficient to confine discussion to  $f(t, \mathbf{E})$  since, typically,  $\varepsilon(t, \mathbf{E})$  and  $b(t, \mathbf{E})$  are less critical in reliability calculations than is  $f(t, \mathbf{E})$  (Melchers 2006a).

## 3 Inadequate regard for underlying theoretical principles

Many so-called 'models' for corrosion are little more than representations of data, with scant regard for underlying theoretical principles. This means that they are largely (semi-) empirical. Typically they are obtained by fitting a plausible curve through a set of data. In corrosion engineering several such models exist. Perhaps the most widely known is the 'power-law':

$$c(t, \mathbf{E}) = A(\mathbf{E})t^{B(\mathbf{E})}$$
<sup>(2)</sup>

where  $A(\mathbf{E})$  and  $B(\mathbf{E})$  are constants that are, for a given environment **E**, obtained from fitting the function to the data. It has been noted repeatedly in the literature that the power-law does not always fit the data very well throughout the whole data range. However, this is often dismissed as the result of inadequate data or the result of systematic error (e.g. Benarie and Lipfert 1986). In other cases, significant changes in the values of A or B or both with longer period data sets from the same exposure site were observed but essentially ignored (Hou and Liang 2004). In part this may be the result of plotting the data on log-log axes – thereby tending to even-out irregularities and giving the appearance that the relationship is close to a (log-log) straight line, equivalent to Eqn (2). Equation (2) is so well-established in the atmospheric corrosion literature that it is sometimes even considered a 'natural law' (Vera et al. 2003). But it is not easy to discover its precise origins in theory. The best that can be said is that it is based loosely on the theory of oxidizing metal surfaces first proposed by Tammann (1923) and subsequently refined by Booth (1948) and Evans (1960) amongst others. Under certain significant simplifications (Melchers 2003a) that theory can be simplified to Eqn (2). One is the assumption that Eqn (2) applies from t = 0. This is impossible as the corrosion rate would then approach infinity. Another is that the rust layers are uniform through their thickness, an assumption considerably at odds with field observations. These simplifications are seldom discussed in the application of Eqn (2) to field data.

The theory of oxidizing surfaces should apply also for corrosion under immersion conditions in aerated near-surface seawater conditions. For these there is ample evidence that Eqn (2) has only limited applicability. May be as a result, a number of other empirical models have been proposed (Mikhailovskii et al. 1980, Benarie and Lipfert 1986, Chernov and Ponomarenko 1991, Feliu et al. 1993, Hoerle et al. 2004). Some of these include the assumption that long-term corrosion essentially is a linear function, an observation supported by field data (Southwell et al. 1979). There are also some other, completely empirical, models proposed for ship corrosion. These are discussed later. Some of the above inconsistencies can be resolved by reviewing the fundamental theory of metal surface oxidation. It will then be clear that the processes governing oxidation in the first few years (the period covered by most experiments) cannot go on 'ad infinitum'. The build-up of corrosion products can be postulated increasingly to impede the diffusion of oxygen to the cathodic parts of the corroding surface but other processes are at work as well. Thus, account must be taken of the loss of corrosion products, for example due to erosion effects (Melchers 2003b), and the mass balance between the metal that is lost and the amount of metal that is oxidized and deposited in the rust layers (Garcia et al. 2006). There also may be potential for changes in the oxidation mechanism from largely chemical oxidation kinetics involving oxygen as the electron acceptor to chemical kinetics influenced by microbiological activity, with or without the involvement of oxygen. For example, for marine immersion corrosion there is now ample evidence that eventually there is a change in the electrolyte at the corroding surface. This change results from the presence of a variety of bacteria including the anaerobic sulfate reducing bacteria (SRB) for which sulphur is a possible electron acceptor, or, in some circumstances, manganese. There also is evidence that iron oxidizing bacteria and iron reducing bacteria may be involved in microbiologically influenced corrosion (Jeffrey and Melchers 2003). In many of these cases the longer-term corrosion loss should be modelled by a relationship more complex than Eqn (2). An appropriate model is shown in Figure 1. It shows, in schematic form, the changes that occur in the corrosion process as it progresses with time.

Figure 2 shows some typical examples of the application of the model of Figure 1 to long-term corrosion loss data obtained in the immersion, tidal, coastal atmospheric and inland atmospheric exposure zones. All are relevant for the corrosion of ship components and for harbour and coastal structures. There are considerable



Figure 1: Schematic model of corrosion loss of steel as a function of exposure period. In phases 1 and 2 mainly oxygen diffusion controls the rate of the corrosion process and phases 3 and 4 in bacterial activity may play an important part, depending on the availability of suitable nutrients. More details are available in Melchers and Jeffrey 2008.

differences in the amount of corrosion loss as a function of time for the various exposure zones, but in each case the pattern of Figure 1 is evident. It is also clear that the time  $t_a$  (Figure 1) is reflected in the data in Figure 2, and that  $t_a$  increases with an increase in atmospheric exposure, that is, with reduced 'time of wetness'. This is as would be expected from first principles.

Figure 1 has been found to be relevant also for localized corrosion such as pitting. This is not surprising given the known inter-relationship between general and localized corrosion (Jones 1996). Figure 3 shows an example of maximum pit depth as a function of exposure time for immersion conditions (Melchers 2004). It is clear, again, that apart possibly for short-term exposures, Eqn (2) cannot adequately describe the maximum pit depth as a function of exposure time. Attempts to do so have arisen from a pre-occupation with shorter term exposures. It is also the result of failure to distinguish changes in the nature of the pitting process, as will be described in the next section.

#### 4 Use of inhomogeneous populations

For localized corrosion such as pitting it is necessary to be aware of the mechanics by which it is initiated and by which it progresses. Local inhomogeneities in the metal are thought to produce pit initiation (Butler et al.1972, Wranglen 1974). This gives rise to anodic regions (where metal loss is concentrated, such as at pits) in electrical equilibrium with the cathode regions where the oxidation of metal ions leads to rust deposition and there is little or no metal loss. The topography of the



Figure 2: Examples of the pattern of corrosion loss of mild steel shown schematically in Figure 1, for immersion, tidal, coastal atmospheric and inland atmospheric exposure zones in the Panama Canal Zone. The trends shown were interpreted from the data.

surfaces of corroding metals sometimes is in accord with conventional corrosion science theory. It considers each idealized pit (anodic region) is surrounded by its own (much larger) cathodic region. An example is shown in Figure 4a. However, there are also observations for pit patterns that show wide-spread pitting without obvious evidence of cathodic areas (Jeffrey and Melchers 2007) (Figure 4b). Such observations currently are not easily explained. It has been argued that the mechanics of pitting corrosion of steel in marine immersion conditions must consider the possibility of bacterial involvement (Melchers 2006b).

Conventionally pitting is described as following a number of successive stages (nucleation, initiation and growth). The nucleation and initiation stages are short-term events and have little direct influence on pit depth once pitting has commenced. Figure 3 shows that there is a change in pit growth behaviour as the pit depth increases. A second phenomenon is that not all pits, once initiated, will continue to grow *ad infinitum*. Some (perhaps most) will stop growing, while others will continue to increase in depth and in diameter. These have been called meta-stable and stable pits respectively (Szklarska-Smialowska 1986). They clearly represent two different groups of pit type. In statistical terms they represent two different



Figure 3: Trend line for maximum pit depth as a function of exposure period. Also shown is the interpreted trend for the average of the 6 deepest pits observed.



Figure 4: (a) Conventional deep pit (i.e. the anode) surrounded by roughly circular cathodic region that has corroded much less, (b) A fields of pits showing some pits deeper than the others but no clear cathodic region. Scale: vertical edge of photographs is approximately 25 mm.

populations. At any point in time it is likely that both stable pits and meta-stable pits will be present. However, it will not be possible to discern from a single observation which are the stable, growing, pits and which are not. This distinction is important for engineering purposes since usually only the stable (i.e. growing) pits cause structural and containment problems. It is important also for the statistical analysis of maximum pit depth using Extreme Value statistics. This can be seen from the Gumbel plot shown in Figure 5. It shows a sample set of data taken from Taylors Beach, Australia (Melchers 2006c) with probabilities assigned using the mean rank order approach (Kotz and Nadarajah 2000). A straight line such as AA fitted to all the data is consistent with the Gumbel distribution if there are only minor deviations from linearity. The data in Figure 5 can be interpreted as showing two distinct trends, marked BB for shallower pits and CC for the deeper pits. These two trends have been interpreted (Melchers 2006c) as meta-stable pitting and stable pitting respectively.



Figure 5: Data for maximum pit depth at 1,2 and 4 years exposure at Taylors Beach, Australia shown on a Gumbel plot. w is the standard variable for the Gumbel plot, with the corresponding cumulative distribution shown on the right-hand axis. In each case the lines AA correspond to the usual interpretation of the data as Gumbel-distributed. A different interpretation shows curves BB as the distribution (Exponential) for the meta-stable pits and the curves CC best described by the Frechet EV distribution and corresponding to stable pitting (a different statistical population).

It might be noted this interpretation has been challenged on the grounds that the maximum depth of meta-stable pits observed in laboratory studies is much shallower than seen in Figure 5. To put this in proper context it should be noted that laboratory studies of pitting invariably use anodic polarization (i.e. an applied current). This accelerates ionization of Fe in the pit and thus accelerates the pitting process. However, it cannot speed-up the various associated diffusion processes within the pit and between it and the external environment. The net result is that the

overall pitting process and its progression is distorted. For some pits stable pitting will be forced to occur at an earlier time than would otherwise be the case. Competition for electron acceptors will force the other pits to shut-down (i.e. become inactive) at an earlier time. This will produce metastable pits that are smaller in size than would otherwise be the case. In contrast, the pit depths reported in Figure 5 were obtained under natural conditions. The meta-stable and stable pit depth data trends can each be described by an appropriate extreme value probability distribution. For the meta-stable pit depths the exponential distribution is consistent with earlier observations (cf. Szklarska-Smialowska 1986). For the stable pit depths the Normal, Gumbel or Frechet distribution can be used, depending on the exposure period (Melchers 2006c). The difference between metastable and stable pitting is important for projecting in time and space (the usual reasons for deriving extreme value distributions). This can be seen in Figure 5. The pit depth projected by CC is considerable greater than that projected by AA. Evidently, line AA covers both types of pitting and therefore mixes two different statistical populations - this has been the standard approach in the classical approach in literature for using extreme value distributions for pit depth, but it can now be seen to be not valid.

#### 5 Appropriateness of influencing models

The effect of seawater salinity can be important for marine immersion and tidal zone corrosion. It is well-known from laboratory investigations that the concentration of dissolved oxygen depends on salinity but the effect is slight (Uhlig and Revie 1985, Mercer and Lumbard 1995). While there is some influence of oxygen concentration on corrosion loss, at least while oxidation by oxygen is the 'ratecontrolling' mechanism, the changes do not correlate well with salinity. Cases of high corrosion loss for fresh or very mildly brackish waters have been recorded, but so have cases in which the salinity was high. To understand this it is necessary to have a deeper insight into the mechanisms involved. The salinity of seawater in the oceans is remarkably uniform. It is only where there is significant inflow of fresh waters that the salinity is reduced, such as at river mouths and in estuaries or bays. The alkalinity of the respective waters is important. While seawater is strongly buffered at pH around 8.0-8.2, fresh waters vary considerably in both pH and alkalinity, ranging from pH 7 to much higher (up to 9) for hard, usually highly buffered waters. The introduction of fresh waters to seawater has the potential to lower (or raise) the pH of the resulting mixed waters. Seawater is saturated with CaCO<sub>3</sub>, mainly in the form of aragonite, and an increase of the water pH will result in greater CaCO<sub>3</sub> deposition, including in rusts. This is known to reduce the oxygen permeability of rusts (LaQue 1975) and hence the rate of oxygen diffusion to the corroding surface, thereby reducing the corrosion rate. It is the normal situ-

ation, for example, in Europe where most river waters are 'hard', giving rise to the usual conclusion that brackish waters are less corrosive than seawater. However, where the fresh waters have a pH lower than seawater and are 'soft', corrosion may actually be worse in brackish waters than in seawater since in this case the CaCO<sub>3</sub> is deposited at a rate less than normal (Melchers 2006d). For generally similar reasons it is inappropriate to use (usually laboratory) data for the effect of pH on corrosion rate. Standard texts usually quote the influence of pH on short term corrosion rates in unpolluted fresh water, with the pH adjusted using standard buffers. Under these conditions the corrosion rate increases with pH up to about 4 after which there is no change until pH reaches 10, followed by increasing corrosion rate with increasing pH (e.g. Uhlig and Revie 1985). A similar situation holds for the corrosion potential Eh as a function of pH. A number of relationships between the various species possible as corrosion products must be considered and these conventionally are represented on a Pourbaix (Eh - pH) diagram. The Pourbaix diagram for iron in water is widely quoted in corrosion texts but it must not be taken out of context. It is a function also of the constituents of the water and differs for seawater compared with unpolluted freshwater (Shrier 1994). Moreover, any point on the diagram represents the dominant species under that combination of Eh and pH - other species may coexist at the same Eh-pH (but not be dominant) (Brookins 1988, Pankow 1991).

#### 6 Laboratory test results vs. field results

The preceding section signalled the potential problems with the use of laboratory data instead of in-situ data. There are other examples of interest. One is the effect of water velocity on corrosion rate. Many corrosion texts quote the results reported by LaQue (1948) that showed that initially the corrosion rate of steel in seawater immersion increases sharply and linearly with velocity. However, as the water velocity increases, the incremental effect reduces. What is not mentioned is that these results were obtained in a laboratory study lasting only 36 days and using re-circulating seawater. It was replenished only every few days. The short duration of the tests means that the results might be valid for  $r_0$  in Figure 1 but even this is doubtful since the lack of continual fresh seawater replacement is likely to have influenced bacterial activity during that early period. Moreover, for even slightly longer exposure periods the build-up of corrosion products is almost certain to shield the corroding surface from the action of water velocity. The problem lies not with the original tests, as these did not claim any validity for long-term corrosion, but with the lack of context in its reporting in secondary sources and its subsequent incorrect use in corrosion modelling efforts (Guedes-Soares et al. 2005, 2006). A somewhat similar situation exists with the effect of water temperature on corrosion. In carefully conducted laboratory tests Mercer and Lumbard (1995) reported data that could be interpreted as showing Arrhenius behaviour for the corrosion loss over a period of 72 days both in saline water and in transported sea water. This is entirely consistent with what would be expected for a chemical reaction. Similar behaviour was found for corrosion loss data collected from a number of unpolluted coastal marine exposure sites, but the Arrhenius curve was distinctly different (Figure 6). At first sight this is difficult to reconcile, but a little consideration will show that once again natural seawater is not the same as transported seawater. It also is not the same as either saline water or artificial seawater. The different lies in the amount of nutrient supply for bacterial activity. As mentioned above, this is known to be involved in the corrosion process right from the time of first immersion (Little and Ray 2002, Melchers 2007a, Melchers and Jeffrey 2008).



Figure 6: Initial corrosion rate  $r_0$  as a function of average water temperature for in-situ seawater (field data) and for seawater transported to the laboratory and then only periodically replenished over a period of 72 days. Both data trends show Arrhenius behaviour but the trends are considerably different.

As is well-known, water temperature influences the kinetics of the electro-chemical corrosion process and the solubility of dissolved oxygen. It also influences various aspects of bacterial activity, including the availability of nutrients, particularly nitrogen, and the metabolic rate of bacteria. The currently available evidence sug-

gests that the rate of supply of nitrogen is the rate-controlling process (Melchers 2007a).

### 7 Limitations and conditions

In the literature some empirical models have been proposed for application in the shipping industry. Unfortunately they are inconsistent with expectations and with known facts. For example, there is no known theoretical reason for the corrosion rate to decrease to zero after some years of exposure, as proposed (Figure 7) in the corrosion loss models of Guedes Soares and Garbatov (1998, 1999) and Qin and Cui (2002). If these models were correct, the immediate conclusion would be that provision of sufficient corrosion allowance would ensure long-term safety since eventually the corrosion process would stop - eventually there would be perfect protection against further corrosion. This is not in accordance with actual observations and data obtained for long-term field observations conducted under careful experimental conditions (Schumacher 1979). It also does not allow for the possibility of erosion or loss of corrosion product and rust cracking, both likely to reduce the protectiveness of the rust layers and permitting further corrosion. Both loss of rust and cracking of rust may be caused by applied strains such as result from flexing of ships hulls. It is a matter currently under active investigation (Melchers and Paik 2009).



Figure 7: Schematic view of models proposed for use in the shipping industry for corrosion wastage (loss) of steel plating. Both models include a period for the life of a protective coating (paint) followed by an increase and then a gradual decrease in corrosion rate. Both models predict an eventual zero rate of corrosion.

A further limitation that must be considered carefully is the effect of scale. Most of the results reported in the literature are for relatively small coupons or, in the case of data from ship classification societies, for isolated points on plates, etc. Preliminary results for the effect of size of plate within the one exposure environment show little effect of plate size (Melchers and Ahammed 2004) or its shape (Jeffrey and Melchers 2002). In both cases corrosion is approximately uniform. But this is not the case for plates or strips traversing different exposure environments. Already in early laboratory studies a high level of corrosion immediately below the water-line was found for vertical steel plates partially immersed in sodium chloride solutions (Evans 1960). Later, US naval ships moth-balled in San Diego harbour showed high corrosion immediately below the waterline (Corcoran and Kittredge 1956), attributed eventually to the high levels of sewage pollution accelerating bacterial activity (Peterson and Waldron 1961). A similar effect has been observed for sheet piling (Humble 1949) and more recently this, too, has been associated with bacterial activity (Genim et al. 1993) although a clear causative mechanism remains elusive (Christie 2007). Nevertheless, differential aeration is highly likely to be the primary causative mechanism in all these cases (Evans 1960).

# 8 Changes in conditions with time

Without a proper understanding of the factors that may influence the corrosion process it is possible to make incorrect conclusions about what the data appear to show. Figure 8 shows mass loss results recorded at closely spaced time intervals for atmospheric corrosion in the highly aggressive Arabian Gulf region (Mohamed et al. 1997). The broken line shows the likely trend for average mass loss with time. The pattern is not consistent with the model of Figure 1.

Evidently, there is some systematic variation in the data. This is closely related to seasonal changes. For this geographical region both the temperature and the rainfall vary considerably over each year and this is reflected in Figure 8. Interestingly, for this highly aggressive site the transition time  $t_a$  (see Figure 1) is likely to be around 0.8-1.0 years (Melchers 2007b) but, because of the temperature fluctuation effects, this cannot be discerned directly from the data in Figure 8. At best it can be inferred as shown schematically with the full line for the most likely trend.

# 9 Invoking model simplifications too early

Models of the type given in Figure 1 are sometimes considered to be 'too complex' for industrial application. It is thus tempting to develop simpler, preferably somewhat conservative, models described by fewer parameters. In this context, it has long been assumed, particularly in engineering and naval architecture, that



Figure 8: Variation in atmospheric corrosion in the highly aggressive atmosphere of the Arabian Gulf region, showing evidence of annual fluctuation of corrosion loss. The bold line is the interpretation of the data based on Figure 1.

corrosion can be represented by a 'rate', such as measured in mm/yr, and that this rate does not change with time. Figure 9 shows how sample corrosion data might be interpreted using a linear trend, the slope of which is the 'constant' corrosion 'rate'. Note that in this case there is sufficient data for the 'rate' to be some sort of average value of the data, but this is not always the case in practice (for which only one or two data points are more commonly available). There is considerable uncertainty, as evident from the scatter of the data about the trend line. In the shipping industry, for example, commonly quoted corrosion rates typically have coefficients of variation greater than 1.0, indicating that the standard deviation is greater than the mean value, even after a considerable number of years of exposure. This is not particularly satisfactory.

A better approach to achieve model simplicity is to represent the data initially at as high a modelling level as possible and, only after attaining a good understanding of the factors of importance, simplifying the model for application purposes. Figure 10 shows how this might be done based on the model of Figure 1 (Melchers 2005b). Note that this is a bi-linear model that recognizes that the longer-term corrosion rate is much lower (Southwell et al. 1979), typically, than the initial rate. Since the



Figure 9: Linear trend line fitted to data, ignoring data trends and data scatter.

parameters for the model of Figure 1 are available, it follows that the parameters for the simpler model of Figure 10 also are available. Apart from the intermediate region around  $t_a$ , the uncertainty attached to the simpler model is similar to that of the more fundamental model.



Figure 10: Simplified corrosion loss model (broken lines) for short- and for long-term corrosion losses.

#### 10 Discussion

The above has outlined some examples of the inappropriate use of information in the literature for making predictions about the likely rate of corrosion - general and pitting. A number of these potential problems were noted already many years ago (LaOue 1951, IJselling 1989) but appear not to have been fully appreciated in all modelling efforts (see above). The problem is not confined to some isolated academic papers. It was reflected recently also in specialist workshops convened by the US Office of Naval Research (2006). The disparity between laboratory and field observations was highlighted, as was the need for models that have good prediction capabilities for likely corrosion losses under field operational conditions. One difficulty in model building is that laboratory conditions do not always match field operational conditions. Only seldom is it possible to replicate field conditions in the laboratory. This includes all the qualities of that very complex material - seawater. An additional issue is that artificial techniques to speed-up corrosion processes, such as anodic polarization, higher temperatures, higher reactant concentrations, etc. often are employed in laboratory experiments, even though these add to the difficulty of interpretation vis-a-vis for field conditions. The problem is particularly important where corrosion rates are of interest rather than thermodynamic stability (i.e. when conditions are appropriate for corrosion to occur). Conversely, experiments conducted under field operational conditions seldom have the degree of control desired for good experiments. They usually lack the potential to isolate influencing variables compared to what is possible under laboratory conditions. This adds to the uncertainty in interpreting field observations and adds to the difficulty of making sound inferences. One approach that has been used with some success is to use fundamental scientific understanding to interpret field data, using the supposition that the basic corrosion (and bacterial) processes of interest must be the same for the transition from laboratory to field and back again. Most of the points made herein are based on the results of such an approach.

#### 11 Conclusion

A summary was given of the important issues in the appropriate modelling of the corrosion process for engineering applications. Examples draw on material already been published in the literature. Both good and poor practices were considered. Of particular concern is the application of laboratory results obtained under very short-term exposure conditions using either artificial or transported seawaters. These conditions do not replicate the actual corrosion behaviour of steels in in-situ seawater conditions. One of the main reasons is the involvement of bacteria both in the very early stages and in the longer-term corrosion processes. A important rea-

son is that the corrosion process changes with time due to the build-up of corrosion products. This changes the environment immediately adjacent to the corroding surface relative to the environment in the bulk solution. With time there is a grad-ual reduction in oxygen availability at the corroding surface, causing a change from oxygen-diffusion controlled corrosion kinetics to a more complex scenario that also includes the effect of bacterial activity. These changes have important implications for steel structures undergoing long-term marine corrosion loss.

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