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Influence of pitting corrosion on strength of steel ships and offshore structures

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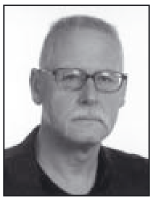
ABSTRACT



The present paper deals with the influence of pitting corrosion on mechanical properties of mild and low alloy steels and strength of steel structures under static and quasi-static loads. Pitting corrosion is a very important phenomenon that influence local strength of ship hull members. The present paper is based mainly on Japanese publications. Analyzing the standard tensile diagrams one can see that that pitting corrosion reduces the load corresponding to yield stress (YS) and, even more markedly, tensile strength UTS, reduces almost to zero plastic flow strains at YS load level and dramatically reduces the total elongation to fracture. Nominal UTS load for uniformly corroded specimens is higher than that for pitted specimens at the same average thickness loss. The strength related to the true fracture surface area (i.e. reduced by pits, taking into account real path of the crack through the pits) is almost independent of the thickness loss and is almost the same as for uniform thickness loss. For wide specimens the tensile strength depends mainly on the local deformation ability, and the maximum loading ability for large members, predicted on the base of the total true fracture surface area, can be overestimated. Concept of equivalent thickness loss for plates under bending and compression and for more complex structural models as well as relation between the average and the equivalent thickness losses has been presented. Approach based on degree of pitting (ratio of pitted area to total plate surface area) has been shown as a real and more convenient than the approach based on the thickness loss.

Keywords: pitting corrosion, strength, shipbuilding steels, ship structures

INTRODUCTION

There are two groups of actions that can lead to damages of real structures:
- Chemical or electrochemical, if undesirable, are identified with corrosion
- mechanical, usually identified with stresses or strains

Interaction of corrosive and mechanical factors is the most general case. Almost all corroding structures are stressed. Almost all stressed structures are exploited in any environment that is not neutral in mechanical damage process. Pure mechanical or pure corrosive damage can be considered as specific and unusual cases. In case of vacuum or eventually inert gas environment we can assume that damage is purely mechanical in nature, while for very low stress levels we can assume that damage is purely corrosive.

The above is especially true for ships and offshore structures that are the main object of the present paper. Corrosive environment of these structures is also the main source of service loads, i.e. static or dynamic pressure of sea water.

The present paper concerns the influence of pitting corrosion on strength of steels and steel structures under static or quasi-static loads. The mild and low alloy steels used for welded marine structures are considered as insensitive to stress corrosion cracking in marine environment. Therefore only the pit nucleation and growth process should be considered as a complex mechanical-electrochemical phenomenon. Fracture process occurs in a relatively short time and influence of corrosive environment on this process can be considered as negligible. Pitting corrosion incubation and growth and the role of strain and/or stress in this process has been discussed elsewhere [1, 2]. The present paper is focused on the influence of pre-existing pits on mechanical properties of mild and low alloy steels and strength of the steel structures.

Previous pitting corrosion influences the fatigue strength and life by the following ways:

I reduction of the average material thickness that influence the nominal stress in the structure;

II pitting-corrosion-induced roughness of the material surface that leads to local stress concentrations at some locations at the surface.

The role of pitting in fatigue of materials and structures is commonly appreciated. The problem has been discussed in [2] on the wide base of references concerning different materials. In common opinion, pits, if they are present at the material, are almost always the potential sites of the fatigue crack initiation, thus they reduce the fatigue life. If strength of steel structures under static or quasi-static loadings is considered, the opinion is not so unanimous.

Melchers [3] has formulated opinion that pitting corrosion has very little influence on the strength of well maintained structures, such as ships – general corrosion (loss of thickness) is more important. This opinion has been accepted by Wang et al. [4]. These authors have elaborated models for the time-related growth of the maximum depth of pitting because, in their opinion, the main menace is perforation of the structure walls and it can be dangerous especially for pipelines and tanks. However, extensive studies of the influence of pitting corrosion on the behaviors of materials and structures under static loading has been carried out in Japan by Nakai, Matsushita, Yamamoto and, in some papers, Arai [5 - 10], and they have shown that the influence of pitting on the steel strength is not negligible. General strength of ship hull is mainly affected by general corrosion that reduce thickness of shell and stiffeners therefore reduce midship section modulus. Pitting corrosion is a very important phenomenon that influence local strength of ship hull members.

International Association of Classification Societies (IACS) [11, 12] and Polish Register of Shipping (PRS) [11, 12] have defined the required minimum thickness of plating in pits or other local corrosion areas (is to be greater than 70-75% of the as-built thickness), or average thickness across any cross section in the plating (is to be greater than the renewal thickness for general corrosion). These requirements are surely based on unknown considerations of strength of pitted steel.

TENSILE DIAGRAM FOR PITTED STEEL

The mentioned Japanese authors tested only conical pits that are observed on hold frames of bulk carriers. The pits were generated artificially by spot drilling of the both steel surfaces. Different pit patterns were manufactured with different values of degree of pit intensity DOP (ratio of pitted area to entire area of the specimen). In the Rules of Classification Societies DOP is called simply the pitting intensity. In order to verification of validity of such artificial pits testing, the results were compared to the results for actually corroded specimens [9]. It has appeared that specimens with orderly located artificial pits which had a fixed diameter equal to the average pit diameter in actual corroded specimens could simulate the actual corroded specimen where the pit size and distribution are random. Results of standard static tensile tests of pitted and smooth specimens are described in [6, 7, 9]. Exemplary tensile diagrams (load versus displacement) for small specimens are shown in Fig. 1 [7]. It is evident that pitting:

(i) reduced the load corresponding to yield stress;
(ii) reduced almost to zero plastic flaw strain at the level of yield strength;
(iii) reduced load, corresponding to ultimate tensile strength, even stronger than yield stress;
(iv) markedly reduced total elongation to fracture;
(v) total elongation for 13mm and 11mm uniformly thick specimens is the same.

The same investigations [7] have shown that the effect of pitting depends on the specimen thickness, i.e. the nominal tensile strength and total elongation dropped more

a)

b)

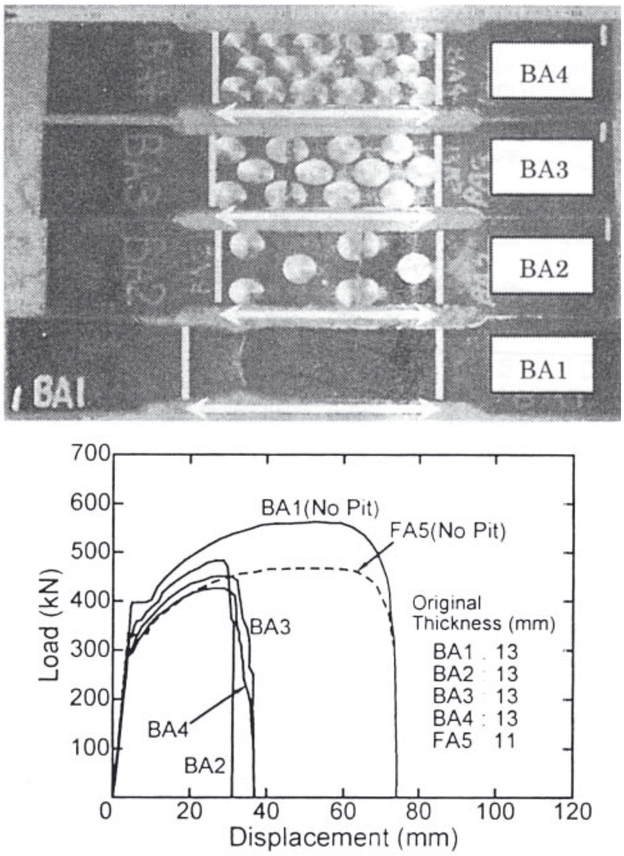


*Fig. 1. Results of small tensile specimens testing: **a)** view of specimens after testing; **b)** tensile diagram "load – displacement" [7]*

significantly for higher pit-depth-to-plate-thickness ratios. For thinnest plated (10 mm) total elongation dropped from 30% to about 5%.

Matsushita et al [6] realized tensile tests of specimens with different DOP from a single one-side pit up to more than 80% of two-side surfaces covered by pitting. Pitting corrosion causes not only unevenness of the material surface but reduction of the average thickness too. The larger DOP leads to the larger average thickness loss. Results are plotted as a function of the thickness loss in Fig. 2 and Fig. 3.

Trend lines for ideally uniform corrosion are also plotted in Fig. 2. All over the range of thickness loss values, the nominal strength for pitted specimens is lower than for "uniformly corroded" ones. The specimens fractured at the smallest area where the local thickness reduction was larger than the average value. Meanwhile, strength of the "uniform corrosion" specimen with a value of uniform thickness loss is always compared with the pitted specimen strength of the same average (not local) thickness loss. True fracture surface does not develop close to one surface approximately perpendicular to load axis, as that in non-pitted specimens, but jumps from one plane to another according to pits distribution. True fracture surface area can be evaluated as the area of the fracture surface before loading projected to the plane perpendicular to the load axis and practically can be substituted by the minimum cross-sectional area (i.e. locally reduced by pits) before loading perpendicular to the load axis [9]. In Matsushita et al opinion, the true strength that is based on the true fracture surface area is the same for uniform and non-uniform thickness loss (Fig. 2b). In our opinion, however, the above explanation is only partially valid. If the only specimen of another type (wide specimen – type B) is not taken into account, the strength of pitted specimens for average thickness loss below 2 mm will be 527-600 MPa, while for average thickness loss above 2 mm

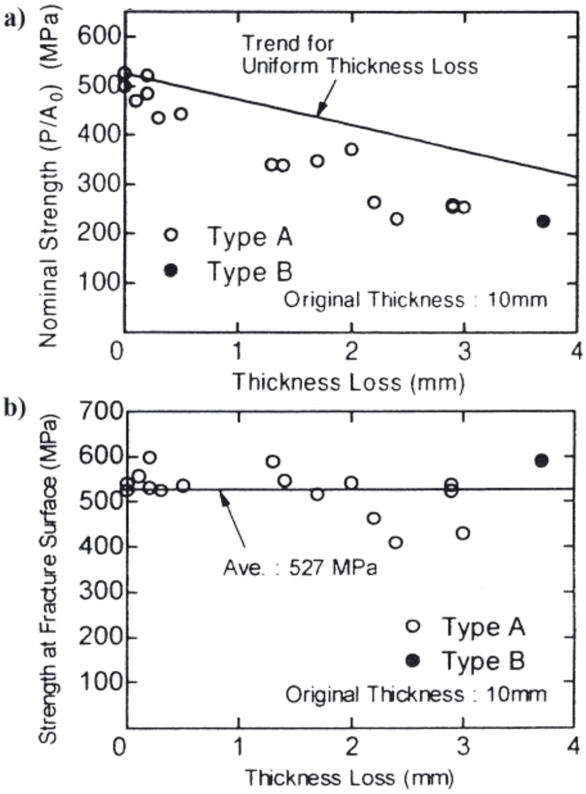


Fig. 2. Tensile strength of pitted steel versus thickness loss for type A (small specimens) and type B (wide specimens): ***a)*** *nominal strength P/A_0 (P is the load, A_0 is the initial cross-section area);* ***b)*** *true strength P/A (A is the true area of fracture surface, i.e. reduced by pits) [6]*

the strength will be 400-527 MPa thus it is not independent of the intensity of pitting. In spite of that, the maximum load that can be carried by a specimen can be approximately predicted by the above approach based on true fracture surface or minimum cross-sectional area [6, 9].

The last conclusion concern so called small specimens. The situation is more complex in case pf large (much more wide) specimens. Fracture of small specimen occurs when plastic deformation develops throughout the minimum cross section. In much more wide specimens, having areas with pits of different size and distribution, the deformation ability differ from location to location. As a result, fracture occur locally at this regions where elongation reaches critical value first, i.e. where the elongation ability is the lowest due to local pits sizes and distribution, this local fracture is the dominant factor that determines the maximum load ability of the specimen modeling a structural member [9]. That is why the maximum loading ability for large members, predicted on the base of total true fracture surface area, is overestimated, while for small members this approach was successful [10].

Analogous diagram for total elongation is shown in Fig. 3. The uniform thickness loss does not cause reduction of total elongation (see also Fig. 1). Thus the observed very significant drop of values of total elongation has to be entirely attributed to non-uniform character of pitting corrosion. The drop is very rapid for small values of thickness loss (also values DOP are small). Then relationship saturates and the total elongation does not depend on thickness loss and DOP. Nakai et al [7] noted the minimum, and next even an increase of total elongation as DOP is increased further. This is perhaps due to decrease of the ratio of pit depth to average thickness loss. These data are for 10 mm thick material. For thicker materials the reduction of elongation is also evident but not so dramatic.

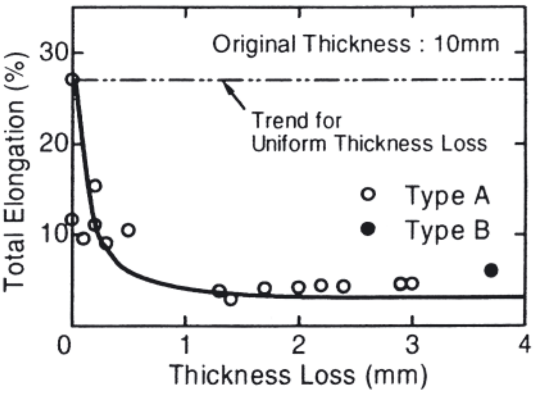


Fig. 3. Relationship between thickness loss and total elongation in tensile test [6]

ULTIMATE STRENGTH OF STRUCTURAL MODELS

Lateral-torsional buckling of whole hold frames, and local buckling and fracture of web and face plates in the lower parts of hold frames, is damage typically seen in the hold frames of bulk carriers [5]. Therefore extensive program of FE analyses has been realized [5] with square plates containing conical corrosion pits (aspect ratio depth-to-width of pit equal to 0.125) of different size and distribution. Compressive load plus bending moment have been applied in different proportions: from pure compression (stress gradient equal 0) to pure bending (gradient equal 2).

As for tensile test, for these loads it also has appeared that ultimate strength of pitted plates is smaller than or equal to that of uniformly corroded plate for the same average thickness loss. There is a tendency for the strength reduction to increase as the pit diameter and depth is increased. Thus a prediction of the strength of pitted plates using the average thickness loss would lead to non-conservative results. However, the average thickness loss or maximum pit depths are not always dominant factors for ultimate strength but the strength depends also on type of pit distribution on the both sides of the plate [5, 9].

Nakai and co-workers analyse equivalent thickness of plate for ultimate tensile strength (t_e) that is defined as the thickness of an uniformly corroded plate whose ultimate strength is the same as that of pitted plate. Value of the equivalent thickness is almost independent of the loading mode: from pure compression, through different combinations of compression and bending, up to pure bending [5]. Nakai and co-workers have compared these values of equivalent thickness to the values evaluated by tensile test, where the following proportion is valid:

$$t_e / t_0 = \sigma_u / \sigma_{u0} \tag{1}$$

where t_0 is the original plate thickness, σ_u and σ_{u0} are the nominal UTS for the plate with and without pits, respectively. The comparison has been made for the same degree of pit intensity (DOP). It has appeared that equivalent thickness evaluated in tensile test of pitted specimens is smaller than that for evaluated for plates subjected to in-plane compression and bending, especially for the thinnest specimens. Thus tensile test represent the most dangerous case. If an evaluation method for the effect of pitting corrosion on the equivalent thickness (t_e) under tensile loading is established, a reduction of t_e of pitted plates under in-plane compression, bending and shear will be predicted conservatively by the same method.

Equivalent thickness of plates with pitting corrosion (t_e) for the tensile strength is almost equal to average thickness at the minimum cross section ($t_{ave,min}$)[10]:

$$t_e = t_{ave,min} \tag{2}$$

Equivalent thickness loss (t_{el}) is defined as thickness loss of uniformly corroded plate that has the same tensile strength as a plate with pitting corrosion. It can be calculated by:

$$t_{el} = t_0 - t_e \tag{3}$$

Average thickness loss (t_{al}) of pitted plates is defined by:

$$t_{al} = t_0 - t_{ave} \tag{4}$$

where:

t_{ave} – the average thickness of the pitted plates.

Finite Element (FE) analyses of pitted square plates under uniaxial compression, biaxial compression, shear and combinations if the above mentioned loadings showed that the equivalent thickness can conservatively be predicted by equation (3) and the following equation [10]:

$$t_{el} = 1.25 \cdot t_{al} \tag{5}$$

Thus ultimate strength of pitted plate of an average thickness (t_{ave}') is lower than the strength of uniformly corroded plate of the same thickness. This means that unevenness of the plate surface due to pitting corrosion reduce ultimate strength of the plate.

FE analyses of structural model: beam (web plate, face plate and shell) under 4-points bending has been done [10]. Web plates were pitted. It has appeared that for the following cases: (i) the ultimate strength is reached accompanying local buckling; (ii) the structural models collapse without buckling; (iii) shear buckling of web plates occurs; and (iv) web crippling occurs, equivalent thickness of the web plates can be predicted by equation (3) and the following equation:

$$t_{el} = 1.44 \cdot t_{al} \tag{6}$$

The above equations mean that the influence of the pitting-corrosion-induced unevenness of the plate surface on the ultimate strength of more complex structural models is more detrimental than for simple square plates.

APPROACH BASED ON DEGREE OF PITTING (DOP) INSTEAD THICKNESS LOSS

Nakai and co-workers conclude that for non-uniform random pitting, the average thickness loss of a whole plate, or for the minimum cross section, is often difficult to determine. Each pit is covered with a heavy rust blister which is difficult to remove, even with hammers. Even if the rust blisters and rust from non-pitted areas are removed, correct thickness measurement is difficult due to great unevenness of the surface. [9, 10]. The average thickness loss or the average thickness loss at the minimum cross section cannot be determined directly by observation of the plate surface. Meanwhile, degree of pitting (DOP) can be approximately evaluated by observation of the plate surface also without removing the heavy rust blisters, because Nakai and co-workers has shown that the diameter of the rust blisters and that of the corresponding pits are almost the same [10] and degree of blisters intensity (ratio of the surface area covered with rust blisters to the entire surface area) corresponds to DOP. Therefore, to elaborate a method of evaluating the tensile strength of pitted members using the value of DOP, is a task of primary importance.

First attempt to solve this problem has been made by the same authors [10]. Diagrams of thickness loss of plates versus values of DOP are shown in Fig. 4. The diagrams include average thickness loss t_{al} and effective thickness loss t_{el} for ultimate strength calculated for different cases: square plates under combined loading of compression and shear [equation (5)], more complex structural models (equation (6)) and for ultimate tensile strength. From ultimate-strength point of view, average thickness loss is not so important as effective thickness loss. Equivalent thickness loss for all three cases is increases almost linearly with the increase of DOP when DOP is smaller than approximately 75% [10]. The trend is especially evident foe equivalent thickness loss for ultimate tensile strength. Equivalent thickness loss for tensile strength (that equals to average thickness loss at minimum cross section) is larger than that for other loading conditions; only for largest values of DOP it is equal to $1.44t_{al}$ that is specified for structural models The same observation has been made for plates under in-plane compression and bending [5] described above. Therefore, it is possible to ensure the structural integrity if the average thickness loss at the minimum cross section is within the allowable corrosion level specified in rules for uniformly corroded members [10]. Allowable value of DOP could be evaluated on the base of allowable thickness loss for uniform corrosion, equivalent thickness loss for the pitted plate, and Fig. 4.

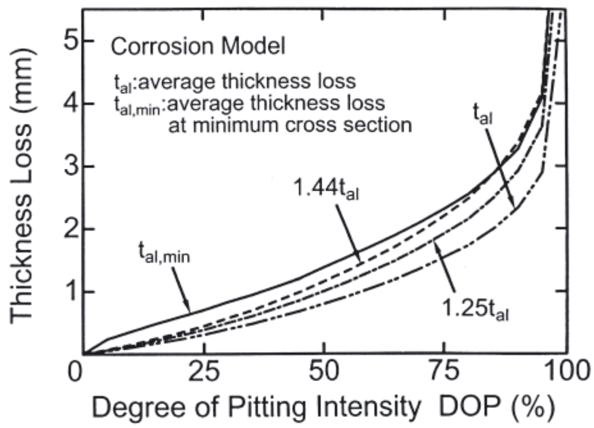


Fig. 4. *Diagram of average thickness loss t_{al}, equivalent thickness loss under combination of compression and shear ($1.25t_{al}$), equivalent thickness loss for ultimate strength of structural models ($1.44t_{al}$) and equivalent thickness loss for tensile strength at minimum cross section ($t_{al, min}$) versus degree of pitting (DOP) [10]*

Analyzing progress of pitting corrosion as a function of DOP, it has appeared [10] that average thickness loss and standard deviation of the thickness loss vary with small scatter band, while large scatter band is observed for extreme values like maximum pit depth or average thickness loss at the minimum cross section. When average thickness loss exceeds about 2 mm for one side of plate, then DOP equals about 100%. After this stage the form of corrosion tends to a change from pitting corrosion to general corrosion.

The same authors [8] have investigated experimentally and analytically (FEM) strength of 4 point bent welded frames contained of web plate, face plate and shell (tensile load act on the face plate). Artificial pits were made over a separated areas of the web plate. Lowest strength had a frame with a band of pits close to the compressed shell, higher strength had the frame with a band of pits situated at the center of the web height, highest strength had the frame with pits close to tensed face plate. Pits situated at the center of the frame length (pure bending segment) more significantly reduced strength than that situated close to ends (high shear stress). It means that localization of pitting corrosion at the web plate surface is an additional factor influencing the strength of frame. Influence of this position of pitting corrosion on the frame strength for longer, slender frames is less pronounced than for short frames.

CONCLUSIONS

1. Uniform thickness loss dos not influence the total elongation of specimens in tensile test. Pitting corrosion, even of small degree of pit intensity, very significantly reduce total elongation of the specimens. Pitting corrosion reduces the ultimate tensile strength of steels stronger than the uniform corrosion
2. For tension and any combination of in-plane compression and bending, the ultimate strength of pitted plate is smaller than that of uniformly corroded plate with the same average thickness loss. There is a tendency for the strength reduction to increase with the as the pit diameter and depth is increased. Thus a prediction of the strength of pitted plates using the average thickness loss would lead to non-conservative results
3. The equivalent thickness (t_e), defined as the thickness of uniformly corroded plate whose ultimate strength is the same as that of pitted plate, for tensile loading is smaller than for any combination of in-plane compression and bending. Therefore it can be applied for conservative prediction of strength of members subjected to each of the loading modes.
4. It is possible and convenient to analyze the ultimate strength of pitted structures as a function of degree of pitting (DOP – the ratio of the total pitted area to the entire area of the plate) instead as a function of the plate thickness loss.
5. Ultimate buckling strength of pitted plates and frames depends also of the position of the pitted areas and the type of pit distribution in every area.

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