Computation of ultimate strength of locally corroded unstiffened plates under uniaxial compression

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Abstract

Over the past decades there have been many losses of the merchant vessels due to either accidents or exposure to large environmentally induced forces. The potential for the structural capability degrading effects of both corrosion and fatigue induced cracks are of profound importance and must be both fully understood and reflected in vessel’s inspection and maintenance programme. The present study is focused on assessing the effects of localized pitting corrosion which concentrates at one or several possibly large area on the ultimate strength of unstiffened plates. Over 256 non-linear finite element analyses of panels with various locations and sizes of pitting corrosion have been carried out. The multi-variable regression method is applied to derive new formulae to predict ultimate strength of unstiffened plates with localized corrosion. The results indicate that the length, breadth and depth of pit corrosion have weakening effects on the ultimate strength of the plates while plate slenderness has only marginal effect on strength reduction. Transverse location of pit corrosion is also an important factor determining the amount of strength reduction. When corrosion spreads transversely on both edges, it has the most deteriorating effect on strength. It is also found out that the proposed formulae can accurately predict the ultimate strength of unstiffened plate with localized corrosion.

Keyword : Corrosion, Pitting corrosion, Ultimate strength, Multi-variable regression, Unstiffened plate, Finite element analysis

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1. Introduction

Sea water is an aggressive corrosive environment because it is a good electrolyte and contains corrosive salts. The marine environment is a sea water environment and this means that corrosion in marine structures, which are generally fabricated from various grades of steel and low alloy steel, is often very severe, not only under sustained immersed condition in ballast tanks but also under general exposure to atmospheric conditions.

Clearly either general or localized corrosion will reduce the residual strength of ageing ship structures. Improperly maintained ageing ship structure could finally lead to disastrous casualties in rough seas and heavy weather. Thus it is important to assess the residual strength of ageing ship structure properly either with corrosion or with other type of defects in order to reflect vessel’s inspection and maintenance programme.

Over last decades there have been significant development of computer hardware and finite element analysis (FEA) software. The finite element analysis method has now become the most common, powerful and flexible tool in rational structural analysis and makes it possible to predict the strength of complex structures more accurately than existing classical theoretical methods.

The objective of this paper is to investigate the effects of localized corrosion, which concentrates at one or several possibly large area, on the ultimate strength and strength reduction of unstiffened plates under uniaxial compression. Over 256 non-linear finite element analyses have been carried out to systematically investigate the effects of plate slenderness, locations, sizes and depths of pitting corrosion. Finally the results of these analyses are used to derive new empirical formulae to predict the ultimate strength and strength reduction of unstiffened plates with localized corrosion under uniaxial compression. Considering corrosion pattern on ship structural members, the target structural members which can apply the proposed formulae are bottom structures in ballast tanks for all ocean going ships and cargo oil tank for crude oil tanker. In addition the proposed formulae can also be applied to any ship structural members with concentrated pitting corrosion at one or several possibly large areas.

2. Strength assessment for localized corrosion

Generally in the case of uniform corrosion, the buckling or ultimate strength of stiffened and unstiffened plates can be easily estimated by reducing the plate thicknesses from their original values. Several empirical formulae are available to obtain the ultimate strength of plates under general corrosion [1-6]. However the calculation of strength degradation due to localized defects, such as pitting corrosion, are more difficult and complex than general area-wide corrosion and there have been relatively few research activities and guidelines have been published until now [7-9].

Diadola et al. [10] proposed that an initial determination of the acceptability of a plate panel with pitting can be made on the basis of the pit depths. They proposed that individual pits with a depth less than 50% of the residual thickness can be repaired by epoxy and individual pits with a depth greater than 50% of the residual thickness may be welded if at least 6.5 mm of material remains at bottom of pit, the distance between
adjacent pits is at least 76 mm, the maximum diameter of any welded pit does not exceed 305 mm and the total cross sectional area lost in any section of the pitted plate should not be more than 15%.

IACS [11] S31 specifies that if pitting intensity is higher than 15% in area, thickness measurement is to be taken to check pitting corrosion and the minimum acceptable remaining thickness in pits or grooves is equal to: 75% of the as built thickness for pitting or grooving in the frames, brackets, webs and flanges or 70 % of the as built thickness for pitting or grooving in the side shell, hopper tank and topside tank plating attached to the side frame, over a width up to 30 mm from each side of it.

IACS [12] Z10.1 also requires that any bottom plate with a pitting intensity of 20% or more, with wastage in the substantial corrosion range or having an average depth of pitting of 1/3 or more of actual plate thickness is to be noted.

Paik el al. [13-15] performed a series of experimental and numerical studies on steel plated structure with pits under axial compressive loads and under edge shear. They found that the ultimate strength of a steel plate with pit corrosion under edge shear is governed by the degree of pit corrosion intensity. Whereas the ultimate strength of a pitted plate element under axial compressive loads is governed by the smallest cross section area of plate taken through the pitted region. A simplified strength knockdown factor for plates with various pitting corrosion was introduced using the following formulation:

\[
R_{st} = \frac{\sigma_{st}}{\sigma_{st0}} = \left( \frac{A_0 - A_r}{A_0} \right)^{0.73}
\]

(1)

where \( R_{st} \) is a factor of ultimate compressive strength reduction due to pit corrosion, \( \sigma_{st} \) is ultimate compressive strength with pit corrosion, \( \sigma_{st0} \) represents ultimate compressive strength for an uncorroded member, \( A_0 \) indicates original cross sectional area of the uncorroded member and \( A_r \) is cross sectional area involved by pit corrosion at the smallest cross section. However in this study, the effects of different pitting locations and pitting lengths, which may contribute significantly to the strength reduction, were not considered.

Dunbar, Pegg et al. [16] investigated the effect of localized corrosion in stiffened plates by finite element analyses. A stiffened plate was divided into four main sections, each of which was further divided into four sub-sections in longitudinal direction and three sub-sections in the transverse direction. 10%, 50% and 75% by volume of the initial plate thickness over local sub-section were applied and it was found that 10% of corrosion has little effect on the ultimate strength of stiffened plate. Corrosion at higher levels (50% and 75% volume) caused local buckling at the corroded region, which affected the global collapse mode of the stiffened panel and the ultimate load was decreased as the corrosion location was closer to the centre of the panel span.

Recently some important research have been carried out to investigate the effects of pitting corrosion on strength degradation for stiffened plates. Amlashi and Moan [17] have presented an overview of recently studies and existing guidelines, and the strength reduction of pitted stiffened plates under biaxial compression loading has been studied.
using a series of finite element analyses with different degrees of pit corrosion intensity (DOP), pit depth and the location of the densest pitted zone. It is found that the ultimate strength of pitted stiffened plates is governed not only by the level of DOP, but also by the smallest sectional area and the location of densest pitted zone.

Nakai et al. [18, 19] discussed the structural integrity of hold frames of aged bulk carriers and shapes of corrosion pits observed on hold frames of bulk carriers. They found that the shape of the corrosion pits is a circular cone and the ratio of the diameter to the depth is in the range between 8 to 1 and 10 to 1. A series of actual test with structural models and finite element analyses have been carried out to investigate the effects of pitting corrosion on collapse behaviour and lateral distortional buckling behaviour. The ultimate load of the structural models with regular pittings on the web under the compression load was found to be almost the same as that of the structural models whose web has uniform corrosion corresponding to the average thickness loss.

When a slender plate is under compression, the material near the edges would normally take most of the loading while the material in the central area is less effective than those near the edges. So it would be expected that the damage/corrosion around the central area would have less weakening effects on the strength of a panel. A study of the effects of perforations on the ultimate strength showed that the ultimate compressive strength with edge holes is considerably smaller than that with a central hole [20].

Based on the above discussions it is obvious that there is a need for further research to systematically investigate the effects of plate slenderness, pitting location, length, breadth and depth on the ultimate strength of unstiffened plates and to develop empirical formulae which include all the important parameters.

3 Modelling details in finite element analysis

Currently the most frequently used grades of steel for ship structures are mild steel with a yield stress, $\sigma_y$, of 235 N/mm$^2$ and higher strength steels with $\sigma_y = 315N/mm^2$ (LRS AH32, ABS HT32, DNV NV-32) and $\sigma_y = 355N/mm^2$ (LRS AH36, ABS HT36, DNV NV-36). In this research, both mild steel and a higher strength steel with yield stress $\sigma_y = 355N/mm^2$, a Young’s modulus, $E$, of 209000 N/mm$^2$, and Poisson’s ratio of 0.3, were used in the finite element analyses, which were undertaken by using ANSYS software [21].

There are many proposals available for the typical value of welding induced initial deflection [1, 22-24]. An average value ($= 0.1 \beta^2$), where $\beta = \frac{B}{t} \sqrt{\frac{\sigma_y}{E}}$, $B$ and $t$ are width and thickness of the plate respectively, of welding induced initial deflection suggested by Smith et al. [24] is adopted in this study.
Planning FEA Approach

- Define element types and real constraints
- Define material properties
- Creating the model geometry
- Create nodes and elements by meshing
- Apply boundary conditions
- Apply load for buckling analysis

Buckling Analysis

Update Geometry
(Input initial deflection)

Apply Load and Nonlinear Control

Solve (Numerical analysis)

Check the Results

Fig. 1. General procedure of finite element analysis

ANSYS SHELL181 element was used to assess the ultimate strength of unstiffened plates with pitting corrosion. SHELL181 is suitable for analyzing thin to moderately-thick shell structures and for layered applications for modelling laminated composite shells or sandwich construction. It is a 4-node element with six degrees of freedom at each node, namely translations in the x, y, and z directions, and rotations about the x, y, and z-axes. This type of element is well-suited for linear, large rotation, and/or large strain nonlinear applications. In addition, simply supported boundary condition with uniaxial compression load is considered for the overall finite element analyses. Fig. 1 illustrates the general procedure of nonlinear finite element analysis which is used in this study.

4. Modelling strategy for rectangular plate with pitting corrosion

Localized corrosion often starts from the areas where the highest stresses occur, which can lead to coating break-down and stress corrosion cracking, or where water flows and drains, places of water and sediment accumulation, such as along longitudinal stiffeners and transverse bulkhead. Fig. 2 shows a typical localized corrosion pattern in a ballast tank.
The localized pitting corrosion can be concentrated at one or several possibly large areas as shown in Fig. 2. Another type of localized corrosion is of a regularly pitted form and caused by microbiologically influenced corrosion (MIC), such as sulphate-reducing bacteria (SRB).

Fig. 2. Typical localized corrosion in ballast tank [25].

Fig. 3. Patterns of pitting corrosion (S: Single side, C: Centre, B: Both sides).
Generally the shape of individual pitting corrosion could be a semi-sphere or a cone. Although it is possible to model these pits as they are using three-dimensional FE models, it is impractical to run these analyses in the early design stage. In order to simplify the FE model, a more pragmatic approach is adopted in this study. This approach is recommended by a British Standard BS7910 [26], and was also adopted in the studies of Paik, et al [13, 15, 16]. In pipeline industry, strength reduction due to corrosion is also assessed in a similar way [27, 28]. In this approach, instead of modelling the individual pits, the multiple flaws are grouped together with a rectangular shape if they are fairly close to each other as shown in Fig. 3. As indicated in Fig. 3 a, the length and width of the rectangle is determined by the maximum length and width of the group of flaws. The depth of the rectangle is determined by the effective cross-section area as illustrated in Fig. 3 b. The reason for using effective cross-section area is based on the belief that ultimate strength of a corroded plate under uni-axial compression is influenced the most by the smallest cross-section area. Based on the above strategy, if there is only one rectangle corrosion at the edge, it is called ‘single side’ corrosion, if it is at the centre, it is called ‘centre’ corrosion. If there are two rectangles spreading at two edges, it is called ‘both sides’ corrosion.

There are several finite element techniques available to model pitting corrosion. The easiest way is to reduce the thickness of the plate in pitted area, carry out buckling analysis to get the buckled shape of plate with pitting corrosion and finally to perform non-linear finite element control to get the ultimate strength of plate by using stress versus strain relationship. Paik et al. [6] have assumed that the plate thickness is subdivided into several layers and the material properties of the pitting corrosion region are supposed to be zero. The former method cannot represent proper modelling of pitting corrosion because if the thickness of plate on pitted area is simply reduced then the node on pitted area will be located on midplane as illustrated in Fig. 4. The latter method also cannot represent the real situation and easily tends to fail to converge during non-linear control based on author’s experience.

![Fig. 4. Shell layers with nodes at midplane.](image)

In order to represent the real structure with a pitted area, ANSYS Shell Layer model was adopted and the midplane nodes in pitted area were artificially moved to the bottom surfaces and aligned with intact area as shown in Fig. 5 and Fig. 6.
5. Finite element analyses of typical square plates with pitting corrosion

The patterns and locations of localized corrosion observed in service are various so it is impossible to predict exactly when and where the corrosion will start, how it will progress and at what general rate. Localized corrosion can also start at the places where with high fatigue stresses, welds of seams and crack initiation areas. Sometimes bacteria induced corrosion can be the cause of pitting corrosion. It is clearly very important to assess the remaining structural integrity under localized corrosion correctly not only to determine the schedule for repair but also to decide proper future inspection and maintenance periods for structures with defects.

In this study, over 256 nonlinear finite element analyses have been carried out to investigate the effects of different material and geometry parameters such as plate slenderness, location, size and depth of pits on the ultimate strength of square plates.

Higher strength steel of 1m x 1m plate with a yield stress of 355 N/mm² was used for this study. Five different B/t ratios (41.7, 45.5, 50.0, 55.6, 62.5) have been chosen by changing plate thickness. The location of pitting corrosion was assumed to start at aft bay (aft end) and the sizes of pitting corrosion have four different length values (0.25L, 0.5L, 0.75L, 1.0L), in which L is the total length of the plate. The depths of pits are classified into two cases (0.25t and 0.5t). For simplifying the finite element analyses the area of pitting corrosion is assumed to have rectangular shape with single side or both sides corroded pattern as illustrated in Fig. 5 in order to reduce the modelling cost.

The initial deflection is assumed being equal to \(0.1\beta^2 t\) and the pitting corrosion depth is considered 50% of plate thickness. However the effect of welding-induced residual stresses was not considered in this specific study. Fig. 6 illustrates the mesh...
details of the square plate with pitting corrosion at centre and Table 1 summarizes some of the results of finite element analyses. $\sigma_c$ and $\sigma_0$ represent the ultimate strength of plate with localized corrosion and uncorroded plate respectively, $x_1$ is plate slenderness parameter ($\beta$), $x_2$ denotes the ratio of pit breadth over plate width, $x_3$ indicates the ratio of pit length over plate length and $x_4$ is the ratio of pit depth over plate thickness. Fig. 7 compares the average stress-strain curves for a rectangular plate with various pitting corrosion sizes and locations. It is shown that the simultaneous pitting corrosion at both sides (edges) causes the most strength reduction while corrosion at the centre results in the least strength reduction. The strength of pitting corrosion at both sides is only 90.4% of that of pitting corrosion at centre location.

Fig. 6. The mesh details of the square plate with typical pitting corrosion at central region

Table 1
Ultimate strength of unstiffened plate with pitting corrosion

<table>
<thead>
<tr>
<th>No</th>
<th>Pit location</th>
<th>B/t</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>$A_0$ - $A_i$</th>
<th>$\sigma_c$ N/mm²</th>
<th>$\sigma_c / \sigma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Centre</td>
<td>50.0</td>
<td>1.68</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
<td>1.000</td>
<td>188.30</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>Centre</td>
<td>50.0</td>
<td>1.68</td>
<td>0.3</td>
<td>0.3</td>
<td>0.50</td>
<td>0.888</td>
<td>165.41</td>
<td>0.878</td>
</tr>
<tr>
<td>3</td>
<td>Single side</td>
<td>50.0</td>
<td>1.68</td>
<td>0.3</td>
<td>0.3</td>
<td>0.50</td>
<td>0.888</td>
<td>155.59</td>
<td>0.826</td>
</tr>
<tr>
<td>4</td>
<td>Both sides</td>
<td>50.0</td>
<td>1.68</td>
<td>0.3</td>
<td>0.3</td>
<td>0.50</td>
<td>0.888</td>
<td>149.53</td>
<td>0.794</td>
</tr>
</tbody>
</table>
Fig. 7. A comparison of the average stress-strain curves

In addition, the effects of corrosion length along plate edges in the longitudinal direction on the ultimate strength of mild steel plate have been investigated based on a pitting width of 20% of plate breadth and a pitting depth of 0.5t.

Table 2
Results of finite element analyses based on various pitting lengths

<table>
<thead>
<tr>
<th>No</th>
<th>Pit location</th>
<th>FEM Input Variables</th>
<th>$A_i - A_i$</th>
<th>$\sigma_C$</th>
<th>$\sigma_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_i$</td>
<td>N/mm²</td>
<td>$\sigma_C$</td>
</tr>
<tr>
<td>1</td>
<td>Both sides</td>
<td>50.0 1.68 0.0 0.0 0.00 1.00</td>
<td>188.30</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Both sides</td>
<td>50.0 1.68 0.2 0.25 0.50 0.90</td>
<td>168.85</td>
<td>0.897</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Both sides</td>
<td>50.0 1.68 0.2 0.50 0.50 0.90</td>
<td>157.01</td>
<td>0.834</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Both sides</td>
<td>50.0 1.68 0.2 0.75 0.50 0.90</td>
<td>150.76</td>
<td>0.800</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Both sides</td>
<td>50.0 1.68 0.2 1.00 0.50 0.90</td>
<td>147.49</td>
<td>0.783</td>
<td></td>
</tr>
</tbody>
</table>

The results are presented in Table 2 and Fig. 8. It is shown that the both sides pitting corrosion up to 50% of length (see cases 2 and 3) can reduce the strength of plate significantly, whereas the differences between 50% and 75% or between 75% and 100% of pitting length (cases 4 and 5) are relatively smaller than the former. Fig.8 shows the effects of corrosion length on the strength. With the increase of corrosion length, the strength reduction is increased. However their post-buckling strength is fairly close to each other.
Fig. 8. Effects of pitting corrosion length

Fig. 9. A comparison of the present FEA results with those of Eq. (1) based on both sides pitting corrosion
The above results clearly show that the strength reduction due to pitting corrosion depends on the width, length, depth and location of the corrosion. To further demonstrate this, a comparison between the results of these finite element analyses based on both sides pitting corrosion and Eq. (1), which is proposed by Paik et al. [13-15], is shown in Fig. 9. It indicates that increasing pitting length leads to decreasing the ultimate strength of the plate based on the present FE results. However Eq. (1) cannot reflect this effect. In addition, the current results are more conservative than those of Eq. (1). This large difference might be attributed to the fact that both sides pitting corrosion has the most weakening effect on strength.

Fig. 10 illustrates the effects of pit corrosion length, breadth and depth on the ultimate strength. It further demonstrates the importance of these three parameters.

6. Proposed formulae for predicting ultimate strength reduction

In this section, new formulae for predicting strength reduction due to pitting corrosion are derived by using multi-variable regression model. The general form of a multi-variable regression is given by:

$$ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m + \epsilon $$ 

(2)
The dependent variable $Y$ can be calculated as a function of $m$ independent variables $x_1, x_2, \ldots, x_m$. The random error term ($\varepsilon$) can be added to allow for deviation between the right hand sides of equation, $\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m$, and the value of the dependent variable $Y$. The value of the coefficient $\beta_i$ determines the contribution of the independent variable $x_i$ and $\beta_0$ is the Y-intercept.

The multiple coefficient of determination $R^2$ can represent how well a multiple regression model fits a set of data. $R^2 = 0$ means a complete lack of fit of the model to the data, and $R^2 = 1$ implies a perfect fit and which can be expressed by:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

(3)

where $y_i$ is arbitrary data point, $\bar{y}$ denotes the mean of the data points and $\hat{y}_i$ represents the predicted value of $Y$ for the model. $R^2$ represents the fraction of the sample variation of the $y$ values and which is explained by the least-squares prediction equation.

In this study, two formulae were derived for predicting the ultimate strengths of square plates with pitting corrosion under uniaxial compression. One of them is for the plates with pitting corrosion on one side (edge) of the plates, the other is for the plates with pitting corrosion on two sides (edges). Four variables, $x_1$, $x_2$, $x_3$ and $x_4$, have been chosen as independent variables, where the valid ranges of $x_1$ is 1.719 to 2.576, which corresponds to $B/t = 40$ to 65, $x_2$ is 0 to 0.4, $x_3$ is 0 to 1.0 and $x_4$ is 0 or 0.5. 128 sets of finite element analyses results for single side type pitting corrosion on the plate and another 128 sets with both sides type pitting corrosion are used to derive the formulae.

The ultimate strength reduction of plates with single side (SS) corrosion can be formulated by:

$$\left(\frac{\sigma_C}{\sigma_0}\right)_{SS} = \begin{cases} 
1 & x_2 \cdot x_3 \cdot x_4 = 0 \\
1.25 - 0.0144x_1 - 0.336x_2 - 0.166x_3 - 0.434x_4 & x_2 \cdot x_3 \cdot x_4 \neq 0
\end{cases}$$

(4)

The ultimate strength reduction of plates with both sides (BS) corrosion can be expressed by:

$$\left(\frac{\sigma_C}{\sigma_0}\right)_{BS} = \begin{cases} 
1 & x_2 \cdot x_3 \cdot x_4 = 0 \\
1.43 - 0.0414x_1 - 0.603x_2 - 0.220x_3 - 0.576x_4 & x_2 \cdot x_3 \cdot x_4 \neq 0
\end{cases}$$

(5)
Figures 11 and 12 illustrate the correlation of finite element results and the derived formulae where FEM denotes finite element analyses method. The formula for plates with single side type pitting corrosion has a coefficient of variation (C.O.V) of 0.030 and a mean of 1.001, and the multiple coefficient of determination \( R^2 \) is 0.907. In the case of plates with both sides type pitting corrosion, the coefficient of variation (C.O.V) is 0.0595, the mean is 0.998, and the multiple coefficient of determination \( R^2 \) is 0.863. So the proposed formulae are quite accurate. It should be pointed out that the ultimate strength reduction predicted by Eqs. (4) and (5) should be always less or equal to 1. However when \( x_2 \), \( x_3 \), and \( x_4 \) are very small, Eqs. (4) and (5) could possibly produce a value, which is slightly greater than 1. In this case, the ultimate strength reduction should be set as one.

From Eqs. (4) and (5) it is observed that corrosion depth has the most weakening effects on strength reduction among the four parameters when the corrosion is on one side of the edges of the plates. Corrosion width is the second most important parameter, while plate slenderness has only marginal effect on the strength reduction. However when corrosion is on both sides of the edges the corrosion width is the most important parameter, which is followed by corrosion depth, and then corrosion length. Again plate slenderness has very little effect on the strength reduction.

Fig. 11. Pitting corrosion at a single side area.
7. Conclusions

In this research, the ultimate strength of square plates with pitting corrosion has been investigated by using nonlinear finite element analyses. The effects of pitting corrosion width, depth, length and its transverse location on ultimate strength have been systematically studied. A total of 256 nonlinear finite element analyses have been carried out, which is the full combination of two cases of transverse pitting locations, five cases of plate thicknesses, four cases of pitting breadths, four cases of pitting lengths and two cases of pitting depths. The results can be summarized as follows:

The length, breadth and depth of pit corrosion have weakening effects on the ultimate strength of the plates while plate slenderness has only marginal effect on strength reduction.

The depth and width of the corrosion are the two dominant parameters. So this finding, to some extent, justifies the formula proposed by Paik, et al. [13-15], in which the corroded cross sectional area was chosen as the only parameter related to corrosion.

Transverse location of pit corrosion is also an important factor determining the amount of strength reduction. When corrosion spreads transversely on both edges, it has the most deteriorating effect on strength.

The multi-variable regression method has been applied to derive empirical formulae to predict strength reduction due to pitting corrosion. The derived formulae are quite accurate. The formula for single side type pitting corrosion is slightly more accurate than that for both sides type pitting corrosion.
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