Proceedings of OMAE2005
24th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2005)
June 12-17, 2005, Halkidiki, Greece

OMAE2005-67232

ON THE STRENGTH ASSESSMENT OF PITTED STIFFENED PLATES UNDER BIAXIAL COMPRESSION LOADING

Hadi K.K. Amlashi
Department of Marine Technology
Norwegian University of Science and Technology (NTNU),
Norway

Torgeir Moan
Department of Marine Technology
Norwegian University of Science and Technology (NTNU) ,
Norway

ABSTRACT

Structural components of ships are subjected to corrosion, especially when exposed to sea environment. It is, therefore, essential to seek rational standards for the structural integrity of aging structures without economic penalties with respect to the repair and maintenance costs incurred over the life cycle of the structure. To make proper decisions about costs and safety, knowledge about the effect of corrosion and other degradation phenomena on the strength is of crucial importance. The main objective of the present study is to investigate the strength of pitted stiffened plates under biaxial compression loading. For this purpose, systematic numerical FE investigations of ultimate collapse and post-ultimate responses for the stiffened plates with pit corrosion wastage are undertaken, varying the degree of pit corrosion intensity (DOP), pit depth and the location of the densest pitted zone. The focus here is on local plate failure mode which is desired to be governing failure mode in designing of stiffened plates. Geometric imperfections and residual stresses were included in the models. It is found that the ultimate strength of a stiffened plate can be significantly decreased due to pitting corrosion. 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. This improved knowledge of the damage tolerance assessment of stiffened plates can be used to schedule repairs more efficiently, while risk or reliability assessment schemes are normally applied for that purpose.

INTRODUCTION

Due to a number of circumstances, the Steel structures such as ships and offshore structures are subjected to various types of damage and may not always be properly protected as they get older. This issue can be very complex in nature usually influenced by the many variables of operational condition and maintenance practices. Corrosion may be one of the most important types of damage in aging ship's structures. Clearly, in such cases, the structure that started out being adequate may become marginal later in life or even reach the catastrophic failure state.

It is of vital importance to estimate the residual strength of damaged structures as, for instance, it is essential to seek rational standards for the structural integrity of aging structures without economic penalties with respect to the repair and maintenance costs incurred over the life cycle of the structure, while risk or reliability assessment schemes are normally applied for that purpose.

The two types of corrosion found to occur most frequently on ship's structures are general corrosion and (localized) pitting/grooving corrosion among others (Stambauch and Knecht; 1991). This kind of wastage can reduce ultimate strength of stiffened panels. For general corrosion, which uniformly reduces thickness, the panel ultimate strength calculations are typically carried out excluding the thickness loss due to corrosion. For localized corrosion, the residual strength calculation procedure can be more complex. Some studies, in a simplified pessimistic way, suggest that the corroded elements may be idealized using an "equivalent general corrosion", e.g. TSCF (1984, 1993). While, the treatment of general corrosion in the ultimate strength assessment is considered to be easier as long as the real pit corrosion condition can be defined as an equivalent general corrosion condition, however, this treatment is not always relevant since it is not straightforward to define the 'equivalent general corrosion' properly.

There are obviously some situations where a ship's hull girder can experience local loading (cargo weight and sea pressure) in addition to overall bending. The bottom plating of the empty hold tank is subjected to transverse thrust exerted by the bending of bottom structure, while carrying out longitudinal thrust due to global bending. This problem, therefore, is to be considered in view of combined local and global loading. Recent publications on the residual strength assessment of pitted plate panels have applied a closed-form formulation considering compressive thrust loading and shearing force individually, e.g. Paik et al (2003, 2004). No account of combined loading is considered.

The main objective of the present study is to investigate the residual strength characteristics of pitted stiffened plates under combined loading. For this purpose, systematic numerical studies for the ultimate strength assessment of stiffened plates with pit corrosion wastage are undertaken, varying the degree of pit corrosion intensity, pit depth and the location of the densest pitted zone.

NOMENCLATURE

Some symbols may have different meanings in different places and these are clearly defined when used. The most commonly used notations are listed in the following:

Abbreviations

ABS	American Berue of Shipping
BV	Bureau Veritas
DNV	Det Norske veritas
GL	Germanischer Lloyds
JBP	Joint Bulker Project
JSQS	Japanese Shipbuilding Quality Standard
JTP	Joint Tanker Project
LR	Lloyds Register of Shipping
NK	Nippon Kaigi Kioka
TSCF	Tanker Structure Co-operative Forum

Superscript

u	ultimate value

Subscript

u	uniaxial
0	yielding

Roman Symbols

R_x	Longitudinal strength ratio in biaxial ($=\frac{\sigma^u_{mx}}{\sigma^u_{mux}}$)
R_y	Transverse strength ratio in biaxial ($=\frac{\sigma^u_{my}}{\sigma^u_{muy}}$)

Greek symbols

σ_x (σ_y)	Membrane longitudinal (transverse) stress
ε_x (ε_y)	Membrane longitudinal (transverse) strain
ε_{mx} (ε_{my})	Mean longitudinal (transverse) strain ($=\frac{\varepsilon_x}{\varepsilon_0}$ or $=\frac{\varepsilon_y}{\varepsilon_0}$)
σ_{mx} (σ_{my})	Mean longitudinal (transverse) stress ($=\frac{\sigma_x}{\sigma_0}$ or $=\frac{\sigma_y}{\sigma_0}$)
σ_{mux}	Mean uniaxial longitudinal stress ($=\frac{\sigma_{ux}}{\sigma_0}$)
σ_{muy}	Mean uniaxial transverse stress ($=\frac{\sigma_{uy}}{\sigma_0}$)

LOCALIZED CORROSION

Pitting corrosion- An overview

Pitting is a localized form of corrosion that occurs on a ship's steel structure. Pitting is self-generating, starting from impurities or in-homogeneity in the metal or from scale or other deposits (Stambauch and Knecht; 1991). Pitting corrosion, if left unchecked, can bring about severe problems on the horizontal and internal bottom surfaces of tanks in the form of loss of strength and hull integrity leading to perforation of the plate and possibly to serious pollution. This type of corrosion is most common in cargo and cargo/ballast tanks of oil carriers and to a less extent, in the ballast spaces of tankers and other types of vessels.

Historically, thickness has been considered as the variable affected by pitting. As pitting affects the geometry of a panel and translates directly to material wastage, the use of thickness has a physical meaning. However, other candidate variables may exhibit more rational sense, such as Degree of Pitting (DOP) and critical sectional area.

Pitting data

Eleven of the twenty-three vessels surveyed by the Tanker Structure Cooperative Forum, TSCF (1986), had significant corrosion problems in their cargo/ballast tanks. All eleven of these experienced bottom pitting corrosion and six experienced general corrosion. In crude oil cargo tanks, seven of twenty-three vessels had significant corrosion problems reported. Of these, six experienced bottom pitting and five experienced general corrosion. One weld related pitting corrosion problem (grooving) was reported.

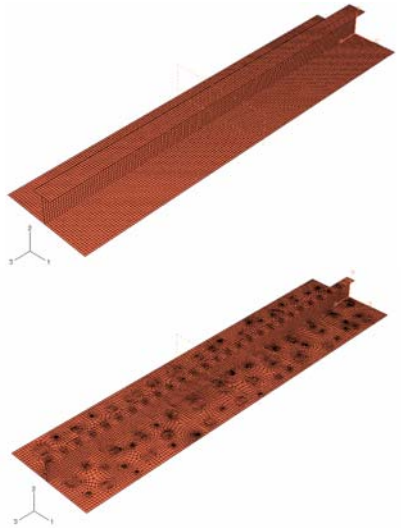

Figure 1. Typical stiffened plate model used in the FE analyses, above= intact plate; below=DOP37.5%

In uncoated cargo/ballast tanks, as pitting progresses, it can form shallow but wide pits resembling general corrosion in high density circumstances. This pitting can be very severe in cargo/ballast tanks used to carry, alternatively, sour crude oil cargo and dirty or clean ballast.

For coated cargo/ballast tanks, wastage can take the form of localized pitting and grooving in way of coating failure.

Existing practises/Guidelines

Regulatory and statutory guidance for determining the residual strength of localized corroding stiffened panels does not exist. Several agencies provide some guidance regarding the replacement of pitted plates based on empirical measures related to the amount of wastage observed. Classification Societies does not refer specifically to the residual strength that can be expected from a localized corroding panel.

Table 1 lists several sources regarding their treatment of pits. The table should not be considered complete since not all entries were fully available. Where information was lacking or unobtainable, the table entries were left blank. As noted in the table, ABS allows a maximum 15% area loss due to pitting in the cross section of a plate before replacement is required, while the new JTP and JBP have proposed a 1.6 mm deterministic pitting wastage on Cargo Oil Tanks. The TSCF, ABS and two oil companies, were found to give specific information for repair, but did not indicate residual strength expectations. In general, repairs are based on the density of pitting.

Treatment for pitting corrosion is usually consisted of filling the pits with epoxy, as long as the depth of the pit is not greater than 15% of the plate thickness and the cross-sectional area lost is not greater than 15% in any transverse section of the strake. Welding of the pits is allowed as long as there is at least ¼ inch of material remaining at the bottom of the pit, at least 3 inches distance between adjacent pits and the maximum diameter of any pit does not exceed 12 inches.

Table 1. Existing guidelines for corrosion and pitting controls in bottom of tanks in tankers (partly reproduced from Daidola et al, 1997)

Reference	Allowable bottom corrosion wastage	Residual strength check	Pitting wastage	Repairs
TSCF	10-20% on rule "t"	a) s/t = 50-55 MS b) s/t = 49-52 H36 Equivalent thickness reduction		Pitting or grooving filled by welding
ABS	a) single bottom: 15% b) all others: 20%	a) max. s/t = 65 MS b) max. s/t = 60H32 c) max. s/t = 55 H36 Equivalent thickness reduction	15% max. area loss in critical section	15%t wasted: just repair coating 50%t wasted: epoxy filled Girth gauging during special surveys
DNV	20% on rule "t"	Equivalent thickness reduction		Girth gauging during special surveys
LR BV	25% original thickness minus constructional margin (rule "t")	Equivalent thickness reduction		Girth gauging during special surveys
NK	20% plus 1 mm subject to verification of residual longitudinal strength			Girth gauging during special surveys
EXXON	a) SM= 15% below min. rule or 18% on area b) 85 % rule "t" or 75% design value			pit & groove < 1/3t recoat pit & groove > 1/3t weld pit & groove > 2/3t renew
Chevron				Pits < 8mm epoxy Pits > 8mm weld
JTP JBP	$t_{gr}= t_{Net}+ t_{CA}$, t_{gr}=gross thickness; t_{Net}=Net scantling; t_{CA}=Corrosion allowance, tabulated in different corrosion environment	Equivalent thickness reduction	1.6 mm in COT	Not specifically for pits, $t_{renewal}= t_{Net}+ t_{Corr-2.5}(=0.5)$

Residual strength determination

Chapkis (1967) discusses the influence of pit corrosion on the strength of steel plating. He defines an equivalent thickness plate considering the reduction in ultimate due to pitting. The equivalent thickness, t_e, suggested by Chapkis is given by $t_e = t/k$, where $k = u_p/ u_{up}$, with u_p = average edge deformation at a pitted plate and u_{up} = average edge deformation at an un-pitted plate. Tensile tests were carried out to define the mean edge deformations of steel plates. However, determination of the coefficient k at the ultimate limit state is normally not an easy task.

Flaks (1978) describes a mathematical method for assessing the influence of pits on the ultimate strength of aluminium plates under tensile loads. A coefficient that accounts for the loss of tensile strength, yield strength and hardness under tension was derived from experimental testing of naturally corroded aluminium plates. However, no evaluation of compressive ultimate capacity is provided.

TSCF Project 300 (1984) on the effects of pitting upon the strength of plates undertook a study to determine the strength of uniformly machined pitted plate models subjected to bending with uniform pitting intensities of 14, 23.5 and 33.5 percents, and uniform variation of pit depth from 5 mm to 15.4 mm. The tests determined the residual thicknesses of plate by using the edge deformations of pitted and un-pitted plate panels. The results of the tests showed a 25.8% maximum reduction in bending capacity for the plates in the tests.

The major concern with pitting is with regard to bottom plating which is under bending and biaxial loading. The tests of Project 300 were conducted on uniformly pitted plates under bending loads only. There was no account of biaxial loading and no reference to non-uniform pitting. The investigation of Project 300 accomplished an important step in determining the residual strength of pitted plates.

SSC-372 (Bea, R.G. et al., 1993) depicts a model for predicting the residual thickness of pitted plate based on a homogeneous plate of reduced thickness based on the average volume and density of pits, as follows:

$$t_r = t_0 - \frac{V_{pit}}{A_0}\frac{1}{DOP}$$

where t_r= reduced thickness; t_0= original thickness; A_0= original surface area; V_{pit}=the average volume of pits; and DOP= Degree of Pitting, which is defined as:

$$DOP = \frac{A_{pit}}{A_0}\times 100(\%) = \frac{\sum_i A_{p_i}}{A_0}\times 100(\%)$$

This reduced plate thickness is derived by using the uniform distribution of an average pit from inspection data to create a mesh arrangement of pits; but no evaluation of residual strength is provided.

SSC-394 (Daidalo, et al, 1997) predicts a model for the residual strength assessment of pitted plates based on their own

PIT software which is able to propose a uniform thickness reduction based on an extensive database, referring to the use of existing design formula in rules to evaluate residual strength.

Recently, some studies (Paik et al.; 2003, 2004) undertook to investigate the ultimate compressive and shear strength reduction characteristics of a steel plate due to pit corrosion. They developed a simple design formula for predicting the ultimate strength of steel plating with corrosion. For this purpose, experimental and numerical studies were carried out. However, it was not deemed sufficient for use in developing a method for determining the residual strength of randomly localized corroding stiffened plate as they considered the regular through-thickness pits as a dominant case and most of the judgments are based on the test carried out with this assumption.

A CASE STUDY

Geometry and material properties

Plates and stiffened plates are common structural components with their strength and structural stability being the subject of numerous researches. There are three different modes of failure, which may act independently or in combinations, namely: plate buckling, column buckling and stiffener tripping. But, the focus here is on local plate buckling which is a desired failure mode in designing of stiffened panels. The geometric and material properties of the panel are as follows, Figure 1:

Panel length; a = 2000 mm
Panel breadth; b = 500 mm
Plate aspect ratio; a/b = 4
Plate thickness; t = 10 mm
Flange thickness; t_f= 8 mm
Web thickness; t_w = 6 mm
Flange breadth; b_f= 200 mm
Web height; h_w = 137.5 mm
Cross-sectional area of the panel; A_y= 6625 mm^2
Longitudinal-sectional area of the panel; A_x = 20,000 mm^2
Plate slenderness ratio; $\beta = \frac{b}{t}\sqrt{\frac{\sigma_0}{E}}$ = 2.26
Shape of pit corrosion; circular
Diameter of pit corrosion; d_p = 20, 30, 50 70 mm (spreading randomly)
Depth of pit; t_p = 0.25t, 0.5t, 0.75t
Degree of pitting; DOP = 12.5%, 25%, 37.5%, 50%
Elastic modulus; E = 208,000 Mpa
Shear modulus; G= 80,000 Mpa
Poisson's ratio; ν = 0.3
Material yield stress; σ_0 = 235 Mpa
Long. edge deformation at yielding; $u_0 = a\frac{\sigma_0}{E}$ = 2.256 mm
Trans. edge deformation at yielding; $v_0 = b\frac{\sigma_0}{E}$ = 0.564 mm

The model analysed, Figure 1, was representative of stiffened steel plate with slenderness ratio value of 2.26 within the usual range of slenderness ratio encountered with ships and offshore structures, e.g. from 1 to 4 (Smith et al, 1988). The material yield stress chosen in the model is the representative value for mild steels which is widely used in ship structures. The stress-strain relationship of the material is approximated by the Ramberg-Osgood formula:

$$\varepsilon = \frac{\sigma}{E} + \alpha\frac{\sigma_0}{E}\left(\frac{\sigma}{\sigma_0}\right)^m$$

where, m is Ramberg-Osgood parameter and α is yield offset (m=20 and α =0.002 in the case study).

Initial imperfection and residual stresses

Imperfections are always present in structural plating, primarily as a result of distortions originating from welding and other production processes involved in the manufacture of grillages. As described by Smith et al (1987), the distortion induced by welding is dominated by an approximately sinusoidal half-wavelength equal or somewhat less than the plate dimension (length or width, depending on the direction of loading). It has been recognized that the initial imperfection may greatly affect the ultimate strength behaviour of steel stiffened plates, e.g. Czujko, J. and Kmiecik, M. (1975), Smith C.S. and Kirkwood, W. (1977); and Carlsen, C.A. and Czujko, J. (1978). Both initial imperfection and residual stresses are included in the model considered in a rational manner.

FINITE ELEMENT MODEL

Since the model was expected to experience large displacements and plastic deformations, finite element analyses had to be performed using programs offering combined geometrically and materially nonlinear capabilities. In this study, the commercial program ABAQUS (2004) under academic licence was utilized.

Shell element formulation

A four-node quadrilateral shell element, S4R, was used to model plate and stiffener. The kinematical assumption of large displacement and rotation but small strain was made. The material property of the stiffened plate was idealized as elasto-plastic with the Von Mises yield criterion. In order to obtain the entire load-shortening curve, the automatic time-stepping method with displacement control and the arc-length method (Riks method) were used in the analyses.

Finite element mesh

A convergence study indicated a finite element mesh with 160 elements in the longitudinal direction of the panel was sufficient to capture the true buckling behavior. A 11×160 mesh was utilized for the web; a 8×160 mesh for the flange; and a 40×160 mesh for the plate. A total number of 9440 elements were created. Localized mesh refinements were made on the pitted area, which will be described in the subsequent part.

Pitting model

The pitting is modelled as shell elements with reduced thickness wherever they are appeared in the model. Pitting distribution in the plate is random in view of likely occurrences in the plate and stiffener. Localized mesh refinement were made on the localized corroded areas merging the common nodes in a way satisfied the equilibrium state. Different levels of DOP are considered.

Eccentricity of pits in the FE modelling

The reference surface for conventional shell elements is defined by the shell's nodes and normal definitions. When modelling with shell elements, the reference surface is typically coincident with the shell's mid-surface. To study the effect of this kind of eccentricity when modelling pits with shell elements, the reference surface needs to be changed. Using another reference surface with an offset of half the shell's thickness from the mid-surface, will represent the true situation.

For this purpose, a rectangular plate was considered with the dimensions of $2\text{m} \times 0.5\text{m} \times 10\text{mm}$, corroded in middle 50% area with depth of ***25%t***. It was observed that the effect of eccentricity is negligible, as shown in Figure 2. Since considering pit eccentricity gives lower strength, it seems clear that the practice of neglecting eccentricity in the finite element model of pitted stiffened plates is a favourable conservative assumption.

Boundary conditions

At the short ends symmetry boundary conditions are prescribed (Figure 1); rotations about the transverse and vertical directions are set to zero. Prescribed uniform displacements are applied at either ends of the panel in opposite directions.

At mid-span (transverse girder), all nodes in plate plane are fixed in vertical direction. Nodes in the stiffener are fixed in the transverse direction in order to simulate the support given by the transverse girder. Nodes in plate plane are free to slide in vertical direction. All the nodes at mid-span are fixed in longitudinal direction.

At the longitudinal edges, symmetry boundary conditions are prescribed; rotations about vertical and longitudinal directions are set to zero. Transverse load is implemented by prescribing translation in the transverse direction along both edges in opposite directions.

Al the nodes along the junction lines of the plate and stiffener are restrained in transverse direction.

The four edges of panel were modelled under "plane section remains plane" condition. One master node was created at each edge of the panel. The edge nodes were designated as slave nodes so that they would displace together with master ones. The same constraint was applied at mid-span to keep it straight during the course of the loading.

Imperfections

Three kinds of initial imperfections are accounted for, namely: plate out of plane displacement, referred to as plate buckling mode; stiffener out of straightness relative to the plate plane, referred to as Euler buckling mode; and sideways sway of the stiffener's top, referred to as stiffener tripping.

When relevant initial imperfection measurements are not available, their amplitudes may be approximately defined by assuming an appropriate initial imperfection configuration based on some empirical formulations. The ultimate strength capacity is calculated using a set of geometrical imperfections consistent with the tolerances given in DNV CN30.1, as follows:

a. Plate out-of-plane displacement, 1%b
b. Stiffener out-of-plane straightness relative to the plate plane, 0.15%L
c. Sideways sway of the stiffener's top, 0.15%L

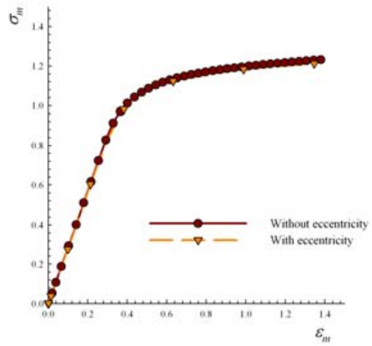

Figure 2. The effect of eccentricity on the strength behaviour of a pitted plate, DOP = 50%, *25%t.*

Residual stresses

One common assumption in studying the effect of residual stresses on the nonlinear behaviour of the stiffened panels is that their pattern forms rectangular tensile and compressive stress blocks in the transverse direction and is constant in the longitudinal direction. However, the residual stress in a real panel is a more general 3D form with variations not only in the transverse direction but also parallel to the weld.

It was decided to introduce the residual stresses in the panel in a way that mimicked the actual welding procedure. That was to generate the residual stresses through thermal stress analyses in which a nonzero coefficient of thermal expansion of $11.7 \times 10^{-6}/\,^{\circ}\text{C}$ was only assigned at the nodal points adjacent to the weld areas. By applying a temperature cycle along the welds, the desired residual stress pattern could be generated.

However, the procedure for generating thermal residual stresses caused additional deformation in the structure. To preserve the initial imperfection, a procedure for automatic generation of welding residual stresses, developed by Hu et al. (1998), was utilized described in the following stages:

Stage 1: Assign a positive temperature variation at the nodes adjacent to the welded areas just before the linear buckling step to produce reversed residual stresses where the panel is strained in the opposite sense to the actual residual stress distribution and then store it in an intermediate file.

Stage 2: read the geometry from the intermediate file and use it as the original geometry in the subsequent thermal analysis. Assume that the structure is free of residual stresses. Apply a negative temperature variation, before the post-buckling nonlinear analysis is started, which results in a stiffened panel with both the desired residual stresses and imperfections.

Combined loading

Plate elements and stiffened panels in bottom structures of ships are more likely to be subjected to biaxial in-plane loads, rather than just uni-axial compression. However, the load in one direction usually predominates and this determines the ultimate strength, with the load in the transverse direction providing an additional destabilising influence. The information that exists for this type of loading is mainly of theoretical form, limited usually to studies of the elastic buckling behaviour.

The loads are applied in a systematic way in order to provide consistent data. The procedure is as follows:

1. Individual loading: The pure longitudinal and pure transverse loadings were considered as two individual loading cases. The longitudinal and transverse loadings were introduced by individually prescribing in-plane displacements of the corresponding edges, to completely acquire the stress-strain pre- and post-buckling behaviour of the stiffened plate. The pure longitudinal compression was introduced by prescribing uniform displacements of all nodes in the x-direction at both short edges in opposite directions. The pure transverse compression was introduced by prescribing uniform displacements of all nodes in the y-direction at both longitudinal edges in opposite directions.

2. Combined loading: The biaxial compressions were introduced by prescribing proportional in-plane displacements of the transverse edges relative to the longitudinal edges. The proportionality factor can be defined as:

$$\text{Proportionality factor} = k_{\propto} = \frac{\varepsilon_y}{\varepsilon_x}$$

Two biaxial compressions cases were considered as summarized in Table 2.

NUMERICAL RESULTS

Effect of pitting corrosion on strength reduction

Figure 3 shows the mean stress- mean strain curves for the stiffened plate with DOP12.5% and depth of pits 0.75***t*** including the intact plate, i.e. with 0 percent DOP and reduced thickness assumption's case.

The reduced thickness case is based on equivalent thickness reduction assumption (i.e., ***0.925t***). It is clear that this pessimistic way does not present true behaviour and it is over-predicting in either of longitudinal and transverse capacities.

It should also be burned in mind that there are different cases of a certain level of DOP, e.g. 12.5%, that may correspond to a fixed case of reduced thickness, e.g. ***0.925t***, thus producing different behaviours. This effect will be studied in subsequent sections.

Table 2. Loading conditions

$k_{\propto} = 0 \; (\varepsilon_y = 0)$	Pure Long.	$u = 2u_0 = 4.512$	$v = 0$
$k_{\propto} = 0.2$	Long. Predominate	$u = 1.8u_0 = 4.0608$	$v = 1.8v_0/5 = 0.20304$
$k_{\propto} = 1.0$	Trans. Predominate	$u = u_0 = 2.256$	$v = v_0 = 0.564$
$k_{\propto} = \infty \; (\varepsilon_x = 0)$	Pure Trans.	$u = 0$	$v = 2v_0 = 1.128$

Effect of Degree of Pitting (DOP) and sectional area

Figure 4 to 5 and 9 to 13 show the nonlinear behaviour of the stiffened panel with varying levels of DOP and pit depths, until and after the ultimate strength is reached. Table 3 summaries the computed results for the all cases**.**

The displacement profiles are used to aid in explaining the results of the elasto-plastic buckling collapse of the stiffened panel; see Figure 6 to 8. The Von Misses stress contour is also shown in Figure 16. The following observation may be made:

i. The post-buckling shape at one side of the stiffener is opposite to the other side, forming in an alternating fashion (Figure 16). This full sine wave shape in the transverse direction of the panel is the same form as the second classical column buckling mode with a central support, i.e. the stiffener in this case. However, after initial buckling, high stresses occurred locally at the corrosion locations. It might be due to the deformation occurring in the opposite direction of the overall buckled shape and resisting moment induced by compressions in both directions, thus making severe bending deformation in those locations, but no local buckling appears.

ii. It is evident that, at least in the present model, the failure mode itself, which was primarily plate buckling mode, is not sensitive to the levels of DOP up to 50% and maximum depth of pits 0.75t, although the post-collapse behaviour may change depending upon the level of DOP and pit's depth.

iii. Displacement profiles for the stiffened plates were found to remain periodic well into the post-collapse range at compressive strains of up to $1.5\varepsilon_0$ (Figure 6 to 8). In the case of biaxial loading with the predominant transverse loading, the displacement profile is different.

iv. In deeply pitted plates, 0.75t, having initial deformation in the form of ripple distortions, collapse is associated with a sudden transition (snap) deformation, tending to become localized close to the plate ends in the case of DOP 12.5% as shown in Figure 8. This may be explained by the effect of concentration of pits near to the web frame and the appearance of critical sectional area in that location.

v. Apart from making a small contribution to periodic initial distortion and hence to growth of elastic pre-buckling displacements, the main effect of localized corrosion appears to be to cause a local amplification of plate bending which accelerates localized yielding, leading to loss of flexural stiffness and hence inelastic failure.

vi. It is apparent that although longitudinal ultimate strength is gradually decreased, the post-collapse behaviour is different. In general, it appears that characterization of localized corrosion by the level of DOP only, may be misleading and non-conservative; this approach will be particularly unsatisfactory when biaxial compressions present.

vii. As long as the depth of pits is kept less than 0.5t, there are no large discrepancies in the biaxial interaction curves if the DOP varies up to the level of 50%. Most of the differences take place for deeply pitted panels. The two main parameters influencing the shapes of the biaxial interaction curves are the DOP and the critical sectional area. Plates having deep pits seem to have a little stronger interaction (the stronger is meant to the closer the interaction to the linear one), but there are no general trends, as observed in the case of DOP50%, which may be related to the effect of the concentration of the pits over a certain area of the plate. This effect is studied in subsequent part.

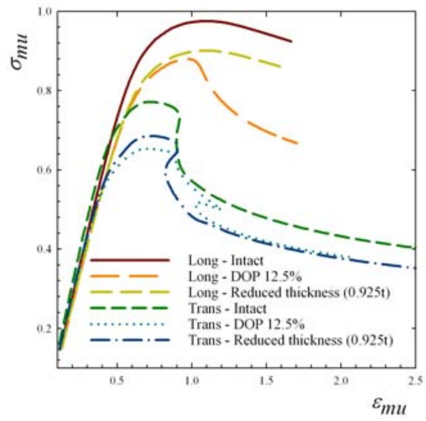

Figure 3. The effect of Pitting corrosion on strength reduction, DOP=12.5% and depth of pit = 0.75*t*; pure longitudinal and pure transverse loadings

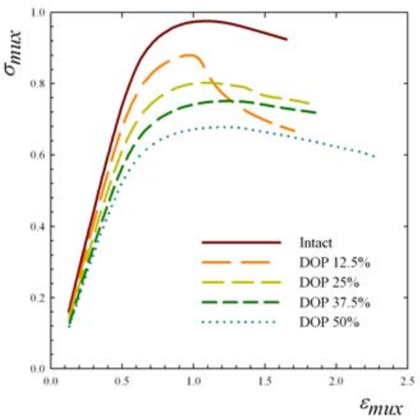

Figure 4. The effect of DOP on the strength reduction, depth of pit = 0.75*t; Pure Longitudinal*

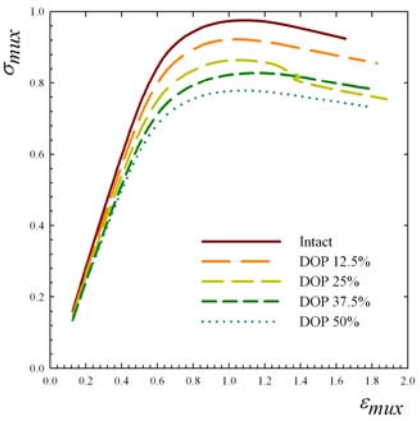

Figure 5. The effect of DOP on the strength reduction, depth of pit = 0.5*t; Pure Longitudinal*

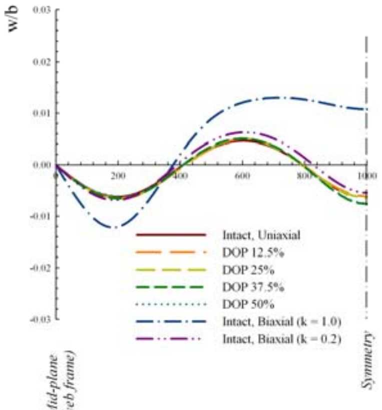

Figure 6. Displacement profiles, depth of pit = 0.75*t*, $\varepsilon = 0.5\varepsilon_0$ *; Pure Longitudinal*

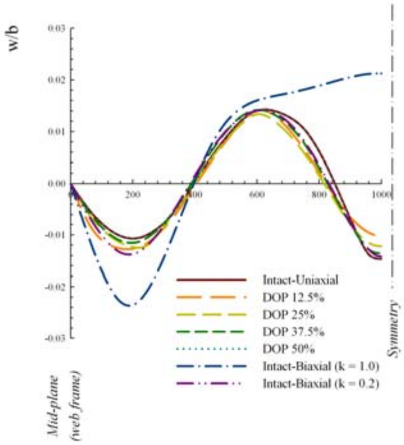

Figure 7. Displacement profiles, depth of pit = 0.75*t*, $\varepsilon = \varepsilon_0$ *; Pure Longitudinal*

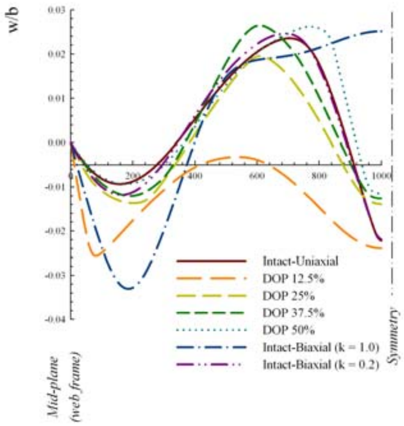

Figure 8. Displacement profiles, depth of pit = 0.75*t*, $\varepsilon = 1.5\varepsilon_0$ *; Pure Longitudinal*

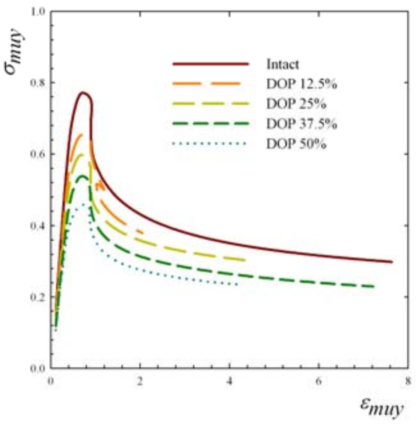

Figure 9. The effect of DOP on the strength reduction, depth of pit = 0.75*t; Pure Transverse*

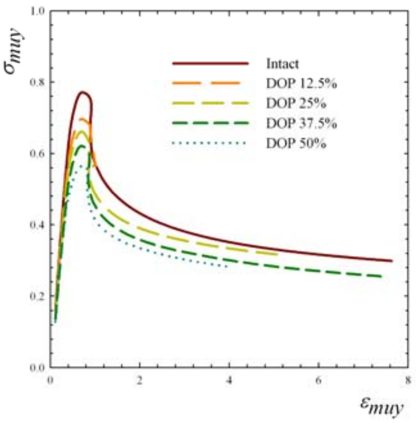

Figure 10. The effect of DOP on the strength reduction, depth of pit = 0.5*t; Pure Transverse*

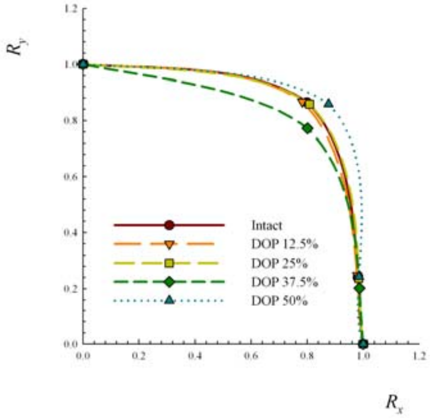

Figure 11. Biaxial interactions; 0.75t

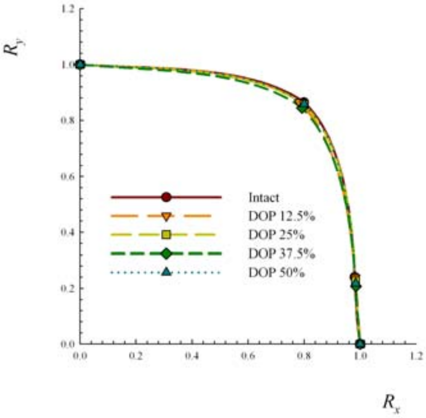

Figure 12. Biaxial interactions; 0.5t

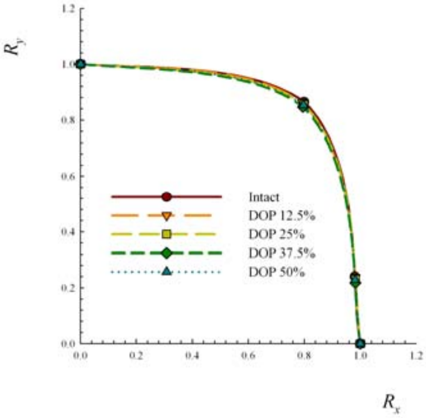

Figure 13. Biaxial interactions; 0.25t

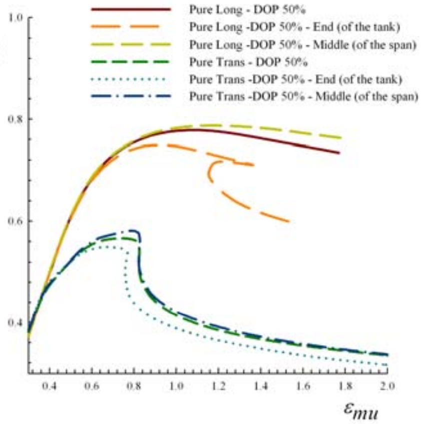

Figure 14. The effect of the location of densest pitted area; depth of pit = 0.5*t*.

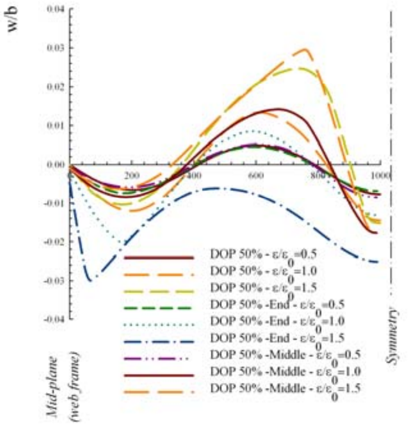

Figure 15. Displacement profiles, depth of pit = 0.5*t; Pure Longitudinal*

viii. For plates having the depth of pits smaller than 0.5t, the reduction in pure longitudinal capacity is a little smaller than the reduction in pure transverse capacity, Table 3. This effect is not large enough to significantly alter the relationship between longitudinal and transverse ultimate capacity in biaxial loading condition. For deeply pitted plates, the reduction in pure transverse capacity is double that of the pure longitudinal.

ix. The maximum reduction of the ultimate capacity in biaxial loading conditions, Table 3, takes place in transverse capacity almost near to the pure transverse.

x. The above conclusions are relevant for the plate with aspect ratio of 4 and slenderness ratio of 2.26. There might be different behaviour in relation to biaxial curves for different aspect ratio and different plates (sturdy vs. slender).

Effect of the densest pitted area

To study the effect of concentration of pits on the surface of the panel, two extreme cases were considered: densest pitted zone located at the end of the model (i.e., middle of the span) and densest pitted zone at the middle of the model (i.e., end of a tank). Among, the later is more likely to happen, in the way of trapping of the water, see Figure 14.

Displacement profiles for the two extreme cases, Figure 15, state that while they were well periodic in pre-buckling circumstances, they became localized in the location where the densest area appears.

Stiffened plate with the densest pitted area near to the end (of the tank) has the largest reduction in ultimate capacity in both pure longitudinal and pure transverse loadings, followed by a completely different post-buckling behaviour. In the case of densest pitted area near to the middle (of the span), the trend is more likely to be an upper bound with a little higher post-buckling range. This conclusion is consistent with the experimental observations recently carried out by Nakai et al (2005).

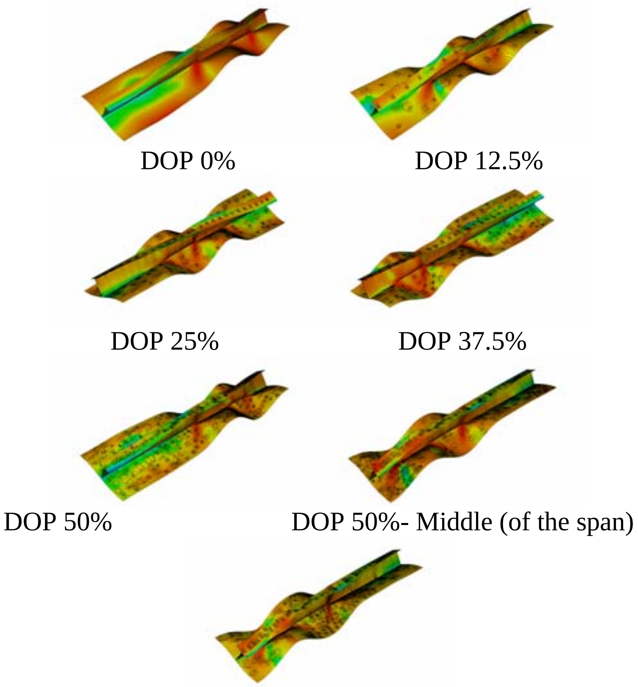
DOP 0%
DOP 12.5%
DOP 25%
DOP 37.5%
DOP 50%
DOP 50%- Middle (of the span)
DOP 50%- End (of the tank)

Figure 16. Stiffened plates with different level of DOP in the post-collapse circumstances, depth of pit = 0.25*t* (Magnified by 5).

DECISION MAKING TOOLS

Up to the present, the means of assessing residual strength of pitted stiffened panels were either non-conservative, inaccurate, or left to past experience to determine which plates to replace or repair. These procedures can be modified by incorporating the knowledge gained above.

Although information available from service life experience can be used as a starting point for residual strength assessment, its application has limited scope. Assessing the impact of localized corrosion requires an understanding of the total load-deflection relationship, i.e. the pre- and post-buckling behaviour. A better tool, however, will be the compromised residual strength criteria taking into account the service life experience. This is particularly useful for the ultimate limit state-based reliability and risk assessment of plated structures with localized corrosion wastage. The following proposed decision tool for a plate under consideration may be utilized:

1. Considering different sample squares 300mm × 300mm (12in × 12in), that is representative of pitting of the full plate in terms of intensity, depths and diameters of pits, making clear of the possible densest pitted location.
2. Estimating the residual strength of pitted stiffened plate by an appropriate tool, considering the level of DOP, critical sectional area and the location of concentrated pits.
3. Evaluation of the fulfilment of the compromised residual strength criteria.
4. Making a decision to repair or replace.

Table 3. Percentage reduction of ultimate strength of a stiffened panel, with plate buckling as the predominant mode of failure due to pitting as a function of DOP and depths of pits

		Ultimate strength reduction (Versus intact panel)					
		Depth of pits, 0.25t		Depth of pits , 0.5t		Depth of pits, 0.75t	
	Level of DOP (%)	Long.	Trans.	Long.	Trans.	Long.	Trans.
Pure Longitudinal	0	0	0	0	0	0	0
	12.5	2.51	0	3	0	7.5	0
	25	4.93	0	6.7	0	13.5	0
	37.5	6.94	0	8.7	0	17.3	0
	50	9.3	0	12	0	23.3	0
Biaxial ($k_z = 0.2$)	0	0	0	0	0	0	0
	12.5	2.3	5.8	5.2	10.3	10.02	12.4
	25	4.7	9.9	11	19.1	17.4	23.7
	37.5	6.7	16.9	14.7	30.3	22.5	36.4
	50	9.2	16.6	19.9	33.4	30.1	39.8
Biaxial ($k_z = 1$)	0	0	0	0	0	0	0
	12.5	3.4	4.9	7.6	9.7	11.8	15.1
	25	5	7.3	11.2	15.1	16.9	23.1
	37.5	7.5	10.4	15.8	21.4	22.8	32.5
	50	9.6	13.5	20.2	27.1	23.8	40.9
Pure Transverse	0	0	0	0	0	0	0
	12.5	0	4.7	0	9.7	0	15.3
	25	0	6.2	0	14.2	0	22.4
	37.5	0	8.5	0	19.5	0	24.4
	50	0	12.3	0	26.6	0	40.5

CONCLUDING REMARKS

This paper deals with stiffened plate with pitting corrosion assuming the plate buckling as the predominate mode of failure. The stiffened plate is subject to biaxial loading. The possible effect of the eccentricity in the plate, when modelling pits with shell elements, has been investigated by considering a rectangular plate, which was found to be negligible. The level of pit corrosion intensity and depth of pits have been varied. Based on the numerical results obtained, the following conclusions have been reached:

1. The ultimate strength of a stiffened steel plate can be significantly reduced due to pitting corrosion.
2. The ultimate strength of a steel stiffened plate with pit corrosion and under biaxial compression is governed not only by the level of DOP (Degree Of Pitting), but also by the smallest sectional area and densest pitted zone.
3. In the present model, there needs to be more than 50% locally corroded area on the stiffener's top to make a change in the type of failure mode, i.e. developing a tripping collapse mode.
4. The insight developed in the present study will be very useful for the damage tolerant design of plated structures with pit corrosion as well as establishing a decision making tool aiming at scheduling repairs more efficiently. The methodology developed can be utilized for the ultimate limit state-based reliability and risk assessment of plated structures with localized corrosion wastage.
5. The focus here has been on a stiffened plate collapsing locally in plate buckling mode. More analyses need to be done on individual pitted plate and on pitted stiffeners, as to consider the effect of lateral pressure on the collapse and post-collapse behaviour.

REFERENCES

ABAQUS (2004), User's manual, Ver. 6.4, Pawtucket, RI02860-4847, ABAQUS, Inc.

Bea, R.G., Hutchison, S.C., (1993), "Maintenance of marine structures; a state of the art summary", Ship Structure Committee, SSC-372

Carlsen C.A. and Czujko, J. (1978), "The specification of post-welding distortion tolerances for stiffened plates in compression", The Structural Engineer, 56A (5), 133-141

Czujko, J. and Kmiecik, M. (1975), "Post-welding distortions of ship shell plating", Ship research institute, Technical university of Szczecin, Report No 4-S

Daidola, J.C., Parente, J., Orisamolu, I.R. and Ma, K.T., (1997), "Residual strength assessment of pitted plate panels", Ship Structure Committee, SSC-394

Dhruba J. Ghose, Natale S. Nappi and C.J Wienicki (1995), "Residual strength of damaged marine structures", Ship Structure Committee, SSC-381

DNV CN30.1 (1992), "Buckling strength analysis", Classification Notes, Høvik, Norway

Hu S.Z. and Jiang, L. (1998), "A finite element simulation of the test procedure of stiffened panels", Marine Structures, 11, 75-99

JBP (2004), "IACS Joint Bulker Project; IACS Common Rules for Bulk carriers", draft for comments, July 2004

JTP (2004), "Joint Tanker Project; Common Structural Rules for Double Hull Oil Tankers", ABS, DNV and LR, draft for comments, June 2004

Nakai T., Matsushita H., Yamamoto N. and Arai H. (2005), "Effect of pitting corrosion on local strength of hold frames of bulk carriers (1st report)", Marine Structures, Vol. 17, No. 5, 403-432

Paik JK, Lee JM, Ko MJ. (2003), "Ultimate compressive strength of plate elements with pit corrosion wastage" Journal of Engineering for the Maritime Environment, 217(M4):185–200

Paik JK, Lee JM, Ko MJ. (2004), "Ultimate shear strength of plate elements with pit corrosion wastage", Thin-Walled Structures 42, 1161–1176

Smith, C. S., Davidson, P. C., Chapman, J. C. and Dowling, P. J. (1988), "Strength and stiffness of ships' plating under in-plane compression and tension", RINA Trans., 130, 277-296

Smith C.S. and Kirkwood, W. (1977), "Influence of initial deformations and residual stresses on inelastic flexural buckling of stiffened plates and shells", Steel Plated structures, Ed. P.J. Dowling, et al, London, 838-864

Stambauch and Knecht (1991), "Corrosion experience data requirements", Ship Structure Committee, SSC-348

TSCF (1984), "Experimental and theoretical investigation of the strength of corroded hull elements", Project 300, Report No. 84-3438, Tanker Structure Co-operative Forum

TSCF (1993), "Guidelines for the inspection and condition assessment of tanker structure", Tanker Structure Co-operative Forum