REINFORCEMENT OF AGEING SHIP STRUCTURES

(DOI No: 10.3940/rina.ijme.2018.a3.482)

D Chichì and **Y Garbatov,** Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

SUMMARY

The objective of the present study is to investigate the possibility to recover the ultimate strength of a rectangular steel plate with a manhole shape opening subjected to a uniaxial compressive load and non-uniform corrosion degradation reinforced by additional stiffeners. Finite element analyses have been carried out to verify the possible design solutions. A total of four finite element models are generated, including 63 sub-structured models. The non-uniform corrosion has been generated by the Monte Carlo simulation. The reinforcement process covers three scenarios that include mounting of two longitudinal stiffeners, two longitudinal and two transverse stiffeners and the flange on the opening. The positioning of the stiffeners has also been studied. A total of 10 cases has been selected and tested for the numerical experiment. Three different assessments have been performed to evaluate the ultimate strength, weight and cost. Two additional studies on the effect of the plate thickness and slenderness have been also carried out.

NOMENCLATURE

A_0	Sectional area of the plate (m^2)
A_{plate}	Sectional area of the simple plate (m^2)
A_{stiff}	Sectional area of the stiffener (m^2)
ASR	Average stress ratio
a	Coefficient of the maximum local imperfection
a_G, b_G	Parameters
b	Breadth of the plate (m)
b_{eff}	Effective breadth
b_{ln}	Local breadth "n" of the plate (m)
β	Plate slenderness
C_0	Parameter for lateral shifting of the stiffener (mm)
C_{profit}	Profit of the shipyard
CSR	Classification Society Rules
C_{steel}	Cost of the material of the stiffeners (€)
C_{weld}	Cost of the welding material (€)
C_{labour}	Labour cost (€)
$d(t\|x, y, z)$	Corrosion depth (mm)
d_∞	Long-term corrosion wastage of the plate (mm)
δ_{steel}	Weight density of steel
E	Elasticity modulus (N/m^2)
ES	Element size (mm)
h_w	Height of the stiffener web (mm)
h_{work}	Hours needed to complete the process (hour)
k	Number of nodes
l	Length of the plate (m)
l_{weld}	Length of the welds (m)
$\bar{\lambda}$	Relative column slenderness
m, n	Number of half waves
$R_{y,i}$	Reaction force in the y-direction at the ith node with coordinates $(x_i, 0, 0)$
σ_{max}	Maximum compressive stress (N/mm^2)
σ_{YP}	Yield point of the material
σ_u	Ultimate strength (N/mm^2)
t	Time (year)
$t_{effective}$	Effective thickness (mm)
t_{stiff}	Thickness of the stiffener (mm)
t_p	Thickness of the plate (mm)
$t_p^{corroded}(t\|x, y, y)$	Non-uniform corroded plate thickness (mm)
$t_p^{intact}(x, y, z)$	Thickness of the intact plate (mm)
τ_c	Coating life (year)
t_i	Average net thickness for an intact or corroded plate (mm)
τ_t	Transition period (year)
ν	Poisson coefficient
V_{hole}	Volume of the hole (m^3)
V_{plate}	Volume of the plate (m^3)
V_{stiff}	Volume of the stiffener (m^3)
w_{Gmax}	Parameter of the imperfection between girders (mm)
w_{Lmax}	Parameter of the imperfections (mm)
W_{stiff}	Weight of the stiffener (kg)

1. INTRODUCTION

Plated structures are the main part of ships, platforms extracting natural resources from the sea and the renewable energy offshore installations. The environment where they operate is harsh. The structures are subjected to corrosion degradation due to a severer corrosion environment. Marine structures are composed of different structural components, including stiffeners, frames and plates and experience complex environmental conditions and loadings.

Corroded plates lose the structural capacity to withstand loads as the corrosion degradation progress. Marine structures spend almost the entire service life in a severe cession environment. In the case when the metal structures are protected against corrosion, it is a matter of time until corrosion degradation starts. The protections are not perpetual; they have an effective time after which the corrosion process starts. The structure can be renewed or reinforced, but it costs as has been demonstrated by Caridis, (2001).

The Classification Societies define the lower limit of the net thickness after which the structural component must be replaced. A way to avoid the substitution of a part of the structure, it is to recover the initial structural capacity.

Recovering of the structural capacity is generally done by replacing the deteriorated parts or entire structures, but it is also acceptable to reinforce it applying different solutions.

The possibility to recover the capacity of the structure by additional reinforcing stiffeners to the already aged plates has not been studied yet. It is also important, from an economical point of view, to be able to predict when a structural component must be reinforced, repaired or substituted.

The reinforcement process is intended to recover the capacity of deteriorated structures and can become a reasonable trade-off between the containment of the cost, safety and prediction of the ageing structures. It can also open a new flourishes market for marine industries to not only replace, but also apply preventive maintenance and protection of structures.

The principal structural components in marine structures are plates. Numerous studies have been conducted on the assessment of the ultimate strength of steel plates. Several research studies have been conducted on the ultimate strength of plates and stiffened plates with an opening.

Shanmugam et al., (1999) investigated the variation of ultimate strength in perforated thin plates and the incidence of the different positioning of the opening affecting the ultimate strength. They also analysed the post buckling behaviour and the ultimate strength of perforated plates under uniaxial or biaxial compression.
Paik et al., (2001) proposed formulae for the assessment of plates under the combination of the biaxial compression and edge shear.

Kim et al., (2009) derived a formula for the assessment of ultimate strength of a perforated plate under axial compression. This study was implemented by a further formulation of Kim et al., (2015) with experiments, both numerically and in scale, of perforated plates. In this study, it has been proved the influence of different kind of stiffeners on the ultimate strength.

To investigate experimentally and numerically the severe non-uniform corrosion Garbatov et al., (2017) studied the degradation effect on the load carrying capacity of stiffened plates, where different factors leading to a reduction of structural capacity have been investigated, including the material properties, degree of degradation, equivalent thickness and testing support conditions.

Saad-Eldeen et al., (2016a, b) studied the influence of large openings on side shell plating demonstrating that the relation between the increase of the number of holes and the diminution of the ultimate strength bending capacity is not linear.

The present study investigates the possibility to recover the ultimate strength of a rectangular steel plate with a manhole opening subjected to non-uniform corrosion degradation reinforced by additional stiffeners and three different assessments are performed to evaluate the acceptance of the possible solutions.

2. FINITE ELEMENT ANALYSIS

The corrosion deterioration modelling may be classified as linear and non-linear ones. The traditional approach is the linear one that considers the corrosion growth as a linear one and brings to an overestimation of the deterioration.

The corrosion deterioration model used in the present study is the non-linear one as developed by Guedes Soares and Garbatov, (1999) and lately updated by Garbatov et al., (2007) with the implementation of experimental data from Wang et al., (2003). The model considers that the corrosion deterioration is divided into three phases: in the first one there is no corrosion degradation due to the coating protection of the plate, the second phase is the start of corrosion deterioration due to the coating protection failure with a high corrosion rate, the third phase consists in the reducing and stop of the corrosion deterioration. The model is based on the solution of a differential equation and the corrosion depth is defined as:

$$d(t) = \begin{cases} 0 & , t < \tau_c \\ d_\infty \left[1 - \exp\left\{-\frac{t-\tau_c}{\tau_t}\right\}\right] & , t \geq \tau_c \end{cases} \quad (1)$$

The descriptors of Eqn (1), valid for ballast tanks of tanker deck, as defined by Garbatov et al., (2007) are $d_{\infty,ballast}$=1.85 mm, $\tau_{c,\ ballast}$ = 10.54 years $\tau_{t,\ ballast}$=17.54 years and t is time. The corrosion depth is assumed to be described by the Log-normal distribution with a mean value of Mean[d(t)] as defined by Eqn (1) and standard deviation as:

$$\mathrm{StDev}[d(t)] = a_G \,\mathrm{Ln}(t) - b_G \quad (2)$$

where the coefficients a_G and b_G are defined as 0.384 and 0.710.

The non-uniformity of the corrosion degradation is given by a randomization of the plate thicknesses at each nodal location of the finite element model developed here to evaluate the ultimate strength by employing the Monte Carlo simulation, Hammersley and Handscomb, (1975). Every node of the finite element model is described by the x, y and z coordinates and a thickness of $t_p(x,y,z)$.

The intact plate thickness corresponds to the as built thickness with a mean value of Mean[t_p^{intact}]=10 [mm] and standard deviation of StDev[t_p^{intact}]=1 mm and follows the Log-normal probability distribution.

The Monte Carlo simulation is used to generate the intact plate thickness and corrosion depth, which are used to define the resulting corroded plate thickness as a function of the time, Garbatov and Guedes Soares, (2017):

$$t_p^{corroded}(t|x, y, y)=t_p^{intact}(x, y, z)-d(t|x, y, z) \tag{3}$$

where $t_p^{intact}(x, y, z)$ is the random thickness of the intact plate at the finite element nodal location with coordinates x, y, z, at time t, d(t|x, y, z) is the random corrosion depth and $t_p^{corroded}(t|x, y, y)$ is the resulting random non-uniform corroded plate thickness. $t_p^{intact}(x, y, z)$ and d(t|x, y, z) are assumed to be independent random variables due to the fact that the variation in the intact plate thickness depends of the manufacturing process and the corrosion degradation is a function of the corrosion environment.

The randomization of the plate thickness with respect to $t_p^{intact}(x, y, z)$ and d(t|x, y, z) is applied to both, plate and stiffeners, except for the edge at y = 0 being the edge where a node is placed to assure the symmetry and read the reaction forces. The corroded plate surface, $t_p^{corroded}(t|x, 200,0)$ at t=15, 20 and 25th year can be seen in see Figure1.

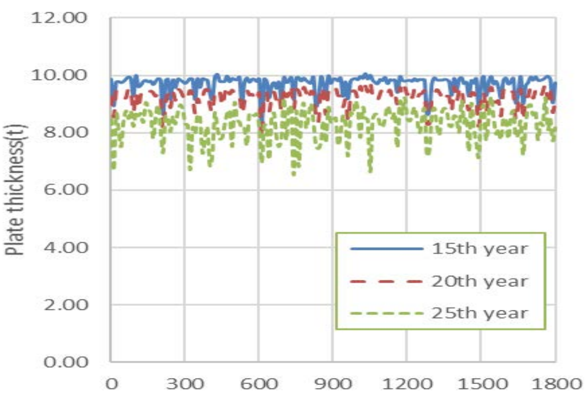

Figure 1: Corroded plate surfaces, $t_p^{corroded}(t|x, 200,0)$ at t=15, 20 and 25th year

Depending on the type of the load, the steel plate is experiencing, different response regimes are developed. When a steel plate is under predominant axial tensile loads, it fails by gross yielding, while when the steel plate is under predominant compressive loads, the regimes are: (i) pre-buckling, (ii) buckling, (iii) post-buckling, (iv) collapse (ultimate strength) and (v) post-collapse, Paik et al., (2001).

The pre-buckling regime generally presents a linear behaviour between the load and displacement. In this regime, the structure is stable and elastic. The increase of the compressive loads and the consequent reaching of the critical load causes the occurrence of buckling. It must be noted that for plates, buckling might happen in the elastic regime, but the structure can be considered stable, which means that more loads can be sustained, until the ultimate strength.

With the increasing of the applied loads, the plate reaches the ultimate limit state. The post-collapse regime is characterized as a highly unstable one. The initial imperfection of the plate leads to deflect at an early stage with the increasing of compressive loads. In this case, the bifurcation buckling phenomenon does not appear, Paik et al., (2001).

The ultimate strength of a plate is a function of different factors such as the geometric and material proprieties, initial imperfections, boundary conditions, loading conditions, corrosion, cracks, dents and openings.

The plate considered in the present study has a rectangular shape characterized by the following parameters: l is the length, b is the width and t_p is the thickness. A manhole opening type, as shown in Figure 2, is present with a beam of the opening, $b_{opening}$=600 mm, length of the opening, $l_{opening}$=800 mm, radius of the opening, $r_{opening}$=300 mm.

The elastic modulus, E considered for the study is 205.8 GPa, yield stress and the Poisson coefficient are considered as 235 MPa and 0.3 respectively. The load applied to the plate is uniaxial, the displacement in the z-axis on all edges is fixed, the rotations, respectively, to the x-axis and y-axis directions are constrained at the edges, y = 0 and y=L for the first and x = 0 and x = b for the second one.

The node with the coordinates (b/2; 0; 0) is constrained to secure the symmetry and to have an accurate determination of the displacement of the plate.

The initial global imperfection, considered in this study, is defined as proposed by Faulkner, (1975). It is also assumed that the parameters defining the imperfections between the stiffeners, w_{Lmax}, girders, w_{Gmax} and lateral shifting of the stiffener, C_o is followed:

$$w_{Lmax} = a\, t_p \beta^2 \tag{4}$$

$$w_{Gmax} = 2 \text{ mm} \tag{5}$$

$$C_0 = 0.00323\, l \tag{6}$$

where β is the slenderness of the plate, t_p is the thickness of the plate, a is the coefficient assumed here as 0.1, Faulkner, (1975), and l is the length of the plate.

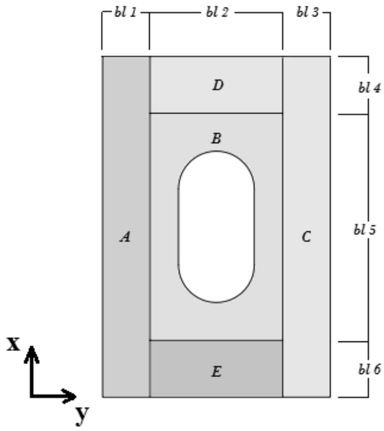

Figure 2 - Imperfection zones, case 2

The plate slenderness β is defined as:

$$\beta = \frac{b}{t_p}\sqrt{\frac{\sigma_y}{E}} \quad (7)$$

where b is the width of the plate between stiffeners, t_p is the thickness of the plate, σ_y is yield stress and E is the Young modulus.

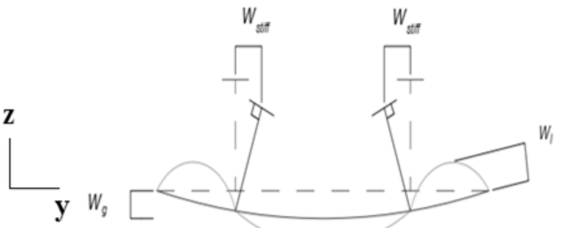

Figure 3 - Global and local imperfection

For a simply supported rectangular plate, with a central opening, the global imperfection, W_g is estimated as:

$$W_g(x,y) = w_{gmax}\,\sin\left(\frac{m\pi x}{l}\right)\,\sin\left(\frac{n\pi y}{b}\right) \quad (8)$$

where l is the length of the plate, b is the breath of the plate, m and n are parameters defining the number of half waves considered. The study is carried out for the half waves, m = n =1, where x ϵ [0, l] and y ϵ [0, b] as can be seen in Figure 3.

In the cases of a plate with a reinforcement made with longitudinal stiffeners, it is necessary to consider the local imperfection, W_l. The local imperfection between the stiffeners is defined as:

$$W_l(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{l}\right)\,\sin\left(\frac{\pi ny}{b}\right) \quad (9)$$

In the case of the reinforcement made only with longitudinal stiffeners, the imperfection function used here is defined as (see Figure 3):

$$W_{l\ zone\ A}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{l}\right)\,\sin\left(\frac{\pi ny}{b_{l1}}\right) \quad (10)$$

$$W_{l\ zone\ B}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{l}\right)\,\sin\left(\frac{\pi ny}{b_{l2}}\right) \quad (11)$$

$$W_{l\ zone\ C}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{l}\right)\,\sin\left(\frac{\pi ny}{b_{l3}}\right) \quad (12)$$

where b_{l1} is the local width between the girder and stiffener (zone A), b_{l2} is the local width between two stiffeners (zone B) and b_{l3} is the local width between stiffener and girder (zone C). In all cases was assumed $b_{l1} = b_{l3}$. In the case that the reinforcement is made of two longitudinal and two transverse stiffeners, b_{l1}, b_{l2} and b_{l3} are defined as in the previous case, b_{l4} is the local length between the edge of the plate and the transversal stiffener, b_{l5} as the local length between the two transversal stiffeners and b_{l6} is the local length between the second transverse stiffener and the edge of the plate:

$$W_{l\ zone\ D}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{b_{l4}}\right)\,\sin\left(\frac{\pi ny}{b_{l2}}\right) \quad (13)$$

$$W_{l\ zone\ B}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{b_{l5}}\right)\,\sin\left(\frac{\pi ny}{b_{l2}}\right) \quad (14)$$

$$W_{l\ zone\ E}(x,y) = w_{lmax}\,\sin\left(\frac{\pi mx}{b_{l6}}\right)\,\sin\left(\frac{\pi ny}{b_{l2}}\right) \quad (15)$$

In the case of the flange reinforcement of the central hole, the only imperfection considered is the global imperfection of the plate.

In all cases, the lateral shifting of the stiffener is given by:

$$W_{stiff}(x) = C_0\,\frac{t_{stiff}}{h_w}\,\sin\frac{\pi x}{l} \quad (16)$$

where t_{stiff} is the thickness of the stiffener, h_w is the height of the stiffener web.

The finite element type used in the non-linear finite element analysis is shell element SHELL181. The element has four nodes with six degrees of freedom at each node. SHELL181 is well-suited for a linear, large rotation, and/or large strain nonlinear applications. The finite element analyses are performed using the commercial software ANSYS, (2009).

The convergence iteration method employed in the numerical simulation is the Arc-length method, which was set to the minimum arc length of 10^{-7} (default is 10^{-3}) to get a convergence in the finite element solution process and most accurate value of the ultimate strength.

The analysis is carried out applying an axial load in the y direction on the edge y = l, while the reaction forces are calculated on the opposite edge, where y = 0. The averaged stress ratio, ASR is defined as a sum of the reaction forces $R_{y,i}$ in the y-direction of the i^{th} node with coordinates $(x_i, 0, 0)$, k is the number of nodes at $y = 0$, A_0 is the sectional area, σ_{YP} is yield point of the material, Silva et al., (2013):

$$ASR = \frac{\sum_{i=1}^{k} R_{y,i}}{A_0 \sigma_{YP}} \quad (17)$$

where the plate area is defined as:

$$A_0 = b\, t_i \quad (18)$$

and the sectional area of the stiffened plate is defined as:

$$A_0 = A_{plate} + A_{stiff} \quad \text{stiffened plate} \quad (19)$$

The sectional areas are always calculated at the edge of reaction forces at $y = 0$.

3. SCENARIOS

The gradient of the ultimate strength, σ_u of the plate with respect to the element size is estimated as follows:

$$\text{Gradient} = \lim_{\Delta ES \to 0} \frac{\Delta\sigma_u(ES)}{\Delta ES} \cong \frac{\sigma_{u,i} - \sigma_{u,i+1}}{ES_i - ES_{i+1}} \quad (20)$$

The selected element size, ES for all analyses of this study is 20 mm. This element size gives the best conditions and time needed in the finite element analysis

3.1 SCENARIO 1

A series of non-linear finite analyses with different uniform thicknesses for an intact plate are carried out to study the variation of the stress-strain relationship.

Figure 4 shows how the decrease of thickness affects the capacity of the plate to withstand axial loads and gives an idea of how the corrosion degradation, as well, reduces the structural capacity.

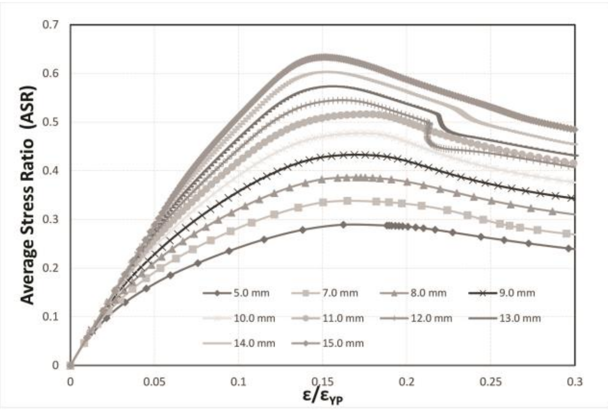

Figure 4 - Stress-strain relationship, intact plate

3.2 SCENARIO 2

In this study, a constant thickness of the plate of 10.0 mm is kept, and the shape of the opening is varied. As demonstrated by Saad-Eldeen et al., (2016b) and experimentally by Kim et al., (2009), the size and orientation of the opening significantly influence the ultimate strength of the plate to withstand loads. In this case, the brief study conducted at this stage is used to show the effect of different sizes of the opening on the studied plates (see Figure 5).

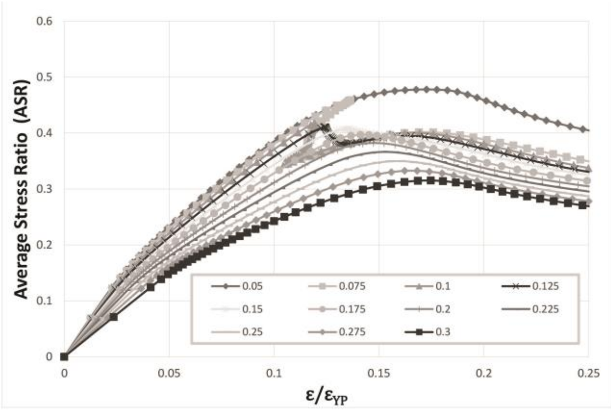

Figure 5 - Stress-strain relationship, different opening size

It can be noticed that in some of the analysed plates, as can be seen in Figure 4 and Figure 5, the curve representing the stress-strain relationship is jumping, which can be explained with a creation of local hinge during the loading process formed in the lateral to the manhole zones, (see Figure 2)

The relation between the ultimate strength of thin plates and the plate thickness may be expressed as:

$$\frac{\sigma_u}{\sigma_{YP}}(t_{p,i}) = -1.0541\left(\frac{t_0 - t_{p,i}}{t_0}\right) + \frac{\sigma_{u,0}}{\sigma_{YP}} \quad (21)$$

which is valid for $t_{p,i} \leq t_o$, where t_o=10 mm,

The opening size selected for the analysis carried out in this study is a standard manhole size as specified by IACS, (2015). The assumption taken in the study, comprehend a limit for the wastage allowance due corrosion degradation of the plate, a limit to the ultimate strength and a selection of the position and type of reinforcement used is needed.

3.3 SCENARIO 3

The Common Structural Rules for Bulk Carriers and Oil Tankers, IACS, (2015) specify the regulation to follow for the renewal criteria (Part 1, Chapter 13). For a strength assessment performed by FEA, the corrosion addition, $t_{c,FEM}$ is taken equal to the corrosion addition, t_c determined by:

$$t_{c,FEM} = t_c = \text{Roundup}(t_{c1} + t_{c2}) + t_{res} \quad (22)$$

where $t_{c1} = t_{c2} = 0.7$ mm is for the present case study (void spaces, the spaces that are not normally accessed), residual thickness, t_{res} equals to 0.5 mm. IACS specify as well that the steel renewal is required if the measured thickness, t_m in mm, is less than the renewal thickness, t_{ren} defined as:

$$t_{ren} = t_{as-built} - t_c - t_{vol-add} \quad (23)$$

where the thickness as built of the plate, $t_{as-built}$, equals 10 mm, the voluntary addiction thickness, $t_{vol-add}$, equals to 0.5 mm. The difference between the thicknesses considered at the design stage and in service showing the permitted wastage allowance due to corrosion degradation and the limit is defined by IACS, (2014).

For this scenario, once the corroded plate is below 7.5 mm, it is replaced.

3.4 SCENARIO 4

A limit equals to 75% of the ultimate strength of the intact plate with an opening is set. This limit marks the necessity to reinforce the plate to regain the ultimate strength.

Figure 6 shows the stress-strain relation of the intact plate with an opening, $t_{p,i}$=10 mm, severely corroded plate with an opening, $t_{p,i}$ =7.5 mm and the limit of 75% of the ultimate strength.

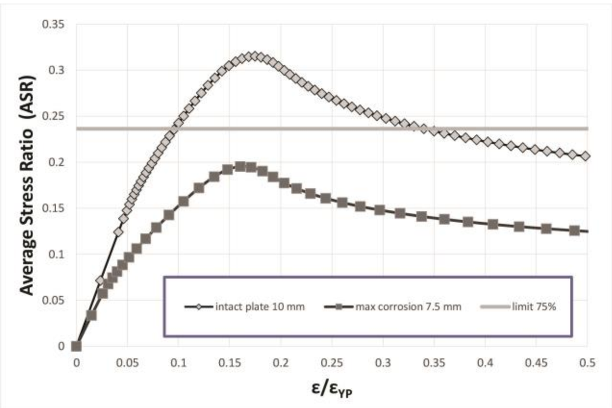

Figure 6 - Stress-strain relationship of intact, $t_{p,i}$=10 mm and corroded, $t_{p,i}$ =7.5 mm plates with opening

The reinforcement process has preliminary been studied with a uniform thickness of $t_{p,i}$ =8.5 mm due the fact that its ultimate strength corresponds to the limit of 75% of the ultimate strength of an intact plate with an opening.

The solutions adopted in the reinforcement process are: (i) two longitudinal stiffeners, (ii) two longitudinal and two transversal stiffeners and (iii) flange reinforcement on the opening.

The potential reinforcement solutions are analysed to define, which solutions could have been worthy to be applied and if the one selected provides a reasonable improvement with regards to the ultimate strength. The global and local imperfections are considered.

Stiffeners mounted at different locations are analysed to verify their contribution to the recovery of the ultimate strength and only the ones with a significant impact is considered in the final selection.

The locations, in the case of "two longitudinal stiffeners" and "two longitudinal and two transversal stiffeners" are predefined. In addition to that, it was decided to not place the stiffeners too close to the edges of the plate or to the opening due to excessive edge corrosion that could have caused a problem in the modelling.

For the case of "opening flange" the free edge corrosion is not considered, and only the global initial imperfection is considered.

In the case of two longitudinal stiffeners, the scenarios selected are: (i) 2x50x10 at [0.15-1.05m], (ii) 2x100x100x10x10 at [0.2-1.0m], (iii) 2x300x80x10x10 at [0.25-0.95 m].

In the case of two longitudinal and two transverse stiffeners the scenarios selected to keep the same span between the longitudinal stiffeners as in the previous cases: (i) 2x50x10+2x50x10 at [0.4-1.4], (ii) 2x100x100x10x10 +2x100x10 at [0.4-1.4], (iii) 2x300x80x10x10 2x300x8 at [0.4-1.4] and (iv) 2x300x80x10x10+2x300x20 at [0.4-1.4]

In the case of the flange reinforcement on the opening, the selected scenarios are: (i) 100x10, (ii) 200x10 and (iii) 300x17.

4. REINFORCEMENT

The Classification Societies mark the wastage allowance for a corroded steel plate and indicate the guidelines to follow for repairs. In many cases, it is recommended to substitute the steel plate with a new one when the thickness of the plate, measured at three different points of it, is under the required net thickness. When a plate is severely corroded, the usual procedure is to add new material to the plate or to replace it to regain the ultimate strength.

The numerical analysis carried out here has the prerogative to find different possible solutions to this issue demonstrating that a corroded plate, treated with new coating and an additional reinforcement, can withstand the load and permits a longer service life of the original plate. As stated in DNV-GL, (2017) Sec.4 Allowable material diminution for general corrosion "Areas found with diminution more than acceptable limits are normally to be repaired with inserted material of the same grade and scantlings as the original one". Alternative dimensions, materials and repair methods may, however, be accepted provided they are specially considered and approved, typically regarding the refined minimum thickness calculations" giving possibilities to find different solutions with respect to the corroded plate.

The numerical analysis consists in a series of FEAs of corroded plates with an opening to which are applied different reinforcement profiles. The following assumptions are adopted here: (i) random, non-uniform and time dependent corrosion, (ii) perfect welding between stiffeners and plate and (iii) perfect cleaning after repair.

It was decided at first to carry out the study with the randomized, non-uniform and time dependent corrosion degradation. The model used to simulate the corrosion degradation is the one as defined by Garbatov et al., (2007).

The initial geometrical imperfections are only applied to the plate. Perfect cleaning is assumed because it will permit a stop in the corrosion process. The new coating life (4 years) takes more than 1/3 of the initial coating life (10.54 years) giving a reasonable assumption for the time dependent quality of the coating after the repair.

The limits adopted for the numerical experiment for each scenario are: 75% of the ultimate strength of the intact plate and required net thickness.

Once the average thickness of the plate analysed is under the required net thickness, the plate needs to be substituted. The limit defined as 75% of ultimate strength of an intact plate marks the limit at which the plate must be reinforced to regain strength.

It can be observed that there is a rapid growth in the corrosion rate after the end of the coating protection applied to the plate. This growth continues after the transition time and then decreases. This behaviour can be explained with the fact that, after the 25th year, the plate is severely corroded, and the residual thickness is way lesser than the original one, leaving less material to be corroded. Also, the corrosion effectiveness is not that stable as before. On the other hand, the corrosion wastage follows the idealized pattern, but with a slower growth. Anyways, it kept the asymptotic behaviour corresponding to a stabilization of the corrosion degradation at a lower corrosion rate.
In fact, the plate is not any more effective with respect to the definition given by CSR after the 21th year due to the plate thickness limit. However, accordingly to the limit of 75% of the ultimate strength of the intact plate with an opening, the effectiveness of the corroded plate is lost in-between the 18th and 19th year.

The reinforcement assessment is carried out with a series of finite element analyses at any year of the service life for each reinforcement solution selected. The total number of finite element analyses is 1,273, with only 400 have given a final solution due to the convergence problems in the finite element analyses. The 20th year is marked as the year at which the simulations start. The study has been carried for the plate subjected to corrosion degradation with a reinforcement made by mounting additional stiffeners. Furthermore, a cleaning process of the plate is made, and a new coating is applied to the plate. It is considered that the corrosion degradation process stops for some time when the coating is effective.

The new coating life considered in the study has a life of four years (from year 19th to 23rd) and the new corrosion process starts at the 24th year (see Figure 7).

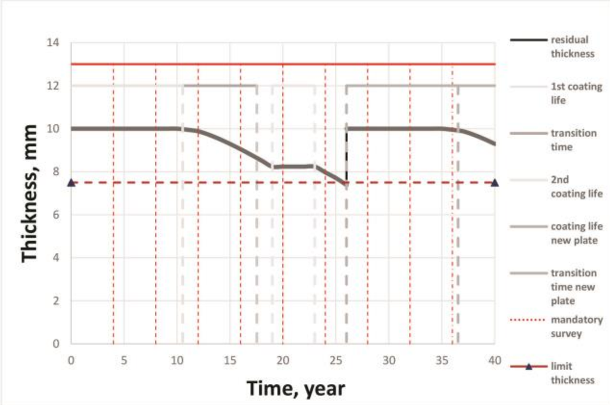

Figure 7 – Residual thickness of plate with opening

4.1 CASE 1

The reinforcement, made with two additional longitudinal stiffeners, welded to the plate with an opening, increases significantly the strength of the plate. It is important to observe that the capacity to withstand the axial load is greater than the one of the intact plate (see Figure 8).

The ultimate strength ratio of the three solutions analysed here does not cross the limit of 75%, but the plate is replaced due to the low residual thickness. The corroded plate, reinforced with stiffeners still had enough capacity to withstand the applied load. This gives an idea of the aspect that concerns the cleaning and coating process: improving them, it is possible to prolong further the service life of the plate, reducing the cost associated with the replacing of the plate.

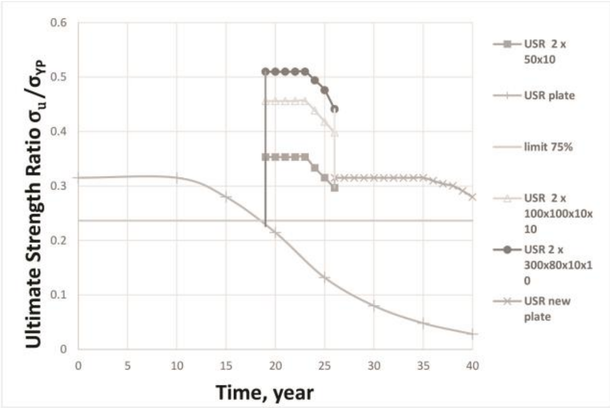

Figure 8 – Reinforcement, 2 longitudinal stiffeners

4.2 CASE 2

A reinforcement made of two longitudinal and two transverse stiffeners confers to the plate a limited recovery of strength. The principal cause is due to the transverse members that significantly weaken the plate.
An evaluation of the ultimate strength denotes an actual acceptable solution for the four-different scenarios. The service life of the corroded plate has been improved by five years for the three scenarios and for six years for one scenario. As for the case one, the substitution of the plate occurs only in one of the solutions due to the minimum residual thickness, in all other cases, the replacement of corroded plate needs to be done one year before reaching the minimum required thickness.

4.3 CASE 3

The flange reinforcement on the opening of the plate confers a regain of the strength of the level of the intact plate. It is also important to observe that the different dimensions of the flanges tested, increase slightly the structural capacity of the plate to withstand loads.

The thickness of the flange significantly influences the ultimate strength more than in the case of increasing the height of the stiffeners itself (see Figure 9).

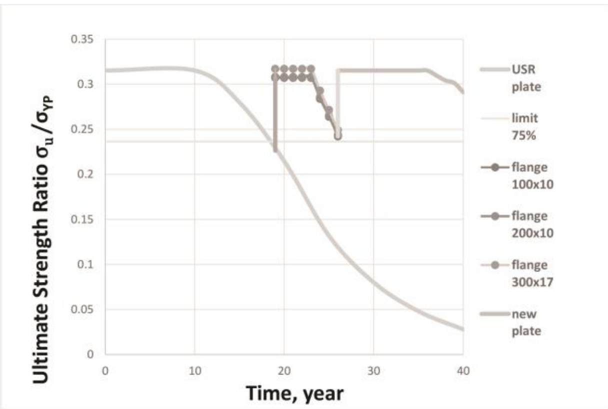

Figure 9 - Reinforcement of flange on opening

This solution provides a good compromise between the recovery of the ultimate strength that can be improved with a better cleaning and coating of the plate. The service life of the plate has been improved by 6 years, reaching the limit of 75%.

5. WEIGHT ASSESSMENT

When a steel plate starts to corrode, it loses thickness and in a consequence its weight. It is important to mark that this study does not consider the additional weight of the new coating film applied, but just the net weight of the plate, including the reinforced members and the welding legs between the plate and stiffeners. The type of welding considered here is Shielded Metal Arc Welding (SMAW).

There is a weight difference between the intact and corroded plates of about 40 kilograms. The weight difference can be used as a control factor in verifying the reinforcement effectiveness.

5.1 WEIGHT OF WELDING

The weight of welds is directly related to the length of the welding and thicknesses. It is considered that the welding is continuous on both sides of the stiffeners. It has been assumed that the equal leg and unequal leg profiles were already assembled. The indication of the length and thickness of welding legs, is as given by DNV-GL Classification Society Rules (Part 3, Chapter 13: Welding) DNV-GL, (2017). The thickness leg, t_{leg} is defined as:

$$t_{leg} = f_c\, f_1\, f_2\, t_w \tag{24}$$

where f_c is a coefficient depending on the environment, f_1 is a coefficient depending on the welding type, f_2 is a coefficient depending on the edge preparation and t_w is an effective thickness of the abutting plate.

5.2 WEIGHT OF CASE 1

The two longitudinal stiffeners increase the total weight of the reinforced plate starting from the year 19th, when the reinforcement is performed, until the year 26th, when the substitution of the plate takes place.

Only the stiffeners with a flat bar profile of 50x10 remains under the intact plate weight, the other two scenarios surpass that limit adding weights to the original plate weight. The reinforced profiles 100x100x10x10 add about 18% to the weight of the plate, while 300x80x10x10 adds about 49%.

5.3 WEIGHT OF CASE 2

It can be observed that four profiles of 50x10 remain the weight below the weight of the intact plate with an actual decrease of 4%. The other three scenarios increase the weight by 26%, 66% and 91% with respect to the initial plate weight. It can be affirmed that those case scenarios are not a viable way to reinforce the corroded plate due to the excessive weight and a limited recovery on the ultimate strength.

5.4 WEIGHT OF CASE 3

The profiles 100x10 and 200x10 result in a weight close to the intact plate weight, giving a good repair solution.
A flange of 300x17 is over dimensioned and it is not a viable solution, according to the tight difference in the ultimate strength between the scenarios. The percentage of added weight is -6.5%, 4.5% and 38%.

6. DESIGN SOLUTION

6.1 COST IMPACT

Every reinforcement introduces additional cost. Furthermore, the cleaning, coating and welding processes, increase the cost that must be destined to the reinforcement of the corroded plate. In addition to that, it must be considered the cost associated with the labour, transport of material, electricity, administrative costs and others. The capital cost associate to the reinforcement process is assumed as:

$$\mathrm{Capex} = \{W_{stiff}C_{steel} + C_{weld}l_{weld} + C_{labour}H_{work}\}\,(1 + C_{profit} + C_{overhead}) \quad (25)$$

For this study, the price of steel has been taken as 700 €/ton; the total cost of the welding is given by different factors; the labour cost is a direct function of the time needed to do the welding process; the labour cost is taken as 20 €/hour (this value can vary sensibly depending where the reinforcement process has been commissioned with a difference from 4 €/hour to 40 €/hour); the cost of the profit has been taken as 5% and the overhead as 30%. The cost of the profit and the overhead cost are also sensitive to the shipyard where the reinforcement process has been done. Table 1 defines different scenarios and the associated costs are shown in Figure 10.

Table 1 – Reinforcement scenarios

scenario 1	2 x 50x10	scenario 6	2 x 300x80x10x10 + 2 x 300x8
scenario 2	2 x 100x100x10x10	scenario 7	2 x 300x80x10x10 + 2 x 300x8
scenario 3	2 x 300x80x10x10	scenario 8	100x10
scenario 4	2 x 50x10 +2 x 50x10	scenario 9	200x10
scenario 5	2 x 100x100x10x10 + 2 x 100x10	scenario 10	300x17

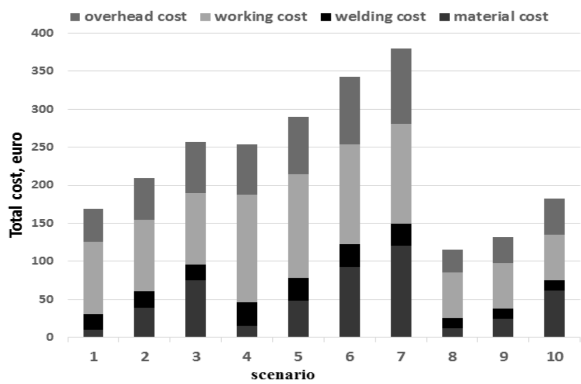

Figure 10 - Capital cost of reinforcement process

6.2 EFFECTIVE THICKNESS

An interesting comparison among all scenarios studied here can be done considering the effective thickness. The effective thickness is calculated considering the cross sections, including the net sectional areas of the plate and stiffeners. In this case, the total volume of the plate is estimated and later the effective thickness:

$$t_{effective} = \frac{V_{plate}+V_{stiff}}{A_{plate}} \quad (26)$$

where the volume of the plate V_{plate} with a thickness, t_p is defined as:

$$V_{plate} = l\,b\,t_p - V_{hole} \quad (27)$$

The effective thickness of a corroded plate that possesses the same ultimate strength for the different reinforcement scenario at the 2oth year is shown in Figure 11.

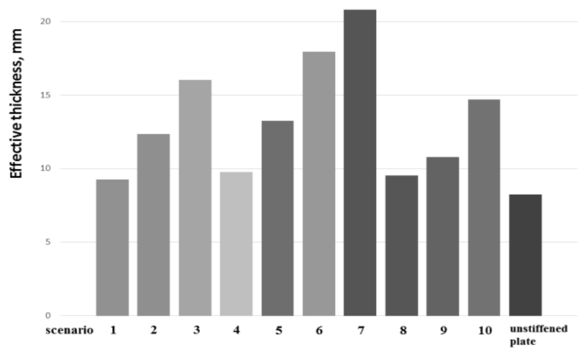

Figure 11 – Effective thicknesses at year 20th of corroded plate

7. CONCLUSION

The study presented an analysis on the possibility of reinforcing an ageing marine structure in extending its service life. It was observed in the cost analysis that the case with two longitudinal stiffeners gives a higher ultimate strength with a reasonable cost. On the other hand, the flange reinforcement on the opening provides an additional ultimate strength, recovering the original intact plate ultimate strength with a lower cost. It is noticed that the lowest weight is estimated for the reinforcement made of the smaller longitudinal stiffeners of 50x10. This scenario introduces a reasonable recovery of the ultimate strength. On the other hand, the grillage of two longitudinals and two transverse stiffeners provide an unfavourable solution to the reinforcement process with respect to the weight, cost and ultimate strength. It is important to enlighten that many assumptions have been taken that could have influenced the results.

8. ACKNOWLEDGMENT

This work was performed within the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering (CENTEC), which is financed by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia-FCT).

9. REFERENCES

1. ANSYS, 2009, Online Manuals, Release 12.
2. CARIDIS, P., 2001, *Inspection, Repair and Maintenance of Ship Structures*, Witherby.
3. DNV-GL, 2017, DNVGL-RU-9111:2015-7, Rules for Classification, Oslo, DNV GL.
4. FAULKNER, D., 1975, *A Review of Effective Plating for use in the Analysis of Stiffened Plating in Bending and Compression*, Journal of Ship Research, 19, 1-17.
5. GARBATOV, Y. and GUEDES SOARES, C., 2017, *Spatial corrosion wastage modelling of steel plates subjected to marine environments*, Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway, paper OMAE2017-61751.
6. GARBATOV, Y., GUEDES SOARES, C. and WANG, G., 2007, *Nonlinear Time Dependent Corrosion Wastage of Deck Plates of Ballast and Cargo Tanks of Tankers*, Journal of Offshore Mechanics and Arctic Engineering, 129(1), 48.
7. GARBATOV, Y., TEKGOZ, M. and GUEDES SOARES, C., 2017, *Experimental and numerical strength assessment of stiffened plates subjected to severe non-uniform corrosion degradation and compressive load*, Ships and Offshore Structures, 12(4), 461-473.
8. GUEDES SOARES, C. and GARBATOV, Y., 1999, *Reliability of maintained, corrosion protected plates subjected to non-linear corrosion and compressive loads*, Marine Structures, 12(6), 425-445.
9. HAMMERSLEY, J. and HANDSCOMB, D., 1975, *Monte Carlo Methods*, London, Methuen.
10. IACS, 2014, *Common Structural Rules for Bulk Carriers and Oil Tankers*.
11. KIM, U. N., CHOE, I. H. and PAIK, J. K., 2009, *Buckling and Ultimate Strength of Perforated Plate Panels subject to Axial Compression: Experimental and Numerical Investigations with Design Formulations*, *Ships and Offshore Structures*, 4(4), 337-361.
12. KIM, J. H, JEON, J. H., PARK, J. S., SEO, H. D., AHN, H. J., LEE, J. M., 2014, *Effect of Reinforcement on Buckling and Ultimate Strength of Perforated Plates,* International Journal of Mechanical Sciences 92, (2015) 194–205
13. PAIK, J. K., HUGHES, F. and MANSOUR, A. E., 2001, *Advanced Closed-Form Ultimate Strength Formulation for Ships*, Journal of Ship Research, 45(2), 111-132.
14. SAAD-ELDEEN, S., GARBATOV, Y. and GUEDES SOARES, C., 2016a, *Experimental investigation on the residual strength of thin steel plates with a central elliptic opening and locked cracks*, Ocean Engineering, 115, 19-29.
15. SAAD-ELDEEN, S., GARBATOV, Y. and GUEDES SOARES, C., 2016b, *Experimental strength assessment of thin steel plates with a central elongated circular opening*, Journal of Constructional Steel Research, 118, 135-144.
16. SHANMUGAM, N. E., THEVENDRAN, V. and TAN, Y. H., 1999, *Design Formula for Axially Compressed Perforated Plates*, Thin-Walled Structures, 34, 1–20.
17. WANG, G., SPENCER, J. and SUN, H., 2003, *Assessment of Corrosion Risks to Aging Ships using an Experience Database*, Proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering, Paper OMAE 2003-37299, ASME.