Inspection and Control of Ageing Ship Structures

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Abstract: Ships have been a significant function to transport cargo around the world for centuries, and nowadays this industry is still responsible for a large share of the world's goods transportation, keeping the trade and economy flowing. With hundreds of vessels going around the world daily, it is necessary to have maintenance and inspection methods to keep the ships functioning and to prevent accidents, although this actions take time and make the ships stop, decreasing their productivity.
The main objective of this work is to investigate a method for the inspection of steel plates, which constitute part of the panels that are a central part of a ship's hull structure. The method that will be analyzed in this study consists of using the dynamic response of a corroded steel plate submitted to a mechanical shock to check what the ultimate strength level of the plate is. Having this ultimate strength value, it would be possible to determine if the plate needed to be repaired or replaced or if it could remain on the ship as it is. This method could represent significant savings in both money and time when it comes to the ship's inspections.

1. INTRODUCTION

The modern world economy and trade rate determine transport methods become increasingly more efficient, either by having more massive speeds, being able to carry more substantial amounts of cargo or both.
In the case of sea trade, the tendency is to build larger ships, which can carry large and heavy cargoes around the world. This tendency, along with today's technology, lead to the modern structural ship design. With a wide range of materials with different advantages available in the market, steel continues to be the most used material in shipbuilding, especially in larger ships.
With the demand for large and economic ships, there is also the demand for more reliable structures and safety in shipbuilding. The most used solution to have cheap, light and reliable structures is the thin-walled structures (Figure 1).

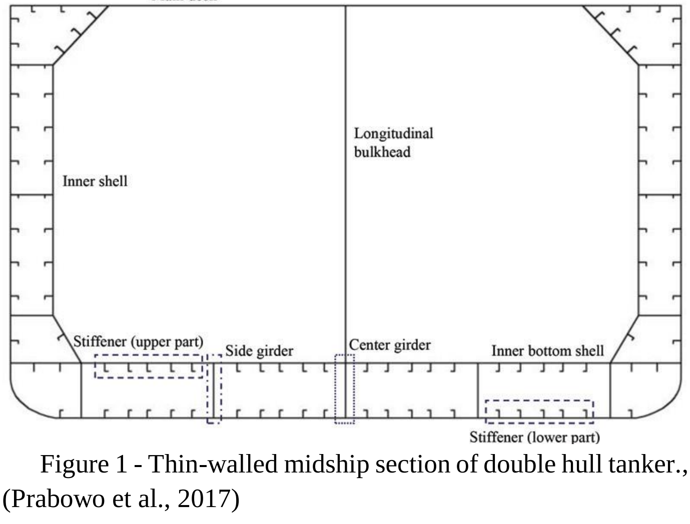

Figure 1 - Thin-walled midship section of double hull tanker., (Prabowo et al., 2017)

Although steel has many advantages for this type of structures, like having good mechanical properties and being cheap, it also has disadvantages, being one of them, its deterioration over the years.
Over the years, corrosion in shipbuilding has been getting more attention regarding control and prevention. Measures have been taken, and rules must be followed regarding this matter. However, even with the effort to account for this phenomenon, when designing the structures, the existing prevention measure is not enough. The corrosion phenomenon is complex, and it is not possible to know when a structural component will fail due to corrosion degradation, so, control and inspection are also an essential part of the ship maintenance and safety.
Most ships are obliged to take periodic surveys, on which they are "required to carry out overall examination and thickness measurement of hull structures." (Lloyd's Register Marine (a)).
Although in some parts of the world, wheel-tapper was a very common job in the 20th century where large rail stations and cargo train yards continuing using a hammer to tap the train's wheels (Figure 2) to check if they are cracked/damaged or good "*From Wheel-Tappers to Porters*".
Inspired on this type of inspection performed on trains for so many years, it was suggested that it might be a good idea to investigate if it is possible to create a similar type of inspection for the marine industry. This inspection technique, would consist in measuring the sound and/or vibration produced by a plate when submitted to a shock, like a hammer tap (manual or automatic) and being able to relate the vibration measured

with an actual mean thickness of the plate and/or its equivalent ultimate strength, in order to determine the ship's overall strength. If this method works, it could eventually complement or even replace the usual thickness measurements by ultra-sonic and spare time in the ship's periodic surveys.

2. CORROSION MODELLING

Figure 1 - Wheel-tapper testing a train's wheel by hammering (cf.: https://www.industryforum.co.uk)

Corrosion degradation is a process in which the material deteriorates when is exposed to an environment, resulting in a loss of that material, being the corrosion of metals by water, the most common cases.

A definition of corrosion can be: "*Corrosion is an interaction between a material, usually a metal, and its environment that results in deterioration of the material, and the environment." (Groysman, 2009).* Corrosion is an electrochemical process, involving oxidation reactions where the metal ions and free electrons travel through a conducting solution, and cathodic reactions where the cathode reduces the electrons. One example of the conducting solution can be water (Groysman, 2009):

$$F_e \xrightarrow{H_2O} F_e^{\,2+} + 2e^- \qquad (1)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (2)$$

$$2H^+ + 2e^- \rightarrow H_2 \qquad (3)$$

Moister can act as a reactive compound in the cathodic reactions Eqn (2) or Eqn (3) (Melchers, 1998), and it allows the transfer of metal ions (Eqn 1) to occur more easily. The cathodic reaction that is more associated with corrosion in maritime structures is the one in Eqn (2), as it is the dominant reaction when pH is greater than 5 (Tomashov, 1996).

Regarding corrosion modelling, three fundamental approaches can be used. The first one is assuming that the corrosion rate is constant, but the use of a linear approach would cause errors in the calculation of the wastage thickness that could cause an overestimation of the corrosion effects.

The second approach for the corrosion modelling would be using results of experiments for the specific conditions of the problem that would model laws of corrosion for specific parameters. For this, it would be necessary to know the exact environmental conditions of the problem, that would affect the corrosion, and, there is the problem of generalisation of the experiments to full-scale conditions.

The approach used here was the third one that considers a trend that is derived from the dominating mechanism and then fitted to field data. A model for the non-linear time-dependent function of corrosion wastage was proposed by Guedes Soares and Garbatov (1999). In this model, corrosion is separated into three phases. In the first phase, it is considered that there is no corrosion due to the effectiveness of the metal face protection. The second phase is when the corrosion takes place, after the metal face protection is damaged, and the thickness of the plate decreases as the corrosion takes place. The third phase is when the corrosion stops and the corrosion rate is reduced to zero.

The model that was proposed by Guedes Soares and Garbatov (1999) can be described by the solution of the differential equation of corrosion wastage in Eqn (4)

$$d_\infty \dot{d}(t) + d(t) = d_\infty \qquad (4)$$

where d_∞ is the long-term thickness of the corrosion wastage, d(t) is the corrosion waste on a given moment of time and $\dot{d}(t)$ is the rate of the corrosion.

This differential equation leads to the following particular solution:

$$d(t) = \begin{cases} 0, \ t \leq \tau_c \\ d_\infty(1 - e^{-\frac{(t-\tau_c)}{\tau_t}}, \ t > \tau_c \end{cases} \qquad (5)$$

where τ_c is the time that the metal surface protection is effective and τ_t is the transition time. The values for the parameters of the exponential function used in Eq (5) were assumed as $d_\infty = 1.85mm$, $\tau_c = 10.54\,years$ and $\tau_t = 17.54$ as given by for ballast tanks of tankers Garbatov et al., (2007).

Another essential statistical parameter to model the corrosion degradation is the standard deviation, that was also used as found in Garbatov et al., (2007) for deck plates of ballast tanks, by fitting the standard deviation as a function of time to a logarithmic function (6) which is shown in figure 3.

$$St\ Dev(t) = aLn(t) - b \qquad (6)$$

where a and b are defined based on the regression analysis of the logarithmic function.

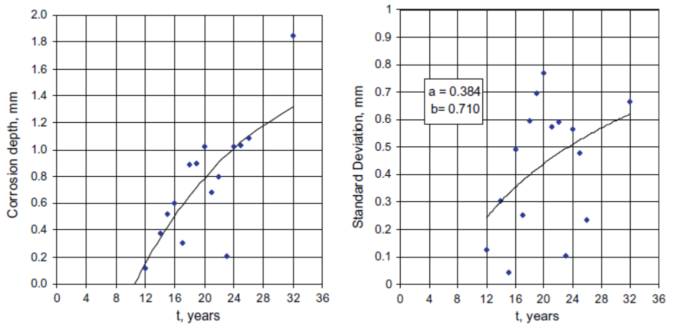

Figure 3 - Corrosion depth of plates - mean value (left) and standard deviation (right)

This model was used to create the corroded plates with intact thickness of 11, 12, 13, 14 and 15 milimetres and ages of 15, 18, 20, 23 and 25 years. For each plate, 2627 thickness values were created, one for each node of the plate's chosen mesh. Several corroded plates were created, using both different as-built thicknesses and ages as on the example of figure 4.

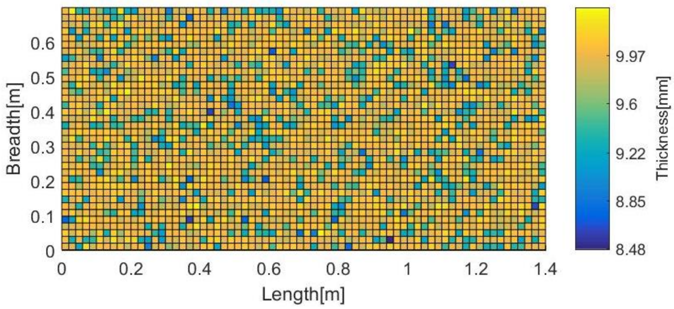

Figure 4 - Node thicknesses for 12 mm (as-built) and 20 years old plate

3. ULTIMATE STRENGTH ASSESSMENT

The plate's geometry used for the present study (figure 5) has a rectangular shape oriented perpendicularly to the *z*-axis, with a length *L* along the *y*-direction, a width *b* in the *x*-direction and an initial thickness of *tp*. This plate has a Young modulus (*E*) of 205.8 GPa, a Poisson coefficient (*v*) of 0.3 and the density of $7.8t/m^3$.

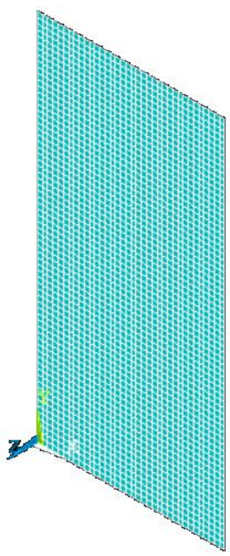

Figure 5 - Mesh of plates used in the study

The boundary conditions used, taken from Silva et al. (2013), are resumed in table 1 (C for constrained and F for free):

Table 1 - Plate's boundary conditions for Ultimate Strength Analysis

	Ux	Uy	Uz	rotx
y=0	F	C	C	C
y=L	F	F	C	C
x=0	F	F	C	F
x=b	F	F	C	F
x=b/2, y=0	C	C	C	C

If this was a real plate, as a part of a ship, it would have manufacturing and welding defects, so the presence of these defects was considered, to make this study closer to reality. These initial imperfections were considered as proposed by Smith et al. (1998):

$$w(x,y) = w_0 \sin(\tfrac{x}{b}\pi)\sin(\tfrac{y}{L}\pi) \tag{7}$$

$$w_0 = 0.1 h_0 \beta_{pl,0}^2 \tag{8}$$

$$\beta_{pl,0} = \left(\frac{b}{t_p}\right)\sqrt{\frac{\sigma_{\gamma p}}{E}} \tag{9}$$

where x, y, z are the plates' coordinate system, $\beta_{pl,0}$ is the intact plate slenderness as proposed by Faulkner (1975), w_0 is the maximum out of the plane deflection and E and $\sigma_{\gamma p}$ are, respectively, the elasticity modulus and the yield stress.

The finite elements used in the FE analysis is SEHLL181, having four nodes (one on each corner) and six degrees of freedom on each node. When using this type of elements, the thickness can be defined for each node of the element, resulting then on the thickness of the elements.

The axial load of the analysis performed were applied on the edge y=L, and the reaction forces on the edge y=0 were used to calculate the average stresses. Then, the average stress ratio (ASR) was calculated, using the following formulae, from Silva et al., (2013):

$$ASR = \frac{\sum_{i=1}^{k} R_{y;i}}{A_0 \sigma_{\gamma p}} \tag{10}$$

where $R_{y;i}$ is the reaction force at the ith node in the y direction (these nodes are on the edge y=0), k is the number of the nodes at y=0, $\sigma_{\gamma p}$ is the yield stress point of the material and A0 is the sectional area of the plate at y=0.

The ratio between the strain and the yield strain of the plate is also computed:

$$\frac{\varepsilon}{\varepsilon_{\gamma p}} = \frac{U_{y,p}}{L\varepsilon_{\gamma p}} \tag{11}$$

where ε is the plate strain, $\varepsilon_{\gamma p}$ is the yield strain of the material, L is the plate length and $U_{y,p}$ is the displacement in y direction at the point (b/2, L, 0).
A total of 86 plates were used for this analysis, including the 25 corroded plates and 61 intact plates with thickness varying 0.1 milimtres from 9 to 15.
The results of the analysis can be presented by plotting the ASR against $\varepsilon/\varepsilon_{\gamma p}$, as in figure 6 and the non-dimensional collapse strength of each of the plates as in figure 7.

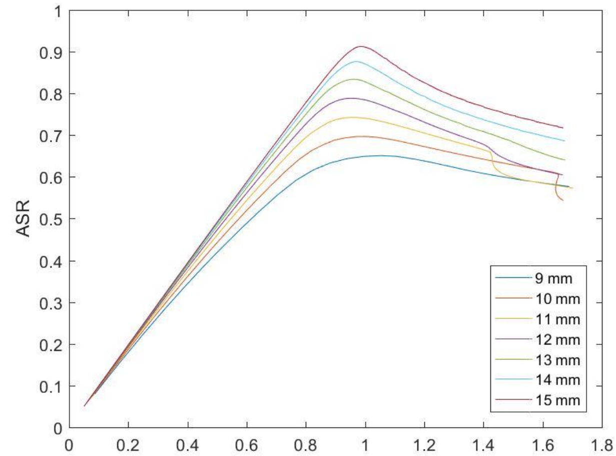

Figure 6 - Stress-strain response of intact plates with thickness between 9 and 15 millimetres

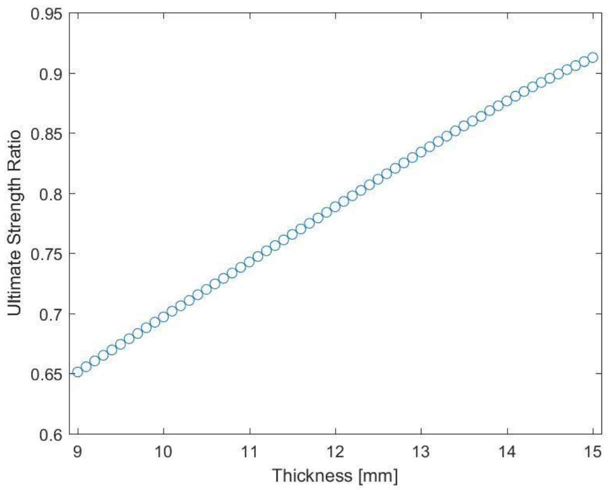

Figure 7 - Ultimate Strength Ratio of all the intact plates

4. TRANSIENT ANALYSIS

In the present study, the vibration of a plate induced by a shock in the centre area of the plate is studied using the Finite Element Method (FEM). The software that is used is ANSYS® Mechanical APDL 15.0 with the Newmark time integration method.
For most dynamical problems of structural mechanical systems, the principle of virtual work in conjunction with the finite element method gives the semi-discrete equation of the motion:

$$M\ddot{u}(t) + C\dot{u}(t) + F^i(t) = F^a(t) \quad (11)$$

where M is the structural mass matrix, C the structural damping matrix, $\ddot{u}(t)$ the nodal acceleration vector, $\dot{u}(t)$ the nodal velocity vector, $F^i(t)$ the internal load vector and $F^a(t)$ the applied load vector.
As in the linear systems, the structural stiffness remains constant, and the internal load is linearly proportional to the nodal displacement, Eqn (11) can be rewritten as:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F^a(t) \quad (12)$$

where K is the structural stiffness matrix, and $u(t)$ is the nodal displacement vector.
In the Newmark method, the semi-discrete motion equation for the single step algorithm can be rewritten as Hughes (1987), resulting in:

$$M\ddot{u}_{n+1} + C\dot{u}_{n+1} + Ku_{n+1} = {F^a}_{n+1} \quad (13)$$

where $\ddot{u}_{n+1}$, $\dot{u}_{n+1}$, u_{n+1} are respectively, the nodal acceleration, velocity and displacement vectors ($\ddot{u}(t_{n+1})$, $\dot{u}(t_{n+1})$, $u(t_{n+1})$), at time t_{n+1}.
In addition to Eqn (13), the Newmark method also requires that using the following equations:

$$\dot{u}_{n+1} = \dot{u}_n + ((1-\delta)\ddot{u}_n + \delta\ddot{u}_{n+1})\Delta t \quad (14)$$

$$u_{n+1} = u_n + \dot{u}_n\Delta t + \left(\left(\frac{1}{2} - \alpha\right)\ddot{u}_n + \alpha\ddot{u}_{n+1}\right)\Delta t^2 \quad (15)$$

to solve Eqn (13) by an implicit algorithm.

Starting by the boundary conditions, in this case, these will differ from the ones used in the previous chapter, for the ultimate strength analysis, opting for a simply supported case, as can be seen in table 2:

Table 2 - Plate's boundary conditions for Transient Analysis

	Ux	*Uy*	*Uz*	*rotx*
y=0	C	C	C	F
y=L	C	F	C	F
x=0	F	F	F	F
x=b	F	F	F	F

Next step is to simulate the shock force. There were some options for applying this force, for example, a rectangular pulse, a triangular pulse, negative exponential, or a half sine pulse. In this case, the force was modelled with the half-sine pulse with 0.1-second duration, as:

$$Fz = 50 * \sin(10\pi t)\,, 0 \leq t \leq 0.1\ [N] \quad (16)$$

where Fz is the force perpendicular to the plates' plane, and t is the time.
To perform a transient analysis, it is needed to choose the parameters to be adequate for this study and possible to perform with the available computing power. First, there is a need to choose between an analysis with the full method, mode-superposition method or variation technology method. For this case, a full analysis of the Newmark's method is seen as the most adequate. After defining the number of load steps, it is necessary to choose between the two types of loading

for the steps. A ramped stepped loading is chosen instead of a stepped one. This options and parameters are defined according to Ansys (2015).
Another critical parameter is the time that is simulated in the analysis. To define this parameter, several test-simulations are made for the intact plate of a thickness of 10 millimetres. The analysis of these simulations show that after 5 seconds the displacement in the plate's centre would follow the same pattern and tend to 0, so 5 seconds would be enough to characterise the plate's response, and it would not take too long to compute each analysis. The results taken from the transient analysis were the displacement (Uz) in the z-direction of a node near the centre of the plate. The displacement Uz is only stored after the first sub-step, that coincides with the peak of the half sine pulse.
Finally, it is also essential to choose the number of sub-steps for the simulation, which influences the accuracy of the analysis and its results. Two different time stepping is used, to study its influence on the displacement results, the first option is using 50 sub-steps (Figure 8) and for the second one, 100 sub-steps (Figure 9).

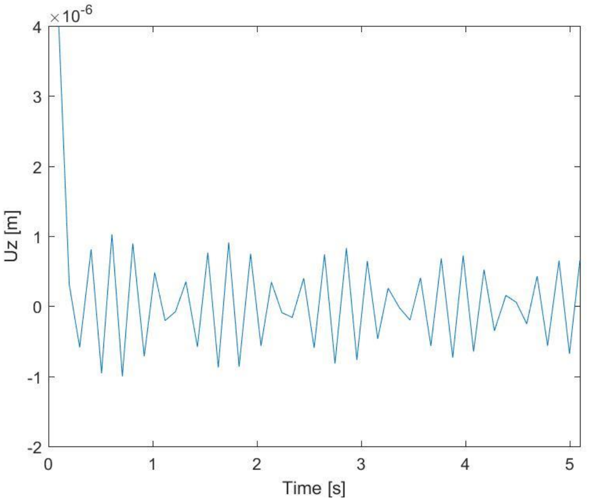

Figure 8 - Uz vs time for 10 mm intact plate using 50 sub-steps

The analysis using 100 sub-steps was chosen since it has more data regarding the vibration of the plate, which will be useful in further analysis.

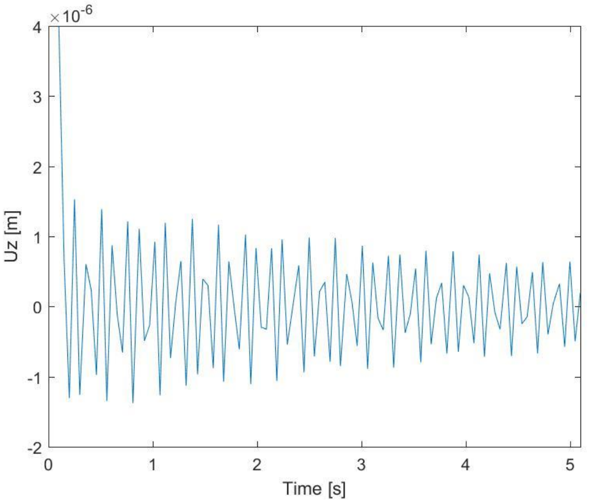

Figure 9 - Uz vs time for 10 mm intact plate using 100 sub-steps

With all the parameters defined, 86 transient analysis is completed, for the same plates used in the ultimate strength analysis.
Having the transient response of every plate studied, the next step is to process this data in a way that it can be quantified and used to compare the responses of the different plates.
To have more simple parameters to use for the discussion of the results, a normal distribution is fitted to the displacements of each plate studied, using the Matlab's function *normfit*. This function gets as input the displacements of each plate and returns the mean and the standard deviation of the distribution of the fitted data. The mean and standard deviation is used to plot the probability density function (PDF) of the fitted normal probability density distribution, evaluated for the displacements of each intact plate, as can be seen from Figure 10.

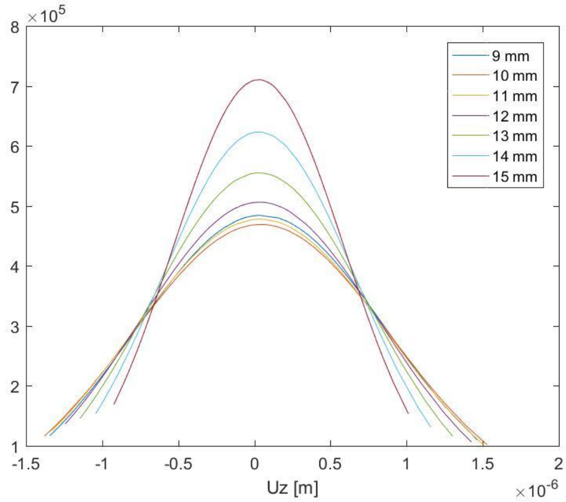

Figure 10 - PDF of the fitted normal distribution of main intact plates

The results of the transient analysis performed on the corroded plates are also fitted to normal distributions.

5. RESULTS DISCUSSION

Finally, the data collected from the transient analysis is used to estimate the ultimate strength of each corroded plate, and the result is compared with the one obtained by the ultimate strength assessment of the corroded plates.
As presented in the previous chapter, the distributions fitted to the corroded plate's transient analysis results tend to have more significant standard deviations as the age increases, resulting in distributions that have a wider shape as the plate gets more corroded, as can be seen in Figure 11.
By analysing the plot in figure 11, and assuming that if the distributions are more distinct from the intact plate's one, the ultimate strength is also more distinguish (with lower values) as well, it may be admitted that for more severe corroded plates the ultimate strength is lower than the ones of a lower corrosion degradation and the intact plate.

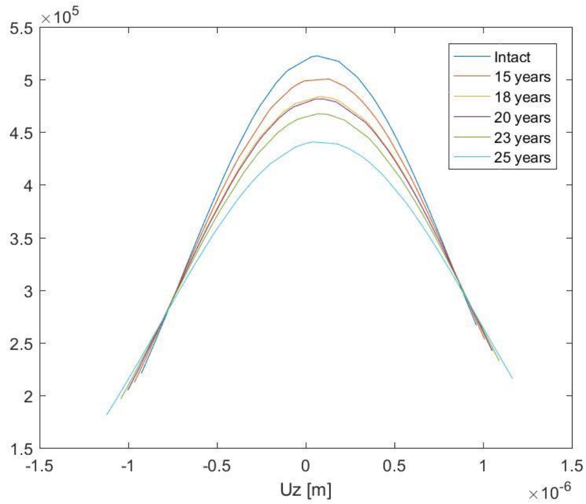

Figure 11 - PDF of the normal distribution of the 12 mm thickness plates

In order to compare the plates the Welch's test will be taken, using the beta index (β) , defined as:

$$\beta = \frac{\mu_1 - \mu_2}{\sqrt{s_1^2 + s_2^2}} \qquad (12)$$

where μ_1, μ_2 are the means of the plates being compared and s_1, s_2 are their standard deviations.
For every corroded plate (with different initial thicknesses and different ages) the beta index is calculated using the mean and standard deviation of the corroded plate and the mean and standard deviation of every intact plate, resulting in a total of 61 values of the beta index for every corroded plate. To find the intact plate that has a transient response closest to each corroded plate, the minimum value of beta is found for each corroded plate, leading to an "equivalent" intact plate that has an ultimate strength ratio associated.
The minimum values of the beta index obtained for each corroded plate can be seen in Table 3.

Table 3 – Beta values for the transient analysis with 100 sub-steps

h [mm]	Age [years]				
	15	18	20	23	25
11	0,00	0,00	0,00	-	-
12	0,32	0,17	0,04	0,01	0,00
13	0,38	0,02	0,02	0,01	0,01
14	0,72	0,54	0,68	0,66	0,64
15	0,01	0,01	0,01	0,01	0,01

The results from the plates with h=11 mm and age of 23 and 25 years are not used since their results would be too close to the lower boundary of the thickness range for the intact plate used as a reference.
For each corroded plate the ultimate strength ratio (USR) of the equivalent intact plate (observed USR) is compared with the USR obtained from the ultimate strength assessment (expected USR) of chapter 5. These expected and observed USR values are assembled in tables by thickness and age of the corroded plates, and then compared, calculating their difference in Table 4, 5, 6, 7 amd 8.

Table 4 - Expected and observed USR and their difference for h=11mm

11mm	Intact	Age [years]				
		15	18	20	23	25
USR exp.	0.743	0.615	0.605	0.535	0.450	0.391
USR obs.	-	0.644	0.634	0.613	0.562	0.562
Diference	-	4.50%	4.55%	12.71%	19.94%	30.51%

Table 5 - Expected and observed USR and their difference for h=12mm

12mm	Intact	Age [years]				
		15	18	20	23	25
USR exp.	0.789	0.775	0.754	0.740	0.704	0.672
USR obs.	-	0.789	0.789	0.789	0.744	0.691
Diference	-	1.70%	4.34%	6.20%	5.45%	2.78%

Table 6 - Expected and observed USR and their difference for h=13mm

13mm	Intact	Age [years]				
		15	18	20	23	25
USR exp.	0.834	0.747	0.706	0.651	0.528	0.517
USR obs.	-	0.834	0.536	0.536	0.536	0.536
Diference	-	10.43%	24.07%	17.70%	1.54%	3.60%

Table 7 - Expected and observed USR and their difference for h=14mm

14mm	Intact	Age [years]				
		15	18	20	23	25
USR exp.	0.876	0.861	0.749	0.810	0.789	0.789
USR obs.	-	0.876	0.876	0.876	0.876	0.876
Diference	-	1.71%	14.51%	7.54%	9.95%	10.02%

Table 8 - Expected and observed USR and their difference for h=15mm

15mm	Intact	Age [years]				
		15	18	20	23	25
USR exp.	0.913	0.896	0.874	0.853	0.820	0.812
USR obs.	-	0.808	0.913	0.913	0.913	0.913
Diference	-	9.78%	4.28%	6.49%	10.12%	11.01%

The results from the tables above present the differences between the expected and observed USR of less than 10% for most cases, with only a few differences above 20%. These results show that a corroded plate can be associated to an intact plate by comparing their transient responses and that it can be assumed that the corroded plate will have the same ultimate strength of the associated intact plate.

6. CONCLUSIONS

The overall objective of this thesis was achieved since the possibility of associating a corroded plate's vibration to its ultimate strength was assessed through the developed method. The method used showed promising results, regarding the estimation of the ultimate strength of a corroded plate, since it was possible to associate a USR to each of the corroded plates studied that was, in most cases, close to expected from the ultimate strength assessment.

Every step of the method developed can be improved in order to get better results, starting by the corroded plates modelling, as well as the transient analysis and statistical method used to associate the plate's transient response with an USR.

One of the problems can be the imperfections that can occur on the corroded plates modelling, presenting an abnormal thickness in the point where the force was applied and the displacement measured, which could cause odd results.

On the transient analysis, a better way to represent a shock force can be studied, which could result in a more realistic transient analysis. A sensitive analysis could be made in order to get the best parameters to use for this analysis.

After having the transient response, the displacement could be taken from several points of the plate instead of just one point. This way, the possibility of an odd thickness point cause a bad result would be lower, and the overall results would probably be more accurate.

It can be concluded that besides being at an initial phase, this is an interesting method and should be further developed in order to reduce the glitches and improve the results, in order to get a method that would be of great value for the inspection and control of ageing ship structures.

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