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SPATIAL CORROSION WASTAGE MODELLING OF STEEL PLATES SUBJECTED TO MARINE ENVIRONMENTS

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1. ABSTRACT
The objective of the present study is to analyse and identify the most suitable corrosion degradation model, fitted with real corrosion depth measurement data sets and to reproduce the corroded steel plate surface as a function of time and spatial distribution using advanced statistical methods. An approach for properly identifying the best fitted model to real corrosion depth measurement data sets is employed. A sequence dependent data analysis is performed based on the fast Fourier transform, which is used as an input for a random field modelling of the corroded steel plate surfaces

2. INTRODUCTION
Corrosion degradation of steel structures in a marine environment is a very complex phenomenon. A common design practice in the marine structures is that the corrosion degradation is assumed as time independent and more recently as time dependent process. Many studies investigated the corrosion degradation through different statistical analyses by using real corrosion measurement data sets. Melchers (1997) proposed a phenomenological model, incorporating different aspects of earlier models achieving a mathematical consistency. Yamamoto and Ikagaki (1998) analysed corrosion wastage in different structural components of many ships, demonstrating the existence of a non-linear dependence of time and developed a non-linear corrosion depth model. Guedes Soares and Garbatov (1998, 1999) and Paik et al. (1998) also suggested models, which define the progress of corrosion degradation into several phases.

The above developed models of corrosion degradation used as a unique governing parameter the time, which leads the progress of the degradation trough different corrosion phases. To enhance the corrosion degradation models, the corrosion environment parameters may need to be included. In this aspect a very deep analysis of identifying the most important environmental factors in corrosion degradation of steel marine structures has been performed by Melchers (2003), Guedes Soares et al. (2008, 2009), Guedes Soares et al. (2013) and a multi parameter corrosion wastage models were proposed accommodating the existing non-linear time-dependent corrosion model of Guedes Soares and Garbatov (1998, 1999) and accounting for various environmental factors, such as salinity, temperature, dissolved oxygen, pH and flow velocity, including the effect of ships service life in different routes.

The presence of corrosion not only reduces the steel plate thickness and destroys the plate surface, but also affects the material properties. In the work presented by Garbatov et al. (2014b), Garbatov et al. (2016), the effect of corrosion deterioration on corroded coupons subjected to tensile loading was analysed, where for the corroded steel specimens with a severe degree of degradation; a significant reduction of mechanical properties of material was identified. The observed material properties change is as a result of corrosion degradation and the consequence stress concentration developed by the local corrosion pits and these two factors are defined as the most important ones in addition to the net section loss.

The study presented by Garbatov et al. (2014a) also showed that severe corrosion degradation may reduce the fatigue strength of steel filled welded plates identified as FAT 100 for intact non-corroded one to FAT 65 MPa for a corroded one, accompanied by a crack propagation, starting from corrosion pits.

The objective of the present study is to compare and identify the most suitable corrosion degradation model based on a multi-criteria approach and to reproduce the corroded steel plate surface as a function of time and spatial distribution using advanced statistical methods. A sequence dependent data analysis is performed based on the fast Fourier transform, which is used as an input for a random field modelling of the corroded steel plate surfaces

3. CORROSION DEGRADATION MODEL ASSESSMENT

When fitting real corrosion measurement data to different regression models, the goal is to verify which model is more suitable to represent the observed data. Normally, the real measurement data points include scatter, which in the case of real corrosion depth measurements is relatively high, and as a result of that, it is not easy to identify which model fits better to the data.

The use of statistical analyses to compare the fits of the two models is acceptable if the results of both fits are sensible and the more complicated model fits better. If the compared models fit the data with similar best-fit values, then the further step is to check the goodness-of-fit, which is based on the sum-of-squares. If the simpler model has the lowest sum-of-squares in a comparison to the most complicated one, then the simpler one should be used since this model is both simpler and fits the data better. The problem is that a model with more parameters gives the regression curve more flexibility than the model with fewer parameters.

It is expected that the regression curve with more parameters fits the data better and in this respect, it is not only enough to check which model generates a regression curve that fits the data with the smallest sum-of-squares, but in addition to that an advanced statistical approach is needed for verification.

An example of such approach is the Akaike's Information Criterion (AIC) (Bozdogan, 1987), which verify which model is more likely to have generated the data, and how much more likely. The Akaike's approach is based on the combination of the maximum likelihood, information theory, and the entropy (Burnham and Anderson, 2002). In the case that the scatter of the measurement points, around the most expected regression model follows the Normal distribution, the AIC is defined (Bozdogan, 1987) by:

$$AIC = n \cdot Ln\left(\frac{SS}{n}\right) + 2k_p \tag{1}$$

where n is the number of observed real measurement data points, k_p represents the number of regression parameters plus one and SS is the sum of the square of the vertical distances of the real data points from the most expected regression model. To compare two different models AIC is employed here. If n is relatively small, AIC is calculated (Bozdogan, 1987) by:

$$AIC_C = AIC + \frac{2k_p\left(k_p+1\right)}{n-k_p-1} \tag{2}$$

where k_p is the number of parameters plus 1.

The model with the lower AIC_C score is the model most likely to be correct. The probability that the correct model is defined can be calculated as (Bozdogan, 1987):

$$P\left(\Delta_{AIC}\right) = \frac{e^{-0.5\Delta_{AIC}}}{1+e^{-0.5\Delta_{AIC}}} \tag{3}$$

where Δ_{AIC} is the difference between AIC_C scores.

Two corrosion degradation models are analysed here. Model 1, which was developed by Guedes Soares and Garbatov (1998, 1999), describes the corrosion depth, $d^{cd}(t)$ as:

$$d^{cd}(t) = \begin{cases} d_\infty\left(1-e^{-\frac{t-\tau_c}{\tau_t}}\right), & t > \tau_c \\ 0, & t \le \tau_c \end{cases} \tag{4}$$

where τ_c is the coating life, τ_t is the transition time and d_∞ is the maximum corrosion depth achieved during the service life and Model 2 represents the corrosion model developed by Yamamoto and Ikagaki (1998) and Paik et al. (1998) is expressed by a power function of time as:

$$d^{cd}\left(t\right) = c_1 t_e^{c_2} \tag{5}$$

where

$$t_e = t - \tau_c - \tau_t \tag{6}$$

where τ_t may be taken as τ_t=0, indicating that corrosion starts immediately after the breakdown of the coating, τ_c, c_1 and c_2 are coefficients to be determined by the statistical analysis of corrosion data.

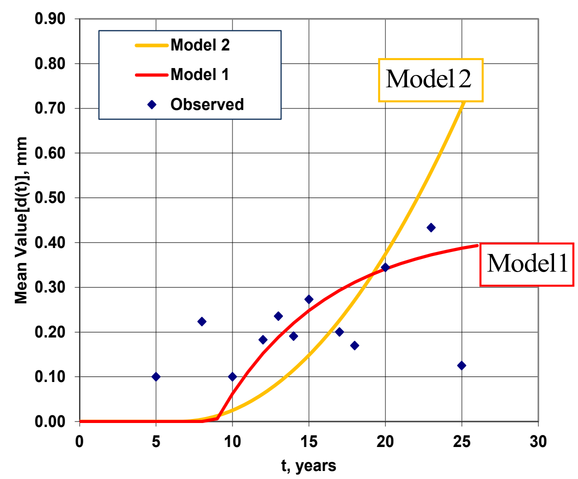

Figure 1 Mean corrosion depth

For the purpose of the comparison 12 data points, representing the yearly mean value real corrosion depths (Garbatov et al., 2007) are analysed (see Figure 1). The Model 1 fits 2 parameters, the coating life, τ_c and the transition time, τ_t. The long-term corrosion depth, d_∞ is defined as the maximum of the yearly mean value of the corrosion thickness during the service life. The Models 2 fits 3 parameters, c_1 and c_2 and the coating life, τ_c respectively. The model descriptors of fitting are shown in Table 1.

Table 1 Model 1 and 2 parameters

	c_1	c_2	τ_t, year	τ_c, year	R^2	Slope	n	k_p	SS, mm^2	AIC_C
Model 1	-	-	7.2	8.9	0.7	0.7	12	3	0.2	-42
Model 2	0.002	2.0	-	6.5	0.5	0.5	12	4	0.3	-24

Table 1 shows the difference in the quality of fitting of the analysed models, where SS, R^2 and the Slope may be compared. The calculated AIC_C scores of the models based on the Akaike criteria is -42.28 and -24.84, which indicates that the probability that Model 1 is admissible is 0.9998, while the admissibility of Model 2 is 0.0002 respectively.

Very extensive corrosion depth measurement data sets of different structural components in different corrosive environments (Garbatov et al., 2007, Garbatov and Guedes Soares, 2008, 2009, 2010) were analysed by the Akaike's Information Criterion to identify which model is more likely to have generated the data, and how much more likely concluding that the power model (Model 2) is identified in 29% to be more likely to have generated the data and the exponential model (Model 1) in 71% respectively.

4. CORROSION SURFACE MODELLING OF NON-CORRELATED PITS

Corrosion degradation may have different nature and therefore the appearance of corrosion degradation on the corroded plates as well as the adopted models need to reflect that. The most common corrosion models consider general degradation in which there is a relatively uniform variation of the corrosion thickness and one may consider that there is some correlation pattern that is reduced as the distance increases. This situation can be modelled by random fields in which there is a well-defined correlation function that relates the statistical properties in points as a function of their distance.

However, in some cases, the corrosion degradation is much more irregular and the correlation of the corrosion degradation is not significant, and the local thickness will vary in a random way, being more localized and more irregular. In these cases, a model of random thickness distribution can be more appropriate.

A different pattern is also observed in some cases, in which corrosion degradation becomes more widespread and several corrosion pits coalesce to form larger areas of a localized plate thickness reduction. In this case, the random variability still is present, but whenever a corrosion area occurs, it is larger than just a local corrosion pit. This is the problem addressed here in which two models are considered, a hexahedron and an elliptical type of corrosion deterioration profile shapes. The first model represents random uniform density and the second one non-uniform density of corrosion wastage spread. An application of those models has been initially used by Silva et al. (2013) in the ultimate strength and reliability assessments of a corroded steel plate subjected to uniaxial compressive load and here they are slightly adjusted to cover more general applications.

4.1 Random uniform density of corrosion wastage

The corroded plate thickness is modelled by random non correlated corrosion pits at the nodes of the artificially meshed plate resulting in a random corroded plate surface at the mesh nodes, equally spaced along the x and y directions.

The corroded plate thickness, $d(i, j)^{cp}$, at any reference point (i, j) with coordinates x=i*Δ and y=j*Δy, where the distance between any reference point is Δx and Δy, is defined by the random thicknesses of the intact plate surface, $d(i, j)^{ip}$ affected by the random corrosion depth, $d(i, j)^{cd}$ as:

$$\mathbf{d}^{cp} = \mathbf{d}^{ip} - \mathbf{d}^{cd} \qquad (7)$$

where **d** are the matrices of the corroded and intact plate thicknesses and the corrosion depths at i and j locations as:

$$d_{ij}^{cp}(t) = F_{ip}^{-1}\left[p_{ij}, E\left(d^{ip}\right), StDev\left(d^{ip}\right)\right] - F_{cd}^{-1}\left[p_{ij}, E\left(d^{cd}(t)\right), StDev\left(d^{cd}(t)\right)\right] \qquad (8)$$

where $F^{-1}[\ ]$ returns the inverse of the Log-normal cumulative distribution function of the probability, p_{ij}, which varies in the interval between 0 and 1, E( ) and StDev( ) stand for the mean value and standard deviation respectively. The corrosion model developed by Guedes Soares and Garbatov (1998, 1999) is used here to identify the corrosion depth as a function of time.

The thickness of the non-linearly corroded plate is defined as a result of randomly distributed plate thicknesses for the randomly defined reference points at a specific time, during the service life of the structure subjected to corrosion degradation. The corroded and intact plate thicknesses are described by a lognormal distribution). The intact plate and the corresponding corrosion depths are considered as non-correlated. However, this assumption is not essential for the model here, and if the correlation between different locations is known, it may be easily incorporated as can be seen in Section 5.

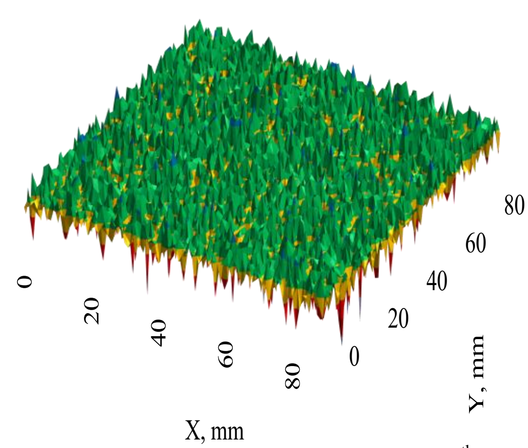

Figure 2 – Simulated corroded plate surface, at 15th year, 3D view

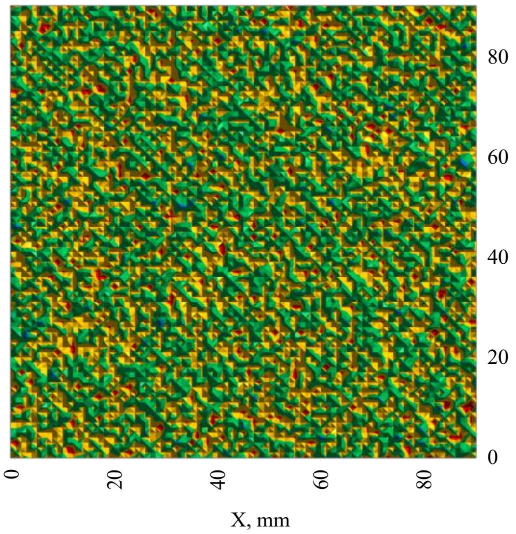

Figure 3 – **S**imulated corroded plate surface, at the 15th year, 2D view

The modelling of the corroded plate surface, of a length of 90 mm and a breadth of 90 mm, with a mean value of an initial plate thickness of 10 mm and standard deviation of 1 mm, is performed using the simulated random thickness at the reference nodes to adjust the plate thickness, where d_∞=0.43 mm, τ_t=7.18 years, τ_c=8.89 years, S_1=18.465, S_2=8.217 and k=1.847 at 15th year may be seen in Figure 2 and Figure 3. The plate thickness reduction due to corrosion is only applied on one side of the plate. If the plate is subjected to two different corrosion environments, then the two side surfaces have to be separately modelled accounting for the severity of the corrosion degradation.

4.2 Random non-uniform density of corrosion wastage

While the hexahedron model (uniform density) randomly sets the corroded thickness at any nodal point of the artificially meshed plate, here a localized form of a corroded plate surface is modelled. The localized hemispherical shape of corrosion degradation may also be transformed into a generalized surface of corrosion when many local corroded surfaces, with a different severity of degradation, are spread around the plate.

A hemispherical shape of corrosion deterioration may be identified as pitting corrosion, which normally appears in a wide variety of shapes and locations. The elliptic paraboloid may be the closest to realistic cases and it is a more adaptive mathematical entity, able to better describe different forms of corrosion. An elliptical paraboloid surface is expressed as:

$$(z-z_o)/a_1=[(x-x_0)/a_2]^2+[(y-y_0)/a_3]^2 \tag{9}$$

where x_o, y_o and z_o are the coordinates of the vertex and a_1, a_2 and a_3 are the shape coefficients and the vertex coincides with the coordinate system origin. The resulting corroded plate thickness is described as:

$$d^{cp(n)}(x, y, t)=d^{ip(n)}(i\Delta x, j\Delta y)-d^{cd(n)}(x, y, t) \tag{10}$$

and accounting for Eqn. (9) leads to:

$$d^{cp(n)}(x, y, t)=\{[(x-x_0^{(n)})/a_x^{(n)}]^2+[(y-y_0^{(n)})/a_y^{(n)}]^2+d_0^{cd(n)}(i\Delta x, j\Delta y)\} \tag{11}$$

where $a_x^{(n)}$, $a_y^{(n)}$ are the shape coefficients that govern the aperture and depth, $x_0^{(n)}$, $y_0^{(n)}$ are the coordinates of the vertex and $d_0^{cd(n)}$ is the distance between the pit lower surface and the centre of the crater and $i\Delta x$ and $j\Delta y$ define the nodal coordinates of a mesh that can be generated on the top of the corroded plate, $z_0=d_0^{cd(n)}e$. The negative value of $d_0^{cd(n)}$ leads to a complete perforation of the corroded plate and on the other hand, if $d_0^{cd(n)}\geq d^{ip}$ there will be no corrosion. Eqn (11) represents a plate thickness with a single pit, but multiple pits may be found in the same plate.

The corroded plate surface is modelled using Eqn (11) in the case of multiple pits, where the variation of the plate thickness is due to the random variation of the various parameters of the pits, $x_0^{(n)}$, $y_0^{(n)}$, $d_0^{cd(n)}$, $a_x^{(n)}$ and $a_y^{(n)}$, n and also by an initial random variation of the plate thickness $d^{ip(n)}(i\Delta x, j\Delta y)$. For a plate of a length, l and width, b are the shape and location parameters of the pits are defined as uniformly distributed and the corrosion depth and the intact plate thickness as log-normally distributed with the following descriptors:

$$x_0^{(n)}=p_{(n),x}b \tag{12}$$

where $p_{(n),x}$ is the probability that the corrosion pit is located in the space interval [0, b] in the x-direction

$$y_0^{(n)}=p_{(n),y}l \tag{13}$$

where $p_{(n),y}$ is the probability that the pit is located in the space interval [0, l] in the y-direction:

$$d_0^{cd(n)}(i\Delta x, j\Delta y, t)=F_{cd}^{-1}\{p_{(n),c,z}, E[d^{cd}(t)], StDev[d^{cd}(t)]\} \tag{14}$$

where $p_{(n),c,z}$ is the probability that the corrosion depth has a mean value of $E(d^{cd}(t))$ and standard deviation of $StDev(d^{cd}(t))$ and it is distributed by the Log-normal distribution, $F_{cd}[\,]$,

$$d_0^{ip(n)}(i\Delta x, j\Delta y)=F_{ip}^{-1}\{p_{(n),i,z}, E[d^{ip}], StDev[d^{ip}]\} \tag{15}$$

where $p_{(n),i,z}$ is the probability that the thickness of the intact plate has a mean value of $E(d^{ip})$ and standard deviation of $StDev(d^{ip})$ and it is distributed by the Log-normal distribution, F^{ip},

$$a_x^{(n)} = a_b p_{n,x} b \tag{16}$$

$$a_y^{(n)} = a_l p_{n,y} l \tag{17}$$

where $a_b \in [0, b]$ and $a_l \in [0, l]$.

The modelling of the corrosion depth mean value and standard deviation as a function of time is calculated as defined by Guedes Soares and Garbatov (1998, 1999) and the number of indentations n is also a random number and since it represents a quantity, it is an integer and may take values from 1 to n_{max}. A corroded plate surface of a plate with l=90 mm, b=90 mm, $E(d^{ip})$=10 mm, $StDev(d^{ip})$=1 mm, a corrosion depth is defined by d_∞=0.43 mm, τ_t=7.18 years, τ_c=8.89 years, S_1=18.465, S_2=8.217 and k=1.847 at 15th year can be seen in Figure 4 and Figure 5.

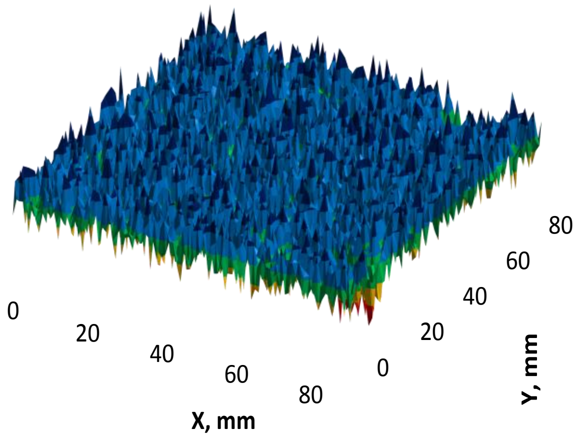

Figure 4 – Numerically simulated corroded plate surface at t=15 year, 3-D, 2860 pits

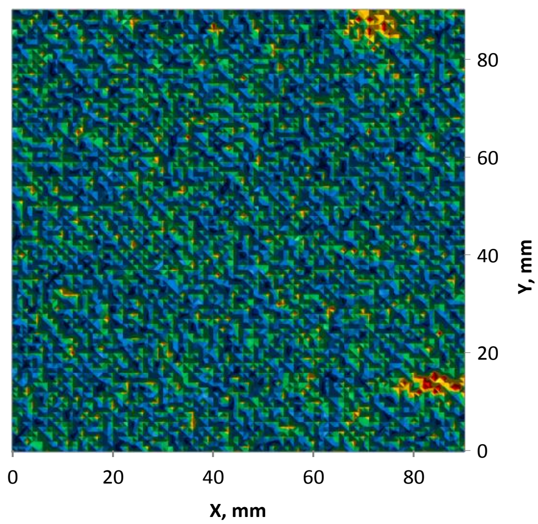

Figure 5 – Numerically simulated corroded plate surface at t=15 year, 2-D, 2860 pits

5. SEQUENCE DEPENDENT DATA ANALYSIS

Methods that take into account the data sequencing within the time or space records are more complex than the sequence-independent methods, and they produce outputs that are more complex. The power spectra assessment is a sequence-dependent analysis estimating the power present at various frequencies included in the corrosion depth real measurement record and here the Fourier transform (Bochner and Chandrasekharan, 1949) method is employed.

The discrete Fourier transform in performed in the form of the fast Fourier transform algorithm. The power spectrum is then determined as an amplitude squared of the sine waves, divided by the frequency separation. The Fourier transform (Bracewell, 2000) is a generalization of the Fourier series.

The periodic records from real measurements, analysed here, are made into two orthogonal directions x and y in a corroded plate that repeats itself, which has been shown in Figure 6 and Figure 7, the record in the x-direction starts at x=0, and stops at x=90 mm, the phase at x=l differs from that at x=0 and the one in the y-direction starts at y=0, and stops at y=90 mm, the phase at y=b differs from that at y=0.

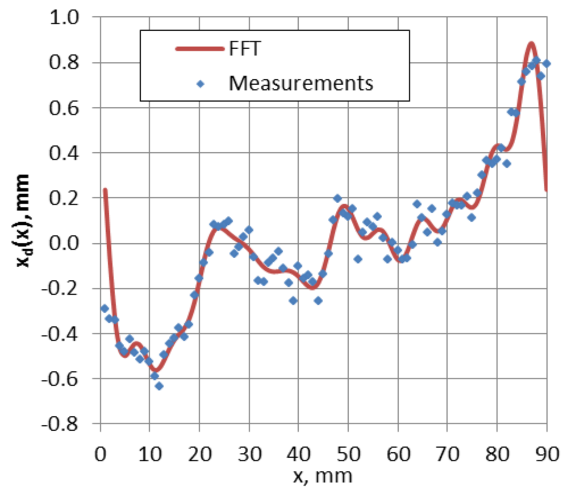

Figure 6 Corrosion depth measured in the x-direction

In the frequency domain analysis Δf is the frequency increment, also called the frequency resolution, of the discrete Fourier transform output, Δf_L=1/l or Δf_B=1/b, F(kΔf), one complex value for each discrete frequency, that provides information about the relative contribution to the record by each discrete frequency.

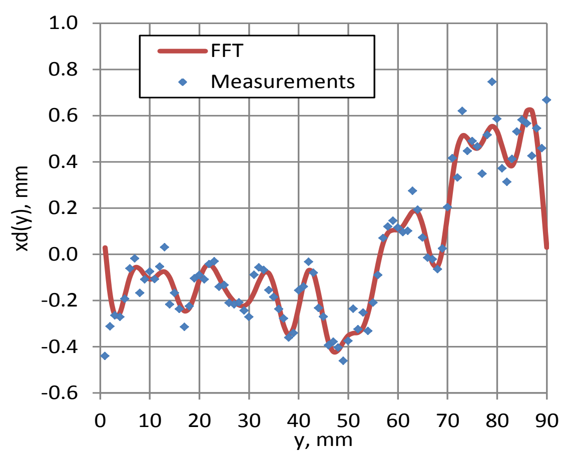

Figure 7 Corrosion depth measured in y-direction

It is assumed here that the scatter of the corrosion depth, $d_{x,y}(i\Delta x, j\Delta y, t)$ around the mean value of the corrosion depth, $E[d^{cd}(t)]$ may be defined as a normal stationary process with a zero mean value and it is assumed that the random process is modelled, in the case of a uniaxial distribution of the corrosion depth, x, by an exponential cosine autocorrelation function:

$$K_d(x) = \sigma^2 \cdot \exp\left(-\alpha_x \cdot |x|\right) \cdot \cos\left(\omega_0 \cdot x\right) \tag{18}$$

resulting in the following spectral function:

$$S_d(\omega) = \frac{2\sigma^2}{\alpha} \cdot \frac{1+\eta^2+\eta_0^2}{\left(1+\left(\eta+\eta_0\right)^2\right)\cdot\left(1+\left(\eta-\eta_0\right)^2\right)} \tag{19}$$

where $\eta=\omega/\alpha_x$, $\eta_o=\omega_{o,x}/\alpha_x$;.

Two single orthogonal line directional records of corrosion depths as a part of the corroded surface that is discretized by a measurement at 90*90 points is analysed here. In the x-direction: α_x=0.0126 [1/mm], $\omega_{o,x}$= 0.0276 [1/mm] and the variance is σ^2_x= 0.0055 [mm*mm] and in the y-direction: α_y=0.0110 [1/mm], $\omega_{o,y}$= 0.0146 [1/mm] and the variance is σ^2_x= 0.0055 [mm*mm]. The autocorrelation functions are shown in Figure 8 and Figure 9.

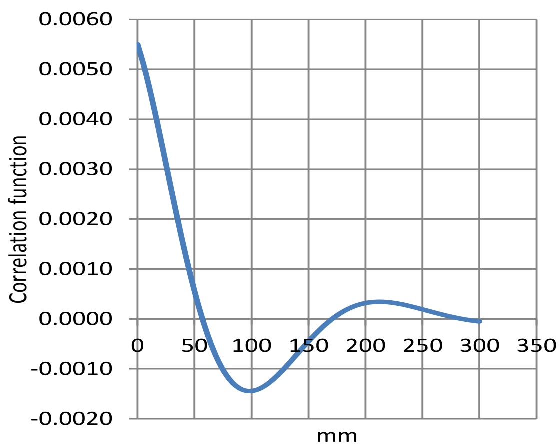

Figure 8 Autocorrelation function, x-record

The random fields are described by the random functions of four variables x, y, z=d^{cp} and t, where x, y and z=d^{cp} are spatial coordinates and t is the time coordinate.

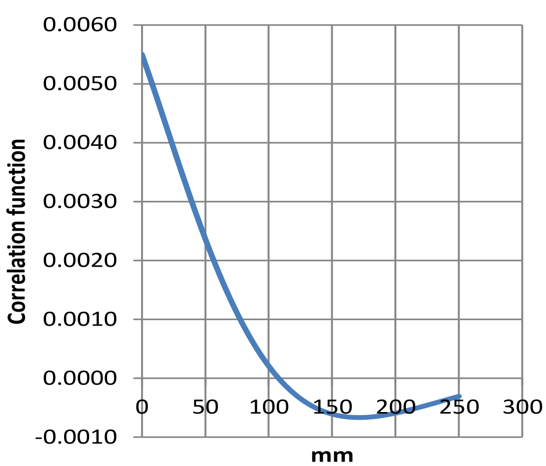

Figure 9 Autocorrelation function, y-record

The modelling of the random field is carried out by the space-time coordinate (x, y, z and t), which is associated with the selected value of the number of the sensor of normal random numbers with a zero mean and a unit standard deviation.

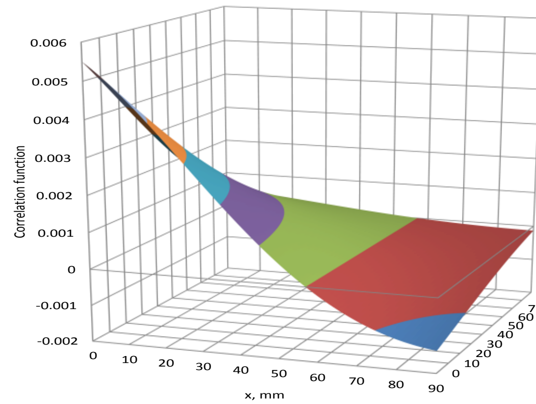

Figure 10: Bi-axial Exponential auto correlation function

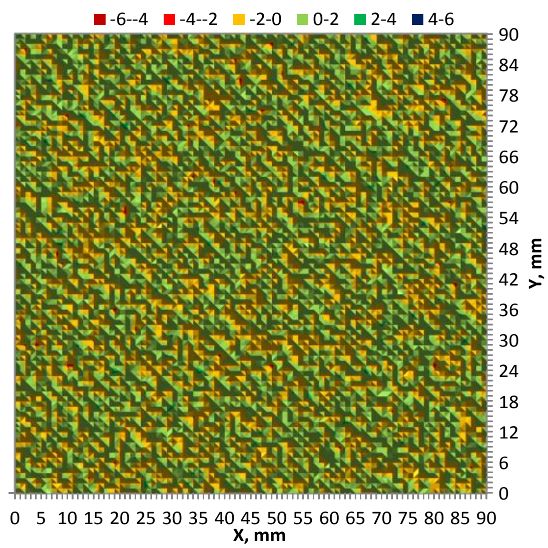

Figure 11: Sensor of normal random numbers with zero mean value and unit standard deviation

Here, a two-dimensional random field is developed, having a standard normal distribution and a correlation function (Figure 11) as:

$$K_d(x,y,t) = \sigma^2(t)\exp\left[-\alpha_x(t)x - \alpha_y(t)y\right]\cos(\omega_x x)\cos(\omega_y y) \tag{20}$$

where the dimension of the field is n_x*n_y and the sampling step in the spatial coordinates is 1 mm.

First, the desired field dimensions are defined and filled with an independent sample using the Gaussian distribution with a zero mean and a unit standard deviation (Figure 11). Based on the simulation algorithms of the random processes (in this case an exponential correlation function (Sethna, 2006)) the z-coordinates as a function of x are given as:

$$d_x(i,j,t) = \rho_x(t) \cdot d_x(i-1,j,t) + \sqrt{1-\rho_x^2(t)} \cdot X_\delta(i,j) \qquad (21)$$

where $\rho_x(t) = e^{-\alpha_x(t)\Delta x} = const$ is the correlation coefficient, which determines the degree of the dependence between the adjacent samples of the random process and $X_d(i,j)$ is a sensor of normal random numbers with a zero mean value and a unit standard deviation (Figure 11).

The procedure for calculating $d_{x,y}$ along the x-y-plane is similar to the one for the x-direction, where $\rho_y(t) = e^{-\alpha_y(t)\Delta y} = const$ is:

$$d_{x,y}(i\Delta x, j\Delta y, t) = \rho_y(t) d_{x,y}(i, j-1, t) + \sqrt{1-\rho_y^2(t)} d_x(i,j,t) \qquad (22)$$

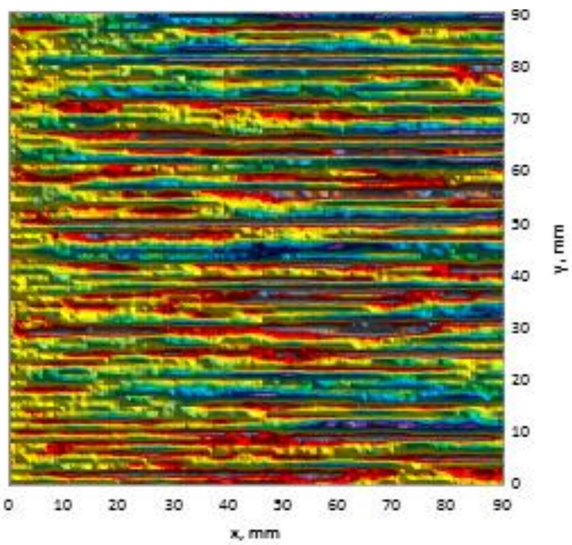

Figure 12: Random field as a function of x, 2D views

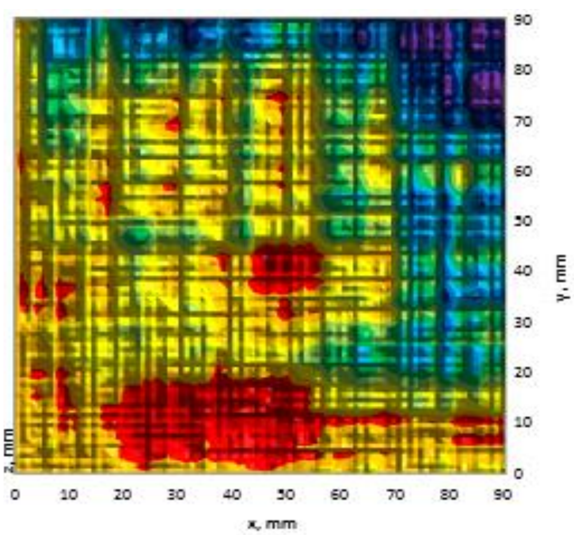

Figure 13: Random field as a function of x-y, 2D views

Finally, the corroded plate surface is described by:

$$d^{cp}(x,y,t) = d^{ip}(i\Delta x, j\Delta y) - d^{cd}(t) + d_{x,y}(i\Delta x, j\Delta y, t) \qquad (23)$$

The random field of a corroded plate surface as a function of x and x-y are given in Figure 12 and Figure 13 respectively, which represents the corrosion depth around the 0 mean value as a function of any x and y around the corroded plate. Figure 14 shows the corroded plate surface as a function of x, y and t (time), resulting in a mean value of the corroded plate thickness value of $E[d^{cp}(t)]$=9.75 mm at t=15th year.

The presented models for defining of the surface of corroded plates based on the real measurements are fulfilling the need of this type of solutions in the case of ageing structures in their structural and risk based maintenance planning and assessment. The formulations just presented are flexible and can be easily adapted to any type of structural components independently of the material and corrosion environmental conditions. The approach presented here is used to analyse corrosion degradation, but it can be applied to any type of surface roughness and structural degradation.

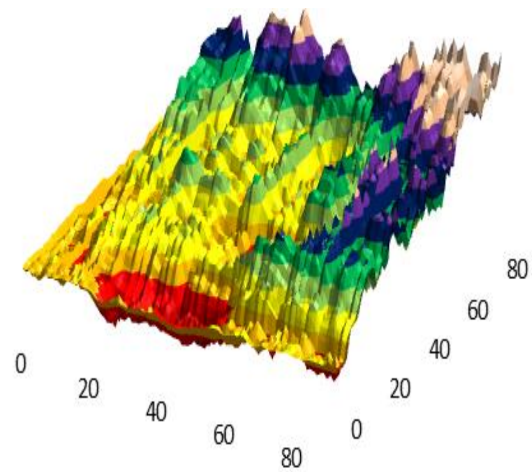

Figure 14: Corroded plate surface, $E[d^{cp}(t)]$= 9.75 mm, t=15 year, 3D view

6. CONCLUSIONS

This work analysed corroded degradation models of steel plates and their evaluation as best fitted to the real measurement data sets using advanced statistical methods. An approach for a proper identification of the best fitted model was applied and proved to be also a good option for identifying the time dependent statistical descriptors of the non-linear corrosion models. In the second part, a sequence dependent data analysis was performed employing the fast Fourier transform, which served as an input in a random field modelling of the corroded plate surfaces.

The output of this study represents very important information for any linear and non-linear finite element analyses of ageing structures accounting for the corrosion degradation and its surface topology. The formulations just presented are flexible and can be easily adapted to any type of structural components. The approach employed here was used in analysing the corrosion degradations of steel plates subjected to marine environments, but it can be used for any type of surface roughness and structural degradations.

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