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COMPARATIVE ANALYSIS BASED ON TWO NONLINEAR CORROSION MODELS COMMONLY USED FOR THE PREDICTION OF STRUCTURAL DEGRADATION OF OIL TANKERS

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Summary

The aim of the paper is a comparison between two widely used non-linear models for the prediction of corrosion wastage on deck plates and stiffeners of oil tankers. Analysis of data is based on real corrosion thickness measurements of ship hull structural elements performed by the Croatian Register of Shipping (CRS), gauged on periodic dry-docking and close-up surveys of three oil tankers in service after 10, 15 and 20 years. The two non-linear corrosion models are fitted to the real corrosion thickness measurements of deck plates and longitudinals in ballast and cargo tanks after 10 and 15 years in order to predict the corrosion loss in the 20th year. The uncertainty of corrosion propagation is then determined by the statistical analysis of the differences between the predicted and the measured corrosion thickness in the 20th year.

Key words: *corrosion wastage, non-linear corrosion models, deck plates and longitudinals in ballast and cargo tanks, hull structure survey of oil tankers*

1. Introduction

Damage to ships due to corrosion is very likely and the possibility of accident increases with the aging of ships. Statistics reveal that corrosion is the main cause of marine casualties in aged ships. Consequences of corrosion wastage can be very serious in some circumstances [1]. Experts in the maritime industry take into serious consideration corrosion wastage as one of the very important degradation factors for ship structural strength. Several models have been proposed to predict the corrosion wastage of structural components [2]. Such a direct approach to corrosion degradation is a useful tool for classification societies and ship owners in order to predict the long-term behaviour of hull structure and to decide whether the renewal of the hull structure is necessary and when it would be the optimal time for the repair [8]. Furthermore, such a direct approach has potential to facilitate the application of more accurate computational methods in design and analysis of oil tankers [9]. Unfortunately, corrosion degradation models that are used today are based on different assumptions and methodologies and consequently great uncertainties are associated with their application. Differences arise from the uncertainties in the thickness measurements and the complexity of the corrosion mechanism [12]. The aim of the present paper is to investigate the practical applicability of two currently used non-linear corrosion wastage prediction models: the model proposed by Guedes Soares & Garbatov [4] and the one of Yamamoto & Ikagaki [2], which has been used by Guo et al. [6] for analysing a large amount of real corrosion thickness measurements. This is done in a way that the mean corrosion wastage of the three ships after 20 years in service are predicted based on the real thickness measurements after the 10 and the 15 year service life. The real corrosion wastage measurements after 20 years are then compared to the predictions and uncertainties are analysed.

The total number of 6,567 measured corrosion thicknesses is used in the analysis. The analysis of the corrosion degradation is performed for the main deck plates and longitudinals, separately for the cargo and ballast tanks. The advantage of the presented approach is that the application of the non-linear corrosion degradation models is investigated for individual ships, while the whole fleets of tankers were considered in the most of previous studies. The proposed individual approach may be particularly useful for small classification societies supervising only a few tanker ships. The findings of the present study can be used for an assessment of the ship hull fitness-for-service and for planning ship hull inspections as well as for reducing maintenance costs of oil tankers in service.

2. Description of Ships

The present study analyses corrosion wastage of three oil tankers with a single-hull structure, built in the eighties. The whole cargo area of the two sister ships (ships no. 2 & 3) is made of mild steel, while the third one (ship no.1) was made of high tensile steel in the bottom and deck areas and of mild steel in the neutral axis area including longitudinal bulkheads. Main particulars of the three oil tankers are shown in Table 1. The central tanks along cargo hold areas are cargo oil tanks, while the wing tanks can serve as the ballast or cargo oil tanks. The main deck longitudinals of ship no. 1 are T-profiles, while the deck longitudinals of the sister ships are flat bars.

Table 1 Main characteristic of three single-hull tankers

		ship no. 1	ship no. 2	ship no. 3
Length	Lpp	237 m	205 m	205 m
Breadth	B	42 m	48 m	48 m
Depth	D	20.5 m	19 m	19 m
Draught	T	13 m	13 m	13 m
Deadweight	DWT	78,000 tons	80,000 tons	80,000 tons

3. Assessment of local corrosion wastage

The mechanism of corrosion wastage in marine environments on ship structures depends on many different factors, such as: the type of cathodic protection, humidity, type of cargo and cargo operations, fluid flow, dissolved oxygen, temperature, and salinity [5], [13]. Therefore, the corrosion wastage for different ship structural elements is defined based on the type of element and its location, and also as a function of the corrosion environmental conditions.

The corrosion degradation needs to be modelled as a function of time in order to predict hull structural deterioration during the service life. In that way, the effect of corrosion degradation in the stage of the ship structural design and construction and during service life may be taken into account.

When more environmental factors that affect corrosion degradation are monitored, then a more sophisticated corrosion wastage model may be developed to account for salinity, temperature, dissolved oxygen, pH, and flow velocity, including the effect of ship service life in different routes [14]. While that model will allow changes in the environmental factors to be reflected in the corrosion rates, the historic data available do not contain that information.

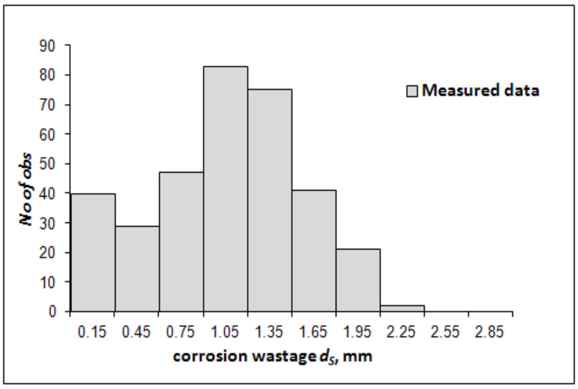
A typical model of corrosion degradation consists of at least two phases: a phase without corrosion because of the protective coating and the second phase in which the corrosion degradation progresses. Duration of the protective coating is an important parameter when analysing corrosion wastage. If the protective coating deteriorates rapidly, then there is an early occurrence of corrosion, and, consequently, that leads to the reduction in the thickness of the structural elements and possibly to the reduction in the ship structural capacity. The protective coating duration depends on a number of factors, primarily on the type of protective coatings, coating processes on the surface, as well as the preparation of the surface to which the coating is applied and the proper maintenance of the protective coating. It is reasonable to consider the lifetime of the protective coating as a random variable that can be described by a log-normal probability density function. In practice, the protective coating life is in the range from 5 to 10 years. After the coating surface protection fails, corrosion progresses in a sufficiently large area, where corrosion wastage can be efficiently measured. Some authors consider a transition period between the coating protection and corrosion progression to be separate phase [4], while some join that phase together with the protective coating life [6], [17].

Corrosion degradation, after coating breakdown, can be described by convex, concave or linear curves. The convex curve represents the degradation when the gradient increases at the beginning and as the degradation progresses, the gradient decreases. This type of corrosion degradation is characteristic of elements that are constantly immersed in sea water and the corrosion degradation can be slowed down with the already created layers of rust. The concave curve represents the case when the corrosion degradation expands as corrosion progresses over time, which means that the corrosion gradient increases as corrosion degradation progresses. This type of corrosion degradation is typical of those structural elements which are subjected to varying environmental conditions (dry-wet-dry). The linear curve is typical of the cases where the layers of rust are continually removed because of abrasive action or smaller surface tension. It is typical of lower parts of the cargo area used for the transport of aggressive media [5].

In the following sections, two corrosion degradation models, which are considered to be most widely applied nowadays, are reviewed and compared. The substantial difference between the models is that the model of [6] enables a practically unlimited increase in the corrosion wastage with time, while the model of [4] limits the progress of corrosion degradation due to the created layers of rust. Therefore, the model [4] will converge to a value of corrosion thickness less or equal to the as-built-thickness that will never be exceeded.

The total number of real corrosion wastage measurements of deck plates and longitudinals used in the present study are 6,567. 2,135 real corrosion wastage measurements are performed for ship no.1, 2,079 for ship no. 2 and 2,353 for ship no. 3. The assessment analysis is performed in a way that all corrosion wastage measurements, for each of the ships, in the cargo hold area are considered and grouped in four categories: deck plates in all cargo tanks, deck longitudinals in all cargo tanks, deck plates in ballast tanks, and deck longitudinals in ballast tanks. The mean values of the corrosion wastage for each of these categories are calculated based on the real corrosion wastage measurements after the 10, 15, and 20 year service life. The real corrosion wastage measurements after 10 and 15 years are used for fitting corrosion prediction models, while mean values of the corrosion wastage measurements after 20 years are used for a comparison between the prediction based on the corrosion degradation models and real corrosion thickness measurements.

Typical histograms of the real corrosion thickness measurements, based on which the mean value is calculated, are presented in Figure 1, where the corrosion wastage of the main deck plates in cargo tanks for ship no. 2 after 15 and 20 years in service are shown.



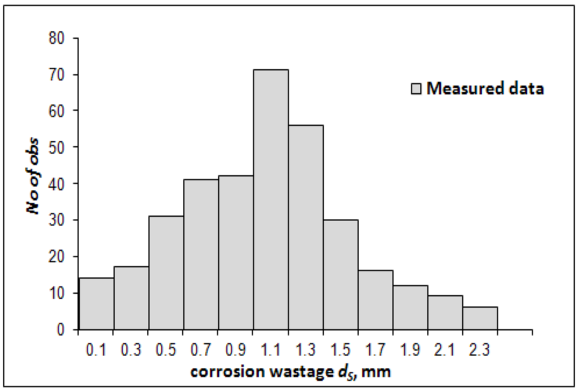


Fig. 1 Corrosion wastage of main deck plates in the cargo tanks of ship no. 2 after 15 years (left) and 20 years (right)

3.1 GS&G corrosion prediction model

The model of corrosion degradation as proposed by Guedes Soares & Garbatov [3], [4], GS&G model, is given as:

$$C(t) = C_\infty (1 - e^{\frac{-(t-t_0)}{t_t}}) \quad \text{,for} \quad t > t_0, \quad 0 \ \text{for}\ t < t_0 \tag{1}$$

where C_∞ is the asymptotic value of the long-term corrosion wastage, while t_t represents the transition time duration corresponding to the initiation of failure of the corrosion protection system, which leads to faster corrosion progress, and t_0 is the coating life.

The model is fitted through the measured average corrosion degradation thickness in the 10th and the 15th year. Since there are three unknown variables in Eq. (1) (C_∞, t_0 and t_t) and only two available known corrosion thicknesses (in the 10th and the 15th year), nonlinear optimization is employed. An additional constraint is employed regarding C_∞: it is limited for the present study here by 1.8 mm and 2 mm. These values are based on the study presented in [18], where the corrosion wastage of deck plates of the ballast and cargo tanks of a large number of tankers from ABS fleet were analysed. In that study, C_∞ was found to be 1.85 mm and 1.91 mm for ballast and cargo tanks, respectively.

3.2 G&A corrosion prediction model

The corrosion wastage model, originally defined by Yamamoto & Ikagaki [2] and later applied in the analysis by Guo et al. [6], G&A model, is given by the following equation:

$$C(t) = \alpha(t - t_0)^\beta \quad \text{,for} \quad t > t_0, \quad 0 \ \text{for}\ t < t_0 \tag{2}$$

where $C(t)$ is the corrosion wastage as a function of time t; t_0 is the coating life; α and β are constants that can be determined based on the real measurement of corrosion wastage data.

The model is fitted through the mean values of the corrosion wastage in the 10th and the 15th year. Since there are three unknown variables in Eq. (2) (t_0, α, and β), and only two available mean values of the corrosion wastage (in the 10th and the 15th year), a nonlinear optimization procedure is employed to identify t_0, α and β. The objective of the optimization is to minimize the difference between the estimated mean values of the corrosion wastage by the model and the real corrosion measurement mean value of the thickness in the 10th and the 15th year.

3.3 Comparative analysis

Results of the analysis for the mean corrosion wastage of main deck plates and longitudinals in the ballast and cargo tanks for ship no. 1 are presented in Figure 2. The difference between corrosion wastage in the 15th and the 20th year of the deck plates is unexpectedly large, indicating that a concave curve would be more appropriate for the corrosion degradation modelling. Therefore, both corrosion models significantly underestimated the measured corrosion wastage of deck plates in the 20th year, while the predictions of both methods are almost the same. The G&A model slightly overestimates the measured corrosion wastage of deck longitudinals while the GS&G model almost perfectly matches the measured corrosion wastage of deck longitudinals in cargo tanks.

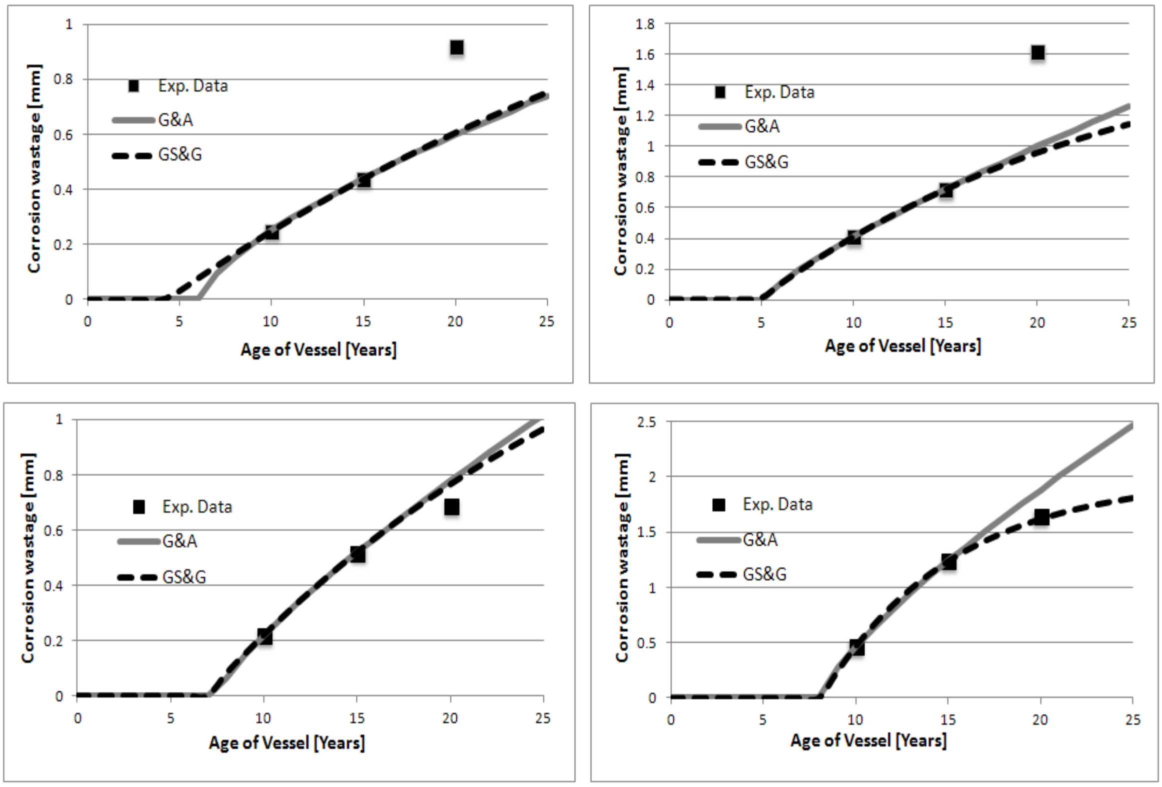


Fig. 2 Measured and predicted mean corrosion wastage for ship no. 1: main deck plates in the ballast (upper left) and cargo (upper right) tanks, main deck longitudinals in the ballast (lower left) and cargo tanks (lower right)

The mean corrosion wastage of the main deck plates and longitudinals for ship no. 2 are presented in Figure 3. A general trend in reducing the corrosion rate between 15 and 20 years has to be noted. Both corrosion models overestimate the measured mean value of corrosion wastage in the 20th year, but a better result is achieved by the GS&G model. The difference is clearer for the deck longitudinals in cargo tanks, where the GS&G model gives a much better prediction.

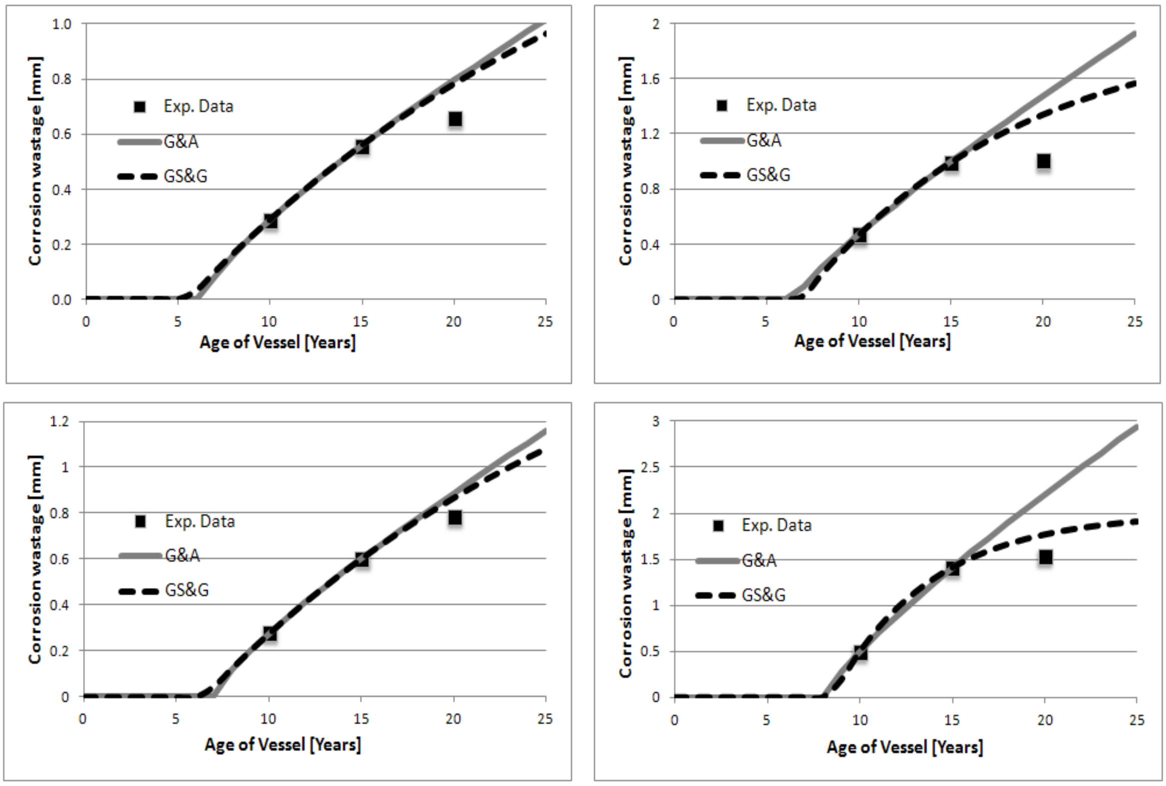
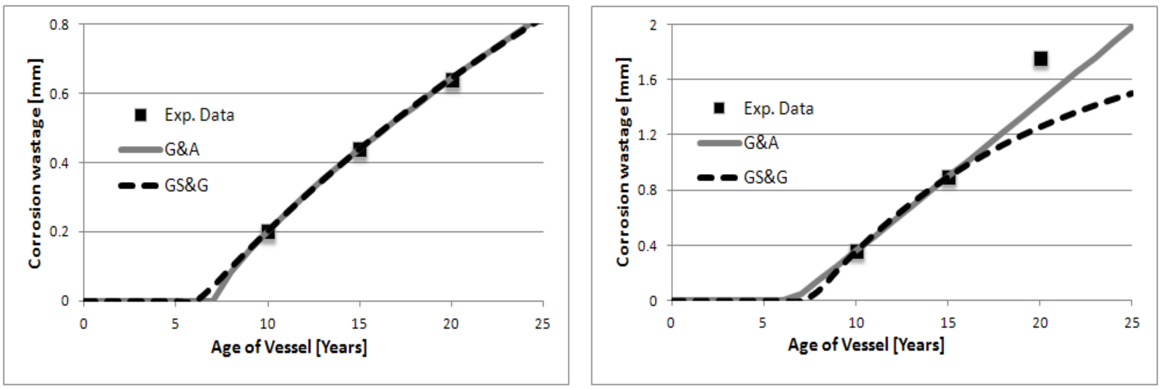


Fig. 3 Measured and predicted mean corrosion wastage for ship no. 2: main deck plates in the ballast (upper left) and cargo (upper right) tanks, main deck longitudinals in the ballast (lower left) and cargo tanks (lower right)

The mean corrosion thicknesses of the main deck plates for ship no.3 are presented in Figure 4. Only in the case of the main deck plates in cargo tanks, both corrosion prediction models underestimated the measured corrosion wastage after the 20th year, although the G&A model represents a better approximation. For the deck longitudinals in cargo tanks, however, the GS&G model provides a much better agreement with the real measurements of corrosion thickness. The coating longevity for main deck longitudinals in ballast tanks of 2.8 years for the GS&G model and 4.7 years for the G&A model has shown unexpectedly low values compared with the coating longevity of main deck plates (around seven years) located in the same tank. Those differences can be explained by measurement uncertainties during thickness gauging.



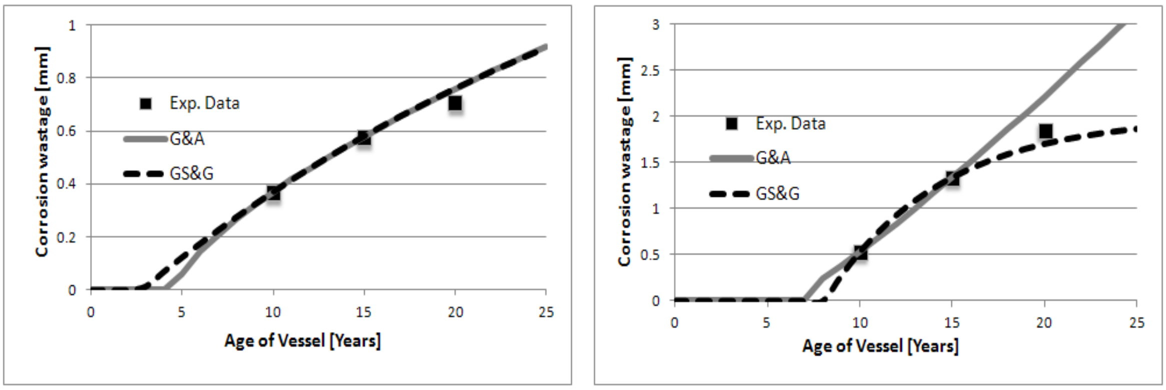


Fig. 4 Measured and predicted mean corrosion wastage for ship no. 3: main deck plates in the ballast (upper left) and cargo (upper right) tanks, main deck longitudinals in the ballast (lower left) and cargo tanks (lower right)

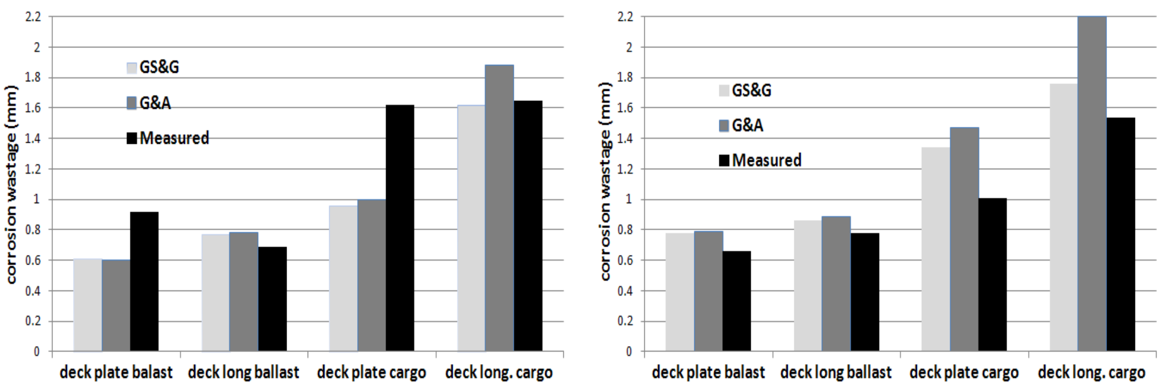
The estimated coating life by both models is presented in Table 2. The predicted coating life of the two models is fairly close. The maximum difference is 2.1 years for the deck longitudinals of cargo tank no. 3, while, on average, the difference is less than 1 year. The average coating life in ballast tanks of G&A and GS&G models is 6.35 and 5.4 years, respectively, while in the cargo tanks it is 6.7 and 7.15 years (for G&A and GS&G models, respectively).

Table 2 Coating life (years)

	Deck plate (ballast tanks)		Deck longitudinal (ballast tanks)		Deck plate (cargo tanks)		Deck longitudinal (cargo tanks)	
	G&A	GS&G	G&A	GS&G	G&A	GS&G	G&A	GS&G
ShipNo.1	6.0	4.3	7.4	6.9	5.1	4.9	8.0	8.1
ShipNo.2	6.2	5.5	6.9	6.5	6.5	6.8	8.0	8.5
ShipNo.3	7.1	6.3	4.7	2.8	6.6	7.5	6.0	8.1
Average	6.4	5.4	6.3	5.4	6.1	6.4	7.3	7.9

4. Uncertainty analysis of corrosion degradation models

In order to quantify the uncertainty of the corrosion degradation models used in the study, complete results for the predicted and measured mean corrosion thicknesses are presented in Figure 5 and are statistically analysed. Figure 5 represents a comparison of the measured and predicted mean corrosion thicknesses over 20 years of service life for all three ships and all measurement locations.



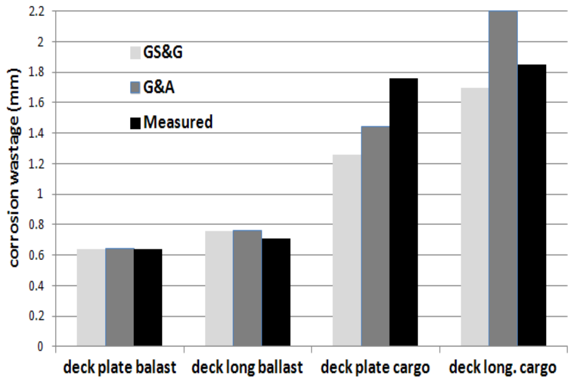


Fig. 5 Measured and predicted mean corrosion wastage after 20 years for ship no. 1 (upper left), ship no. 2 (upper right) and ship no 3 (bottom)

The average ratio of the measured and predicted mean corrosion thicknesses reads 1.00 for the G&A model and 1.07 for the GS&G model, while the corresponding standard deviations read 0.31 and 0.29, respectively. This indicates that the GS&G model underestimates the actual corrosion wastage, while the uncertainty of prediction is rather large for both models.

If only cargo tanks are considered, then the average ratio of the measured/predicted mean corrosion thicknesses is 0.99 for the G&A model and 1.14 for the GS&G model, while the corresponding standard deviations are 0.37 and 0.35, respectively. If only ballast tanks are considered, then the average ratio of the measured/predicted mean corrosion wastage is 1.01 for G&A and 1.02 for GS&G, while the corresponding standard deviation is 0.26 for G&A and 0.25 for GS&G. Therefore, the agreement between predictions and measurements is generally better for the ballast than for cargo tanks.

The degree of correlation between the measured and predicted mean values can be described by the coefficient of determination, R^2. In the present study, R^2 is defined as:

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \tag{3}$$

where SS_{tot} is the total sum of square deviations of the measured values, while SS_{err} is the sum of squares of residuals. If all predicted values are equal to the measured ones, then SS_{err} would be equal to zero and R^2 becomes equal to unity. On the other hand, if deviations between the measured and predicted values are large, R^2 becomes lower while in some cases can even take a negative value.

A graphical representation of the coefficient of determination is shown in Figure 6. The lower triangle area diagram (below the line "estimated"="observed") represents the underestimated area, and the upper triangle the overestimated area.

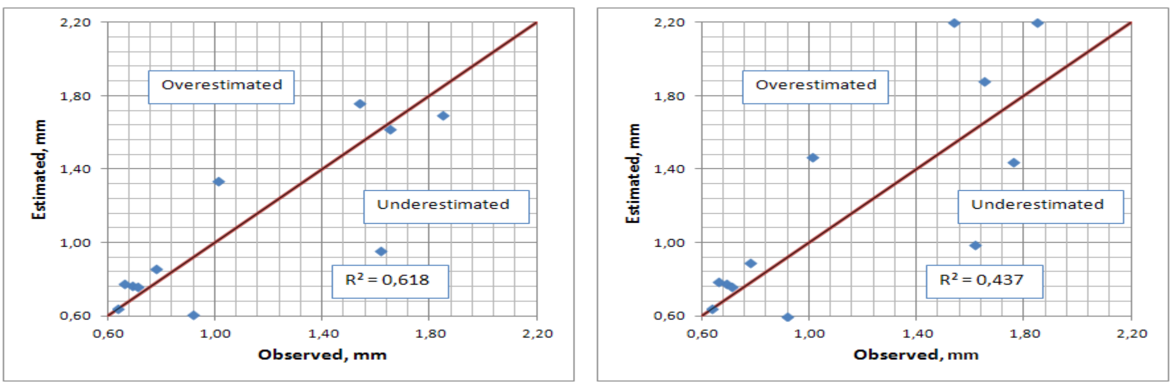


Fig. 6 R-squared analysis of the three ships of the GS&G model (left) and the G&A model (right)

Unlike the statistical analysis of the ratios of the measured and predicted values, the R-squared analysis clearly shows that the GS&G model provides better prediction. From Figure 6 one can see that the scatter of predictions with respect to the line "predicted"="observed", representing the perfect prediction, is much larger for the G&A model. The reason for such discrepancies in the statistical results is that the R-squared analysis does not account for the sign of the prediction, i.e. only deviations are accounted for irrespective of whether they represent underestimation or overestimation of the predictions.

5. Conclusions

The objective of the present study was to compare two widely used non-linear models for corrosion wastage prediction of deck plates and stiffeners on oil tankers. The principal difference between the two models is that the G&A model enables practically unlimited corrosion wastage in the long term, while the model of GS&G assumes that corrosion wastage will converge to a certain upper limit of corrosion thickness, less or equal to the as-built-thickness, which will never be exceeded. The approach used in this study was to fit non-linear corrosion prediction models to the real corrosion wastage measurements after 10 and 15 years and then to compare the predictions with measurements in the 20th year. The analysis of corrosion wastage data was based on the real thickness measurements of ship hull structural components of three single-hull oil tankers built in the eighties. Corrosion wastage is gauged on periodic dry-docking and close-up surveys of ships in service after 10, 15 and 20 years.

The average ratio of the measured and predicted mean corrosion wastage is 1.00 for the G&A model and 1.07 for the GS&G model, while the corresponding standard deviations are 0.31 and 0.29, respectively. The coefficient of determination, R^2, for the GS&G model is estimated as 0.62, indicating that this model is more reliable than the G&A model with R^2=0.44. Corrosion wastage in cargo tanks is larger than in ballast tanks, while deck longitudinals in cargo tanks experienced the highest degree of corrosion wastage of all ship structural components analysed. This trend is well predicted by both methods. The phenomenon has already been observed in [18], based on the explanation of creating sulfur from oil gases in combination with surface rust to the back face of an oil tanker deck. In such a case, corrosion mechanism can cause more damage on cargo tanks than that caused by the sea water in the ballast tank. Both corrosion degradation models provide better predictions in ballast tanks than in cargo tanks. Average coating lifetime is about 6 years in ballast tanks and about 7 years in cargo tanks.

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