Brodogradnja/Shipbuilding/Open access Volume 68 Number 2, 2017

*Paul Jurišić*
*Joško Parunov*
*Yordan Garbatov*

http://dx.doi.org/10.21278/brod68202

ISSN 0007-215X
eISSN 1845-5859

# AGING EFFECTS ON SHIP STRUCTURAL INTEGRITY

UDC 629.5.015.4:629.5.083:620.193
Review paper

## Summary

The most important degradation effects of ship structures are corrosion and fatigue cracks. Both of these aging effects have clear consequences of increasing the level of stresses and degrading the strength of ship structures for almost all relevant failure modes. This study presents an overview of some recent developments on the aging effects on the ship structural integrity. The analysis of the thickness measurements has been undertaken to improve understanding of the corrosion degradation phenomena and to develop prediction models of aging effects suitable for practical applications in the ship structural design and analysis. The study also deals with the application of the non-linear finite element analysis as a suitable tool for a collapse assessment of uniaxially loaded plates and stiffened panels of ship structures weakened by non-uniform corrosion degradation and fatigue cracks. Experimental studies have also been reviewed to better understand the recently found degradation of mechanical properties of corroded steel, while theoretical calculations have been performed to evaluate consequences of such degradation on the ship structural integrity.

*Key words:* *Corrosion; Fatigue crack; Non- linear finite element method; Ship structures*

## 1. Introduction

Corrosion wastage and fatigue cracks are recognized as two most important long-term degradation mechanisms of ship structures. Damages to ships due to these aging effects are very likely and the possibility of accident increases with the ship ages. The consequences of aging related damages can be catastrophic in some circumstances, requiring that experts in the maritime industry, most seriously take into consideration degradation factors on ship structural safety. Furthermore, as the design lifetime of ship structures is at least 25 years, aging effects need to be appropriately addressed already in the design phase. Due to these reasons, much research effort has been spent in the past few decades, aiming to clarify the physical background and to develop practically applicable models for long-term prediction of both these phenomena [1], [2].

There are several consequences of corrosion wastage of ship structures. The most obvious one is that the general stress level is raised as the dimensions of structural components forming hull girder are reduced due to corrosion, and that the structural resistance against the inelastic buckling collapse of unstiffened and stiffened plate panels is decreased [3].

Cracking damage has been found in welded joints and local areas of stress concentrations such as at the corrosion pits in plates and welded intersections of longitudinals and web frames. Fatigue cracking has usually been dealt with as a matter under cyclic loading, but it is also important for residual strength assessment under extreme loading, because fatigue cracking reduces the ultimate strength significantly under certain circumstances [4]. This is particularly true for plates and stiffeners of the main deck structure as their collapse may be dangerous regarding ship longitudinal strength. A model for collapse strength assessment of uniaxially compressed plates and stiffened panels has been developed and tested employing the nonlinear finite element method (NLFEM), using structural analysis software FEMAP with NX Nastran. The objective was to define a model that is simple enough to be applicable in everyday engineering practice. The principal difficulties are related to the choice of an appropriate definition of the model extent and boundary conditions, especially the mathematical description of the initial imperfections that have a dominant influence on final collapse strength [5].

Recent experimental studies indicate that the mechanical properties of corroded steels, as the yield and ultimate strength could be surprisingly reduced compared to the intact steel. Besides the fact that such degradation of mechanical properties needs more experimental evidences, there is a need to study the consequences on the structural integrity as degradation of mechanical properties has not been accounted for in the present rules for ship classification [6].

## 2. Corrosion degradation

One of the most important types of corrosion degradation of ship structures is general corrosion, which is almost uniformly distributed in large structural areas and the other type is localized corrosion, as pitting and grooving. The mechanisms of corrosion wastage of the ship's structure in the corrosively aggressive marine environment depend on many different factors, such as the type of protective coating, temperature, oxygen, humidity, type of cargo, among others. Therefore, the corrosion wastage for different hull structural elements depend on the type of the structural element and its location, and also varying in different types of ships, cargo spaces and tanks of the ship [7].

The marine environment is generally the most aggressive and naturally occurring environment. The hull being constantly exposed to the seawater environment experiences general corrosion, which reduces the plate thickness uniformly but it is also likely to experience pitting, galvanic corrosion and others. Corrosion can interfere with the operation of ships and impose increasing stresses, accelerate deterioration of ship structures and increases the hydrodynamic drag [8].

Corrosion progression models are used by classification societies and ship owners in order to predict the long-term degradation of hull structures and to decide if the renewal of the hull structure is necessary and when would be the optimal time for the repair. A typical model of the corrosion degradation process consists of at least two phases: a phase without corrosion because of the durability or the life of the protective coating and phase of the corrosion progression. Three models for the corrosion degradation in ship structures are those originally developed by Melchers [9], Yamamoto & Ikagaki [10] and Guedes Soares & Garbatov [11] (GS&G) are widely used. Yamamoto & Ikagaki corrosion model has been used by Guo et al. [3] (G&A) for analysing a large amount of real corrosion thickness measurements. A comparison of the two latter prediction models (GS&G and G&A) based on the thickness measurements on three oil tankers is presented in [12]. The principal difference between the two models is that the model G&A enables practically unlimited corrosion wastage in the long term, while the model of GS&G assumes that corrosion wastage will converge to the certain upper limit of corrosion thickness, less or equal of as a built thickness, which will never be exceeded [12].

## 2.1 Prediction of the corrosion wastage

The most frequently used corrosion prediction models are those developed by Guedes Soares & Garbatov and Yamamoto & Ikagaki. The model of corrosion degradation of Guedes Soares & Garbatov (GS&G) [11] 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 $C_\infty$ is the asymptotic value of the long-term corrosion wastage, while $t_t$ represents the transition time duration corresponding to the initiation of the failure of the corrosion protection system, which leads to a faster corrosion progress and $t_0$ is the coating life. $C_\infty$ is limited by 1.85 mm and 1.91 mm, based on the study presented in [11], [13], where the corrosion wastage of deck plates of the ballast and cargo tanks of the large number of tankers from ABS fleet was analysed. $C_\infty$ was found as the maximum average corrosion wastage among all ships for ballast and cargo tanks respectively.

The corrosion wastage model, denoted as G&A, originally defined by Yamamoto & Ikagaki [10] and later applied in the analysis by Guo et al. [3], is given as:

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

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

The comparative analysis of the two methods for the corrosion wastage prediction of the annual corrosion wastage of the main deck longitudinal in cargo tanks of one oil tanker, taken from the CRS (Croatian Register of Shipping) database is presented in Figure 1 [12].

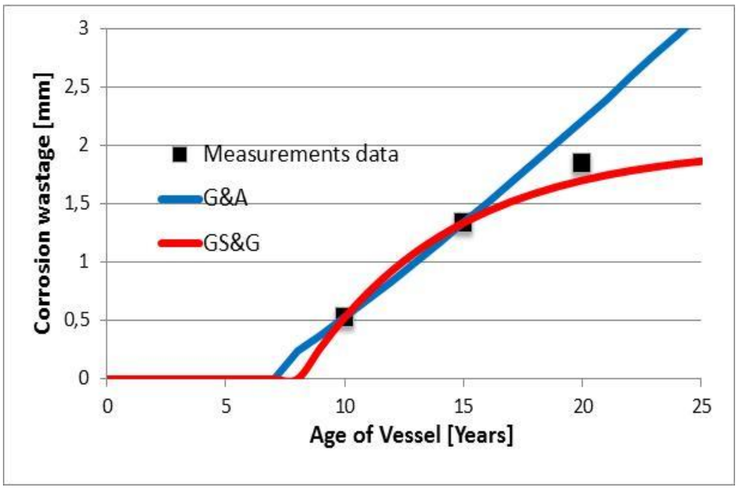


**Fig. 1** Measured and predicted mean annual corrosion wastage for main deck longitudinals in cargo oil tanks (COT) [12]

In order to quantify the uncertainty of the corrosion degradation models, the results for the predicted and measured mean corrosion thicknesses of three oil tankers are presented in

Figure 2. The total number of corrosion wastage measurements of deck plates and longitudinals used in the comparative analysis was 6,567. 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 during the 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 model of G&A and 1.07 for the GS&G model, while the corresponding standard deviations are 0.31 and 0.29 respectively [12].

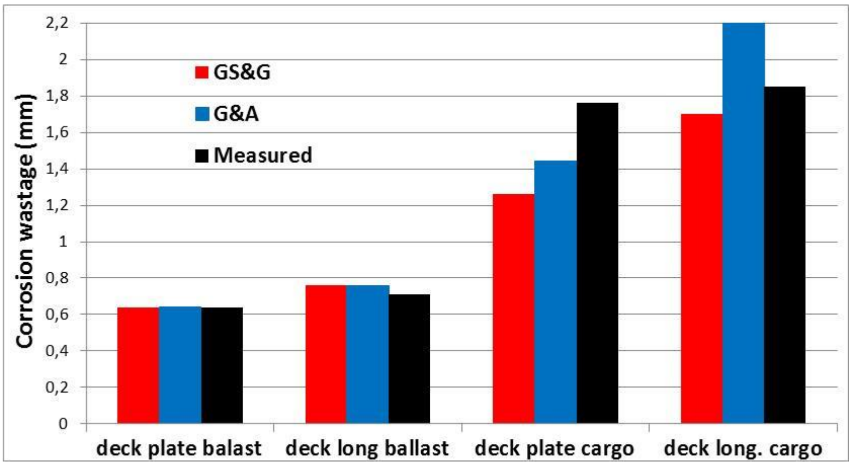


**Fig. 2** Measured and predicted corrosion wastage after 20 years of service [12]

## 2.2 Variability of the corrosion wastage

Corrosion varies not only with the time, but also with the location along the ship at the same time instant. There is a large scatter of the corrosion diminution among e.g. deck plates along the cargo hold region. Such scatter is also analysed in the probabilistic terms.

The probability density function for various structural locations on oil tankers was determined based on a statistical analysis using the Croatian Register of Shipping (CRS) corrosion database. The Weibull distribution has been proven to be the most suitable for representing the variability corrosion wastage at any ship age [14], [15]. Figure 3, represents corrosion wastage of the deck plates in the cargo tanks at year 15 for one of the oil tankers from the CRS corrosion database. The abbreviation N(C) on the vertical axis in Figure 3 represents the number of measured corrosion wastages of deck plating in cargo oil tanks (COT).

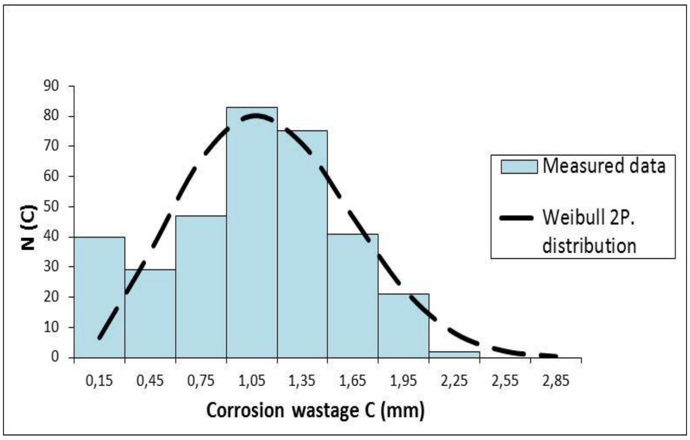


**Fig. 3** Weibull probability density function of the corrosion wastage of deck plating in cargo tanks [15]

## 3. Impact of corrosion degradation on the collapse strength

The overall failure of ship structures is evaluated based on the buckling and elastic-plastic collapse of the plates and stiffened panels in the deck, bottom, and sometimes side shell. Therefore, the accurate assessment of the collapse strength of plates and stiffened panels is an important task in the structural design and safety assessment of ship [16].

### 3.1 Application of Common Structural Rules (CSR) for collapse strength of plates and stiffened panels

For the collapse strength of uniaxially loaded plates, Frankland's equation is used in CSR [17], [18]:

$$\frac{\sigma_u}{\sigma_y} = \left( \frac{2.25}{\beta_E} - \frac{1.25}{\beta_E^2} \right) \text{ for } \beta_E \geq 1.25 \tag{3}$$

$$\sigma_u = \sigma_y \text{ for } \beta_E < 1.25$$

$$\beta_E = \frac{b}{t_{pl}} \sqrt{\frac{\sigma_y}{E}}$$

where $\sigma_y$ represents the yield stress of the material of the plate, $\sigma_u$ is the ultimate collapse strength of the plate, $\beta_E$ is the plate slenderness, $b$ is the plate breadth, $t_{pl}$ is the plate thickness while $E$ the modulus of elasticity. It is easy to observe that the main aging effect, reduction of the plate thickness, increases plate slenderness, while the modification of mechanical properties has contradictory effect, since the reduction of yield strength reduces, while reduction of modulus of elasticity increases plate slenderness [19].

For the collapse strength of stiffened panels, the procedure proposed in CSR assumes that the ultimate compressive strength is the lowest of the three different buckling modes: beam column flexural buckling, stiffener torsional buckling and local buckling of the stiffener web. More details of the procedure employed, including the comparison of the CSR procedure with the non-linear FE method are provided in [20].

Besides the thickness reduction of local structural elements, corrosion causes also global reduction of the ship cross sectional properties, the most important one being the hull girder section modulus (HGSM). The clear consequence of the reduction of HGSM is that the global hull girder stresses are increasing. Therefore, the structural capacity of the main deck decreases as a function of time, while the longitudinal hull girder stresses increase [21].

Information about the corrosion propagation and collapse strength may be analysed jointly to determine the optimal time for an inspection of the deck structure [3]. The procedure is presented in Figure 4, where the curves of the strength reduction and stress increase are presented. Time instant, when structural strength becomes lower than applied hull-girder stresses represent an optimal time for the inspection. Time to when deck plates fail by ultimate strength varies in a wide range, depending on the initial designs and the corrosion severity at both local plate and global hull girder.

Collapse analyses of plates and stiffened panels are determined following the CSR procedures. Green and red curves in Figure 4 represent decreasing of the collapse strength of the main deck plates and stiffened panels because of uniform corrosion. Two sets of results, for the mean (red lines) and extreme (green lines) thickness reductions are shown. The extreme thickness reduction represents corrosion wastage corresponding to 5% most corroded plates or stiffened panels. The extreme corrosion deduction in a certain ship age can be determined from the Weibull distribution, as presented in Figure 3. The blue curve in Figure 4 represents the main deck stress, which is increasing because of the progress of the overall general corrosion. When the green line crosses the blue line that means that the acting stresses exceed the strength capacity of 5% the most corroded plates of the main deck. It means that the strength of those panels is not satisfactory anymore and should be replaced [20].

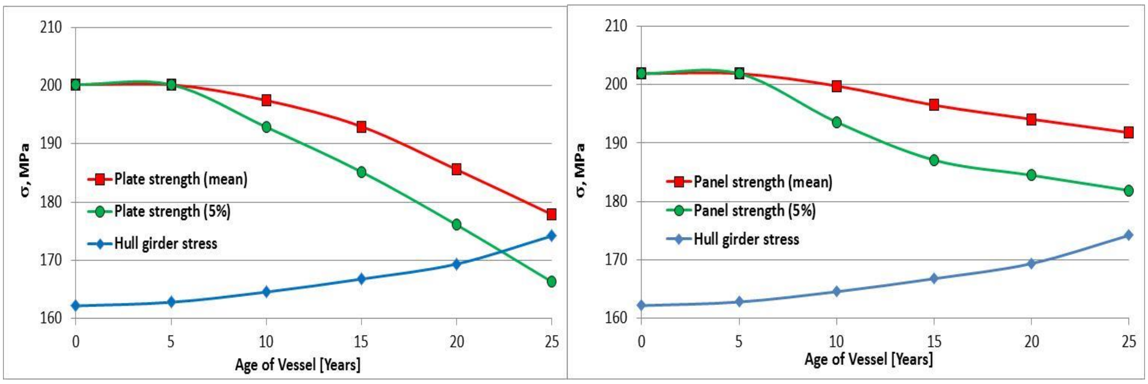


**Fig. 4** Safety margin of plates (left) and stiffener panels (right), COT

It may also be observed in Figure 4 that the ultimate compressive strength of the stiffened panels is considerably higher compared to the ultimate strength of the deck plates. That indicates an appropriate and redundant structural design of the deck structure as the unstiffened plate would always fail earlier than the stiffened panels.

### 3.2 Application of the Non-linear finite element method

The Nonlinear Finite Element method (NLFEM) is an important tool in the analysis of structures with the significant influence of geometric and material nonlinearities. Today NLFEM can be considered sufficiently developed for the use in a daily practice in the design of ship structures and in the assessment of the ultimate compressive strength of plates and stiffened panels. In the ultimate strength analysis of unstiffened plate and stiffened panel both types of nonlinearity appear: geometrical nonlinearity due to large deflection and material nonlinearity due to the nonlinear behaviour of material in the plastic region. The potential solving procedures for this nonlinear static problem are the iterative approximation, incremental method, Newton-Raphson iteration method, modified Newton-Raphson iteration method, and the arc length method [22]. In both cases of collapse analysis, of plates and stiffened panels, the NLFEM procedure consists in gradual application of forced displacement at one (short) edge of the model. The appropriate definition of mesh size, nonlinear material behaviour, boundary conditions and initial imperfections is essential, as discussed in the following paragraphs.

The nonlinear FEM is applied here in using the commercial software FEMAP with NX Nastran [23]. The model for an unstiffened plate is extended between the longitudinals along the longitudinal plate edges and between the transverse web frames along transverse plate edges, as has been shown in Figure 5. The typical element (mesh) size employed is 50×50 mm. This corresponds to about 16 elements in the shorter (transverse) direction and to about 80 elements in the longitudinal direction for an unstiffened plate of large oil tankers. An elastic-perfectly plastic model of material is applied using von Mises yield criteria without considering the effect of strain-hardening for the present NLFEM analysis. The boundary condition significantly affects the plate strength. One bay plate model is used in this study, where the plate is simply supported at longitudinal and transverse edges. This one bay model may be appropriate for uniaxially loaded rectangular plates, and can represent deck plating subjected to compressive load as a result of the bending moment in a ship sagging condition [24].

Welded metal structures during fabrications always have initial imperfections in the form of initial deformations and residual stresses [5]. Initial imperfections in elastic buckling mode with suitable magnitudes were chosen in the NLFEM analyses. The residual stress effect was excluded from the analysis.

The plate initial deformation magnitude is calculated by following equations:

$$w_{opl} = 0.1 \cdot \beta_E^2 \cdot t_{pl} \tag{4}$$

where $w_{opl}$ is the maximum magnitude of plate initial deformation, $t_{pl}$ is plate thickness, $\beta_E$ is the plate slenderness coefficient described in equation (3). The shape of the initial deformation is obtained by linear elastic buckling analysis.

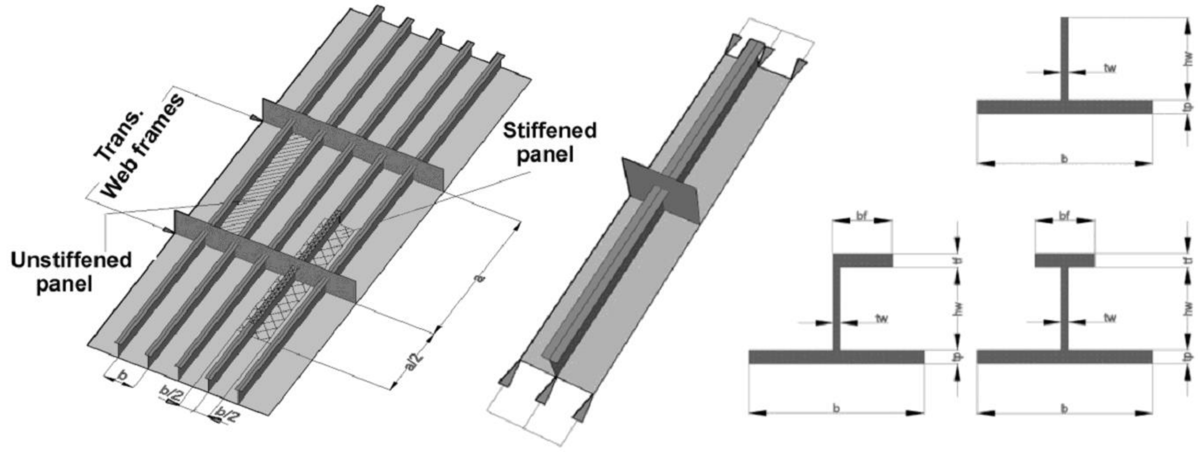


**Fig. 5** Stiffened panel under uniaxially compressive load

The extent of the model used for the stiffened panel is one half of the stiffener spacing on each side of the longitudinal in the transverse direction and half of the web frame spacing on each side of the web frame in the longitudinal direction, as shown in Figure 5. Symmetry boundary conditions are employed at all edges of the model, while vertical movement is restrained at the web frame location, i.e. at the mid-span of the model.

For stiffened panels, three types of initial deformation are considered [22]: the first one is plate initial deflection with maximum magnitude $w_{opl}=b/200$, and shape:

$$w_p = w_{opl} \cdot \cos\left(\frac{m \cdot \pi \cdot x}{a}\right) \cdot \cos\left(\frac{\pi \cdot y}{b}\right) \tag{5}$$

The second one is the beam-column initial deflection with maximum magnitude $w_{oc}=a/1000$, and shape:

$$w_o^c = w_{oc} \cdot \cos\left(\frac{\pi \cdot x}{a}\right) \tag{6}$$

The third one is sideways initial deflection of the stiffener web with maximum magnitude $w_{os}=a/1000$, and shape:

$$w_o^s = w_{os} \cdot \cos\left(\frac{\pi \cdot x}{a}\right) \cdot \sin\left(\frac{0.5 \cdot \pi \cdot z}{h_w}\right) \tag{7}$$

where *b* is the plate breadth along the short edge or spacing between the longitudinal stiffeners, *a* is $t_e$ plate length along the long edge, $h_w$ is the height of stiffener web, *m* is buckling half-wave number of the plate and can be assumed as $m=a/b$.

The model is tested by comparing NLFEM with two widely recognized methods for calculating the structural collapse (ultimate compressive strength) of unstiffened plates and stiffened panels. The first one is a simplified formula of the harmonized rules for the construction of oil tankers with double hulls (CSR), and the second one is the PULS program of the Classification Society DNV [25]. The comparisons are shown in Figure 6 for plates (left) and stiffened panels (right).

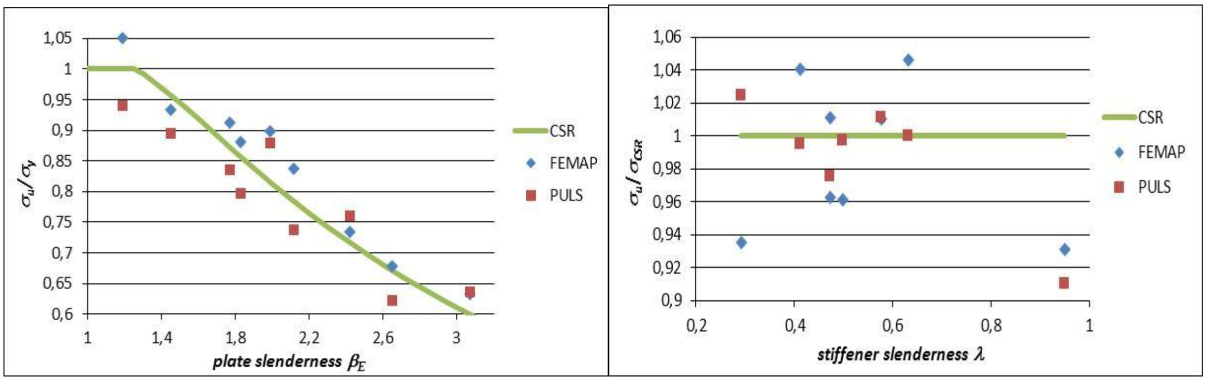
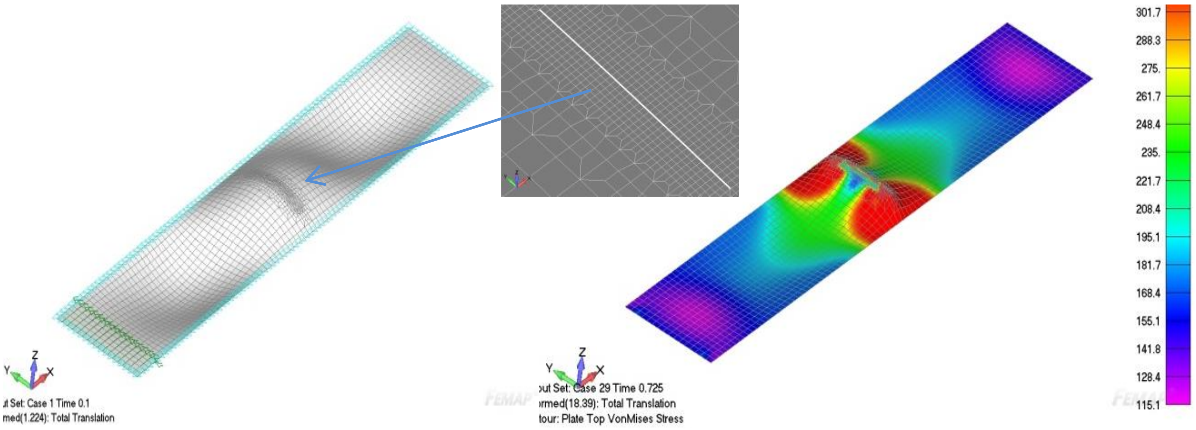


**Fig. 6** Ultimate compressive strength for plates (left) and stiffener panels (right)

It was shown that the developed NLFEM model is effective, applicable, and that it can be used in practice for an evaluation of non-corroded, and uniformly corroded plates and stiffened panels. The advantages of the NLFEM model compared to the analytical formulas of CSR rules and the program PULSE is its ability to change a number of parameters and load conditions that occur during ship's service life. The cracks of plates, cracks of stiffened panels, corrosion in welded joints (grooving), and pitting corrosion often appear in the structure after several years of ship in service. These conditions can be simulated using NLFEM, and then analysed the consequences on structural strength.

As an illustrative example, the model of the plate with a simulated fatigue crack has been shown on the upper left side of Figure 7. Cracks quite often appear in the aged structure after many years of ship in service, see the lower left side of Figure 7. The resulting von Mises stresses at the plate collapse are presented on the upper right side, and for the stiffener panel on the lower right side of Figure 7. It can be noticed that the stress increases in the area of the crack reaching limit condition values of 315 MPa, corresponding to steel AH 32 yield strength.



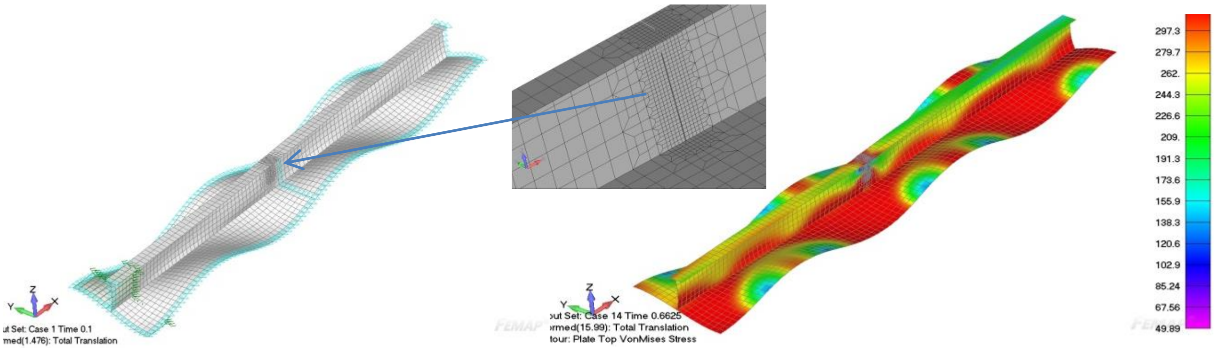


**Fig. 7** Cracks of deck plate and stiffener panel

Figure 8 presents the curves which describe the relationship of stress and strain for extreme loads acting before and after the collapse is reached ("Load-end shortening curves"). It can be noticed a degrading influence of cracks, not only on the ultimate strength, but on the shape of the curves also.

The different load–end shortening curves are shown in plates with crack in a length of 200 mm, 400 mm, and in intact plate on the left side of Figure 8. In the right side of Figure 8 are shown stiffener panel with a crack propagated in a way of a half and whole height of the longitudinal, as well as for an intact stiffened panel. In the pre-buckling regime the structural response between loads and displacement is linear for all curves. As load increases the plate and stiffener panel eventually reaches an ultimate limit state (ULS) due to expansion of the yielding region. A plate and stiffened panel with a large crack starts to deflect from the beginning and because of that buckling phenomena does not appear. ULS of the plate with a crack is normally smaller than of the intact one without a crack [26].

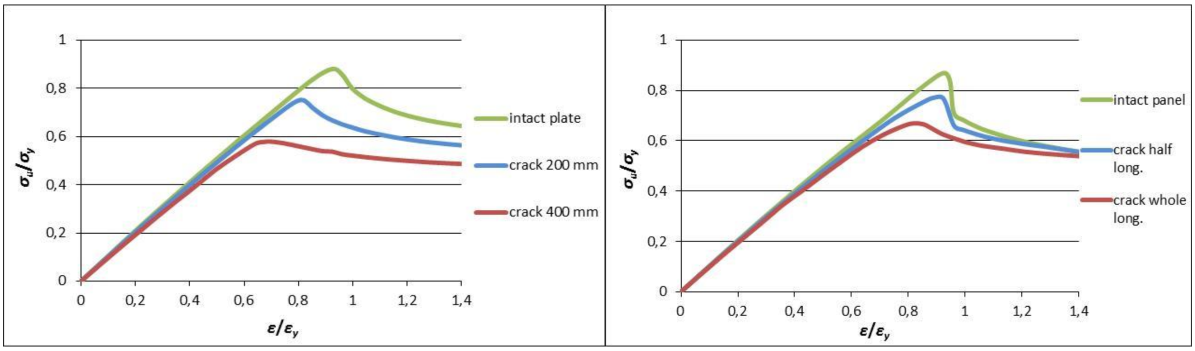


**Fig. 8** Load-end shortening curves (*σ – ε)* of deck plate (left side) and stiffener panel (right side) with and without the crack

## 3.3 Influence on the hull girder ultimate strength (HGUS)

The ultimate hull girder bending moment capacity (or hull girder ultimate strength – HGUS) is defined as the maximum bending moment of the hull girder beyond which the hull will collapse. This moment, generally between the elastic and the plastic moment, is the sum of the contribution of longitudinally effective elements, i.e. the sum of the first moments of the bending stresses around the horizontal neutral axes.

In this paper, two methods for the assessment of the ultimate longitudinal capacity of hull structure are used. The single step method and the progressive collapse analysis method (PCA) using program MARS [27]. Both methods are in accordance with the requirements of CSR DH OT [17], although it should be noted the single-step method has been omitted in the last harmonized version of CSR for tankers and bulk carriers [28]. In the single step method, DNV program PULS can be used for collapse assessment of the main deck panels. Another option is to use NLFEM results for such assessment, in which case non-uniform corrosion effects and fatigue cracks may be included.

HGUS under the effect of uneven corrosion wastages (grooving and pitting) and fatigue cracks is calculated in this work using the simplified procedure proposed in [29]. E.g. the anticipated crack of deck longitudinals is simulated using program MARS in a way that on the model of the midship cross-section one longitudinal is excluded from the HGUS analysis. The crack of deck plate can approximately be accounted for by neglecting the cracked plate. Pitting (uneven) corrosion is approximately modelled by further reducing the thickness of the deck plate with pitting in addition to the thickness decrease because of the uniform corrosion. The additional thickness decrease is estimated based on collapse analysis of isolated deck plates with pitting corrosion using NFEM [24]. The grooving, which occurs in the longitudinal welded joint of the web of deck longitudinal and the flange of deck longitudinal, is modelled by neglecting deck longitudinal flange. It has to be noticed that uniform corrosion wastage is deduced in each of described cases as a long-term function of time.

HGUS analysis is performed on one tanker hull, where details of the analysis are described in [30]. The results presented in Figure 9 confirmed that the degradation effects, such as uneven corrosion wastages (grooving and pitting) and fatigue cracks, could in some cases significantly reduce the global ultimate strength of hull structure [30].

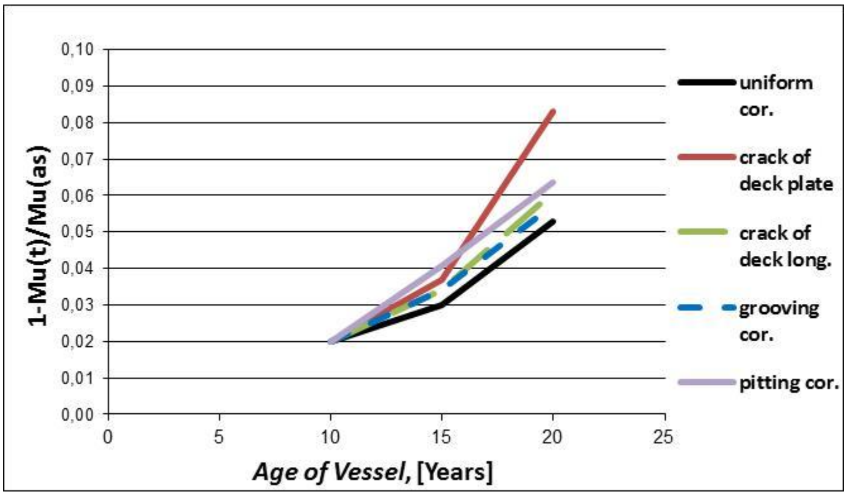


**Fig. 9** Calculated HGUS losses, for example, oil tanker due to uneven (pitting and grooving) corrosion and fatigue crack [30]

It can be seen from Figure 9 that the lowest impact on the HGUS, according to the present study has grooving corrosion, while in the cases of deck plate cracking, having the highest impact, the limit of HGUS with reference to well known "10%" requirement, can be reached between 20-25 years [29].

## 3.4 Influence of the degradation of mechanical properties

Recently a very intensive experimental work was performed in identifying the effect of corrosion on the mechanical properties of ageing marine structures. Corroded box girders have been tested for ultimate strength, showing an important reduction of mechanical properties. Further analyses have been performed using the tensile test specimens that have been cut from corroded box girders [19]. The analysis of the results from specimens confirmed changes in mechanical properties of the corroded steel. This phenomenon is likely based on the complex interaction of various mechanical and chemical processes. It was shown that the modulus of elasticity and yield strength of corroded shipbuilding steel reduces with time. The phenomenon is quite unexpected and still unexplained, as the grain size and chemical composition of the steel are not expected to change due to corrosion.

Further studies have been undertaken to investigate the consequence of such degradation on the local collapse strength of plates and stiffeners and on the ultimate strength of the hull - girder. The main particulars for example oil tanker are: length of 205 m, breadth of 48 m, depth of 19 m, draught of 13 m, and deadweight of 88000 tons. The vertical bending moment, as one of the most important criteria for longitudinal hull girder ultimate strength (HGUS) must be controlled during the ship's service. The result of HGSM's loss and a HGUS's loss for a corroded ship with and without degradation of mechanical properties of hull structure included, obtained using single step method calculations proposed by CSR DH OT [17] are shown in the Figure 10.

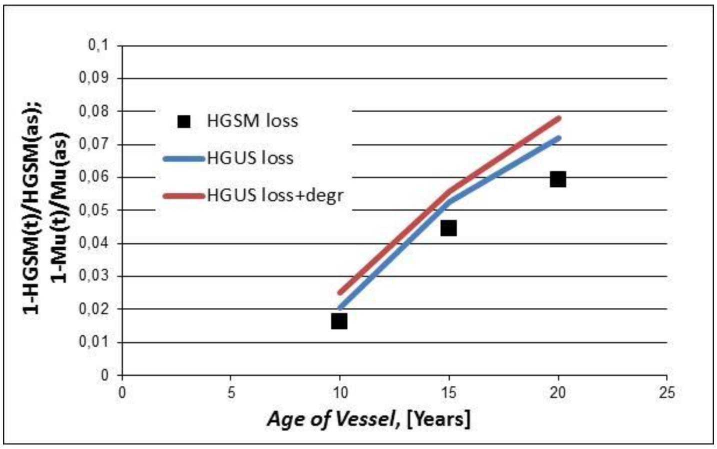


**Fig. 10** Measured HGSM losses and calculated HGUS losses, for example oil tanker [31]

It may be seen from Figure 10 that the degradation of mechanical properties has minor effect on the HGUS. The maximum difference in the reduction of hull girder ultimate strength by taking into account degradation of mechanical properties is about 1% of the initial HGUS, compared to the case when degradation is ignored. However, similar studies performed on plates and stiffened panels indicate that the influence of degradation on local collapse strength may be notified in certain cases. An on-going research on this subject deals with the influence of maintenance on the mechanical properties as well as to build more extensive database of results [6], [31].

## 4. Conclusion

The work presented and overview of some recent developments on the aging effects on the ship structural integrity. The focus was on the long-term prediction of corrosion wastage of ship structures as well as on the application of NLFEM for collapse strength assessment of plates and stiffened panels. Consequences of the recent researches regarding the modification of mechanical properties of the corroded steel are also assessed and commented.

The approach for corrosion prediction applied in this study is different compared to other similar studies, as herein an individual ship is considered, while in other similar studies whole fleets of ships are analysed together. The main goal of the present study was to fit non-linear corrosion deterioration models to measure corrosion thickness for 10 and 15 years of service life, and then to assess how well the corrosion deterioration after 20 years is predicted.

The increase of the deck stress due to the loss of HGSM was analysed and at the same time the reduction of the collapse strength of plates and stiffened panels of the main deck due to the negative effects of corrosion was determined. This simple method shows the point in time when it is expected that the applied stress will exceed the strength of stiffened panels of the main deck. The solution is to replace the corroded plating with a new one in order to avoid an unsafe zone for the aging ships.

Definition of the simple structural FE model that is applicable in everyday engineering practice, its boundary conditions and initial deformations as well as verification of such model represents an important part of the present study. The FE model was tested by comparing with two widely recognized methods for calculating the ultimate compressive strength: CSR method and PULS. The comparison between the results obtained by these three methods shows that a good match was achieved. The mean value of discrepancy of NLFEM compared to CSR is about 3.9%, while the maximal discrepancy reads about 10%. This confirms the reliability of the used finite element model (NLFEM). To illustrate the procedure, the crack of the deck plate and stiffened panel in a typical location for fatigue crack on the ship structure was modelled using NLFEM. In further research this method can be used together with the crack propagation analysis to be able to predict the consequences of the crack growth. In such case of a large crack, NFEM indicates large decrease of the panel ultimate strength [32].

The results of HGUS calculations show that local phenomena in some cases may seriously affect global longitudinal strength. HGUS is particularly sensitive to the fatigue cracks in the main deck plating. Other local degradation effects are less important in this example, but that conclusion should be taken with care rather then as a general rule.

Recently found phenomenon of decreasing mechanical properties of corrosion steel causes a minor reduction of the hull girder ultimate strength. The influence on the ultimate strength of the plates and stiffened panels could be more important.

Implementation of the research can be a useful tool for ship owners and classification societies in: prediction of the corrosion wastage of HGSM until the next periodical special survey (5 years), assessment of the hull ultimate strength of next hull inspection, and applicability of local corrosion for the inspection of the deck’s stiffened panel.

It should be clarified that this study was applied on oil tankers and application of presented results to other ship types should be done with caution. The presented analysis may be applied individually for a specific vessel after proper assessment of the type of corrosion and the level of reduction of the mechanical properties of construction materials.

## 5. Acknowledgements

This work has been fully supported by Croatian Science Foundation under the Project 8658.

## REFERENCES

[1] Wang, G., Boon, B., Brennan, F., Garbatov, Y., Ji, C., Parunov, J., Rahman, T., Rizzo, C., Rouhan, A., Shin, C. and Yamamoto, N. Committee V.6 Condition Assessment of Aging Ships and Offshore Structures. In: 17th International Ship and Offshore Structures Congress (ISSC 2009), Vol. 3. C. Jang and J. Hong, (Eds.), Seoul, South Korea University of Seoul, 2009.

[2] Hess, P., Aksu, S., Blake, J., Boote, D., Caridis, P., Egorov, A., Fjeldstad, A., Hoogeland, M., Murayama, H., Rye Anderson, M., Tammer, M. Committee V.7 Structural Longevity. In: 19th International Ship and Offshore Structures Congress (ISSC 2015), Guedes Soares and Garbatov (Eds.), Cascais, Portugal, Taylor & Francis Group, London (UK), 2015.

[3] Guo, J., Wang, G., Ivanov, L., Perakis, A. 2008. Time-varying ultimate strength of aging tanker deck plate considering corrosion effect. Marine Structures 21. 402–419. https://doi.org/10.1016/j.marstruc.2008.03.002.

[4] Paik, J.K., Melchers, R.E. (Eds.), "Condition assessment of Aged Ship" structures", CRC Press; Cambridge, England: Woodhead Pub, 2008.

[5] Zhang, S., Khan, I. "Buckling and ultimate capability of plates and stiffened panels in axial compression", Marine Structures, vol. 22, No.4, 2009, pp 791-808. https://doi.org/10.1016/j.marstruc.2009.09.001.

[6] Garbatov, Y., Parunov, J., Kodvanj, J., Saad-Eldeen, S., Guedes Soares, C. "Experimental assessment of tensile strength of corroded steel specimens subjected to sandblast and sandpaper cleaning". Marine Structures, vol.49, 2016, pp 18-30. https://doi.org/10.1016/j.marstruc.2016.05.009.

[7] Guedes Soares, C. & Garbatov, Y., 1999, "Reliability of Maintained, Corrosion Protected Plate Subjected to Nonlinear Corrosion and Compressive Loads," Marine Structure, 12, pp.425–445. https://doi.org/10.1016/S0951-8339(99)00028-3.

[8] Guedes Soares, C., Garbatov, Y. & Zayed, A., 2011. Effect of environmental factors on steel plate corrosion under marine immersion conditions. Corrosion Engineering, Science and Technology 46, pp. 524-541. https://doi.org/10.1179/147842209X12559428167841.

[9] Melchers, R.E, 2008. Development of new applied models for steel corrosion in marine applications including shipping. Ships and Offshore Structure, 3:2, pp.135-144. https://doi.org/10.1080/17445300701799851.

[10] Yamamoto, N. & Ikagaki, K., 1998. A Study on the Degradation of Coating and Corrosion on Ship´s Hull Based on the Probabilistic Approach. Journal of Offshore Mechanics and Arctic Engineering 120, 121-128. https://doi.org/10.1115/1.2829532.

[11] Garbatov, Y.; Guedes Soares, C., & Wang, G. 2007. Nonlinear Corrosion Wastage of Deck Plates of Ballast and Cargo Holds of Tankers. Journal of Offshore Mechanics and Arctic Engineering. 129(1):48-55. https://doi.org/10.1115/1.2426987.

[12] Jurišić, P., Parunov, J., Garbatov, Y. 2014. Comparative analysis based on two nonlinear corrosion models commonly used for prediction of structural degradation of oil tankers. Transactions of FAMENA. 38, 2; pp.21-30.

[13] Garbatov Y, Guedes Soares C. 2009. Structural maintenance planning based on historical data of corroded deck plates of tankers. Reliability Engineering & System Safety. 94: pp. 1806-1817. https://doi.org/10.1016/j.ress.2009.05.013.

[14] Parunov, J., Žiha, K., Mage, P., "Corrosion wastage of oil tankers – A case study of an aged ship", Maritime Industry, Ocean Engineering and Coastal Resources, C. Guedes Soares and P Kolev, (Eds.), Taylor & Francis Group, London (UK), pp. 271-276; 2007.

[15] Jurišić, P. Parunov, J, Žiha, K., "Uncertainty in corrosion wastage prediction of oil tankers", IMAM 2011, Guedes Soares & Rizzuto E., Taylor & Francis Group, London (UK) vol.1, pp 395-401; 2011.

[16] Ćorak, M., Parunov, J., Teixeira, A.P., Guedes Soares, C., "Performance of the Common Structural Rules design formulations for the ultimate strength of uniaxially loaded plates and stiffened panels", in: Advanced Ship Design for Pollution Prevention, Guedes Soares & Parunov (Eds.), Taylor & Francis Group, London (UK), pp 113-120; 2010.

[17] AMERICAN BUREAU OF SHIPPING, DET NORSKE VERITAS, LLOYD'S REGISTER, "Common Structural Rules for Double Hull Oil Tankers", 2010.

[18] Faulkner, D., "A review of effective plating for use in the analysis of stiffened plating in bending and compression", Journal of Ship Research, 19:1-17 1975.

[19] Garbatov, Y., Guedes Soares, C., Parunov, J., Kodvanj, J. 2014, Tensile strength assessment of corroded small scale specimens. Corrosion Science. Vol. 85. pp. 296-303. https://doi.org/10.1016/j.corsci.2014.04.031.

[20] Jurišić, P., Parunov, 2015. Influence of corrosion-related degradation of mechanical properties of shipbuilding steel on collapse strength of plates and stiffened panels. Towards Green Marine Technology and Transport. Guedes Soares, C.; Dejhalla, R.; Pavletić, D. (Eds.). Taylor & Francis Group, London (UK), 427-432.

[21] Wang, G., Lee, A., Ivanov, L., Lynch, T., Serratella, C., Basu, R., "A statistical investigation of time-variant hull girder strength of aging ships and coating life", Marine Structures, vol. 21, 2008, pp 240-256. https://doi.org/10.1016/j.marstruc.2007.10.002.

[22] Hughes, O. S., Paik, J.K., "Ship structural analyses and design", SNAME, New Jersey 2010.

[23] "FEMAP/NX NASTRAN ver.10.0", Structural Dynamics Research Corporation, Exton (USA) 2001.

[24] Jurišić, P., "Ultimate Hull Girder Strength of an Aging Ship", Ph.D. thesis, Faculty of Mechanical Engineering and Naval Architecture – Zagreb, 2012 (in Croatian).

[25] DET NORSKE VERITAS, "PULS ver. 2.0.6, User's manual - software for buckling checks of stiffened plate elements and shells", Oslo (Norway) 2006.

[26] Garbatov, Y., Guedes Soares, C., Parunov, J. 2014. Fatigue strength experiments of corroded small scale steel specimens. International Journal of Fatigue. 59; 137-144. https://doi.org/10.1016/j.ijfatigue.2013.09.005.

[27] BUREAU VERITAS, "MARS software 2000", Paris (France) 2003.

[28] Harmonized Common Structural Rules for Bulk Carriers and Double Bottom Tankers, International Association of Classification Societies, London, UK, 2014.

[29] Paik, J.K., Thayamballi, A. K., "Ship-shaped offshore installation: Design, Building and Operation", Cambridge University Press, New York (USA) 2007. https://doi.org/10.1017/CBO9780511546082.

[30] Jurišić, P., Parunov, J., "Hull girder ultimate strength of aging oil tankers", SORTA, Baška-Krk, Croatia 2014

[31] Jurišić, P., Parunov, J., "Consequences of age-related degradation of mechanical properties of steel on ultimate strength of ship hull", SORTA, Trogir, Croatia 2016.

[32] Paik, J.K., Satish Kumar, Y.V. and Lee, J.M. 2005. "Ultimate strength of cracked plate elements under axial compression or tension", Thin-Walled Structures 43. 237–272. https://doi.org/10.1016/j.tws.2004.07.010.

Submitted: 07.12.2016.
Accepted: 26.01.2017.

Paul Jurišić, Paul.Jurisic@crs.hr
Croatian Register of Shipping, Split, Croatia
Joško Parunov
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia
Yordan Garbatov
Centre for Marine Technology and Engineering, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal