Postprint of: Wołoszyk K., Garbatov Y., Corrosion degradation impact on mechanical properties of structural steel, Advances in the Analysis and Design of Marine Structures. Proceedings of the 9th International Conference on Marine Structures (2023), pp. 751-757

Advances in the Analysis and Design of Marine Structures – Ringsberg & Guedes Soares (Eds)
© 2023 The Author(s), ISBN 978-1-032-50636-4

Corrosion degradation impact on mechanical properties of structural steel

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ABSTRACT: Recently, extensive research was conducted regarding the impact of corrosion degradation on the mechanical properties of structural steel. Studies show that at the material level, the microstructure is somewhat unchanged due to corrosion degradation. However, the corrosion causes pits and structural surface irregularities that consequently impact the mean stress-strain response of typical coupon specimens subjected to tensile loading. Regrettably, the current industrial standards do not account for that phenomenon and treat the impact of corrosion degradation as the uniform thinning of the structural steel. The presented work aims to acknowledge the recent studies regarding the impact of corrosion degradation on the mechanical properties of structural steel, to show future perspectives and to outline the need for more research in this field.

1 INTRODUCTION

Many structures are subjected to a severely corrosive environment (Melchers 1999). This includes, e.g., ships and offshore structures, civil structures (such as bridges), etc. Usually, the structural elements are protected from corrosion by applying a particular coating type. Proper maintenance should typically lead to the detection of coating breaking and re-introducing effective coating. However, it is not always straightforward, and many reasons exist. Primarily, some areas are hard to access during the inspection, and proper cleaning and painting are tough (Zayed *et al.* 2008). Due to that, corrosion is allowed in ships to some extent, governed by the so-called corrosion additions stipulated by the International Association of Classification Societies (2018). A similar condition is allowed in terms of bridges (Křivý 2012). However, in this case, the values of corrosion allowance may vary depending on the local rules.

Since corrosion deterioration is considered an operational condition for various structures, its impact should be included in design codes. This is typically done by performing structural analysis during the design stage, including the so-called 'net thickness'. The 'net thickness' is the design thickness reduced by the corrosion allowance/ corrosion addition value. Thus, it is considered that corrosion degradation is a process that causes the perfectly uniform thinning of the corroded structural component. This approach is very convenient, especially when performing computations using closed-form solutions or simulations using FEM. Moreover, it does not significantly impact the well-established calculation procedures in the Rules of Classification Societies. When only thickness change is considered, the closed forms derived for non-corroded components could be used directly.

Although considering corrosion degradation in a simplified way is helpful in design codes, it should not always reflect the fundamental nature of this complex process and its impact on the structural response. Due to that, many studies tend to evaluate the impact of corrosion degradation on the structural response over the last decades, e.g. (Saad-Eldeen *et al.* 2015, Woloszyk & Garbatov 2023). Recently, it was found that corrosion degradation may significantly impact the structural response of small-scale steel specimens subjected to tensile loading. Some of the first works outlining that issue could be found regarding bars (Almusallam 2001) and flat specimens (Garbatov *et al.* 2014). When mechanical properties (i.e. Young's modulus, yield stress, ultimate tensile strength and total elongation) were evaluated and mean thickness was considered to calculate them, they were smaller than the mechanical properties of non-corroded steel.

Additionally, with the increase in degradation level, the mechanical properties decreased. When corrosion causes the perfectly uniform thinning of the specimen, the mechanical properties evaluated based on the mean thickness should be like the non-corroded material. In the initial stage of this research direction, the origin of this phenomenon was not clearly explained.

Many new studies investigating this problem have been published in recent years, as given in the

DOI: 10.1201/9781003399759-83

presented review. This included different types of corrosion environments (marine immersed, atmospheric, etc.), specimens or steel grades. However, there is a lack of a comprehensive review that will summarize the findings and outline future research needs.

The present work aims to review the recent findings regarding the impact of corrosion degradation on the mechanical properties of structural steels. There are many studies regarding bars, but since they are used mainly as reinforcement for concrete structures and the corrosion process is different, the present work focuses mainly on flat specimens.

Firstly, the origin of this phenomenon is discussed, and different hypotheses existing in the literature are outlined. Then, the experimental works dealing with small-scale testing coupons, including different corrosive environments, are reviewed. The main common findings and differences are discussed.

Further, the numerical modelling techniques that account for corrosion impact on the structural response of steel specimens are reviewed. The difficulty of uncertainty determination inherent in mechanical properties is also discussed. Finally, the main conclusions are outlined, and future research directions are suggested.

2 ORIGIN OF MECHANICAL PROPERTIES REDUCTION

Various hypotheses have been introduced to explain the reason for corroded steel's decreased mechanical properties. The possible hypotheses outlined by various studies can be summarized as follows:

- The variability in the geometry of corroded specimens (H1) (Appuhamy *et al.* 2011);
- The stress concentration due to local corrosion pits (H2) (Garbatov *et al.* 2014);
- The possible impact on the steel microstructure (H3) (Wu *et al.* 2019).

The idea that stays behind the first hypothesis (H1) is that corrosion impacts the specimen's geometry because cross-sections vary. The minimum thickness determines the actual strength. Since the minimum cross-section could be at least the same as the mean one, it will decrease strength (yield stress and tensile strength) and stiffness (Young's modulus). However, a significant reduction in the total elongation was also observed in many experiments.

The second hypothesis (H2) is related to the local variations of plating geometry due to corrosion degradation. In comparison to the first hypothesis, in that case, the cross-section area could not even vary much concerning the mean cross-sectional area (since we can have regions of higher and lower diminutions in one cross-section, that will compensate). However, the corrosion pits spread within specimens will cause multiple points of stress concentration that will lead to the premature yielding and breaking of the specimen. Notably, the effects described in the first and second hypotheses may act simultaneously.

Finally, the last hypothesis (H3) says that corrosion not only causes superficial penetration of the material but also impacts the microstructure of the steel. This could result in, e.g. weaker intergranular connections, etc. In that sense, this will cause the reduction of mechanical properties on the material level.

The first two hypotheses describe the change in mechanical properties on the specimen scale. Thus, if we cut a tiny piece of material and test it, we should get the properties of intact material. The third hypothesis, on the contrary, claims that even on this microscopic scale, the mechanical properties are reduced. This could have a potentially significant impact on the design procedures. This means that the properties will inevitably be reduced even if we allow the elements to corrode and clean them after some time.

Several studies investigate which hypothesis is most probable and which may be classified as experimental and numerical. The following two sections present a review of these studies, and the findings are summarized concerning the discussed hypotheses.

3 EXPERIMENTS

3.1 *Marine corrosion*

One of the first experiments on coupon steel specimens was performed by Garbatov *et al.* (2014). The specimens (see Figure 1) were cut from the thin-walled corroded box girder corroded in the open sea environmental condition with the additional application of an electric current (Domzalicki *et al.* 2009).

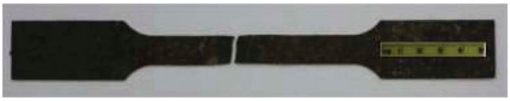

Figure 1. Typical corroded coupon (Garbatov *et al.* 2014).

The main conclusion was that the corrosion causes a decrease in all significant mechanical properties (i.e. yield stress, Young's modulus, ultimate tensile stress and total elongation). However, the study was quite preliminary, and several issues could be outlined. Firstly, the initial mechanical properties were not identified. Thus, the results seemed surprising in regions up to 40% of the degradation level. The yield stress, for example, was higher than the assumed initial one (considered equal to the minimum for this type of steel). Secondly, the specimens were quite heavily corroded, and in the case of structures in operation, that level of degradation is usually not allowed. Finally, the corrosion was accelerated using a DC source, and several studies showed that this could lead to slightly different strength characteristics compared to the natural corrosion process (Yuan *et al.* 2007).

Further studies of that research group included similar specimens, but some were cleaned from corrosion products using different techniques (Garbatov *et al.* 2016). It was found that applying some cleaning techniques (i.e., sandblasting and sandpaper cleaning) will lead to enhance mechanical properties compared to corroded, non-cleaned specimens. The most probable reason for that is the 'smoothing' of the corroded surface, which reduces stress concentration levels. This also supports the second hypothesis (H2) of the origin of changes in mechanical properties. The stresses coming from the cleaning method were not verified in that study. However, since isolated specimens were subjected to cleaning (they could expand freely) and this is mainly a surface process, rather marginal residual stresses were introduced, not influencing the results.

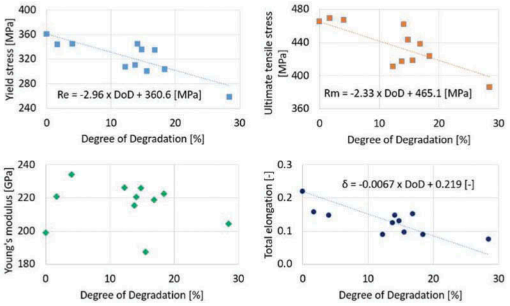

Figure 2. Changes in mechanical properties (Woloszyk *et al.* 2022).

Recent studies regarding the impact of marine immersed corrosion on mechanical properties were reported by Woloszyk *et al.* (2022). The last gaps identified above were covered. Thus, the corrosion testing was performed in the laboratory without applying a DC source. Only natural factors were controlled, i.e. oxygen saturation level, water velocity and temperature. Further, the focus was to investigate the degradation level below 25% of the original thickness, and the mechanical properties of non-corroded steel were identified. It was found that yield stress, ultimate tensile stress and total elongation are reduced even for lower degradation levels. However, the results related to Young's modulus were inconclusive (see Figure 2).

Another recent study was presented by Vukelic *et al.* (2022). In this case, the welded tensile steel specimens of increased strength were evaluated and subjected to different corrosion environments: freshwater, natural seawater and splash zone (mixed seawater with air). The total time of exposure was equal to 24 months. It was found that the fastest progress of corrosion degradation was in the splash zone, where approx. 8% of the mass loss was noted. In all cases, a significant reduction in yield strength was observed. Additionally, the Charpy tests were performed, showing that breaking energy is reduced, too, due to corrosion degradation.

The mechanical properties of Q690-type steel were performed in (Guo *et al.* 2021). The marine splash corrosion degradation was accelerated in the laboratory using the infiltration-humidity-drying cycle method. Thus, the specimens are soaked in NaCl solution and placed in a humid curing box. Then, the cycles were repeated, and the maximum mass loss obtained was equal to 7%. The conclusions were similar to those obtained in previous research, and mechanical property decreased. Additionally, they evaluated the hysteretic behaviour of corroded steel, showing that energy dissipation capacity gradually decreases with the increase of mass loss ratio.

In the case of marine immersed corrosion, there is still a lack of more extensive studies, and most studies related to that field have been reported in recent years.

3.2 *Atmospheric corrosion*

The impact of atmospheric corrosion on the residual strength of steel specimens was studied by Wang *et al.* (2017), where coupons were cut from a naturally corroded truss after eight years of exposure. The detailed 3D reconstruction of the surfaces of the corroded specimens showed that corrosion was quite 'uniform' in this case. Nevertheless, the impact on mechanical properties was observed. In conclusion, they suggested that strength loss is mainly due to the reduction in cross-section area, where elongation is due to stress concentration. Thus, they supported two hypotheses (H1 and H2) simultaneously as a reason for mechanical properties reduction.

In a study by Xiao *et al.* (2020), the salt spray accelerated corrosion (simulating atmospheric corrosion) was compared with electrochemical corrosion (accelerated with a DC source). It was observed that the corrosion method impacts the failure behaviour of specimens. It was also found that in the case of electrochemically induced corrosion, the highest stress was observed in the weakest cross-section. There were multiple points of stress concentration for salt-spray corrosion, relatively evenly distributed within specimens. Thus, both hypotheses of changes in mechanical properties (H1 and H2) were supported in that study.

The comparison between the mechanical properties of structural steel subjected to urban atmosphere corrosion and wet/dry cyclic corrosion was presented by Wu *et al.* (2019). Similarly, as with other studies, the degradation of mechanical properties was evident for both corrosion conditions, and reduction levels were quite similar. However, the authors also analyzed cross-sections of the corroded specimens using an SEM microscope. The three layers of corrosion impact could be classified: outer layer (containing the loose corrosion products), inner layer (transition between corrosion products and base material) and base material zone. It was found that corrosion does not impact the base material.

On the other hand, the thickness of the transition zone is shallow compared to the total specimen thickness. Thus, this shows that mechanical properties reduction is not caused by the impact of properties on the material level (rejecting partially hypothesis H3). However, in the transition zone, many micro-cracks could be found that could be dangerous from the fatigue point of view.

The findings of Wu *et al.* (2019) were similar to those of Jia *et al.* (2020). In this case, the behaviour of new-type weathering steel was studied, subjected to accelerated atmospheric corrosion. In this case, they used an X-ray diffraction test to see the cross-section of the corroded specimens. Similarly to SEM images from the study of Wu *et al.* (2019), the three layers can be distinguished, i.e. base material, transition zone and a layer of loose corrosion products. Further, the base material is intact (no porosity is observed). The thickness of the transition zone does not exceed 0.3 mm for both studies. Thus, the loss of mechanical properties is governed by stress concentration for relatively thick specimens. Although the impact of corrosion degradation on the material porosity in the transition zone is not unsafe for thicker specimens, it could impact thin plating.

The mechanical properties of cold-form steel subjected to natural atmospheric corrosion were studied by Nie *et al.* (2019). In this case, fragile specimens of an initial thickness of 1 mm were tested. A dramatic loss for all material properties was observed, and for 40% of mass loss, the yield strength decreased by approximately 80%. Further, the observed failure modes for higher corrosion levels were similar to those obtained for brittle materials.

Recently, the study of the corrosion behaviour of high-strength steel subjected to atmospheric corrosion was presented by Li *et al.* (2022). In this case, even though a shallow corrosion degradation level was achieved (about 2.3%), the loss of mechanical properties was quite significant. The authors indicated that significant pitting occurred from the beginning of the corrosion progress.

3.3 *Analysis*

To compare the results obtained by various researchers, Table 1 contains the studies that experimentally investigated the impact of corrosion degradation on the mechanical properties of structural steel. For not comparing all mechanical properties, the yield strength was chosen as a comparative control factor since it is essential from a structural safety point of view (typically, the maximum allowable stress in the structure is determined based on the yield strength).

It can be noted that most of the studies investigated the corrosion degradation of mild steel specimens. This is reasonable since it is still the most used structural material. Other studies investigated diverse types of higher-strength steels. Further, most of the studies dealt with atmospheric corrosion degradation. This corrosion degradation can be found primarily in civil engineering (urban atmosphere) and offshore structures. The remaining studies investigated marine corrosion, considering constant immersion or dry/wet cyclic conditions (splash zone). This type of corrosion is typical for ships.

Regarding the impact of specific corrosion conditions on the reduction of mechanical properties, it isn't easy to draw general conclusions. Firstly, the reference thickness used to calculate the mechanical properties differs. Some studies used initial thickness, and some of them used average thickness. In a study by Wang *et al.* (2017), the maximum residual thickness was used, i.e. peak thickness from the entire specimen measured using 3D scanning. However, some studies give no information about reference thickness, which is crucial.

Table 1. Comparison between studies in yield strength reduction.

Study	Corrosion type	Steel type	t_0 [mm]	RT	MML [%]	YSR [%]	Supported H
Garbatov *et al.* (2014)	A, DC, Marine, I	Mild steel	4	Average	70	36	H1
Woloszyk *et al.* (2022)	A, Marine, I	Mild steel	5 – 8	Average	25	10	H1
Vukelic *et al.* (2022)	N, marine splash	AH36	12	Average	8	12	H1
Guo *et al.* (2021)	A, marine splash	Q690	10	Not given	7	5	H1
Wang *et al.* (2017)	N, atmospheric	Mild steel	6 – 9	Max. residual	34	17	H1 and H2
Xiao *et al.* (2020)	A, atmospheric	HPS	8	Initial	24	50	H1 and H2
Xiao *et al.* (2020)	A, DC, immersed	HPS	8	Initial	29	60	H1 and H2
Wu *et al.* (2019)	N, atmospheric	Mild steel	6	Not given	9	14	H1
Wu *et al.* (2019)	A, atmospheric	Mild steel	6	Not given	10	12	H1
Nie *et al.* (2019)	N, atmospheric	Mild steel	1	Initial	40	77	H1
Li *et al.* (2022)	N, atmospheric	30CrMnSi	3	Initial	2.3	7.7	H1

A - accelerated, N - natural, DC - DC source accelerated, I –immersed, t_0 - initial specimen thickness, RT - reference thickness for calculation of mechanical properties, MML - maximum mass loss, YSR - yield strength reduction, H - hypothesis

In most studies presented in Table 1, simplified models to estimate the loss of mechanical properties were developed too (see, e.g. Figure 2). This allows for predicting the loss in mechanical properties, considering a specific mass loss ratio. This could be very useful in terms of structural modelling. The applications of such models can be found, e.g. in Woloszyk *et al.* (2018) or Wang *et al.* (2020). In both cases, the structural elements (stiffened plates in the first case and beams in the latter) were modelled using the Finite Element Method. The corrosion degradation was considered a simultaneous reduction in thickness and mechanical properties, leading to very good results compared to experiments.

Concerning the hypotheses outlined in Section 3, all the studies directly supported hypothesis H1 by measuring the specimens' geometry and showing a direct linkage between cross-sectional loss and mechanical properties. Additionally, two studies verified positive hypothesis H2 by additional FE simulations and measurements using Digital Image Correlation Technique. Nevertheless, other studies also supported that hypothesis without direct verification. Finally, hypothesis H3 was rejected in the study of Wu *et al.* (2019) by X-ray scanning showing that the properties of the base material are rather not changed.

4 NUMERICAL MODELLING

Apart from the main focus of investigating the mechanical properties being oriented mainly in experiments, the authors also model the structural behaviour numerically. The Finite Element method mainly represents the corroded specimens' structural behaviour. In Wang *et al.* (2017), the surfaces of the corroded specimens were measured, and the FE models representing the experimentally corroded specimens were introduced. Both stress-strain curves and strain distributions were compared to compare the experimental and numerical results. The strains in experiments were measured using DIC (Digital Image Correlation) technique, and perfect similarity was obtained with FE modelling, e.g. zones of high strain (stress) concentration were correctly identified.

Due to the long duration of corrosion testing, some efforts were made towards simulation techniques that could represent the corrosion morphology in steel specimens. One of the possible techniques is random field modelling (Li & Der Kiureghian 1993), which is the set of random variables correlated spatially. Such a technique was used by Woloszyk & Garbatov (2020), where corrosion impact was modelled using this method. By controlling the parameters of the random fields, different types of corrosion could be modelled with either more shallow or more deep pitting (see example in Figure 3). This depends on the strength of the correlation between single thickness points.

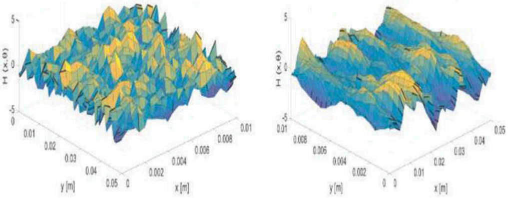

Figure 3. Random field with weak (left) and strong (right) correlation (Woloszyk and Garbatov 2020a).

In this case, the methodology was validated against the experimental results of Nie *et al.* (2019), showing some differences for a higher mass loss ratio. The further development of that method was presented in (Woloszyk & Garbatov 2020b), where additional sensitivity studies were performed to establish what parameters of the random field are influencing mainly resulting mechanical properties. The results were compared with the experiments of Wang *et al.* (2017), showing very good agreement. Finally, the comparison between the experiment (presented by Woloszyk *et al.* (2022)) and two numerical models was presented by Woloszyk & Garbatov (2022).

The first numerical model represented the corroded surfaces of the specimens based on microscope scenes. Thus, there were geometrical representations of the corroded specimens. The second numerical model accounted for the corroded surfaces generated using random fields satisfying the statistical parameters obtained from scans. An example of the comparison of the results is presented in Figure 4. Based on the results, it is noted that the regression tendencies between models are similar. However, there are observed notable differences in single points. Nevertheless, the credibility of this methodology was presented.

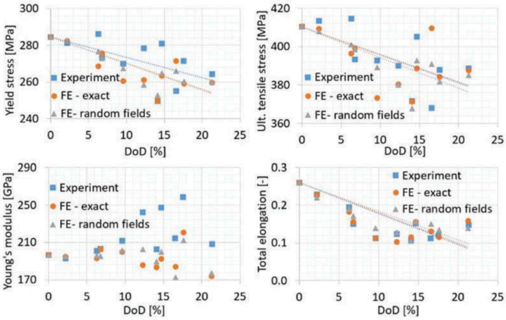

Figure 4. Numerical modelling and experiment in mechanical properties of 6 mm specimens (Woloszyk and Garbatov 2022).

Random field modelling was furtherly adopted in the study of Wang *et al.* (2022) and based on the significant number of samples. They formulated the functions to determine the changes in mechanical properties.

5 UNCERTAINTIES

The final problem that should be discussed when dealing with the impact of corrosion degradation on mechanical properties is the introduced uncertainties. Typically, the uncertainties can be divided into aleatory (inherent) and epistemic (Ditlevsen & Madsen 1996). The first type is related to the phenomenon investigated here, and this uncertainty cannot be reduced (e.g. nature of corrosion). The second is related to modelling and measuring techniques, and here this uncertainty can be reduced by providing more accurate models and more accurate measuring techniques.

Regarding the subject analyzed within this work, two types of aleatory uncertainties can be identified, i.e. the uncertainty related to the corrosion degradation, which may cause different morphology of the corroded surfaces for the same mass loss ratio.

The second inherent uncertainty is related to the mechanical properties of the intact material. Even for the same steel plate, the mechanical properties may vary for different specimens cut from different regions of the original plate.

The uncertainty level seen from experiments is presented as an example in Figure 5. The normalized yield strength (related to initial yield strength) is a degradation level function. It is noted that there is a certain uncertainty level for non-corroded specimens. Thus, it is related to the inherent uncertainty of mechanical properties. However, with the increase in the degradation level, the uncertainty also increases. This is justified since, for higher corrosion levels, possible uncertainties due to corrosion characteristics will increase as well.

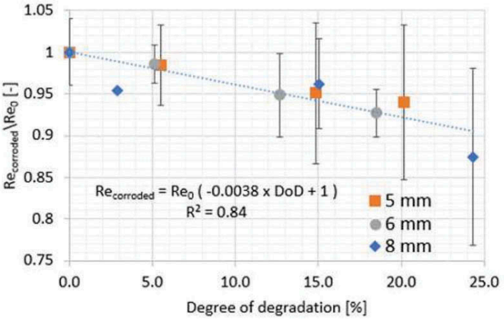

Figure 5. Normalized yield strength as a function of degradation level (Woloszyk *et al.* 2022).

Similar observations were made in (Vukelic *et al.* 2022), where with the increase in the degradation level, the uncertainties in the tensile strength increased also.

6 CONCLUSIONS

In the presented study, recent investigations were revised regarding the impact of corrosion degradation on the mechanical properties of structural steel. Based on the experimental results, it could be concluded that the impact of corrosion degradation on mechanical properties originated from the localized non-uniformities of the plating surface. This causes multiple stress concentration points, which lead to premature yielding and breaking of the specimens. The corrosion degradation has no impact on mechanical properties at the material level, shown in SEM and X-ray scans of the cross-sections of the specimens.

It is noted that the research topic has been exciting recently, and most of the referred studies have been performed within the last three years. In each study, a significant reduction of mechanical properties was observed. However, still more general conclusions cannot be withdrawn. One of the main reasons is the lack of standard procedures, e.g. different studies use different reference thicknesses to calculate the mechanical properties, and some authors did not indicate which one was used. Nevertheless, still more studies are needed.

The following research questions remain open: is there any effect of steel type, the initial thickness of the specimen or the type of corrosive environment? Notably, more studies were investigating atmospheric corrosion compared to marine corrosion. On top of that, the experimentally measured mechanical properties are subjected to a significant uncertainty level.

The focus of future research should also be aimed at the quantification of such uncertainties.

Finally, some research was also focused on the numerical modelling of the corrosion process. The random fields were found to be a very effective tool. However, more calibration is still needed to use this tool universally.

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