Time-Dependent Corrosion Wastage Model for Wrought Iron Structures

F. Rizzo[1]; G. Di Lorenzo[2]; A. Formisano[3]; and R. Landolfo[4]

Abstract: Damage due to atmospheric corrosion on metal structures is a significant aspect for both the design of new construction and the maintenance of existing buildings. This problem is particularly felt for nineteenth-century wrought iron constructions, because of both lack of proper maintenance and architectonic value. The main objective of the current paper, framed within a more comprehensive research project, is to provide a time-dependent model able to predict the corrosion wastage thickness on historical metal structures as a function of the protection coating life variability and its renovation cycles. Average damage curves, calculated on a sample of 20 buildings experimentally monitored for 20 years, were taken as literature references to calibrate the model, based on the hypothesis that the durability, due to phosphorus content, of historical wrought irons are between that of recent mild carbon steels and that of weathering steels. The reference damage curves for two environmental conditions (marine and urban–industrial) and two different materials (mild carbon steel and weathering steel) were interpolated, fitted, and extended to 125 years. A comparison was made between experimental damage curves and some significant models from literature, and the percentage error with respect to the tolerance and confidence intervals of the reference damage curves is discussed. Results definitely confirm a substantial difference between experimental values and those predicted by literature models. As an application example, the model was applied to estimate the remaining life of the metal structural elements of the Umberto I Gallery in Naples, one of the most significant monuments of the largest city in Southern Italy. **DOI:** **10.1061/(ASCE)MT.1943-5533.0002710.** *© 2019 American Society of Civil Engineers.*

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Introduction

It is well known that the durability of metal structures is strongly influenced by damage due to corrosion (Rozenfeld 1972; Barton 1976; Kucera and Mattsson 1987; Costa et al. 1989; Morcillo et al. 1998; Tidblad et al. 1998, 2012; Leygraf and Graedel 2000; Dean et al. 2010; Landolfo et al. 2010). Even nowadays, corrosion of metals has a nonnegligible economic impact that is evident if one looks at the costs sustained in this field by the most advanced and developed countries. For the sake of example, the US economy estimated a corrosion protection cost of almost $300 billion per year at current prices (ASM International 2000). The inappropriate and noncontinuous maintenance of metal structures has a substantial effect on the economy because reconstruction costs are generally greater than periodic costs for maintenance (Davis 2000; Drisko and Jenkins 1998; Dolgikh et al. 2014). For this reason, control and monitoring are two key aspects for the design of new construction and, above all, for the safeguard of historical buildings.

The research described in the present paper investigates prediction models regarding corrosion propagation due to the lack of adequate information regarding this issue provided by current codes. In fact, in section "Codes Overview," a short synthesis of the main codes in the field of metal corrosion is given with the aim to discuss the state of the art and its weaknesses. Moreover, in the same section, it is shown that codes do not specifically give instructions to predict the corrosion depth for both newly and already built structures.

The research goal discussed in this paper is to optimize a time-dependent model to predict corrosion propagation in wrought iron members (Guerrieri et al. 2005; Landolfo et al. 2007; Di Lorenzo et al. 2016, 2017a, b), so as to use corrosion damage as a yard stick to determine the material's remaining mechanical strength. The focus on wrought iron is due to many reasons. Firstly, in literature there is a lack of corrosion prediction models for this material, which is also neglected by current codes. The section "Literature Overview" deals with an overview of these prediction models in order to compare them with experimental data on corrosion of wrought iron structures. The general feature of these models is a crucial issue for the corrosion model application. In addition, a great deal of information is available regarding short- and mid-term periods. Therefore, information on long-term exposure (10–20 years) is much less abundant, and no consistent data are available for exposure times over a period of 50 years (Morcillo et al. 2011).

Secondly, corrosion propagation affects ferrous alloys differently from one to another even under the same boundary conditions, i.e., air quality and hygroscopic parameters, environmental and meteorological circumstances, etc. For example, the primary critical relative humidity for metal surfaces without corrosion

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seems to be virtually the same (around 60%) for all metals (Leoni 1984), but the secondary humidity values (i.e., between 70% and 80%) (Roberge et al. 2002) vary quite widely (Syed 2006). For this reason, the maintenance process should be done on the basis of the chemical composition of structural materials.

Thirdly, this category of ferrous alloys was widely used in the past as basic materials for metal structures. In fact, many historical buildings and bridges, also with very important architectural and structural value (i.e., galleries, roofs, and memorials), were made of wrought iron alloys. This use reached its peak in 1860s. Very well-known examples of wrought iron alloy structures are the Britannia Bridge in North Wales (1850), Paddington Station in London (1854), St. Pancras Station in London (1868), and the Eiffel Tower in Paris (1889). Wrought iron, with its high tensile strength, was widely used during the Railway Age and also when the shipbuilding practice achieved fabricated structures by riveting rolled wrought iron sections to each other. It was also commonly used in civil construction and, in particular, in building bridges for railways (Lee 2008). In the framework of the latter issue, due to both significant architectonic—cultural value and age of historical buildings, monitoring the decay of metal elements due to the atmospheric corrosion is a preliminary and essential phase for designing proper restoration interventions. The reduction of metal thickness due to corrosion increases the structure vulnerability level toward seismic or wind actions foreseen by the current standards. This is even worse for structures subjected to cyclic loads, where corrosion phenomena may produce a significant reduction in fatigue strength, mainly in zones with high-stress concentrations, such as holes, notches, and connections (Gelfi and Solazzi 2005).

The section "Baseline Experimental Database" describes experimental results estimated on wrought iron structures and used to calibrate the new model proposed in the current research work (Guerrieri et al. 2005; Landolfo et al. 2007). The experimental dataset was compared to some significant literature models (Landolfo et al. 2005), specifically summarized in the final Appendix. In conclusion, the section "Time-Dependent Damage Model for Predicting Corrosion Thickness Wastage in Wrought Iron Elements" comments on the peculiarity of the corrosion propagation model proposed, while the section "Application of the Proposed Corrosion Wastage Model to a Case Study" describes an application of the proposed model.

Codes Overview

Regarding codes, even though corrosion is often a cause of structural failure (NACE 1991; Elliott 2003), and structures made of wrought iron are generally very sensitive to corrosion phenomena, there were no significant provisions concerning a corrosion problem forecast, particularly for existing buildings. In the Italian structural code D.M. 2005 (DM 2005), corrosion is expressly included as one of the loads acting on constructions. Corrosion is classified as a type of entropic load, which comprises deteriorating actions, caused by natural degradation mechanisms in materials and environmental loads and, thus, affecting structural integrity. However, few and insufficient indications are given to predict the corrosion phenomena. Current codes, such as the European Committee for Standardization's EN 1993-1-1 (CEN 2005b) and EN 1993-1-4 (CEN 2005c), which directly refers to EN 1990:2002/A1 (CEN 2005a), give only general principles regarding the protection of steel buildings from possible corrosion damage causes. They provide only general recommendations and basic principles that mainly concern the use of protective coating systems, the choice of corrosion resistant materials, and structural redundancy strategies (Landolfo et al. 2010). A quantitative measurement of environmental corrosivity and its classification is provided by many different provisions, such as EN ISO 9223 (CEN 1992a), 9224 (CEN 1992c), 9225 (CEN 1992d), and 9226 (CEN 1992b), EN 12500 (CEN 1998, 2000) and EN ISO 12944-2 (CEN 2001). In particular, depending on the degree of corrosiveness, EN 12500 (CEN 1998b) defines different typologies of atmospheres, whereas EN ISO 9223 (CEN 1992a) provides a corrosivity classification system to assess the influence of various factors on the damage process. This classification considers both the level of corrosive impurities, characterized by the presence of sulfur dioxide and chloride particles, and the "time of wetness" (TOW), estimated as the number of hours when relative humidity and temperatures exceed 80% and 0°C, respectively. This methodology is quite limited in terms of accuracy and precision. Indeed, the atmospheric parameters conditioning the corrosivity classification do not include the effects of potentially important corrosive pollutants and impurities. Moreover, the effects of wind speed, exposure angle, and sheltering (natural and artificial obstacles) are not properly accounted for. In EN ISO 14713 (CEN 1999b), specific recommendations are provided for each corrosivity class with respect to different coating typologies.

As an alternative to the methodology proposed by the ISO standards [i.e., EN ISO 9223 (CEN 1992a), 9224 (CEN 1992c), 9225 (CEN 1992d), 9226 (CEN 1992b), EN ISO 8044 (CEN 1999a), EN 12500 (CEN 1998, 2000), and EN ISO 12944-2 (CEN 2001)], it is possible to classify atmosphere corrosivity by using the PACER LIME algorithm (Summit and Fink 1980). This algorithm measures the expected corrosion damage related to various parameters opportunely evaluated. A recent example of an improved standard for corrosion assessment is given by the current Italian Ministerial Decree of Public Works (NTC 2008), which considers atmospheric corrosion as an entropic nature action.

While the codes suggest environmental measurements in order to estimate air, temperature, humidity, wind speed and direction, atmospheric precipitation frequency, and exposure to solar and ultraviolet radiation, because of their direct influence on the corrosion phenomenon, they do not give references to any models able to estimate the corrosion depth. However, corrosion predictive models are able to accomplish this goal. The need to have these models was confirmed by research works on wrought iron structures developed in the more comprehensive European research projects devoted to both investigate and protect historical buildings and to evaluate the durability of constructions (COST C25 2006).

Literature Overview

Literature references in the field of civil engineering lack corrosion models appropriately dedicated to historical buildings. However, several models concerning the damage evaluation produced by the atmospheric corrosion are mainly available in the mechanical and naval fields. They follow different approaches depending on the objectives of the model itself.

Simillion et al. (2014) recognized two approaches, namely heuristic and deterministic, to study the damages provoked by corrosion.

Heuristic models referred to experiments and represent the most intuitive approach to predict corrosion. They are also the most diffused methods followed by a lot of researchers (Komp 1987; Svensson and Johansson 1993; Feliu and Morcillo 1993; Mendoza and Corvo 1999, 2000; Corvo et al. 2008, 2005; Karaca 2013; Morcillo et al. 2013). The heuristic approach is based on a regression of experimental data. Generally, it is possible to divide the models belonging to this approach into two categories: the first-level models, founded on laws of physics and chemistry, that interpret the phenomenon starting from the parameters on which they are based; and the second-level models, obtained from observation and interpolation of experimental data, opportunely examined from a statistical point of view (Landolfo et al. 2005; Kucera 2004). These are based on damage curves that predict the thickness of corrosion wastage over time. The first set of models interprets the corrosion phenomenon based on the causes generating the problem. Such models, deduced theoretically or experimentally, are directly correlated to corrosive atmospheres characterized by the main influence parameters.

The second models, instead, simulate the effects induced from corrosion over time, in terms of either corrosion depth or thickness loss, without referring directly to the corrosive atmosphere and, therefore, to the causes generating the damage. Among the second-level models, linear, linearized, and nonlinear models are available. When second-level models available in literature are examined and compared to each other, it is apparent that some of them model the corrosion protection system (*cps*), in particular predicting its effectiveness loss, where some others do not consider the protection option. There is a great variety of different corrosion prediction models, so that a literature overview is considered as an important issue to define an analytical procedure used to implement the new model proposed in the section "Time-Dependent Damage Model for Predicting Corrosion Thickness Wastage in Wrought Iron Elements.". In addition, it is essential to have an outline of the key assumptions (specific experimental data set or explicit kinds of steel or different atmospheres) in literature models compared with those of the new model herein proposed.

In this section, some of the landmark models are briefly discussed with the aim to clarify the mathematical basis of the new proposed model. In Appendix, formulations of the models compared in the section "Baseline Experimental Database" to the experimental dataset used in this work are reported. Most of these models were developed for mechanical and naval engineering, and they were calibrated using experiments based on immersion either in water or in a marine atmosphere. Models calibrated on experimental data of immersed corroded steel are of crucial importance, since they represented pioneering applications in this field. Some of these models were examined by Southwell et al. (1979) and Melchers (1999). Southwell et al. discussed a first-level model of the corrosion loss for immersed mild steel in the tropics. Based on the assumption that long-term corrosion was influenced mainly by anaerobic conditions, this model was represented by a linear expression with a constant at time zero and a steady state corrosion rate. Melchers (1999), based on the experimental data published in Melchers (1998) and on the theoretical approach exposed in Melchers (1987), applied Southwell et al.'s linear equation to fit experimental data related to the thickness loss expressed as a function of the time (in years). It also proposed a second-level model for mild and low alloy steels in immersion conditions with a bilinear equation directly based on experimental data. The model was improved by the same author (Melchers 2003a, b), and it was applied to the marine immersion corrosion of carbon content of low alloy steels.

Three relevant models similar to that of Melchers (1999) were developed by Yamamoto and Ikegami (1996, 1998), who were amongst the first researchers to establish a model that took into account the degradation of painting coatings, as well as the generation and the progress of the pitting points; Guedes-Soares and Garbatov (1999), who tested a ship hull girder subjected to corrosion; and Paik et al. (1998, 2004), Paik and Kim (2012), and Mohd and Paik (2013), who worked on seawater ballast tank structures of ships.

The Sarveswaran's model (first-level model in 1996) was one of the first methods calibrated on environmental corrosion (i.e., non-immersed elements). The model was founded on the varying thickness loss model using a percentage thickness loss calculation. Since the model is evaluated referring to a I-beam profile, it is linear and does not consider the *cps*. In addition, it was only indirectly a time-dependent model. On the contrary, directly compared with the new model proposed in this paper are three models calibrated in atmosphere by Albrecht and Hall (2003), Klinesmith et al. (2007), and International Cooperative Programme (ICP). Albrecht and Hall gave some adjustments to the EN ISO 9224 (CEN 1992c) corrosion laws, proposing a new bilinear model accounting for a modified corrosion rate during the first year of exposure and a steady state during the subsequent years. Klinesmith et al. (2007) developed a model for the atmospheric corrosion of carbon steel, zinc, copper, and aluminum, taking into account the effects of four environmental variables, namely TOW, sulfur dioxide, salinity, and temperature. Finally, the dose-response model was developed within the ICP on "Effects on Materials, including Historic and Cultural Monuments," in the framework of the United Nations Economic Commission for Europe (UN ECE) convention on long range transboundary air pollution. The last model was formulated on different metal materials, and it was based on both long-term exposures and trend analysis founded on repeated one-year measurements, taking also into account unsheltered or sheltered exposure (Landolfo et al. 2010; Kucera 2004). The new model proposed in this paper is directly inspired to the second-level model previously described.

For the sake of completeness, it is necessary to speak about deterministic models. They are basically founded on corrosion mechanisms (connected to the chemical and molecular structure of materials) and are multiscale models generally more complex than others (Simillion et al. 2014). Gas—Interface—Liquid—Deposition—Electrodic—Solid (GILDS) are some examples of these multiscale models. They evaluate the kinetics of the corroding system, including interactions with the gaseous and liquid environments (Venkatraman et al. 2011; Tidblad and Graedel 1996; Tidblad et al. 1998, 2012; Graedel 1996; Thebault et al. 2011, 2012; Cole et al. 1996; Farrow et al. 1996). Moreover, multi-ion transport and reaction models (MITReM) can be considered, they being based on the addition of mass balances for all species in the electrolyte to the Poisson equation to solve the electrolyte potential and the species concentration distributions (Topa et al. 2012). A more general family of deterministic models is founded on an artificial neural network (ANN) algorithm (Jančíková et al. 2013; Vera and Ossandón 2014; Panchenko and Marshakov 2017), which defines a set of artificial neurons distributed according to a determined type of architecture. In the field of corrosion prediction, the variables that are generally chosen are the exposure time, concentration of atmospheric gas, and environmental and thermodynamic parameters (i.e., relative humidity, ambient temperature, and amount of rainfall).

Baseline Experimental Database

Reference Experimental Data

As indicated in the section "Introduction", the research aims to develop a time-dependent model to predict the corrosion depth propagation over a long period of time in wrought iron structures. The literature models briefly described in the previous section fail to provide these data, both because the treated metal materials are

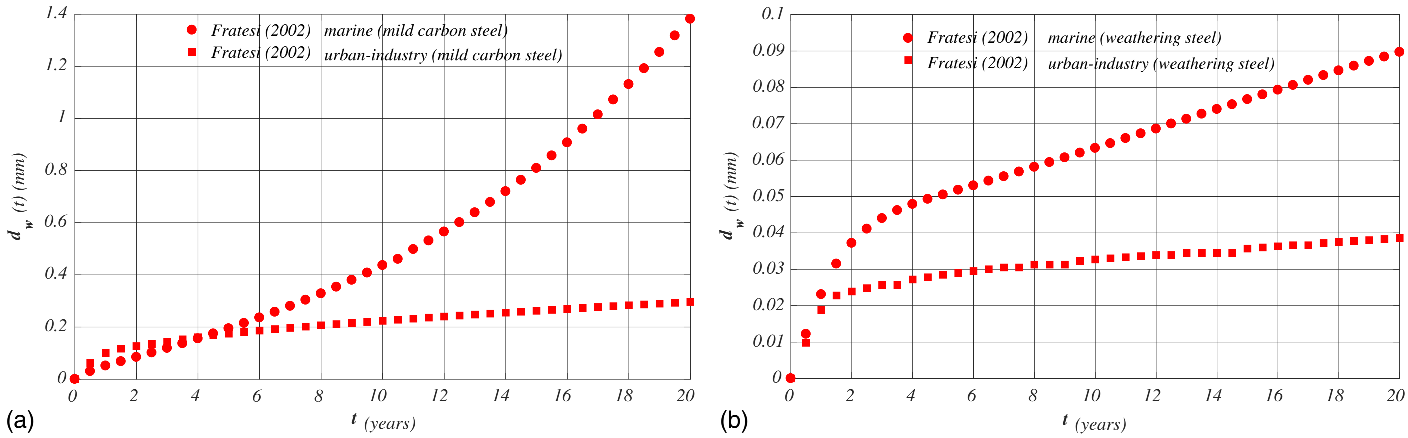

Fig. 1. Experimental curves developed by Fratesi (2002) on structures made of (a) mild carbon steels; and (b) weathering steels.

not similar to wrought iron and they are mostly referred to corrosion from immersion.

However, a similar approach followed by other literature models (Guedes-Soares and Garbatov 1999; Paik et al. 2004) was planned to be used to calibrate the numerical model through damage curves plotted according to experimental measurements. Unfortunately, the present authors could not carry out experiments on historical buildings, since such interventions would be very invasive on these existing structures. For this reason, some hypotheses to develop the study were formulated.

In terms of durability, the phosphorus content closely affects the corrosion resistance of metals (Walker 2002). It seemed, therefore, appropriate to focus the study on the phosphorus content in order to place, in terms of durability, the wrought iron within traditional steels and to cope with the data gap. Studying the chemical composition of wrought irons, its phosphorus content was estimated to be 0.1% (Boubèe 1880; Breymann and Koniger 1925; Rossi 1899; Walker 2002) and that it ranged between 0.025 and 0.045% for mild/law carbon steels and it was equal to 0.16% for weathering steels [EN 10025 Parts 2 and 5 (CEN 2004a, b)]. Therefore, in this research phase, it was assumed that the wrought iron corrosion resistance in terms of durability is an average value between that of mild/law carbon steels and that of weathering ones (Degarmo et al. 2003).

This assumption is crucial for the present study, and it was applied using the damage curves (corrosion depth propagation trends) developed by Fratesi (2002) for mild carbon and weathering steels in both marine and urban–industrial atmosphere. In the section "Time-Dependent Damage Model for Predicting Corrosion Thickness Wastage in Wrought Iron Elements," the mean curves (between mild steels and weathering steels) for both marine and industrial atmospheres, used to calibrate the new model herein proposed, are presented and discussed.

The damage curves developed by Fratesi specifically refer to buildings, located in Italian areas with marine and urban–industrial environmental conditions, made of mild/low carbon steels and weathering steels, recorded over a significant time interval (about 20 years). The curves cover a significantly long time interval of data, which is longer than or in line with models available in literature (Guedes-Soares and Garbatov 1999; Paik et al. 2004). These curves were obtained by measurements performed on 20 Italian buildings, subjected to average environmental temperatures ranging from 0°C to 30°C, over a period of about 20 years. Fratesi's damage curves are illustrated in Fig. 1, where the average material wastage thickness (or corrosion depth) is expressed as a function of time for both carbon mild steels [Fig. 1(a)] and weathering ones [Fig. 1(b)].

It is important to note that the curves of Fig. 1 represent an interpolation of experimental data obtained by Fratesi. In addition, Fig. 1(a) shows a very high accelerating wastage rate for marine atmospheres and mild carbon steels. However, the comparison with literature models, and in particular with Melchers's model illustrated in the following section, shows a similar tendency.

The two pairs of reference damage curves for mild carbon and weathering steels under marine and urban–industrial atmospheres were fitted on the basis of the least squares method by using a third-order polynomial equation of the type $y = p_1x^3 + p_2x^2 + p_3x + p_4(x = t)$ in order to estimate the sample trend over a period of 125 years.

Table 1 gives the coefficients p_i of the above equation for the two materials (mild carbon steel and weathering steel) under the two considered environmental conditions (marine and urban–industrial). The uncertainty of the experimental data sample used for the method calibration is taken into account in the model herein proposed by considering the material wastage thickness due to corrosion as a random variable with a normal distribution (Guedes-Soares and Garbatov 1999). This hypothesis seems to be opportune when referred to Fratesi's data sample, because he obtained his damage curves (Fig. 1) as a mean of the measurements. As a consequence, the experimental damage curves are considered as representative of the average values μ_d (t). Therefore, the mean of random values changing with a normal distribution (Guedes-Soares and Garbatov 1999) is considered, while the standard deviation $\sigma_d(t)$ is defined according to the study of Sarveswaran et al. (1998) on the basis of the relationship $\sigma_d(t) = 0.15\mu d(t)$.

Consequently, a sample with a size of corrosion depth equal to 100 (Desceliers et al. 2007) in both environmental conditions is generated by using a Monte Carlo simulation (Hastings 1970; Rose 2014; Rizzo and Caracoglia 2018). In order to give a measure of the variability of the sample data set, the confidence interval (CI) and the tolerance interval (TI) were estimated for randomly variable corrosion depth $d_w(t)$.

The confidence interval was estimated according to the following expression:

$$CI = \mu d(\mathrm{t}) \pm 1.96 \frac{\sigma d(\mathrm{t})}{\sqrt{n_\mathrm{p}}} \tag{1}$$

where 1.96 = extent of the normal distribution for a degree of confidence equal to 95%; and $n_\mathrm{p} = 100$. CI is valid if the

Table 1. Fitting-damage curve coefficients

Environmental condition	Material	p_1	p_2	p_3	p_4
Marine	Mild carbon steel	1.0×10^{-4}	-3.0×10^{-4}	3.6×10^{-2}	1.0×10^{-2}
	Weathering steel	2.0×10^{-5}	-8.0×10^{-4}	1.1×10^{-2}	1.2×10^{-2}
Urban–industrial	Mild carbon steel	6.0×10^{-5}	-2.4×10^{-3}	3.6×10^{-2}	4.8×10^{-2}
	Weathering steel	1.0×10^{-5}	-5.0×10^{-4}	5.8×10^{-3}	9.7×10^{-3}

unknown error can be described by a normally distributed random variable.

Notoriously, the standard confidence interval equation relies on the population standard deviation. However, since the latter is generally unknown, it is replaced by the sample standard deviation. While this technically means that CI is an approximation of the confidence interval, it is a fairly accurate approximation for large samples (i.e., $n_{\mathrm{p}} \geq 30$). This is commonly referred to as the *large-sample* confidence interval (Walpole et al. 2002).

The TI intervals for each set of data points [i.e., 100 values of $d_w(t)$] are estimated by the algebraic sum expressed through the following equation:

$$\mu d(t) \pm k\sigma d(t) \tag{2}$$

where the quantity k is the tolerance factor for a normal distribution.

In this study, k was set equal to 2.36, so that there was a 99% confidence that the calculated tolerance limits contain at least 95% of the measurements. The limiting confidence interval (i.e., 99%) must be added to the statement, since the bounds given by TI cannot be expected to contain any specified proportion (i.e., 95%) of all the time (Walpole et al. 2002). Fig. 2 shows CI and TI intervals and the randomly varying values, respectively for mild steels [Figs. 2(a and c)] and weathering steels [Figs. 2(b and d)].

Comparison and Critical Remarks

The $d_w(T)$ trends estimated by the literature and code (i.e., EN ISO 9224 and EN 12500) models described in the section "Literature Overview" were compared to both mild carbon and weathering steel damage curves developed by Fratesi for both marine and urban–industrial atmospheres (Fig. 1).

Fig. 3 shows a comparison between the Fratesi curves and the codes (i.e., EN ISO 9224 and EN 12500), respectively for mild carbon [Fig. 3(a)] and weathering [Fig. 3(b)] steels. In particular, these figures show a comparison between experimental data and codes for different corrosiveness categories (i.e., C1, ..., C5). Fig. 3(a) shows that mild carbon in the marine atmosphere curve is between EN ISO 9224 C4 and C5 curves, whereas the mild carbon in the urban–industrial atmosphere curves is between EN ISO 9224 C3 and C4 curves. However, as shown in Fig. 3b, the weathering curve in marine atmosphere is close to the EN ISO 9224 C3 one, whereas the weathering curve in urban–industrial atmosphere is close to the EN ISO 9224 C2 one.

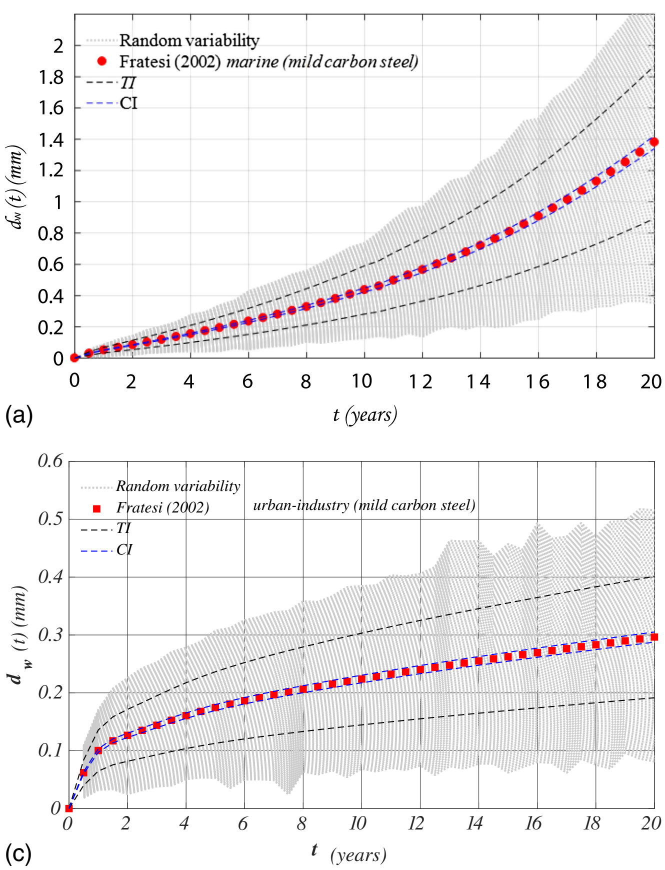

Fig. 2. Random variability, tolerance and confidence intervals in Fratesi's (2002) damage curves in the cases of (a) marine; (b) urban–industrial atmosphere for mild carbon steels; (c) marine; and (d) urban–industrial atmosphere for weathering steels.

J. Mater. Civ. Eng., 2019, 31(8): 04019165

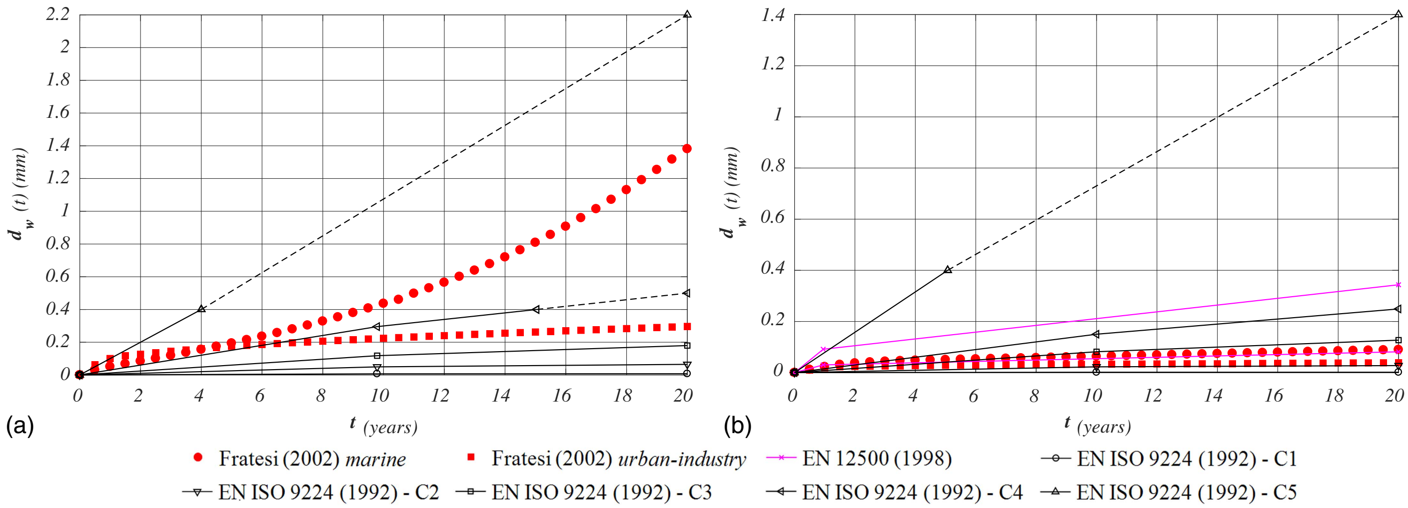

Fig. 3. Comparison between Fratesi's damage curves and codes (i.e., EN ISO 9224 and EN 12500) in C1, …, C5 corrosiveness categories for (a) mild carbon; and (b) weathering steels.

Fig. 4 shows a comparison between some literature second-level models, calibrated from experiments on immersed elements (i.e., Melchers 1999; Guedes-Soares and Garbatov 1999; Qin and Cui 2003; Paik et al. 2004; Paik and Kim 2012; Mohd and Paik 2013), and the Fratesi curves. The comparison shows a high difference between literature and experimental curves, except for Melchers (1999), who provided an acceptable estimation of the mild carbon curve (Fratesi 2002) in marine atmosphere [Fig. 3(a)]. Fig. 4(b) shows that no literature models considered in the comparison give a satisfactory approximation of the weathering curves for both marine and urban–industrial atmospheres.

Finally, Fig. 5 shows a comparison between literature models and results of experiments in atmosphere (i.e., Albrecht and Hall 2003; Klinesmith et al. 2007; IPC and Vera and Ossandón 2014). Fig. 4(a) shows a good agreement between the curve of the mild carbon in urban–industrial atmosphere and the Albrecht and Hall curve, whereas Fig. 5(b) shows a very great difference between literature models and experimental data. The only exception is represented by the weathering steel curve trend in marine atmosphere, which is acceptably reproduced by the Albrecht and Hall's curve, even if detected values are very different.

In order to measure the distance between the literature and codes' (i.e., EN ISO 9224 and EN 12500) models and Fratesi's curves (Fig. 1), the normalized root mean square error (NRMSE) is calculated in the window where curves are overlapped.

The relative errors have been also computed for both TI and CI, and they are defined as

$$\varepsilon_{TI} = \left|\frac{d_w(t) - (\mu d(t) + k\sigma d(t))}{d_w(T)}\right|; \qquad \left|\frac{d_w(t) - (\mu d(t) - k\sigma d(t))}{d_w(T)}\right| \tag{3}$$

Similarly, the relative error between literature models and CI is defined as:

$$\varepsilon_{CI} = \left|\frac{d_w(t) - \left(\mu d(t) + 1.96\frac{\sigma d(t)}{\sqrt{n_p}}\right)}{d_w(T)}\right|; \quad \left|\frac{d_w(t) - \left(\mu d(t) - 1.96\frac{\sigma d(t)}{\sqrt{n_p}}\right)}{d_w(T)}\right| \tag{4}$$

It is important to specify that literature models are comparable with interpolating curves in the range $0 \leq t \leq 20$ years only.

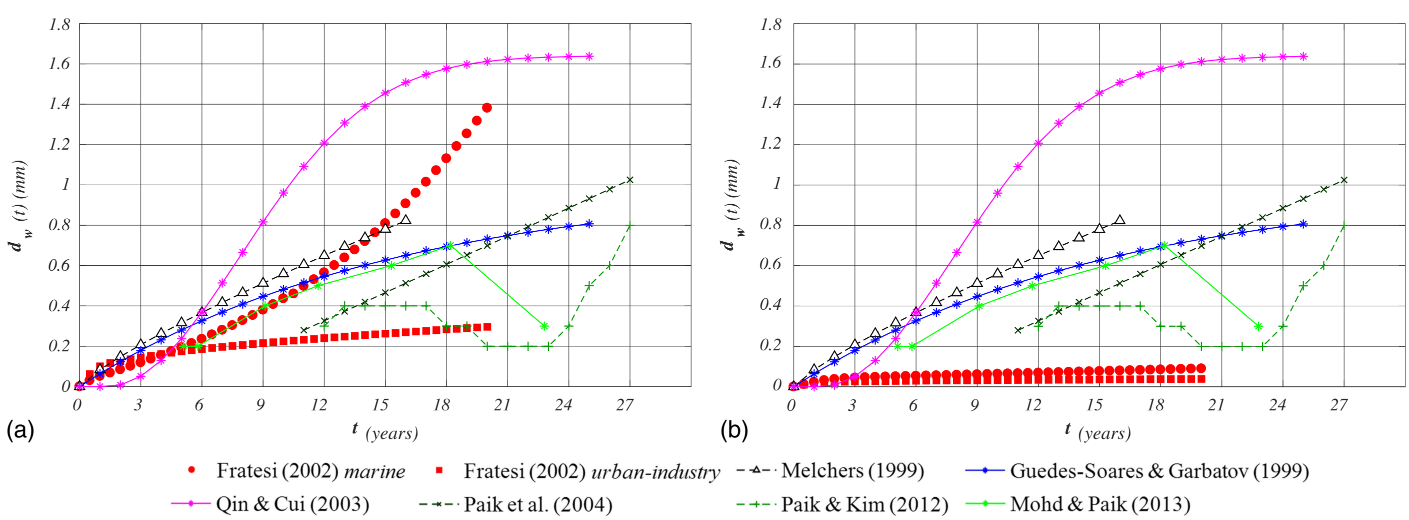

Fig. 4. Comparison between Fratesi's damage curves and 2nd level models calibrated from experiments on immersed elements for (a) mild carbon; and (b) weathering steel.

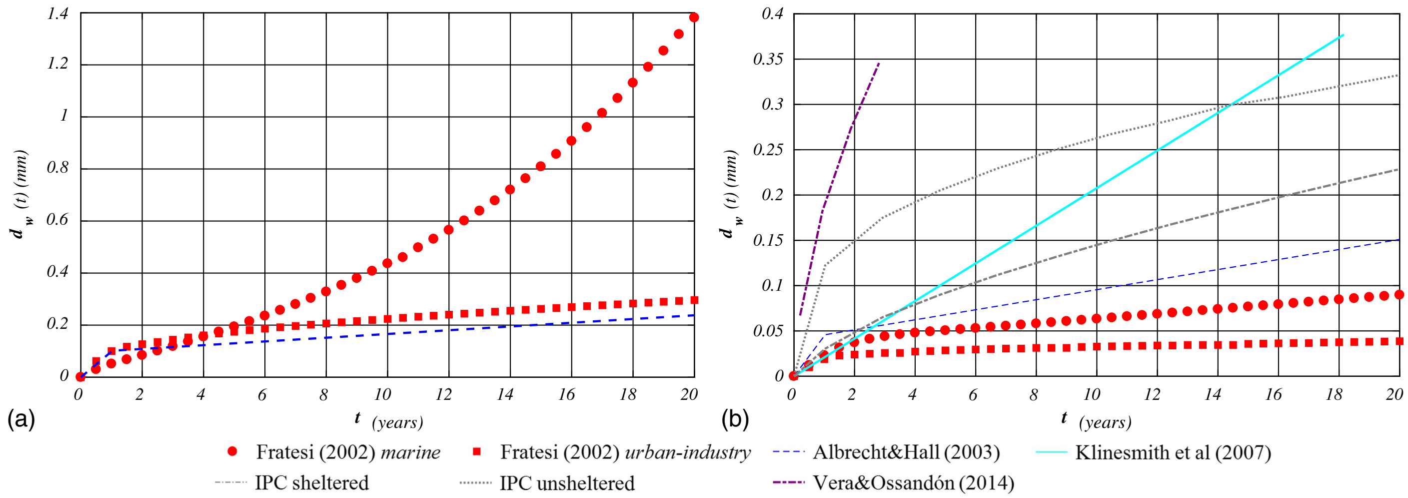

Fig. 5. Comparison between Fratesi's damage curves and literature models calibrated with experiments in atmosphere for (a) mild carbon; and (b) weathering steel.

In Table 2, the negative value means that models overestimate experimental values (Fratesi 2002).

Observing the percentage error listed in Table 2, it is worth noting that for marine atmospheres and mild carbon steels, the best mean error (i.e., −0.6%) compared to TI is given by Qin and Cui (2003). However, observing the maximum and minimum values of this error, it is clear that the range is very large (from about −70.6% to about 612.7%). The same is observed for the mean error compared to CI. The best value (3.5%) is given by Guedes-Soares and Garbatov (1999), but, similarly to TI, the range between the maximum and minimum error is very large. It ranges from about −36% to 83%. The best error range (from minimum to maximum) is given by Melchers (1999) for both TI and CI.

Table 2. Error between Fratesi 2002's damage curves and literature and codes models

	Marine atmosphere							Urban–industrial atmosphere						
	ε_{TI} (%)			ε_{CI} (%)				ε_{TI} (%)			ε_{CI} (%)			
Model	Max	Mean	Min	Max	Mean	Min	NRMSE	Max	Mean	Min	Max	Mean	Min	NRMSE
Mild carbon steel damage curves														
EN ISO 9224	25.5	−8.7	−38.6	88.6	37.2	−7.7	0.584	450.4	54.8	−20.7	727.0	132.6	19.1	1.285
EN 12500														
Melchers (1999)	−13.2	−44.3	−63.3	30.4	−16.3	−44.9	−1.799	−22.9	−69.4	−81.4	15.9	−54.0	−72.0	−0.415
Guedes-Soares and Garbatov (1999) and Guedes-Soares et al. (2006)	21.9	−31.1	−57.1	83.2	3.5	−35.6	5.689	1.8	−62.9	−73.8	52.9	−44.3	−60.7	−0.652
Qin and Cui (2003)	612.7	−0.6	−70.6	970.8	49.4	−55.9	4.766	969.0	22.8	−88.5	1506.1	84.5	−82.7	4.867
Paik et al. (2004)	30.4	11.2	−1.3	95.9	67.1	48.3	0.196	154.9	−28.3	−72.6	283.0	27.7	−58.8	7.591
Paik and Kim (2012)	346.1	46.8	0.4	570.3	120.6	50.8	1.000	159.2	−19.1	−60.0	289.4	23.5	−39.9	3.143
Mohd and Paik (2013)	16.0	−18.5	−36.1	74.3	22.5	−3.9	0.952	65.1	−50.8	−75.1	148.1	−26.1	−62.6	−2.151
Albrecht and Hall (2003)	252.6	78.8	−46.4	429.8	168.6	−19.4	0.805	27.5	−18.2	−25.2	91.5	22.9	12.4	0.622
Klinesmith et al. (2007)														
IPC sheltered														
IPC unsheltered														
Vera and Ossandón (2014)														
Weathering steel damage curves														
EN ISO 9224	201.7	9.8	−35.7	353.3	64.9	−3.4	1.422	3.2	−74.9	−89.7	55.0	−62.2	−84.5	−0.581
EN 12500	−66.4	−71.0	−75.4	−49.6	−56.4	−63.1	−0.069	−79.9	−84.8	−88.7	−69.7	−77.1	−83.0	−0.060
Melchers (1999)	−82.2	−91.3	−94.4	−73.3	−87.0	−91.5	−0.062	−85.5	−95.2	−97.6	−78.3	−92.7	−96.4	−0.050
Guedes−Soares and Garbatov (1999) and Guedes-Soares et al. (2006)	−76.6	−89.5	−92.1	−64.8	−84.2	−88.2	−0.078	−80.9	−94.2	−96.6	−71.3	−91.2	−94.9	−0.064
Qin and Cui (2003)	214.1	−66.6	−96.6	371.9	−49.8	−94.9	−2.471	101.8	−77.6	−98.5	203.2	−66.4	−97.7	−1.268
Paik et al. (2004)	−41.3	−79.9	−91.7	−11.8	−69.8	−87.5	−0.301	−52.2	−88.3	−96.4	−28.2	−82.5	−94.6	−0.201
Paik and Kim (2012)	−40.3	−77.2	−88.5	−10.3	−65.7	−82.7	−0.300	−51.4	−87.1	−94.4	−27.0	−80.6	−91.6	−0.199
Mohd and Paik (2013)	−62.0	−86.2	−92.5	−42.9	−79.2	−88.7	−0.160	−69.0	−92.1	−96.8	−53.5	−88.1	−95.1	−0.118
Albrecht and Hall (2003)	−34.9	−58.8	−64.4	−2.2	−38.1	−46.5	−0.290	−47.0	−77.8	−84.7	−20.4	−66.7	−77.0	−0.197
Klinesmith et al. (2007)	−28.1	−74.1	−86.0	8.0	−61.0	−79.0	−0.400	−41.5	−85.1	−94.0	−12.1	−77.7	−91.0	−0.254
IPC sheltered	−50.9	−68.4	−74.9	−26.2	−52.6	−62.3	−0.231	−60.4	−82.9	−89.2	−40.6	−74.3	−83.8	−0.156
IPC unsheltered	−82.6	−84.1	−87.7	−73.8	−76.1	−81.5	−0.021	−89.9	−91.7	−92.5	−84.9	−87.6	−88.7	−0.014
Vera and Ossandón (2014)	−91.5	−94.2	−95.1	−87.3	−91.3	−92.7	1.422	−93.4	−96.9	−97.9	−90.1	−95.3	−96.9	−0.019

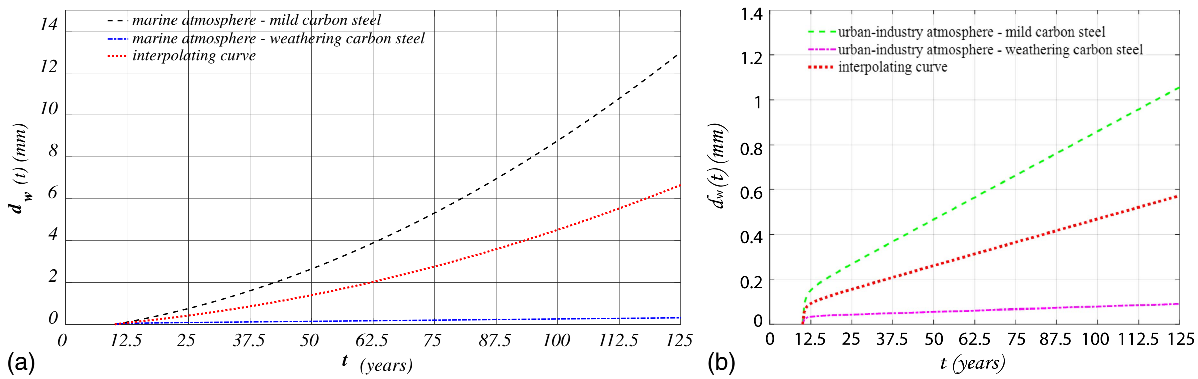

Fig. 6. Extended damage experimental and interpolating curves for (a) marine; and (b) urban–industrial atmospheres.

For urban–industrial atmospheres and mild carbon steels, the best mean error values are given by Albrecht and Hall (2003) for both TI and CI, respectively equal to about −18% and 23%. Albrecht and Hall's model also gives a satisfactory value of NRMSE (i.e., 0.622), even if the best value, provided by Melchers, is equal to −0.41.

Results from the error analyses on marine and urban–industrial atmospheres for weathering steels are worse than those of mild carbon steels. For both marine and urban–industrial atmospheres, the EN ISO 9224 gives the best result in terms of mean error values, respectively equal to about 10% and −75%, compared to TI. EN ISO 9224 also gives the best value of the mean error for CI with urban–industrial atmospheres, approximately equal to −62%. The best value for CI with marine atmospheres, equal to about 38%, is given by Albrecht and Hall (2003). However, the range between maximum and minimum errors varies from −2.2% to −46.5%. Low values of the NRMSE are due to the low values of the compared data. In conclusion, in spite of the trends illustrated in Figs. 3–5, the values of the $d_w(t)$ given by models and codes are only slightly different from the experimental data (Fratesi 2002). It is important to note that the large differences observed between experimental data and literature and codes results are due to the lack of specific models for wrought iron elements.

Time-Dependent Damage Model for Predicting Corrosion Thickness Wastage in Wrought Iron Elements

According to the hypothesis previously mentioned in the section "Baseline Experimental Database", with the aim to calibrate a time-depending model specific for wrought iron elements, the mean curves between mild and weathering steels for both marine and urban–industrial atmospheres were achieved by interpolation.

Fig. 6 illustrates the interpolating damage curves for the two environmental conditions.

Table 3 gives the coefficients of the polynomial relationship that fitted the two environmental conditions (marine and urban–industrial) of the interpolating damage curves.

Table 3. Interpolating damage curves coefficients with $\tau_c = 10$ year

Environmental condition	p_1	p_2	p_3	p_4
Marine	6.0×10^{-5}	-6.0×10^{-4}	2.3×10^{-2}	1.1×10^{-2}
Urban–industrial	4.0×10^{-5}	-1.4×10^{-3}	2.1×10^{-2}	2.9×10^{-2}

Neither of the previously described models are specific for historical buildings, and the comparison between results obtained by Fratesi (2002) and those derived from the reference numerical models confirms this conclusion (Figs. 3–5). Based on this conclusion, this paper discusses a new corrosion depth model calibrated according to both the experimental damage curves given by Fratesi (2002) and the interpolating curves [Figs. 6(a and b)].

The modeling method proposed to predict the corrosion phenomenon is, according to the second-level approach illustrated in sections "Introduction" and "Literature Overview," based on the definition of damage curves for wrought iron elements, which provide the corrosion depth as a function of time (Guedes-Soares and Garbatov 1999; Melchers 1998; Paik et al. 1998).

The reason for this choice, that is, the use of a 2nd level approach, is mostly due to the lack of protection for long-time of historical buildings. Linear models, such as that developed by Southwell et al. (1979), and the models proposed by codes are specifically calibrated on frequent protection periods and are conceived for new structures. However, specific models that consider long periods of maintenance absence have been neglected by literature and codes.

In order to design a model adapted to historical buildings, Fratesi's damage curves were extended from 20 to 125 years using the interpolating curves (illustrated in Fig. 6). This extension was chosen in order to cover the entire period from the beginning of the experiments (1982) up to today. Summing up, Fig. 6 illustrates the interpolating and fitting damage curves for both marine and urban–industrial atmospheres.

The proposed model was obtained by analysis of the residues specifically estimated where the corrosion depth shows the maximum gradients. It allowed for the definition of the formulation expressed through the relationship given in Eq. (5), which represents the rational function that gives the best approximation of the fitted data

$$d_w(t) = \frac{p_1 t^2 + p_2 t + p_3}{t + p_4} \quad \forall t > 0 \tag{5}$$

where according to the nomenclature used in the section "Baseline Experimental Database," $d_w(t)$ = loss of thickness in mm; t = exposure time in years; and coefficients $p_{1\ldots4}$ = constants for each single damage curve as provided in Table 3.

Decay from the corrosion process was added to Eq. (5) as a function of the number of coating cycles, η, and the time slot between two subsequent coatings $\Delta T_{m,i}$, supposed to be more persistent than the design life of the coating τ_c, was assumed as equal to 10 years.

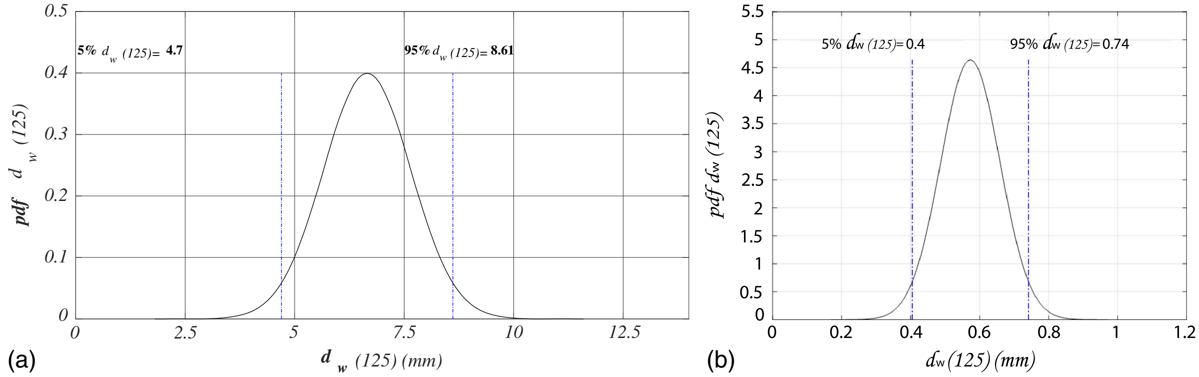

Fig. 7. *pdf* of the corrosion depth at 125 years under (a) marine; and (b) urban–industrial atmospheres.

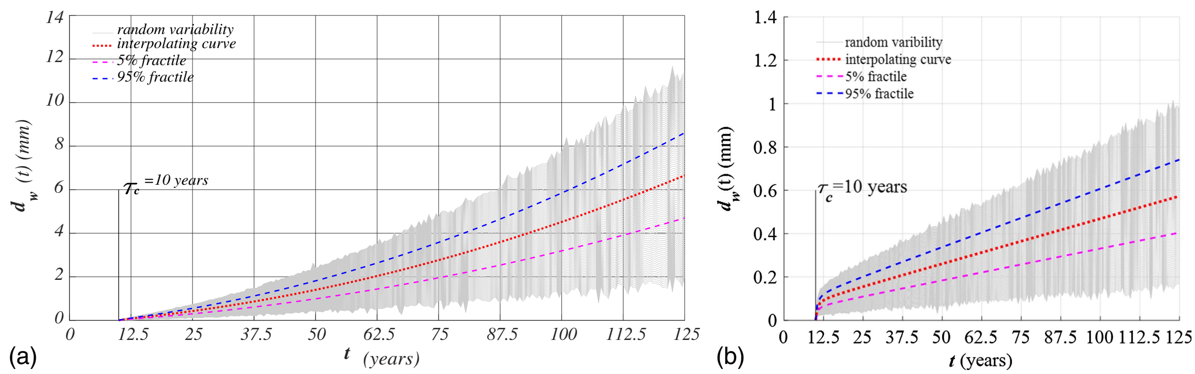

Fig. 8. Random variability of the corrosion depth for (a) marine; and (b) urban–industrial environmental conditions.

Consequently, Eq. (5) takes the form of the following equation:

$$d_c(t) = \sum_{i=1}^{\eta-1}[d_w(t)(\Delta T_{m,i} - \tau_c)] + d_w(t)\left(t - \sum_{i=1}^{\eta-1}(\Delta T_{m,i} - \tau_c)\right);$$
$$\forall t > 0; \quad \forall n \in N; \qquad \Delta T_{m,i} > \tau_c \tag{6}$$

where $d_c(t)$ = function expressing the wastage thickness due to corrosion in case of a protected structure; and $d_w(t)$ is given by Eq. (5) by adding τ_c, (Guerrieri et al. 2005; Landolfo et al. 2007).

If $\Delta T_{m,i}$ is constant (and assumed equal to ΔT_m), then Eq. (6) can be replaced as follows:

$$d_c(t) = (\eta - 1) \cdot d_w(\Delta T_m - \tau_c) + d_w\{t - [(\eta - 1) \cdot \Delta T_m + \tau_c]\};$$
$$\forall t > 0; \quad \Delta T_{m,i} > \tau_c \tag{7}$$

As was shown before, the extended damage curves (Fig. 6) are considered as representative of the average values $\mu d(t)$, intended as a mean of random values changing with a normal distribution, while the standard deviation $\sigma(t)$ is fixed according to Sarveswaran et al.'s (1998) and Sarveswaran (1996) study.

Subsequently, a sample with a corrosion depth size equal to 100 (Desceliers et al. 2007) in both environmental conditions was generated by using a Monte Carlo simulation (Hastings 1970).

Fig. 7 shows an example of the probability density function (*pdf*) of the corrosion depth, under both marine and urban–industrial environmental conditions, after 125 years using only one protection coating cycle [$\eta = 1$ in Eqs. (6) and (7)].

Fig. 8 shows the random variability of the corrosion depth for examined environmental conditions of the interpolating curves (Fig. 6) extended to $t = 125$ years while τ_c equals 10 years. In the same figure the confidence interval (*CI*) of 95% is overlaid as well.

The model was calibrated on structures made of wrought iron, and evaluations extended to predict corrosion in other metals such as reinforcing steel in concrete are in progress, using the proposed model.

Application of the Proposed Corrosion Wastage Model to a Case Study

The time-dependent corrosion wastage model described in the section "Time-Dependent Damage Model for Predicting Corrosion Thickness Wastage in Wrought Iron Elements" was applied to a case study closely affected by corrosion phenomena. The case study is the Umberto I Gallery in Naples, the largest city in Southern Italy. It is a public shopping gallery that was built between 1887 and 1892 as the cornerstone of the *risanamento* (rebuilding of Naples). It was designed by the architect Emanuele Rocco, who employed modern architectural elements reminiscent of the Vittorio Emanuele II Gallery in Milan (Carughi 1996). The gallery has a high and spacious cross-shaped structure. It is composed of four iron and glass-vaulted wings, about 25 m high, and a glass dome having a diameter of 36 m and height of about 56 m, which is braced by 16 wrought-iron ribs (Carughi 1996). The gallery is located in a highly urbanized area of the city, characterized by elevated levels of city traffic and with a distance from the sea, as the crow flies, of just a few hundred meters. The structure is, therefore, subjected to corrosion due to the presence of both

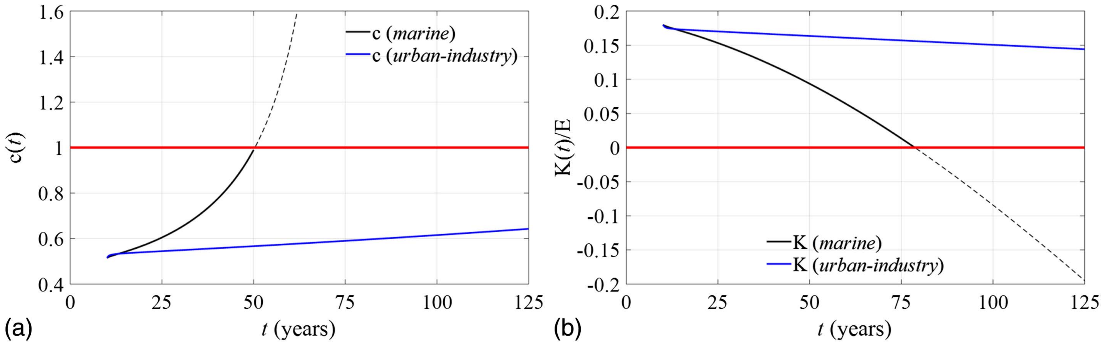

Fig. 9. Damage curves for (a) 1 cycle; and (b) 5 cycles of protection coatings.

atmospheric pollution and marine aerosols (Guerrieri et al. 2005; Landolfo et al. 2007). For these reasons, a mixed atmosphere would be desirable for this case study. However, in order to apply the time-dependent model and to reduce the approximation of Fratesi's (2002) curves, analyses were repeated separately for both marine and urban–industrial atmospheres.

In addition, according to experimental results given by Landolfo et al. (2009), a hypothesis about both the presence of metal protection and the maintenance cycles has been made. In the case study, the protection covering was quantified from experiments carried out on original elements, as discussed in Landolfo et al. (2009). In this case, due to the absence of a maintenance plan, two cases were considered: one (Fig. 8) or five coating cycles during the construction life, assumed as equal to about 125 years (1892–2017). The single protective coating life, τ_c, was assumed equal to 10 years. An additional hypothesis was that the corrosion depth is stopped during the coating life. The assumed hypotheses were validated by measurements of the corrosion depth directly taken on members placed outside and inside the gallery (Landolfo et al. 2009). With reference to an original thickness equal to 3.0 mm, the thickness of outside elements decreased 84%, whereas inside the structure this reduction was about 16% (Landolfo et al. 2009).

In this case study, the effect of the corrosion depth on the elements shows a reduction of the thickness of plates. As an example, in Fig. 9(a), a $3 \times 60 \times 1{,}000$ mm plate taken from the gallery (Landolfo et al. 2009) shows an increase of the coefficient $c(t)$ defined as the ratio N/Af_y, where N is the axial force in newtons, A is the section plate area in mm^2, and f_y is the yield stress of the material, assumed equal to 275 MPa. In this case, in a marine atmosphere $c(t)$ is greater than 1 after 49 years, while on the contrary in an urban–industrial atmosphere, $c(t)$ is less than 1 after 115 years (i.e., always considering the protective coating life, τ_c, approximately 10 years). Similarly, Fig. 9(b) shows a decrease of stiffness (i.e., axial stiffness) of the element. In a marine atmosphere, the stiffness is dangerously close to zero after 60 years.

With the aim to use corrosion damage as a yard stick for determining remaining mechanical strength in the material and also in the entire structure, static and dynamic analyses of the main structures (i.e., truss arches and beams) were carried out, taking into account the time-dependency of the corrosion depth according to the trend illustrated in Fig. 10. With reference to the curves shown in Fig. 7, a sample with a size of corrosion depth equal to 100 (Desceliers et al. 2007) in both environmental conditions and for five cycles of protection coating conditions was generated by using a Monte Carlo simulation, through $\mu_d(\mathrm{t})$ and $\sigma_d(\mathrm{t})$, in order to estimate the maximum and minimum corrosion depth values starting with the average curves illustrated in Fig. 10.

The maximum values were used both to estimate the maximum reduction of thickness in structural elements and, therefore, to perform finite-element analyses on the structure.

At the time of analysis (2017), the maximum value of the corrosion depth was 6.63 mm for the reduced marine condition and 2.37 mm for the urban–industrial situation.

Based on the 100 corrosion depth samples, the reduced sections (100 different sections) of all metallic structural elements (arches) were used to carry out static and dynamic analyses to estimate the limit condition of the structural collapse. The life limit state and the

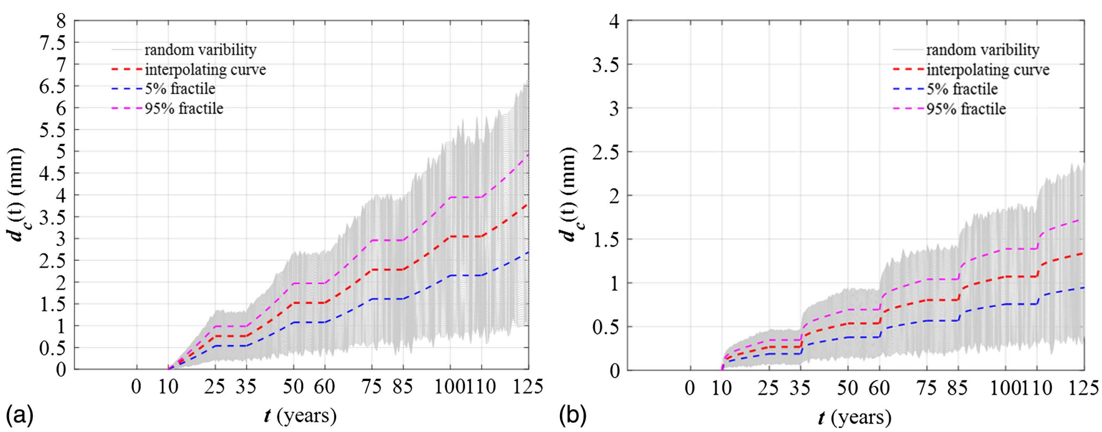

Fig. 10. Random variability of the corrosion depth with five cycles of coating protection under (a) reduced marine; and (b) urban–industrial atmospheres.

probability density functions of tensile or compression actions in the elements were then assessed.

The achieved results say that the remaining life of the construction is zero and equal to 49 years with a reduced marine atmosphere by using one cycle and five cycles (i.e., 1 cycle each 25 years) of protection coatings, respectively. On the other hand, under an urban–industrial atmosphere, the residual life is equal to 285 and 585 years by applying one protection cycle and five protection cycles, respectively.

Concluding Remarks

In the current paper a time-dependent corrosion wastage model has been proposed to help in estimating the corrosion depth in historical metal buildings made of wrought iron. Average damage curves based on a sample of experimental measurements on 20 buildings for 20 years have been taken as a reference to calibrate the model, which is based on the hypothesis that durability in historical wrought iron is similar to that of more recent mild carbon and weathering steels.

The reference curves have been considered as mean values of random variables with a normal distribution and a standard deviation of 0.15. The reference damage curves for two environmental conditions (marine and urban–industrial) and two different materials (mild carbon steel and weathering steel) have been interpolated, fitted, and extended from 20 to 125 years. The variability of protection coating life and its cycles of renovation have been added into the model as well. A comparison between experimental damage curves and some significant literature and codes models has been given and the percentage errors detected have been evaluated and discussed.

Finally, as an applicative example, the model has been applied to estimate the remaining life of the metal structural elements of the Umberto I Gallery in Naples, the largest city in the Southern Italy. In this case study, the computed time-dependent model was applied with the aim to use corrosion damage as a yardstick to determine the remaining mechanical strength of the material. The prediction was carried out by repeating static and dynamic analyses with different environmental conditions and different numbers of coating renovation cycles. In conclusion, the collapse condition of the structures was identified by generating different sets of corrosion depth using a Monte Carlo simulation based on the average damage curves. The achieved results revealed that, under a reduced marine atmosphere, the gallery remaining life is null for one cycle of coating protection and is equal to 49 years using five protection cycles, which means 1 cycle each 25 life years. On the other hand, best performances are obtained under an urban–industrial atmosphere, where the residual life of the construction is equal to 285 and 585 years by using only one cycle and five cycles, respectively.

Appendix. References Overview

Melchers

Melchers (1999) applied Southwell et al.'s (1979) linear equation to fit experimental data, so to obtain the expression given in the following equation:

$$d_w(t) = 0.076 + 0.038 \cdot t \tag{8}$$

where $d_w(t)$ = loss of thickness expressed in mm; and t = exposure time, measured in years, variable from 0 to 16.

The bilinear equation given by Melchers (1999), as stated in the section "Introduction", is valid for mild and low alloy steels in immersion conditions, and it is directly based on experimental data

$$\begin{aligned} d_w(t) &= 0.09 \cdot t && 0 \le t < 1.46 \\ d_w(t) &= 0.076 + 0.038 \cdot t && 1.46 \le t < 16 \end{aligned} \tag{9}$$

$$d_w(t) = 0.084 \cdot t^{0.823} \tag{10}$$

Guedes-Soares and Garbatov

Guedes-Soares and Garbatov's (1999) model on steel plated elements was improved by Qin and Cui (2003), who refined their previous study (Qin and Cui 2002), where they observed that, once the coating system loses its effectiveness in a fixed time interval, a phenomenon of pitting corrosion starts and produces an increase of the damage rate. The model proposed by Guedes-Soares and Garbatov (1999) divided the corrosion process into three phases: in the first *cps* was effective, in the second *cps* was damaged (the phase started when the corrosion started), and in the third the corrosion process was terminated.

The model, updated in 2006, focused on the variation of the thickness loss given by the following relationships:

$$\begin{aligned} d_w(t) &= d_\infty\left(1 - e^{-\frac{(1-\tau_c)}{\tau_t}}\right) && t > \tau_c \\ d_w(t) &= 0 && t \le \tau_c \end{aligned} \tag{11}$$

where d_∞ = long-term thickness of the corrosion wastage (equal to 5 mm into the example used by the authors to calibrate the model); τ_c = coating life in years, equal to the time interval between the beginning of the surface painting and the time when its effectiveness is lost; τ_t = transition time, which may be calculated as $d_\infty / \tan\alpha$, where α = angle formed by the tangent at the origin (equal to 15.2° in the example provided by the authors); and t = time varying from 0 to 25 years.

The model was calibrated assuming that the studied plate, coming from a ship deck, was loaded by wave-induced compressive loads assumed to follow the Weibull distribution. It was applied to the case study presented in Paik et al. (1998) related to bulk carriers. Since the time when anticorrosion coating loses its effectiveness is a random variable following a normal distribution (Cui et al. 1998), the reliability is conditional to the probability of the coating failure time. Assuming that the reliability of the plate can be associated with the generalized index of reliability, which is calculated from a multinormal distribution, the authors concluded that the relative corrosion depth $d_w(t)$ was a function of time under the assumption that the corrosion thickness is approximated to both a linear function and an exponential one.

Qin and Cui

The model proposed by Qin and Cui (2003) gave a generalization of both the Guedes-Soares and Garbatov model and the Paik et al. one. The model assumed that the Weibull function describes the corrosion rate. It was described by the following equations:

$$\begin{aligned} d_w(t) &= d_\infty\left(1 - e^{-\left(\frac{1-T_{st}}{\eta}\right)^\beta}\right) && T_{st} \le t \le T_L \\ d_w(t) &= 0 && 0 \le t \le T_{st} \end{aligned} \tag{12}$$

where β = shape parameter of the Weibull distribution; T_{st} = instant when pitting corrosion starts; d_∞ = long-term thickness of the corrosion wastage; and finally, η = number of coating cycles.

In the example provided by Qin and Cui, t varied between 0 and 25 years, d_∞ was equal to 1.64, T_{st} was equal to 1.38, η was equal to 9.19, and β was equal to 1.99. The corrosion rate estimation probabilistic models developed by Paik et al. from 1998 to 2013 need to be herein described, even if briefly, step by step.

Paik et al. and Mohd and Paik

Paik et al. (1998, 2004), Paik and Kim (2012) on plates, and Mohd and Paik (2013) on offshore subsea oil well tube models developed a probabilistic corrosion rate estimation model for strength assessment of longitudinal members of bulk carriers, based on available statistical data for corrosion of existing structures given by Loseth et al. (1994). In the same period, similarly, the Guedes-Soares and Garbatov (1999) model was based on nonlinear general corrosion wastage in a plate, which was updated in 2006. The model was calibrated assuming that the plate was an element of a ship deck and that it was loaded by wave-induced compressive loads assumed to follow the Weibull distribution. It was applied to the case study presented in Paik et al. (1998) regarding bulk carriers. The model proposed by Paik et al. (1998) for the strength assessment of longitudinal members of bulk carriers, as stated in the section "Introduction", was based on statistical data available from Loseth et al. (1994) related to the corrosion of existing structures. Paik et al.'s (1998) model was divided into two parts: the first part was associated with the coating life, which was assumed to follow the normal distribution, whereas the second one was connected to the corrosion progress, which was predicted on the basis of the Weibull distribution. This model assumed that corrosion starts immediately after coating effectiveness is lost.

Paik et al. (2004) described a model for low alloy carbon steel plates used for seawater ballast tanks in ship structures. This model, based on experimental data, gave three intervals, for ages of 5, 7.5, and 10 years, obtained from experimental corrosion data and related to 100% and 95% of samples, respectively

$$d_w(t) = \begin{cases} 0.0466(t-5.0) \\ 0.0579(t-7.5) \\ 0.0823(t-10.0) \end{cases} \tag{13}$$

$$d_w(t)_{95\%} = \begin{cases} 0.1469(t-5.0) \\ 0.1938(t-7.5) \\ 0.2894(t-10.0) \end{cases} \tag{14}$$

where $d_w(t)$ = corrosion depth expressed in mm; and t = vessel age (variable between 0 and 27 years), respectively equal to t_r and t in Paik et al.'s model. By comparing Eqs. (1) and (7), it can be seen that the Paik et al. model was independent from the long-term thickness of the corrosion wastage.

The model proposed in Paik et al. (2004) was discussed in depth in the work developed by Paik and Kim (2012), who assumed that the Weibull distribution was the best function to represent the corrosion wastage progress. Moreover, they defined the loss of thickness (expressed in mm) as given in the following relationship:

$$d_w(t) = \left[\frac{\alpha}{\beta}\left(\frac{t-\tau_c}{\beta}\right)^{\alpha-1}\right] e^{-\left(\frac{t-\tau_c}{\beta}\right)^{\alpha}} \tag{15}$$

where $t = T - \tau_c$ is the exposure time (in years) after the breakdown of the coating; τ_c = coating lifetime; T = age of the structure (variable from 11 and 27 years); and α and β = shape and scale parameters of the Weibull function, respectively. Finally, they also gave a polynomial expression of the Weibull parameters, also valid for the model proposed by Mohd and Paik (2013) and for t variable from 5 to 23 years, as follows (Paik and Kim 2012; Mohd and Paik 2013):

$$\begin{aligned} \alpha &= 0.0020(T-\tau_c)^3 - 0.0994(T-\tau_c)^2 + 1.5604(T-\tau_c) - 6.0025 \\ b &= 0.0004(T-\tau_c)^3 - 0.0248(T-\tau_c)^2 + 0.4793(T-\tau_c) - 2.3812 \\ \alpha &= -0.0228(T-\tau_c)^2 + 0.6183(T-\tau_c) - 0.9440 \\ b &= 0.0014(t-\tau_c)^2 + 0.0047(t-\tau_c) + 0.2921 \end{aligned} \tag{16}$$

Klinesmith et al.

Klinesmith et al. (2007) developed a model for the atmospheric corrosion of carbon steel, zinc, copper and aluminum, taking into account the effects of four environmental variables (TOW; sulfur dioxide, salinity, and temperature). The general form of the degradation model is the following:

$$d_w(T) = A * t^B \left(\frac{TOW}{C}\right)^D \cdot \left(1 + \frac{[SO_2]}{E}\right)^F \cdot \left(1 + \frac{[Cl]}{G}\right)^H e^{j(Te+Te_0)} \tag{17}$$

where T = age of the structure; TOW = time of wetness (h/year); SO_2 = sulfur dioxide concentration ($\mu g/m^3$); Cl = chloride deposition rate ($\mu g/m^3$/day); Te = air temperature (°C); and finally, A, B, C, D, E, F, G, H, j, and Te_0 = empirical coefficients.

International Cooperative Programme (ICP) model

The International Cooperative Programme (ICP) wrote on "Effects on Materials, included Historic and Cultural Monuments" in the framework of the UN ECE convention on long range transboundary air pollution (Kucera 2004, Landolfo et al. 2010). These functions were formulated for different metal materials and are based on both long-term exposures and trend analysis based on repeated one-year measurements, taking also into account the unsheltered or sheltered [Eq. (9)] exposure. The degradation of metal over time is expressed by means of mass loss (ML) as a function of climatic parameters (Rh; T), gaseous pollutants (SO_2, O_3), and precipitation parameters (rain, H^+Cl^-). In the following, the means of mass loss (ML) for weathering steel unsheltered [Eq. (18)] and sheltered [Eq. (19)] are reported:

$$ML = 34[SO_2]^{0.33} \exp\{0.020Rh + f(T)\} t^{0.33} \tag{18}$$

$$ML = 8.2[SO_2]^{0.24} \exp\{0.025Rh + f(T)\} t^{0.66} \tag{19}$$

where t = exposure time; SO_2 = sulfur dioxide concentration ($\mu g/m^3$), Rh = relative humidity, T = average annual temperature (°C); and $f(T) = a(T\text{–}10)$ when $T < 10$°C, otherwise $b(T\text{–}10)$, with a, b being constant values depending on the specific metal.

Vera and Ossandón

The Vera and Ossandón (2014) model is based on an ANN design to estimate and predict the corrosion rate of metals and alloys (in μm), at different experiment stations as a function of: exposure time, measured in years; concentration of atmospheric pollution, measured in mg m^{-2} day^{-1}; concentration of atmospheric chloride, measured in mg m^{-2} day^{-1}; relative humidity, in percentage; ambient temperature, measured in degrees Celsius; and amount of rainfall, measured in mm. The model was based on training a radial basis ANN (i.e., a type of neural network whose response or output is a function of the distance to a determined center point) to precisely fit known or observed data. Once the weight values have been set, depending on the respective networks and designed for each station, it is possible to predict values for the corrosion rate of metals and alloys as a function of the above input variables. Networks have a two-layer structure: a hidden layer and an output layer. All the connections on the two-layer network are in a forward direction. In addition, as long as the neurons on the hidden layer have radial and nonlinear transfer functions, the neurons on the output layer make linear combinations with the corresponding activation of neurons on the hidden layer.

EN ISO 9224

International standard ISO 9224 specifies the long term corrosion rates for standard structural materials in the five corrosivity classes C1–C5. According to the standard, the average corrosion rate of each material follows a bilinear law. During the first 10 years, the corrosion depth is given by the formula

$$d_w(t)_{10} = rav \cdot t(t < 10 \text{ years}) \tag{20}$$

where $d_w(t)_{10}$ = corrosion depth after the first 10 years of exposure (μm); and rav = average corrosion rate (μm/year). After 10 years of exposure, the corrosion rate is assumed to be constant with time and the thickness loss is given by the formula

$$d_w(t)_i = rav \cdot 10 + r_{lin} \cdot (t - 10) \cdot t(t \geq 10 \text{ years}) \tag{21}$$

where $d_w(t)_i$ = corrosion depth for the considered time interval (μm); and r_{lin} i = steady state corrosion rate (μm/year). The standard provides the guiding values of both rav and r_{lin} for carbon steel, weathering steel, zinc, copper, and aluminum.

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References

Albrecht, P., and T. T. Hall. 2003. "Atmospheric corrosion resistance of structural steels." *J. Mater. Civ. Eng.* 15 (1): 2–24. https://doi.org/10.1061/(ASCE)0899-1561(2003)15:1(2).

ASM (American Society for Metals) International. 2000. *Corrosion: Understanding the basics (#06691G)*. Materials Park, OH: ASM International.

Barton, K. 1976. *Protection against atmospheric corrosion*. London: Wiley.

Boubèe, F. P. 1880. *Trattato elementare teorico-pratico di Costruzioni Metalliche*. [In Italian.] Naples, Italy: Pellerano.

Breymann, G. A., and O. Koniger. 1925. *Costruzioni civili. Vol. 3: Costruzioni in ferro*. Milano, Italy: Vallardi.

Carughi, U. 1996. *La galleria Umberto I. Architettura del ferro a Napoli*. [In Italian.] Sorrento, Italy: Franco Di Mauro Editore.

CEN (European Committee for Standardization). 1992a. *Corrosion of metals and alloys: Corrosivity of atmospheres: Classification*. EN ISO 9223. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1992b. *Corrosion of metals and alloys: Corrosivity of atmospheres: Determination of corrosion rate of standard specimens for the evaluation of corrosivity*. EN ISO 9226. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1992c. *Corrosion of metals and alloys: Corrosivity of atmospheres: Guiding values for the corrosivity categories*. EN ISO 9224. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1992d. *Corrosion of metals and alloys: Corrosivity of atmospheres: Measurement of pollution*. EN ISO 9225. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1998. *Protection of metallic materials against corrosion: Corrosion likelihood in atmospheric environment: Classification, determination and estimation of corrosivity of atmospheric environment*. EN 12500. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1999a. *Corrosion of metals and alloys: Basic terms and definitions*. EN ISO 8044. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 1999b. *Zinc and aluminum coatings*. EN ISO 14713. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2000. *Corrosion likelihood in atmospheric environment*. EN 12500. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2001. *Paints and varnishes: Corrosion protection of steel structures by protective paint systems, Classification of environments*. EN ISO 12944-2. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2004a. *Hot rolled products of structural steels. Part 2: Technical delivery conditions for non-alloy structural steels*. EN 10025-2. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2004b. *Hot rolled products of structural steels. Part 5: Technical delivery conditions for structural steels with improved atmospheric corrosion resistance*. EN 10025-5. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2005a. *Basic of structural design*. EN 1990:2002/A1:2005. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2005b. *Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings*. EN 1993-1-1. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2005c. *Eurocode 3: Design of steel structures. Part 1–4: General rules supplementary rules for stainless steel*. ENV 1993-1-4. Brussels, Belgium: CEN.

Cole, I. S., T. H. Muster, N. S. Azmat, M. S. Venkatraman, and A. Cook. 1996. "Multiscale modelling of the corrosion of metals under atmospheric corrosion." *Electrochim. Acta* 56 (4): 1856–1865. https://doi.org/10.1016/j.electacta.2010.10.025.

Corvo, F., J. Minotas, J. Delgado, and C. Arroyave. 2005. "Changes in atmospheric corrosion rate caused by chloride ions depending on rain regime." *Corros. Sci.* 47 (4): 883–892. https://doi.org/10.1016/j.corsci.2004.06.003.

Corvo, F., T. Perez, L. R. Dzib, Y. Martin, A. Castaneda, E. Gonzalez, and J. Perez. 2008. "Outdoor and indoor corrosion of metals in tropical coastal atmospheres." *Corros. Sci.* 50 (1): 220–230. https://doi.org/10.1016/j.corsci.2007.06.011.

COST C25 (European Cooperation in Scientific and Technology). 2006. *Sustainability of constructions integrated approach to life-time structural engineering (2006–2010)*. Brussels, Belgium: COST.

Costa, J. M., M. Morcillo, and S. Feliu. 1989. "Effect of environmental parameters on atmospheric corrosion of metals." In Vol. 2 of *Air pollution control*, edited by P. N. Cheremisinoff, pp. 197–238. Houston: Gulf Publishing Company.

Cui, W. C., X. D. Xu, and Q. Qiu. 1998. "A fast method to calculate the mean and standard deviation of the function of random variables." *J. Ship Ocean Technol.* 2 (6): 50–60.

Davis, J. R. 2000. *Corrosion, understanding the basics*. Materials Park, OH: ASM International.

Dean, S. W., D. Knotkova, and K. Kresilova. 2010. *ISOCORRAG: International atmospheric exposure program: Summary of results: ASTM data series 71*. West Conshohocken: ASTM.

Degarmo, E. P., J. T. Black, and R. A. Kohser. 2003. *Materials and processes in manufacturing*. 9th ed. Hoboken, NJ: Wiley.

Desceliers, C., C. Soize, and R. Ghanem. 2007. "Identification of chaos representations of elastic properties of random media using experimental vibration tests." *Comput. Mech.* 39 (6): 831–838. https://doi.org/10.1007/s00466-006-0072-7.

Di Lorenzo, G., A. Formisano, and R. Landolfo. 2016. "Structural efficiency assessment of hot-rolled steel profiles." In *Proc., Int. Colloquium on Stability and Ductility of Steel Structures (SDSS'2016)*, 469–476. Hoboken, NJ: Ernst & Sohn.

Di Lorenzo, G., A. Formisano, A. Avallone, and R. Landolfo. 2017a. "Iron alloys and structural steels from XIX century until today: Evolution of processes and mechanical properties." In *Proc., 3rd Int. Conf. on Protection of Historical Constructions*. Lisbon, Portugal: Instituto Superior Técnico, Universidade de Lisboa.

Di Lorenzo, G., A. Formisano, and R. Landolfo. 2017b. "On the origin of I beams and quick analysis on the structural efficiency of hot-rolled steel members." Supplement, *Open Civ. Eng. J.* 11 (S1): 332–344. https://doi.org/10.2174/1874149501711010332.

DM (Ministerial Decree). 2005. *Design rules for buildings*. Rome: Italian Government.

Dolgikh, O., H. Simillion, N. Van den Steen, and J. Deconinck. 2014. "Steps towards atmospheric corrosion modelling." *Chem. Eng.* 41: 283–288. https://doi.org/10.3303/CET1441048.

Drisko, R. W., and J. F. Jenkins. 1998. *Corrosion and coatings: An introduction to corrosion for coatings personnel*. Pittsburgh: Society for Protective Coatings.

Elliott, P. 2003. "Designing to minimize corrosion." In *ASM handbook volume 13A corrosion: Fundamentals, testing, and protection*. Materials Park, OH: ASM International.

Farrow, L. A., T. E. Graedel, and C. Leygraf. 1996. "GILDES model studies of aqueous chemistry. The corrosion of zinc in gaseous exposure chambers." *Corros. Sci.* 38 (12): 2181–2199. https://doi.org/10.1016/S0010-938X(96)00081-9.

Feliu, S., and M. Morcillo. 1993. "The prediction of atmospheric corrosion from meteorological and pollution parameters. Part I: Annual corrosion." *Corros. Sci.* 34 (3): 403–414. https://doi.org/10.1016/0010-938X(93)90112-T.

Fratesi, R. 2002. "The steel corrosion, mechanisms and protection methods." [In Italian.] In *Proc., Promozione acciaio conference L'acciao nell'edilizia sociale, sportive e del tempo libero, Bari, Turin and Rome*. Milan: ACS Acai Servizi Srl.

Gelfi, M., and L. Solazzi. 2005. "Evaluation of the corrosion effects on the fatigue behavior." [In Italian.] In *Proc., Italian National Conf. on Corrosion and Protection.* Milano, Italy: AIM Associazione Italiana di Metallurgia.

Graedel, T. E. 1996. "GILDES model studies of aqueous chemistry.1. Formulation and potential applications of the multi-regime model." *Corros. Sci.* 38 (12): 2153–2180. https://doi.org/10.1016/S0010-938X(96)00080-7.

Guedes-Soares, C., and Y. Garbatov. 1999. "Reliability of maintained, corrosion protected plates subjected to non-linear corrosion and compressive loads, marine structures." *Mar. Struct.* 12 (6): 425–445. https://doi.org/10.1016/S0951-8339(99)00028-3.

Guedes-Soares, C., Y. Garbatov, A. Zayed, and G. Wang. 2006. "Nonlinear corrosion model for immersed steel plates accounting for environmental factors." *Trans. SNAME* 111: 194–211.

Guerrieri, M. R., G. Di Lorenzo, and R. Landolfo. 2005. "Modelling of the damage induced by atmospheric corrosion on 19th century Wrought iron structures." [In Italian.] In *Proc., Italian National Conf. on Corrosion and Protection*. Milano, Italy: AIM Associazione Italiana di Metallurgia.

Hastings, W. K. 1970. "Monte Carlo sampling methods using Markov chains and their applications." *Biometrika* 57 (1): 97–109. https://doi.org/10.1093/biomet/57.1.97.

Jančíková, Z., O. Zimný, and P. Koštial. 2013. "Prediction of metal corrosion by neural networks." *METABK* 52 (3): 379–381.

Karaca, F. 2013. "Mapping the corrosion impact of air pollution on the historical peninsula of Istanbul." *J. Cult. Heritage* 14 (2): 129–137. https://doi.org/10.1016/j.culher.2012.04.011.

Klinesmith, D. E., R. McCuen, and P. Albrecht. 2007. "Effect of environmental condition on corrosion rate." *J. Mater. Civ. Eng.* 19 (2): 121–129. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:2(121).

Komp, M. E. 1987. "Atmospheric corrosion ratings of weathering steels: Calculation and significance." *Mater. Perform.* 26 (7): 42–44.

Kucera, V. 2004. *Mapping effects on materials in manual mapping critical load*. Stockholm, Sweden: ICP Materials Coordination Centre.

Kucera, V., and E. Mattsson. 1987. "Atmospheric corrosion." In *Corrosion mechanisms*, edited by F. Mansfeld, 211–284. New York: Marcel Dekker.

Landolfo, R., L. Cascini, and F. Portioli. 2010. "Modeling of metal structure corrosion damage: A state of the art report." *Sustainability* 2 (7): 2163–2175. https://doi.org/10.3390/su2072163.

Landolfo, R., G. Di Lorenzo, and M. R. Guerrieri. 2005. "Modelling of the damage induced by atmospheric corrosion on 19th century iron structures." In *Proc., Italian National Conf. on Corrosion and Protection*. Milano, Italy: AIM Associazione Italiana di Metallurgia.

Landolfo, R., G. Di Lorenzo, M. R. Guerrieri, O. Mammana, and F. Portioli. 2007. "The Umberto I Gallery I Naples: The influence of corrosion damage on the seismic performance of the iron roofing structure." *Key Eng. Mater.* 347 (1): 345–350. https://doi.org/10.4028/www.scientific.net/KEM.347.345.

Landolfo, R., F. Portioli, M. Parrilli, and M. D'Aniello. 2009. "The seismic protection of Umberto I Gallery in Naples with FRP." In Vol. 1 of *Proc., 1st Int. Conf. Protection of Historical Buildings*, 623–628. Leiden, Netherlands: CRC-Press.

Lee, H.-Y. 2008. "Investigation on the use of iron and steel for restoration purposes during 19th and 20th century." Master's thesis, Structural Analysis of Monuments and Historical Constructions, Technical Univ. of Catalonia.

Leoni, M. 1984. *Elementi di metallurgia applicata al restauro delle opere d'arte: corrosione e conservazione dei manufatti metallici. Lezioni tenute al corso triennale di restauro dell'Opificio delle Pietre Dure (Elements of metallurgy applied to restoration of artworks)*. [In Italian.] Florence, Italy: Opus Libri.

Leygraf, C., and T. E. Graedel. 2000. *Atmospheric corrosion*. New York: Wiley.

Loseth, R., G. Sekkeseter, and S. Valsgard. 1994. "Economics of high tensile steel in ship hulls." *Mar. Struct.* 7 (1): 31–50. https://doi.org/10.1016/0951-8339(94)90009-4.

Melchers, R. E. 1987. *Structural reliability analysis and prediction*. Chichester, England: Ellis Horwood.

Melchers, R. E. 1998. "Probabilistic modelling of immersion marine corrosion." In Vol.3 of *Structural safety and reliability*, edited by N. Shiraishi, M. Shinozuka, and Y. K. Wen, 1143–1149. Rotterdam, Netherlands: A.A. Balkema.

Melchers, R. E. 1999. "Corrosion uncertainty modelling for steel structures." *J. Constr. Steel Res.* 52 (1): 3–19. https://doi.org/10.1016/S0143-974X(99)00010-3.

Melchers, R. E. 2003a. "Effect on marine immersion corrosion of carbon content of low alloy steels." *Corros. Sci.* 45 (11): 2609–2625. https://doi.org/10.1016/S0010-938X(03)00068-4.

Melchers, R. E. 2003b. "Mathematical modelling of the diffusion controlled phase in marine immersion corrosion of mild steel." *Corros. Sci.* 45 (5): 923–940. https://doi.org/10.1016/S0010-938X(02)00208-1.

Mendoza, A. R., and F. Corvo. 1999. "Outdoor and indoor atmospheric corrosion of carbon steel." *Corros. Sci.* 41 (1): 75–86. https://doi.org/10.1016/S0010-938X(98)00081-X.

Mendoza, A. R., and F. Corvo. 2000. "Outdoor and indoor atmospheric corrosion of non-ferrous metals." *Corros. Sci.* 42 (7): 1123–1147. https://doi.org/10.1016/S0010-938X(99)00135-3.

Mohd, M. H., and J. K. Paik. 2013. "Investigation of the corrosion progress characteristics of offshore subsea oil well tubes." *Corros. Sci.* 67: 130–141. https://doi.org/10.1016/j.corsci.2012.10.008.

Morcillo, M., E. Almeida, B. Rosales, J. Uruchurtu, and M. Marrocos. 1998. *Corrosión y Protección de Metales en las Atmósferas de Iberoamérica (MICAT)*. Madrid, Spain: Ibero-American Programme for Science, Technology and Development.

Morcillo, M., B. Chico, I. Diaz, H. Cano, and D. De la Fuente. 2013. "Atmospheric corrosion data of weathering steels. A review." *Corros. Sci.* 77: 6–24. https://doi.org/10.1016/j.corsci.2013.08.021.

Morcillo, M., D. De la Fuente, I. Díaz, and H. Cano. 2011. "Atmospheric corrosion of mild steel." *Rev. Metal.* 47 (5): 426–444. https://doi.org/10.3989/revmetalm.1125.

NACE (National Association of Corrosion Engineers). 1991. *Corrosion engineer's reference book*. 2nd ed., edited by R. S. Treseder, R. Baboian, and C. G. Munger. Houston: NACE.

NTC (Norme Tecniche per le Costruzioni). 2008. *Ministerial Decree of Public Works (M. D.) published on 14/01/08, New technical codes for constructions*. [In Italian.] Official Gazette of the Italian Republic No. 29. Rome: Italian Government.

Paik, J. K., and D. K. Kim. 2012. "Advanced method for the development of an empirical model to predict time-dependent corrosion wastage." *Corros. Sci.* 63 (2): 51–58. https://doi.org/10.1016/j.corsci.2012.05.015.

Paik, J. K., S. K. Kim, S. Lee, and Y. E. Park. 1998. "A probabilistic corrosion rate estimation model for longitudinal strength members of bulk carriers." *J. Ship Ocean Technol.* 2 (1): 58–70.

Paik, J. K., A. K. Thayamballi, Y. I. Park, and J. S. Hwang. 2004. "A time-dependent corrosion wastage model for seawater ballast tank structures of ships." *Corros. Sci.* 46 (2): 471–486. https://doi.org/10.1016/S0010-938X(03)00145-8.

Panchenko, Y. M., and A. I. Marshakov. 2017. "Prediction of first-year corrosion losses of carbon steel and zinc in continental regions." *Materials* 10 (4): 422. https://doi.org/10.3390/ma10040422.

Qin, S., and W. Cui. 2002. "Effect of corrosion models on the time-dependent reliability of steel plated structures." *Mar. Struct.* 15 (1): 15–34. https://doi.org/10.1016/S0951-8339(02)00028-X.

Qin, S., and W. Cui. 2003. "Effect of corrosion models on the time-dependent reliability of steel plated elements." *Mar. Struct.* 16 (1): 15–34. https://doi.org/10.1016/S0951-8339(02)00028-X.

Rizzo, F., and L. Caracoglia. 2018. "Examining wind tunnel errors in Scanlan derivatives and flutter speed of a closed-box." *J. Wind Struct.* 26 (4): 231–251. https://doi.org/10.12989/was.2018.26.4.231.

Roberge, P., R. Klassen, and P. Haberecht. 2002. "Atmospheric corrosivity modelling—A review." *Mater. Des.* 23 (3): 321–330. https://doi.org/10.1016/S0261-3069(01)00051-6.

Rose, D. H. 2014. "A cumulative damage approach to modeling atmospheric corrosion of steel." Ph.D. thesis, Dept. of Materials Engineering, School of Engineering, Univ. of Dayton.

Rossi, L. V. 1899. *Travature in ferro e in legno. Confronto tra i metodi di calcolo delle travature semplici più comuni, considerate come sistemi rigidi ed elastici. Limiti dell'errore usando metodi approssimati*. [In Italian.] Roma: Annuali della Società degli Ingegneri ed Architetti Italiani, anno XV part II.

Rozenfeld, I. L. 1972. *Atmospheric corrosion of metals*. Houston: NACE.

Sarveswaran, V. 1996. "Remaining capacity of corrosion damaged steel structures." Ph.D. thesis, Dept. of Civil Engineering, Univ. of Bristol.

Sarveswaran, V., J. W. Smith, and D. I. Blockley. 1998. "Reliability of corrosion-damaged steel structures using interval probability theory." *Struct. Saf.* 20 (3): 237–255. https://doi.org/10.1016/S0167-4730(98)00009-5.

Simillion, H., O. Dolgikh, H. Terryn, and J. Deconinck. 2014. "Atmospheric corrosion modeling." *Corros. Rev.* 32 (3–4): 73–100.

Southwell, C. R., J. D. Bultman, and C. W. Hummer. 1979. "Estimating of service life of steel in seawater." In *Seawater corrosion handbook*, edited by M. Schumacher, 374–387. Park Ridge, NJ: Noyes Data Corporation.

Summit, R., and F. T. Fink. 1980. *PACER LIME: An environmental corrosion severity classification system*. East Lansing, MI: Metallurgy, Mechanics, and Materials Science, Michigan State Univ.

Svensson, J. E., and L. G. Johansson. 1993. "A laboratory study of the initial stages of the atmospheric corrosion of zinc in the presence of NaCl: Inuence of SO_2 and NO_2." *Corros. Sci.* 34 (5): 721–740. https://doi.org/10.1016/0010-938X(93)90096-Y.

Syed, S. 2006. "Atmospheric corrosion of materials." *Emirates J. Eng. Res.* 11 (1): 1–24.

Thebault, F., C. Allely, B. Vuillemin, R. Oltra, and K. Ogle. 2012. "Reliability of numerical models for simulating galvanic corrosion processes." *Electrochim. Acta* 82 (53): 349–355. https://doi.org/10.1016/j.electacta.2012.04.068.

Thebault, F., B. Vuillemin, R. Oltra, C. Allely, and K. Ogle. 2011. "Modeling bimetallic corrosion under thin electrolyte films." *Corros. Sci.* 53 (1): 201–207. https://doi.org/10.1016/j.corsci.2010.09.010.

Tidblad, J., and T. E. Graedel. 1996. "GILDES model studies of aqueous chemistry. Part III: Initial SO_2-induced atmospheric corrosion of copper." *Corros. Sci.* 38 (12): 2201–2224. https://doi.org/10.1016/S0010-938X(96)00082-0.

Tidblad, J., V. Kucera, and A. A. Mikhailov. 1998. *UN/ECE International co-perative programme on effects on materials, including historic and cultural monuments (ICP materials)*. Rep. No 30. Stockholm, Sweden: Swedish Corrosion Institute.

Tidblad, J., A. A. Mikhailov, and V. Kucera. 2012. "Application of a model for prediction of atmospheric corrosion in tropical environments." *Atmos. Environ.* 55: 1–6. https://doi.org/10.1016/j.atmosenv.2012.02.081.

Topa, V., A. Demeter, L. Hotoiu, and D. Deconinck. 2012. "A transient multi-ion transport model for galvanized steel corrosion protection." *Electrochim. Acta* 77 (Aug): 339–347. https://doi.org/10.1016/j.electacta.2012.06.021.

Venkatraman, M. S., I. S. Cole, and E. Bosco. 2011. "Model for corrosion of metals covered with thin electrolyte layers: Pseudo-steady state diffusion of oxygen." *Electrochim. Acta* 56 (20): 7171–7179. https://doi.org/10.1016/j.electacta.2011.05.009.

Vera, R., and S. Ossandón. 2014. "On the prediction of atmospheric corrosion of metals and alloys in Chile using artificial neural networks." *Int. J. Electrochem. Sci.* 9 (12): 7131–7151.

Walker, R., VII. 2002. "The production, microstructure, and properties of wrought." *Iron J. Chem. Educ.* 79 (4): 443. https://doi.org/10.1021/ed079p443.

Walpole, R., R. Myers, S. Myers, and K. Ye. 2002. *Probability and statistics for engineers and scientists*. Upper Saddle River, NJ: Prentice-Hall.

Yamamoto, N., and K. Ikegami. 1996. "A study on the degradation of coating and corrosion of ship's hull based on the probabilistic approach." In Vol. 2 of *Proc., Int. Offshore Mechanics and Arctic Engineering Symposium (OMAE'96)*, 159–166. New York: ASME.

Yamamoto, N., and K. Ikegami. 1998. "A study on the degradation of coating and corrosion of ship's hull based on the probabilistic approach." *J. Offshore Mech. Arct. Eng.* 120 (3): 121–128. https://doi.org/10.1115/1.2829532.