ANALYSIS OF VARIABLE PARAMETERS OF PREDICTION MODELS

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DOI: 10.31490/tces-2018-0010

Abstract. *The article deals with the calculation of corrosion losses of weathering steels with dose-response functions. The environmental parameters of atmospheric corrosion incoming the dose-response functions are analysed by statistic and probabilistic methods. Between main environmental parameters belong temperature T, concentration of sulphur dioxide, relative air humidity RH, and deposition of chloride. Long-term measurements of environmental characteristics at atmospheric test sites were used for the analysis. All the environmental parameters incoming the dose-response functions are considered random variables represented by corresponding histogram. Using the probabilistic analysis it is possible to predict the expected range of corrosion rates and to analyse the impact of particular environmental characteristic on corrosion process.*

Keywords

Weathering steel; atmospheric corrosion; prediction model; atmospheric parameters; probabilistic approach.

1. Introduction

Between main atmospheric corrosion factors belong relative air humidity; air temperature; deposition rates of corrosion stimulators (sulphur dioxide and chlorides); the amount of dust particles in air; amount of rainfall; pH of rainfall, see [1, 2]. Surface location within the steel structure has also significant influence on corrosion behaviour and development of corrosion products [3, 4].

For the design of structures located in the outdoor environment is suitable to use steel with improved resistance to atmospheric corrosion, so called *weathering steel*. These steels belong to low alloy steel contain up to 2 wt. % of alloying elements such as Cu, Cr, Ni and P. These elements positively affect the corrosion properties of the steel and its corrosion behaviour in outdoor environment [5]. At the surface of the steel a protective layer of corrosion products, so called patina, is formed under suitable exposure conditions [6]. A sufficient patina layer is usually formed after 5 to 8 years of direct exposure, but in case of partially protected surfaces, the development of fully protective patina is slower.

Corrosion rates after one year of exposure r_{corr} are the basic characteristics of corrosion behaviour of weathering steels in a specific environment. Corrosion rates can be directly measured using standard specimens according to EN ISO 9223 [7] or suitable prediction models taking into account the environmental characteristics of the locality may be used to predict the corrosion behaviour.

Environmental parameters entering into prediction models are naturally random variables, so it is appropriate to use probability methods when applying prediction models.

2. Prediction of corrosion losses

It is possible to divide the prediction models into two groups - prediction models for estimating corrosion rate (corrosion loss) after the first year of exposure and prediction models for estimating corrosion loss after long-term exposure of the structure.

2.1. Long-term corrosion losses

Long-term exposure of weathering steel leads, with extended exposure duration, to gradual deceleration of corrosion loss of material on the surface of the structure. The basic input variable for prediction of long-term corrosion loss is the corrosion rate in the first year of exposure of the steel r_{corr}. The value of long-term corrosion loss can be determined in compliance with EN ISO 9224 [8] according to the formula:

$$D = r_{corr} \cdot t^{b} \tag{1}$$

where D is corrosion depth of corrosion [g/m^2 or µm]; t is exposure time [years]; r_{corr} is corrosion rate in the first year of exposure [g/(m^2·y), µm/y] and b is coefficient of time dependence specific for combination iron-environment (usually less than 1).

The input value of corrosion rate (corrosion loss) after one year of exposure can be determined in two ways: using atmospheric corrosion tests, but it is quite time consuming, or using analytical prediction equations, so called the *dose-response functions*. The second method is the most commonly applied. Analytical functions were derived from the statistical processing of a large set of corrosion tests for individual type of steel [7, 9, 10]. The input parameters of dose-response function are annual environmental parameters, which are naturally random variable. It is appropriate to use probability methods when applying prediction models.

2.2. Corrosion losses in the first year of exposure of the steel

In this article are shown three selected dose-response functions for calculating of corrosion losses in the first year of exposure.

Dose-response function according EN ISO 9223 [7], which is derived from large sets of experimentally tests of atmospheric corrosion, is in the following form:

$$r_{corr} = 1{,}77 \cdot P_d{}^{0{,}52} \cdot e^{(0{,}02 \cdot RH)} \cdot e^{f_{st}} + 0{,}102 \cdot S_d{}^{0{,}62} \cdot e^{(0{,}033 \cdot RH + 0{,}04 \cdot T)} \tag{2}$$

Dose-response function derived from program UN/ECE ICP [9] in years 1987 – 1995 is in the following form:

$$r_{corr} = 34 \cdot P_d{}^{0{,}33} \cdot e^{0{,}02 \cdot RH} \cdot e^{f_{st}} \tag{3}$$

Finally, dose-response function derived from program Multi-Assess [9] in years 1970 – 2005 is in the following form:

$$r_{corr} = 29{,}1 + \{21{,}7 + 1{,}39 \cdot P_d^{0{,}6} \cdot RH_{60} \cdot e^{f_{st}} + 1{,}29 \cdot RAIN \cdot [H^+] + 0{,}593 \cdot PM_{10}\} \tag{4}$$

where f_{st} function is calculated separately according to annual temperature; P_d is the average annual deposition rate of SO_2 [mg/(m^2·d)]; S_d is the average annual deposition rate of Cl^- [mg/(m^2·d)]; *RAIN* is the average annual rainfall [mm]; RH_{60} or RH is the average annual relative humidity [%]; H^+ is hydrogen ion concentration in rainfall [mg/l] and PM_{10} is the average annual concentration of dusty deposits (max. diameter 10 µm) [µg/m^3].

3. Long-term monitored environmental parameters

Mentioned prediction model used annual average values of environmental parameters. These values can be obtained from online databases, *e.g.* databases of the Czech Hydrometeorological Institutes of by long-term measurements. In Kopisty locality (Czech Republic) were monitored long-term climatic parameters from 1969, see Figure 1. This locality can be classified as urban environment with corrosivity category C3 [7].

Fig. 1: Locations of tested urban environment Kopisty locality (Czech Republic)

Statistical analysis and creation of histogram of annual humidity for locality Kopisty test site are shown in this article. Average annual values of humidity are shown in Figure 2.

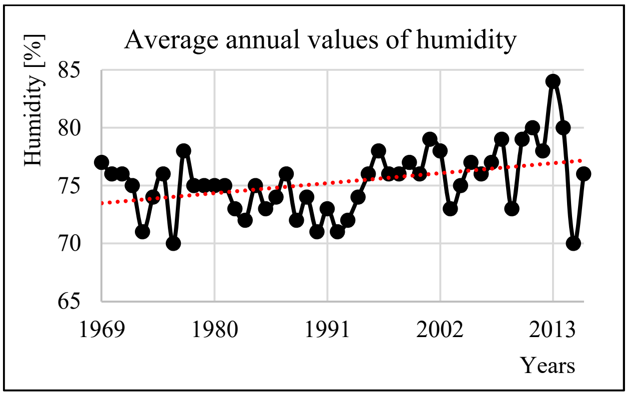

Fig. 2: Average annual values of humidity of Kopisty locality

To determine the expected range of the average annual values of humidity that will correspond to the end-date of the data series (year 2016). A statistical analysis of the measured data has to be carried out taking into account their random nature and the rising trend of humidity. For the set of data a 95% predictive interval was determined to define the area where 95 % of the measured results are situated. By regression analysis of the data, the mean value of the average annual temperature is determined for 2016, whereas the 95% boundary curve of the prediction interval allows for the determination of 2.5% and 97.5% quantile of the distribution respectively. From the above statistical parameters it is possible to determine the standard deviation of the normal distribution of the probability density of the monitored quantity. The mean value and the standard deviation (st. dev.) are the main parameters for construction on the normal probability density distribution. If there is made probability distribution of the entire dataset (not only from extrapolation for final year of the data series, i.e. year 2016), the mean value would not reflect the time trend of the change of the monitored variable and could influence negatively the resulting estimation of corrosion loss by means of prediction models (Figure 3). Created histogram is shown in Figure 4.

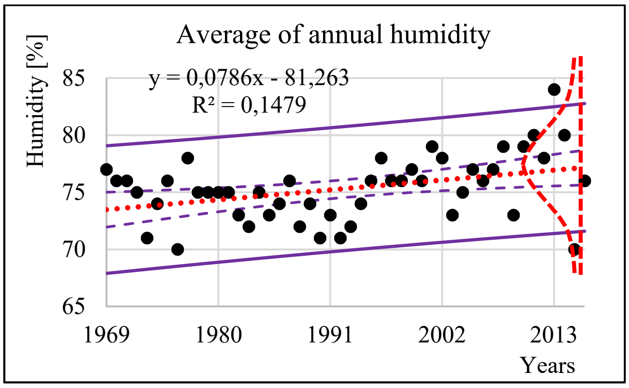

Fig. 3: Statistical analysis of average values of annual humidity for Kopisty locality – regression analysis and prediction interval

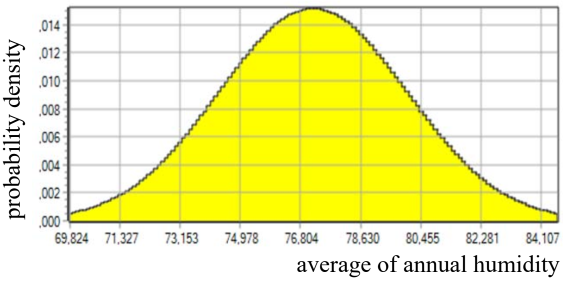

Fig. 4: Statistical analysis of humidity for Kopisty locality– regression analysis and prediction interval

4. Probabilistic calculation of prediction model

Regression analysis and predictive intervals have been calculated for all necessary environmental parameters, the course of which has changed significantly over the last decades. Each random variable was assigned to the corresponding probability density. Probability analysis assumes a normal distribution of the observed climatic variables. In order to eliminate negative values, some environmental parameters assume a log-normal probability distribution. In addition, the created probability density functions are cut off in the value ±3σ [11]. The characteristics of each distribution of randomly variable environmental parameters are given in Table 1.

The environmental characteristics with corresponding probability density were used as the input variables for the calculation of histograms of corrosion loss r_{corr} after one year of exposure.

Tab.1: Basic characteristics of probability distribution functions of environmental parameters for Kopisty locality

variable	distribution	mean value m_x	st. dev. S_x
T [°C]	normal	9.71	0.65
RH [%]	normal	77.23	2.74
RAIN [mm]	normal	447.64	116.63
pH [-]	normal	5.81	0.57
SO_2 [mg.m^{-2}.d^{-1}]	normal	12.64	3.52
PM_{10} [mg.m^{-2}.d^{-1}]	log-normal	21.95	7.49
Cl^- [mg.m^{-2}.d^{-1}]	normal	1.08	0.33

The ProbCalc software was used to determine the corrosion loss probability density for selected prediction models according to EN ISO 9223, UN/ECE ICP and Multi-Assess program. The obtained mean corrosion loss values r_{corr} after one year of exposure including standard deviations S_x and coefficients of variation V_x are given in Table 2. Obtained probability density of corrosion loss r_{corr} after one year of exposure for locality Kopisty is shown in Figure 5 to Figure 7.

Tab.2: Basic characteristics of obtained probability density functions of corrosion losses r_{corr} [μm] after one year of exposure for locality Kopisty

dose-response function	mean value m_x	st. dev. S_x	coeff. of. var V_x
ISO 9223	31.68	4.87	0.15
UN/ECE ICP	45.52	4.93	0.11
Multi-Assess	58.33	10.65	0.18

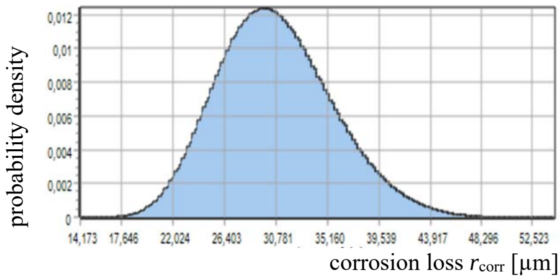

Fig. 5: Probability density of corrosion loss r_{corr} [μm] calculated according to ISO 9223 for locality Kopisty

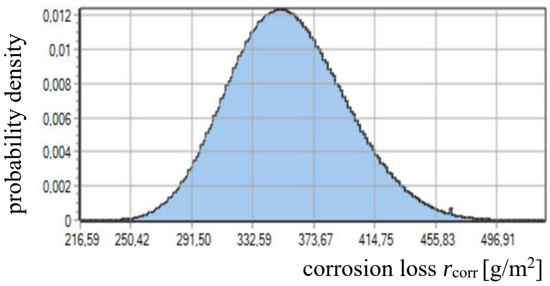

Fig. 6: Probability density of corrosion loss r_{corr} [g/m^2] calculated according to program UN/ECE ICP for locality Kopisty

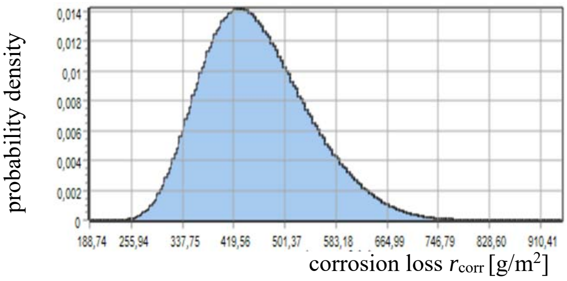

Fig. 7: Probability density of corrosion loss r_{corr} [g/m^2] calculated according to program Multi-Assess for locality Kopisty

5. Discussion

The lowest values of corrosion losses r_{corr} of weathering steel were determined by equation according to EN ISO 9223; the highest values were predicted according formula from the Multi-Asses program. The prediction models according to UN/ECE ICP and Multi-Assess seem to be too conservative.

Corrosion loss in value 21.40 was measured in real atmospheric tests in Kopisty locality during 2008 and 2009 years. This corrosion loss is influenced by decrease of concentration of sulphur dioxide. Obtained corrosion loss from real tests is lower than the values obtained from prediction models with real environmental parameters. To determine the most suitable model for prediction of weathering steel corrosion loss, analysis that is more detailed is needed. It should be based on comparing more atmospheric test results with corresponding prediction models. The values of the variation coefficient V_x of the predicted corrosion loss histograms are within the range from 0.11 to 0.18. The variability of predicted corrosion losses r_{corr} is therefore relatively high, and it is inappropriate to use only one value (*e.g.* the mean value m_x) for an accurate description of the expected corrosion loss. Probabilistic expression of the predicted corrosion loss is much more accurate.

6. Conclusions

Apposite prediction model of corrosion losses for the required design service life of the weathering steel structure is one of the basic presumptions for reliable dimensioning of structural elements. In the practical design of structures, predicted corrosion losses are usually replaced by a reasonable corrosion allowance to the thickness of structural elements. The expected corrosion loss after one year of exposure r_{corr} is the basic input variable incoming the long-term prediction models of corrosion development on weathering steel. The r_{corr} value is dependent on the random variable characteristics of the outdoor environment, and this value is therefore also a random variable. Some of the environmental parameters that affect corrosion processes show significant time trends. This fact has to be taken into account when analysing the inputs into the probabilistic prediction model.

Acknowledgements

This paper has been achieved with the financial support of the Ministry of Education, specifically by the Student Research Grant Competition of the Technical University of Ostrava under identification number SP2018/103 and part of this research has been achieved with support of project under identification number MSMT 8X17039.

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