NSS TEST OF STRUCTURAL STEEL CORROSION

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Keywords: *corrosion of steel, neutral salt spray test, corrosion rate.*

1. General information

Corrosion of structural steel represents one of the most significant degradation effects on the reliability and durability of steel bridges. It has a direct impact on the ultimate limit states and causes considerable costs for maintenance and reconstruction of infrastructure objects. As a basis for good protection of steel structures, information about an aggressive environment should be used. This data can only be reliably derived from long-term measurements. It is important to know the conditions of the environment in order to estimate and assess the build-up of metallic construction materials and to choose an effective chemical action.

The paper presents the results of experimental measurement of corrosion losses carried out on 30 specimens of structural steel in the test corrosion chamber. The presented results were obtained within solution of a research project focused on the measurement of corrosion losses from both structural steel and concrete reinforcement [14] under conditions of their real exploitation and under laboratory conditions, as well. Simultaneously with the tests in corrosion chamber, the investigation of corrosive losses on the specimens placed on bridge structures has also begun. At present, 180 specimens are laid on 12 bridges across the entire Žilina Region [16]. The measurement data will also be used to specify input data for corrosion maps in Slovakia. In many European countries, these data are processed for structural steel [9, 12], and extensive research is also devoted to weathering steel [10, 15]. Our pilot dose-response function for determination of the corrosion rate were published by authors [7, 8].

2. Experimental programme

Specimens of structural steel have a dimension of 150 mm x100 mm, in accordance with [5]. Because the specimens are used for corrosion chamber tests as well as for in-situ corrosion monitoring, their thickness was chosen to be 3 mm. The sheet provided has an average thickness of 3.08 mm. The weight of one structural steel specimen was about 360 g. A total of 360 pieces of specimens of S355 grade steel (Fig. 1a) were produced with the chemical composition and material characteristics according to Table 1.

For the laboratory tests described in this article, 30 pieces of specimens were used. Each of the specimens was precisely measured, labelled and weighed on calibrated scales. The volume of each specimen was determined using the hydrostatic weights. Based on the statistical evaluation of this data, the mean density of the steel used was 7823.53 kg/m^3.

Table 1. Characteristics of the used structural steel.

Steel			Standard		Yield strength		Ultimate		Ductility		CEV	
S355J2			EN 10025-2		442MPa		587MPa		26.20%		0.44%	
Chemical composition [%]												

	C	Si	P	S	Cr	Cu	Ni	Mn	N	Mo	Al	Nb	As	Sn	Ca
Fe	0.190	0.025	0.010	0.005	0.050	0.050	0.030	1.400	0.003	0.010	0.059	0.010	0.004	0.030	0.003

Experimental measurements of the corrosion loss were performed on the specimens in the test corrosion chamber (Fig. 1b) by the method of accelerated corrosion test in the spray of neutral sodium chloride solution (Neutral Salt Spray test = NSS test). The environment in the chamber was simulated by means of salt spray of a 5% NaCl according to [6], which represents the concentration of 50 g/l, while maintaining a temperature of 35°C ± 2°C and pH from 6.5 to 7.2 inside the chamber. Constant 100% RH was kept during the test. Such an environment simulates the conditions in which, generally, several-day period in the chamber corresponds to one year of outdoor exploitation, depending on a class of corrosive environment according to [3]. The tests presented here lasted for 140 days.
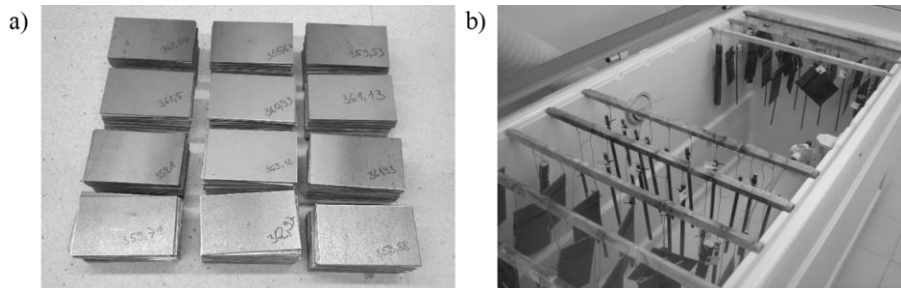

Fig. 1. Specimens: a) fabricated specimens of structural steel; b) placing specimens in the chamber together with the specimens of reinforcing steel.

A total of fourteen measurements of corrosive loses were performed. Selected intervals for measuring the corrosion rate of individual specimens are shown in Table 2. After removal from the chamber, each specimen intended for the corrosion test was visually inspected, photographed and subjected to mechanical removal of corrosive products from its entire surface. Subsequently, the specimen was weighed. Each time the test chamber was opened, the timekeeper stopped. The procedure described above was carried out in these modes (the same indications from "a" to "d" are also used in Table 2 below):

a always on a new pair of previously unselected specimens, to obtain corrosion on uncleaned steel material;

b in addition to "a" mode, seven pairs of specimens (9-22) were removed from the chamber once again at the interval of three measurements, to obtain the effect of one additional removal of corrosive products;

c from about one quarter of the duration of the experiment, a pair of specimens (5-6) began to be repeatedly checked each time the chamber was opened, to record the impact of repeated removal of corrosive products on the corrosion itself;

d finally, all specimens were removed from the chamber and corrosion effects measurements were repeated.

Table 2. Progression of measurements of specimens in the corrosion chamber.

	Measurement number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Time in chamber														
hours	51.8	119.0	220.0	336.2	436.0	654.9	870.8	1088.	1304.	1517.	1945.	2384.	2855.	3362.
days	2.2	5.0	9.2	14.0	18.2	27.3	36.3	45.4	54.4	63.2	81.1	99.3	119.0	140.1
Specimen number versus applied procedure (mode)														
1, 2	a													d
3, 4		a												d
5, 6			a				c	c	c	c	c	c	c	c, d
7, 8				a										d
9, 10					a			b						d
11, 12						a			b					d
13, 14							a			b				d
15, 16								a			b			d
17, 18									a			b		d
19, 20										a			b	d
21, 22											a			b, d
23, 24												a		d
25, 26													a	d
27, 28														a, d
29, 30														a, d

3. Observed corrosion losses

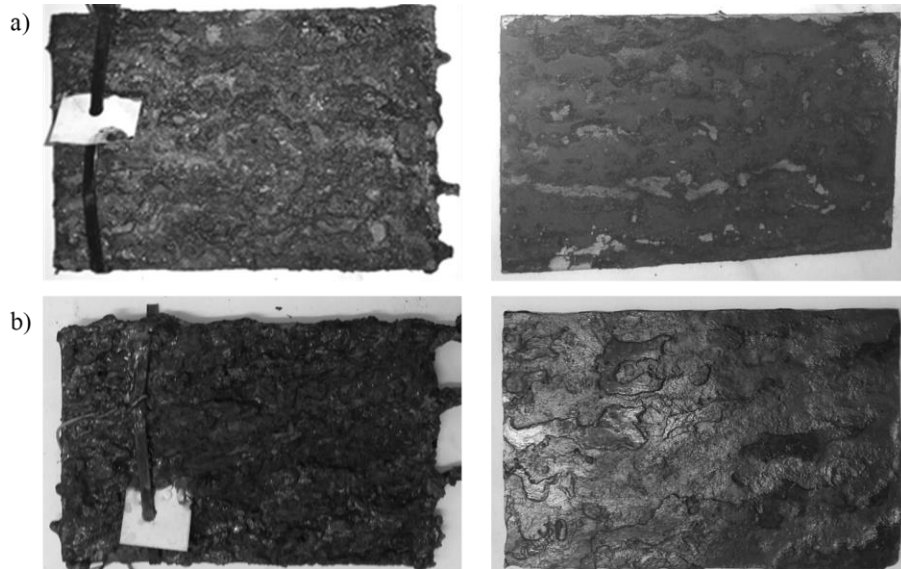The following photos show two specimens before and after cleaning process.

Fig. 2. a) Specimen no. 5 at the 1st removal during the 3rd measurement and after cleaning process; b) Specimen no. 30 at the 1st removal during the 14th measurement and after cleaning.

In Fig. 2a, specimen no. 5 is shown during its first removal (during the 3rd measurement), and photos in Fig. 2b show specimen no. 30 after its first removal (the end of the experiment).

From the measured weight loss data at the time $t_{ch,i}$, the mass corrosion loss D_{ch} was calculated. For practical use in the building practice, it is better to express the corrosion attack by its depth D'_{ch} in micrometres, which was determined by means of equation (1).

$$D'_{ch}(t_{ch,i}) = D'_{ch}(t_{ch,i-1}) + \frac{\Delta m(t_{ch,i} - t_{ch,i-1})}{\rho S(t_{ch,i-1})} \qquad (1)$$

The graph in Fig. 3a shows the course of corrosion attack of the specimens. Each displayed value represents the mean of the measurements on two specimens. From the graph, it is evident almost linear progress of corrosion. From the data evaluated by the "b" and "c" methods, it is also evident that corrosion progressed faster on specimens that were cleaned during the test than on the uncleaned specimens (mode "a"). The increase of the corrosion loss depth of the specimens repeatedly cleaned (mode "c") compared to the untreated specimens at all (mode "a") was approximately 15-20% at the end of the test. However, the faster corrosion process in the early stages was not confirmed.
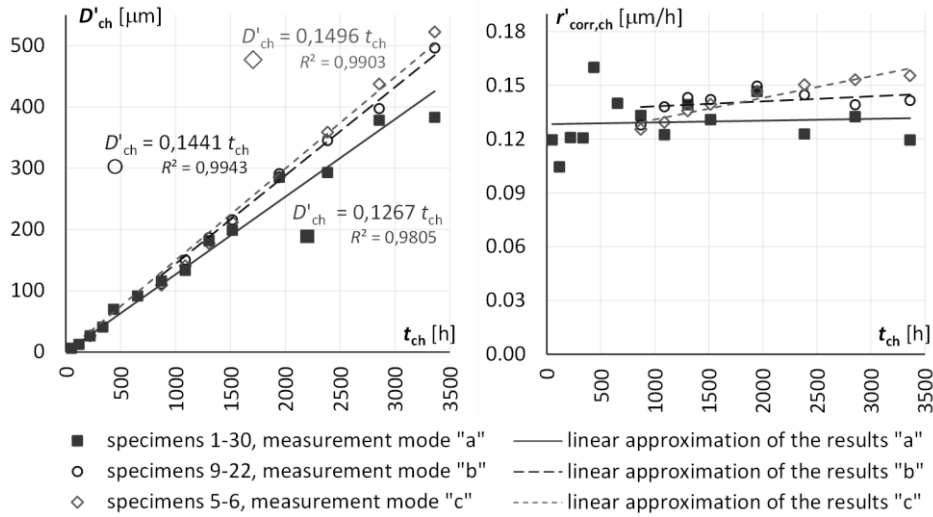

Fig. 3. Test results from the corrosion chamber:
corrosion attack D'_{ch} and corrosion rate $r'_{corr,ch}$.

The graph in Fig. 3b represents the calculated corrosion rate in chamber $r'_{corr,ch}$ using equation (2), again determined alternatively not in weight but in thickness units [5].

$$r'_{corr,ch}(t_{ch,i}) = \frac{\Delta D'_{ch}}{\Delta t_{ch}} = \frac{D'_{ch}(t_{ch,i}) - D'_{ch}(t_{ch,i-1})}{t_{ch,i} - t_{ch,i-1}} \qquad (2)$$

From the graph of corrosion rate, the effect of specimen cleaning can be seen. The corrosion rate of the uncleaned specimens (mode "a") is almost constant, while one cleaning (mode "b")

resulted in a slight increase in the corrosion rate. In the case of specimens cleaned at regular intervals (mode "c"), a relatively rapid increase in corrosion rate is evident.

4. Discussion

In the corrosion chambers, it is possible to accelerate the corrosion process. Based on their comparison with results measured in-situ or with standard estimates, it is then possible to use the results of accelerated tests for further studies, numerical simulations, or for monitoring statistically significant numbers of specimens, and so on. At present, the data collection of corrosion losses of specimens placed on bridge structures is carried out [14]. However, it is still necessary to evaluate further data for correct estimation of material degradation due to corrosion. There are several required parameters according to the used methodology. In accordance with [3], it should be at least an indication of the average annual temperature, the total rainfall, the relative humidity of the surrounding environment and the SO_2 and Cl^- concentration in the air.

However, if a method for comparing the total corrosive attack with the guide values is chosen, we will use the possibility to express the total corrosive attack according to [4]. Equation (3) characterizes the effect of corrosion in the initial approximately 20 years of the exploitation. For a longer duration of exposure, the modified relationship (4) can be used to describe the corrosive attack.

$$D'_{(t \leq 20 \, \text{years})} = r'_{\text{corr}} \, t^b \tag{3}$$

$$D'_{(t > 20 \, \text{years})} = r'_{\text{corr}} \left[20^b + 20^{b-1} b \left(t - 20 \right) \right] \tag{4}$$

In equation (4), the dimensionless exponent b is defined as the metal-environment-specific time factor. As the composition of steel is known, it was determined by the methodology of [1] which is generally accepted and is also part of the annex part of the standard [4]. From the mass fractions of the decisive alloying elements C, P, S, Si, Ni, Cr and Cu listed in Table 1, the resulting coefficient can be determined according to (5) taking into account the partial coefficients of the alloying elements presented in [4]. As far as the approximate comparison of average values is concerned, no variation or additional value was taken into account.

$$b = 0.569 + \Sigma(b_j \, w_j) = 0.5252 \tag{5}$$

The problem is mainly to determine the ratio of time in the chamber t_{ch} to the actual time t of exploitation in a certain class of corrosive environment. For the purpose of this article, therefore, two ratios of time in hours in the chamber relative to the real time were chosen. The first ratio is taken from [16] when one year in the real environment corresponds to 72 hours in the corrosion chamber. The second ratio was chosen so that one-year duration t in the real environment corresponds to 24 hours (a day) in the chamber time t_{ch}. Subsequently, the corrosion rates were selected iteratively, which faithfully match the measured data, particularly from long-term aspect. The graphical evaluation of the specimens tested by the "a" mode (Fig. 3) shows a virtually constant rate of corrosion attack. Based on this finding, therefore, the variable rate of corrosion over time was not anticipated. The results of this approximate procedure are presented in Fig. 4. The comparison in Fig. 4a indicates that if

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there was a presumption that the aggressive environment of the salt spray in the chamber can accelerate the actual year in the external environment for three days, then the corrosive environment can be most closely represented by the corrosion rate $r'_{corr} = 48$ μm/year. For comparison with the corrosion values for carbon steel in [4], the graph shows an interval corresponding to the environment with corrosive aggression degree C3. Alternatively, if there was an assumption that the one-day environment in the chamber corresponds to one year in the external environment (Fig. 4b), we would find that this medium would have a degree of aggression C2 and a corrosion rate of approximately $r'_{corr} = 20$ μm/year.
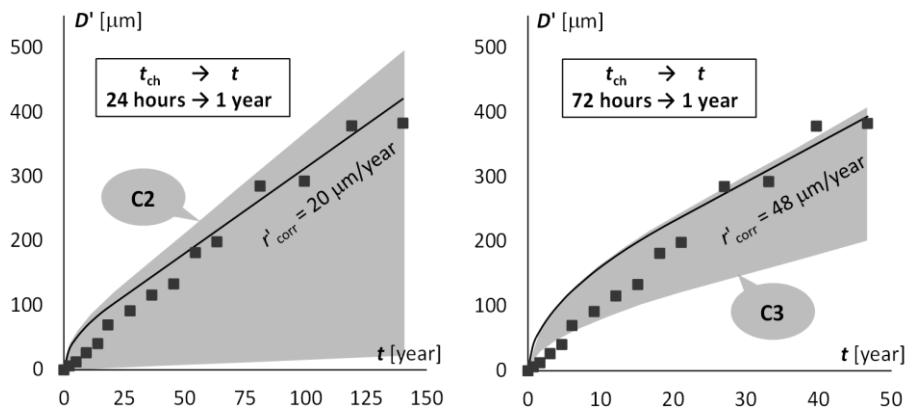

Fig. 4. Comparison of the guiding values with measured results in the corrosion chamber at two selected ratios of time the chamber to the actual year of exploitation.

The experiment could therefore be evaluated for different corrosive environments with different exploitation times or for different environments defined by the degree of corrosive aggression. However, it should also be noted that the guide values give much higher corrosion rates in the early years of exploitation. In contrast, in the chamber, the rate of corrosion was almost constant throughout the whole experiment. It seems the experiment is more suitable for comparison with longer-term experiments in the external environment with lower aggressiveness.

Alternatively, to the scaling time procedure described above, the non-constant change can be assumed in the ratio of time in the chamber to the real time. In that case, the standardised curves could be approximated more precisely. However, such consideration means acceptation the premise that corrosion process in chamber is running in a different relation to the time of exposure to the surrounding environment, as is the case in real nature. It is therefore clear that further research should also be able to address this consideration. Based on [13], several factors could influence the correlation between accelerated and atmospheric tests of corrosion.

5. Conclusion

The results of experimental measurements of the corrosion losses of structural steel in the test corrosion chamber, in the salt spray environment, show an almost linear course of corrosion over time. It has been demonstrated the suitability of this test for rapid approximation of especially long-term measurements in less aggressive outdoor environments. However, the faster corrosion process in the early stages was not confirmed.

It is obvious that the experimental measurements in corrosion chambers have their significance. In their evaluation and confrontation with data measured in real conditions, much more data would be needed. Similarly, the simulated salt-spray based environment is only partially able to represent the immense variability and changes in real atmospheric conditions. Therefore, the data collection of corrosion losses from specimens placed in a real environment seems to be of great importance. Mapping of corrosion losses and corrosive aggressiveness in the real environment appears to be the most effective in terms of assessing the behaviour of metallic materials and their surface treatments. However, even detailed map processing does not take into account local factors resulting from design of structures or their individual elements. Especially, in the case of larger structures such as bridges, the position in construction appears to be one of the decisive factors influencing the origin and progression of corrosion [2, 11].

Acknowledgement

Denotations of symbols

b – dimensionless overall metal-environment-specific time factor, [-];
b_j – partial coefficients of the alloying element in overall b factor, [-];
m – weight of a specimen, [kg];
$r'_{corr,ch}$ – corrosion attack obtained from measurement in chamber, [μm/h];
r'_{corr} – corrosion attack observed in real environment, [μm/year];
$t_{ch,i}$ – time in chamber at specific measurement point i, [h];
t – real time, [year];
w_j – mass fractions of the decisive alloying element, [%];
D_{ch} – mass corrosion loss; [g];
D'_{ch} – corrosion attack in chamber, [μm];
D' – corrosion attack in real environment, [μm];
S – specimen surface, [m^2];
ρ – density of steel used for specimens' fabrication, [kg/m^3];
Δ – designation for change of any variable in time.

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Summary

Corrosion of structural steel represents one of the most significant degradation effects on the reliability and durability of steel bridges. Relevant data needed for good protection of steel structures can only be reliably derived from long-term measurements. For acceleration of corrosion process, measurement in the corrosion chambers can be utilised. The article summarized the results of experimental measurements of corrosion losses carried out on 30 specimens of structural steel corrosion in the test chamber during 140 days. The environment in the chamber simulates the conditions in which, generally, several-day period in the chamber corresponds to either months or even years of outdoor exploitation. Discussion focused on the results interpretation to corrosion progress in real conditions is given, as well. The obtained measurement data should be used to refine the input data for corrosion maps in Slovakia. The presented results are part of a research project focused on measuring corrosive losses of structural steel in situ and as well as in laboratory conditions.