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Experimental Measurement of Structural Steel Corrosion

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Abstract

Corrosion is recognized as the most significant degradation effect of structural steel. This degradation process is affecting the cross-sectional and structural element resistance and deformation parameters of the structure. To estimate the speed of corrosion loss in the case of steel plates, rapid tests in the corrosion chamber were done. Such measurements have their significance; however, much more data from corrosion processes observed in the actual environment are still needed for their evaluation and confrontation with the results measured in situ. Therefore, the paper also presents the results of the first round of experimental measurement of corrosion losses carried out on specimens of structural steel placed on several bridge structures built in different places. Effects of local microclimate factors on corrosion process resulting from the type of bridge structures or their individual element is pointed. To underline justification of experimental program, the influence of corrosion on a flexural load-carrying capacity of three chosen structural elements from bridges in service is presented, as well.

***Keywords**: - Corrosion, structural steel, experimental measurement, corrosion losses, rapid test.*

INTRODUCTION

In the area of steel bridges, the corrosion of structural steel represents one of the most significant degradation impacts on their reliability and durability. Because of considerable costs for maintenance and reconstruction of infrastructure objects, good protection of steel structures based on information about the aggressiveness of the environment should be applied. Moreover, corrosion losses have a direct impact on the load-carrying capacity of structural elements and consequently on the overall safety of bridge structure. Relevant data for valuation of the influence of corrosion on any steel structural bridge element 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 summarizes the results of experimental measurements of corrosion losses carried out on 30 specimens of structural steel in the test corrosion chamber, Odrobiňák et al. (2017). The presented results were obtained within the solution of a research project focused on the measurement of corrosion losses from both structural steel and concrete reinforcement under conditions of their real exploitation and under laboratory conditions, as well, Koteš et al. (2018). Simultaneously with the tests in the corrosion chamber, the investigation of corrosive losses on specimens placed on bridge structures has also begun. At present, 180 specimens are laid on 12 bridges across the entire Žilina Region. 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 for many years, as is refereed either by Morcillo at al. (1995), or by Kreislová and Knotková (2017), or in the paper by Tidblad (2012). Extensive research is also devoted to weathering steel, Morcillo et al. (2013); Křivý et al. (2014) and Pauletta et al. (2015). The pilot dose-response function for the determination of the corrosion rate in Slovakia was published by authors Koteš et al. (2016), but much more data are needed for enhancement of precision for regions.

EXPERIMENTAL MEASUREMENT OF CORROSION PROPAGATION

Rapid NSS test

As it was referred by Odrobiňák (2017), the experimental program includes specimens of structural steel plates 3.08 mm thick with dimensions 150x100 mm following EN ISO 9226 (2012). The specimens were fabricated from structural steel S355 with known chemical composition. Experimental measurements of the corrosion losses were performed on specimens in the test corrosion chamber by the method of accelerated corrosion test in the spray of neutral sodium chloride solution (Neutral Salt Spray test) in accordance with EN ISO 9227 (2012). The concentrated environment was simulated by means of a salt spray of a 5% sodium chloride (NaCl) while maintaining 100% RH and a temperature of about 35°C ± 2°C together with pH from 6.5 to 7.2 inside the chamber. The tests presented here lasted for 140 days, while 14 measurements of corrosive losses were performed, during which these four modes of corrosion losses observation was taken into account:

- a-mode - always a new pair of specimens was cleaned and weighted at each measurement point, to obtain corrosion on uncleaned steel material;
- b-mode - in addition to a-mode, seven pairs of specimens (#9 - #22) were removed from the chamber once again to obtain the effect of one additional removal of corrosive products;
- c-mode - from about one-quarter of the duration of the experiment, one pair (#5 & #6)of specimens began to be repeatedly checked, to record the impact of repeated removal of corrosive products on the corrosion itself;
- at the end, all specimens were removed from the chamber and measured at the end of the experiment.

From the measured weight loss data at the time in corrosion chamber t_{ch}, the mass corrosion loss D_{ch} was estimated. Consequently, the corrosion attack D'_{ch} in micrometers was calculated, which better suits practical use as it describes losses in per plates' thickness. The graph in Fig. 1a shows the course of corrosion attack of the specimens. Each displayed value represents the average measurement on two specimens. From the graph, it is evident almost linear progress of corrosion. From the data evaluated according to the b-mode and c-mode, it is also evident that corrosion progressed faster on specimens that were cleaned during the test than on the uncleaned specimens (a-mode). The increase of the corrosion loss depth of the specimens repeatedly cleaned (c-mode) compared to the untreated specimens at all was approximately 15-20% at the end of the test. However, the faster corrosion process in the early stages was not confirmed. The graph in Fig. 1b represents the calculated corrosion rate in chamber $r'_{corr,ch}$, again determined alternatively as corrosion speed in thickness units. From the graph of corrosion rate, the effect of specimen cleaning can be clearly seen. The corrosion rate of the uncleaned specimens (a-mode) is almost constant, while one cleaning (b-mode) resulted in a slight increase in the corrosion rate. In the case of specimens cleaned at regular intervals (c-mode), a relatively rapid increase in corrosion rate is evident.

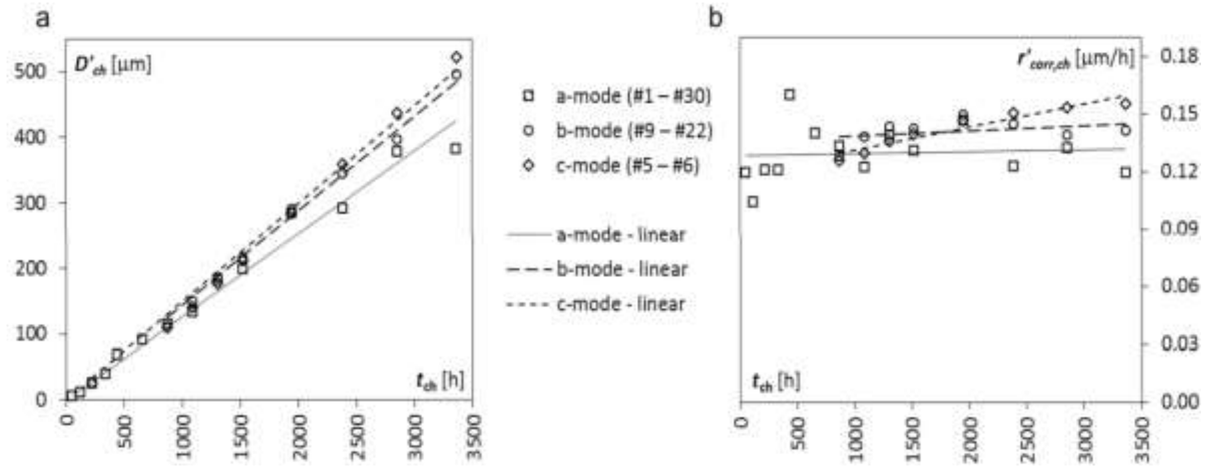

Fig. 1: Test results from corrosion chamber: (a) corrosion attack in D'_{ch} ***micrometers; (b) corrosion rate*** $r'_{corr,ch}$ ***in micrometers per hour.***

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. 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, Lin and Wang (2005).

For the purpose of this article, a linear relationship is presented with two different scaling factors between the time in the chamber and the real- time. The first ratio is taken from Strieška et al. (2017) when a presumption that the aggressive environment of the salt spray in the chamber can accelerate the actual year in the external environment during three days (Fig. 4a).

Then, the corrosive environment can be most closely represented by the corrosion rate r'_{corr} = 48 µm/year, which is the value within the interval corresponding to the environment with corrosive aggression degree C3 by EN ISO 9224 (2012).

Alternatively, if there was an assumption that the one-day environment in the chamber corresponds to one year in the external environment (Fig. 4b), it could be found that this atmosphere would have a degree of aggression C2 and a corrosion rate of approximately r'_{corr} = 20 µm/year.

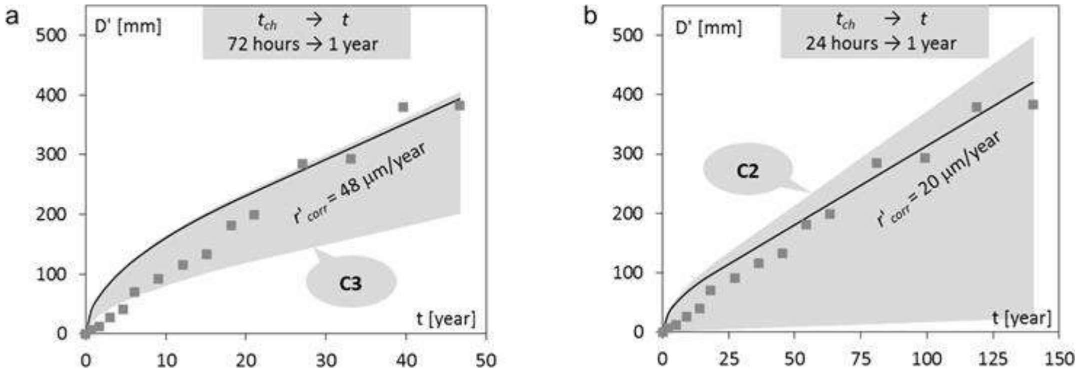

Fig. 2: Comparison of the values given in EN ISO 9224 (2012) with measured results in the corrosion chamber at two selected ratios of the chamber time to the actual year of exploitation

One year results from in-situ measurement

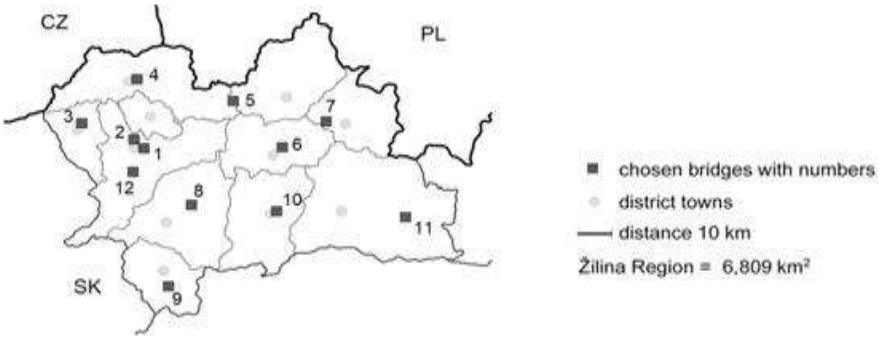

Fig. 3: Location of chosen bridges in northwest part of Slovakia, self-governing Žilina Region

In order to measure the real propagation of corrosion in the actual environment, 15 specimens were located directly on each of twelve chosen bridges across the entire Žilina Region. The map in Fig. 3 shows the location of the bridges throughout the region. Basic information concerning the bridges is given in Table 1. Specimens were placed on 10 bridges in summer 2016; the rest two bridges were met last summer in 2017. As the next measurement is planned for this year’s summertime, the results from the first one-year measurement on ten bridges only are given in last columns in Table 1. Actually, the data from nine bridges are relevant, as the specimens from bridge No. 10 have been destroyed or stolen. The measurement values represent the particular results of this long-term observation experiment. Anyway, they can be used for a rough estimation of corrosion environment aggressiveness. Together with the measurement of air pollution, temperature and humidity, the data can be used to specify inputs for corrosion maps in Slovakia.

Table 1: Information about bridges with installed specimens for corrosion measurement and partial results - one-year corrosion losses

Bridge No.	Bridge identification				Location of specimens on the bridge	Start of experiment [month/year]	Time at 1st measurement t [days]	Corrosion loss per area D [g/m^2]	Corrosion rate r'_{corr} [□m/year]
	Locality	Material	Traffic	Obstacle					
1	Silica	steel-concrete	road	road	main girder	07/2016	371	47.206	5.936
2	Budatin	steel-concrete	road	river	main girder	07/2016	371	58.380	7.341
3	Bytča	steel	road	channel	cross beam	07/2016	371	72.660	9.137
4	Čadca	concrete	road	river	pier	07/2017	-	-	-
5	Nová Bystrica	concrete	road	valley	abutment	09/2016	309	45.565	6.880
6	Medzibrodie	steel	railway	river	cross beam	09/2016	309	22.576	3.409
7	Podbiel	steel	road	river	main girder	07/2016	367	121.699	15.471
8	Sučany	steel-concrete	road	highway	main girder	09/2016	310	27.702	4.169
9	Horná Štubňa	concrete	motorway	railway	abutment	09/2016	310	41.943	6.312
10	Ružomberok	steel	railway	river	pier	09/2016	*destroyed or stolen specimens		
11	Hybe	concrete	road	highway	abutment	09/2016	309	91.641	13.836
12	Poluvsie	steel	railway	stream	main girder	07/2017	-	-	-

From the partial first-year results listed in Table 1, confronted with the location of the individual specimens, it can be concluded that except for the aggressiveness of the environment in which the specimens are placed, corrosion rates are significantly affected by their location on the bridge as well. Evidently, in the case of bridges with No. 7 and 11, which are placed in a very severe atmosphere with a high saturation of the chlorides Cl^- from icing salts, very fast corrosion process was confirmed. On the other hand, bridge numbered as No. 5 shows unexpectedly high corrosion losses, although the bridge is placed in a rural land-protected area with forbidden use of icing salt during winter. Contrary to that, the corrosion losses on specimens installed on bridge No. 8 built above a highway are almost half. It means that position within the cross-section and the fact whether specimens are protected against water or not have a very strong influence on corrosion propagation. A specimen placed in a relatively mildly corrosive environment exposed directly to weather or water flown from communication surface can corrode much more strongly than another one located in the zone with significantly higher aggressiveness but placed in a sheltered microclimate somewhere under the bridge deck in the leeward.

The next collection of data concerning corrosion losses of specimens placed on bridge structures are going to be carried out this year. However, it is still necessary to evaluate further data for correct estimation of material degradation due to corrosion, Syed (2006). There are several required parameters according to the used methodology. Basically, an indication of the average annual temperature, the total rainfall, the relative humidity of the surrounding environment and the SO2 and C1- concentration in the air should be measured in situ, at least, Ivašková (2015).

CORROSION LOSS VERSUS BENDING LOAD CARRYING CAPACITY

Introduction

As already mentioned, the corrosion degradation of structural steel has a significant effect on the reliability of the bridge, particularly its safety and durability. Corrosion losses reduce the effective cross-sectional area of the supporting members and thus decrease their mechanical resistance to the effects of loads acting on the bridge superstructure. Depending on the level of the design safety of the individual supporting elements, during the bridge service life, it may happen that the element weakened by progressive corrosion is no longer able to transmit the load effects, in particular the traffic loads. The ability of the bridge structure to carry the effects of traffic loads is quantified by so-called load-carrying capacity, which represents a basic quantification indicator in evaluating existing bridges.

The study

As an example of how corrosion losses can reduce the bending resistance of a bridge member and its load-carrying capacity, respectively, the next study was worked out. Different types of structural members of three real bridges in service were chosen located in similar corrosion conditions. The first bridge, marked as “A” in the next, is the three-span road bridges across a river, Fig 4a. The issue was the main girders of the bridge with the cross-section welded from hot-rolled I400 and U80 profiles, Fig 5a. When diagnostics of corrosion losses were executed, the age of the bridge was 39 years. The second bridge (“B”), showed in Fig. 4b, is located on a local service road across a river canal. The main girder has been chosen for this study again. However, it consists of steel and concrete composite cross-sections made of unsymmetrical welded steel beam and prefabricated reinforced concrete deck, Fig 5b. Finally, the third bridge structure (“C”) is built on the main railway line, Bujňák et al. (2016). The main span bridges a river by the riveted truss girder superstructure with open member deck, Fig. 4c. To estimate the influence of corrosion on bending resistance, the stringer of the open bridge deck was chosen with the I-shaped cross-section, Fig. 5c.

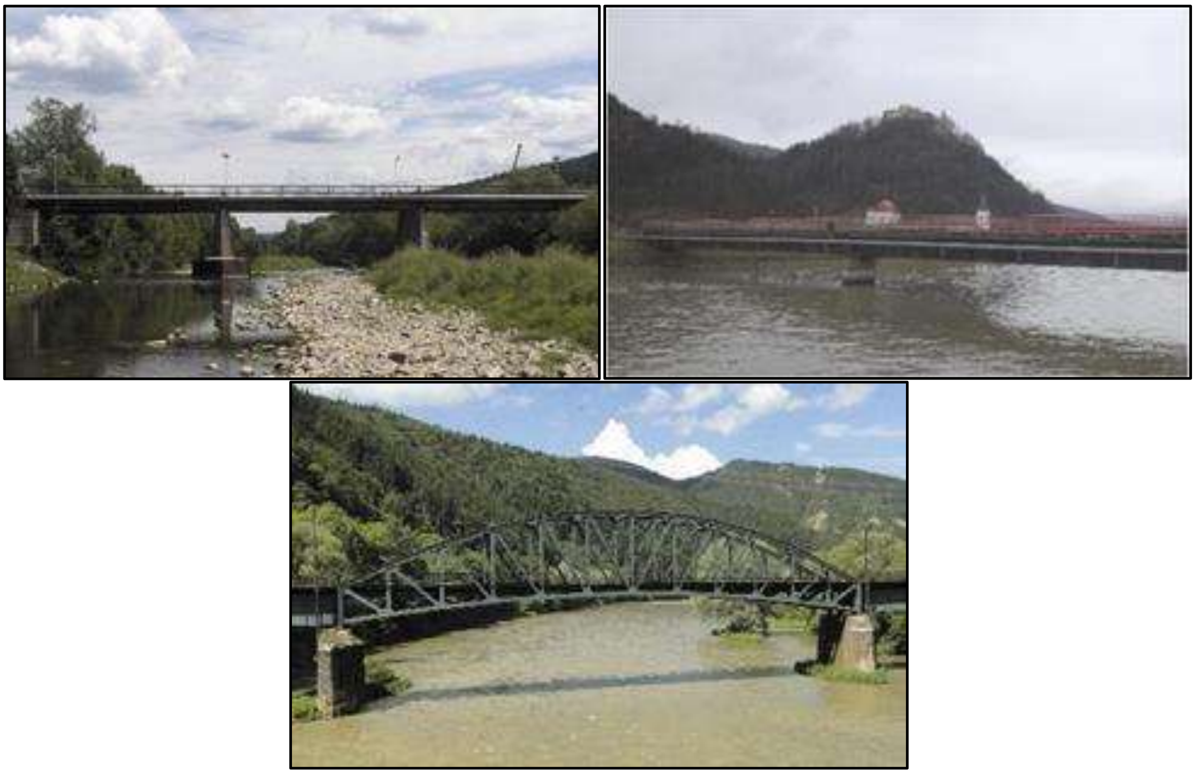

Fig. 4: a) the road bridge A across a river; b) the bridge B on a local service road across a river canal; c) the railway bridge C across a river.

Load-carrying capacity (LCC) is generally defined as a ratio of the limit effects of the vertical variable traffic load (in terms of the corresponding ultimate or serviceability limit state, respectively) to the effects produced by the design load model in the given element. This ratio represents the factor by which multiplied effects of the design load model (stresses, internal forces, deformations, …) cause, in combination with other acting loads, the occurrence of the corresponding limit state.

In the case of railway bridges, this factor defines a multiple of the load model 71, EN 1991- 2 (2003). In the case of road bridges, the load-carrying capacity is, for practical reasons, usually indicated directly by the weight of the vehicle (usually in tons), either in normal operating conditions (standard LCC) or in specially defined operating conditions (singular LCC) on the bridge, which is also defined as a multiple of the corresponding design vehicle weight. More details concerning the load-carrying capacity estimation can be found in the two papers prepared by Vičan et al. (2016).

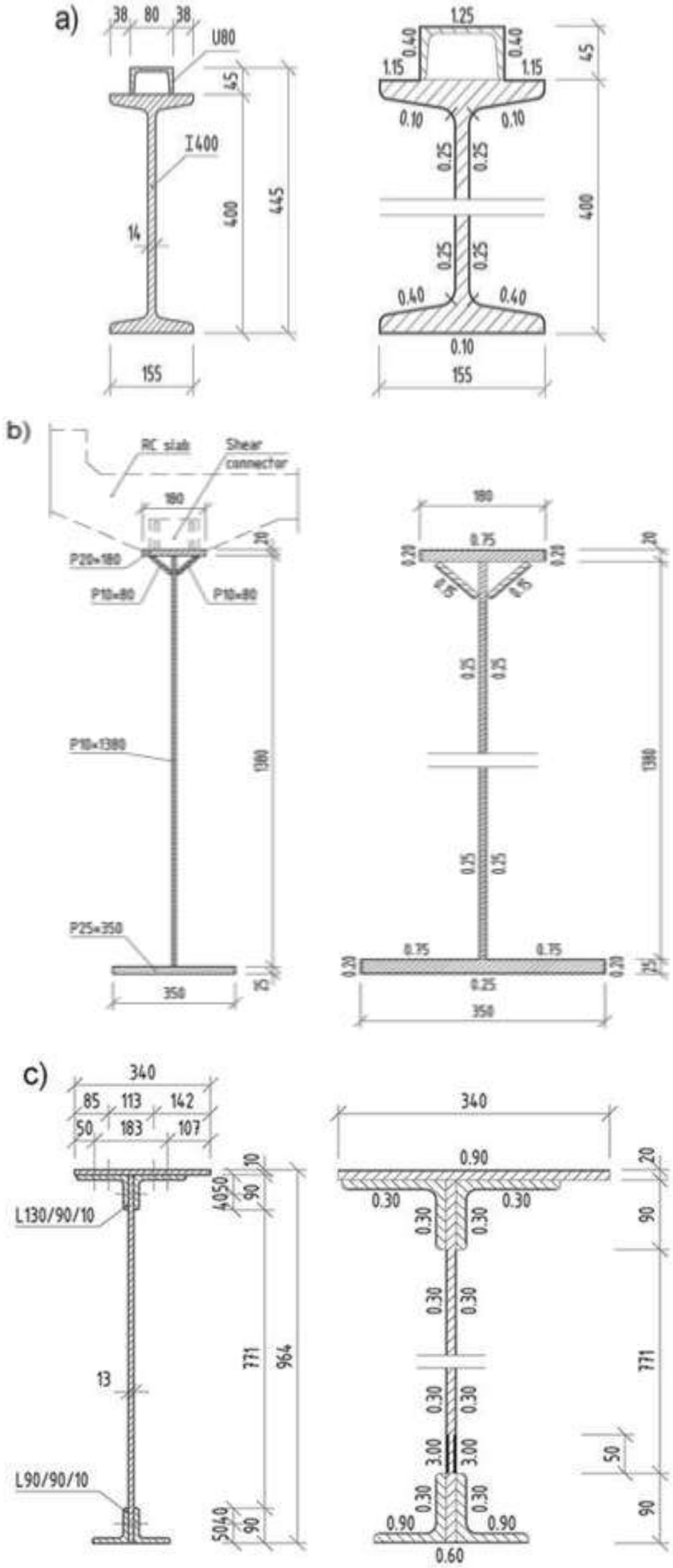

Fig. 5: Cross-sections and measured corrosion losses of: a) the main girder of the read bridge A; b) the main composite girder of the bridge B on service road; c) the stringer in open deck of the railway bridge C; dimensions in millimeters.

The results of the study are summarized in Table 2 and Figure 6, where the relative decrease of the cross-section area A, cross-section modulus *W* and the load-carrying capacity due to increasing corrosion losses during the service life of the bridges are presented. The load-carrying capacity of the chosen bridge members was determined from the elastic bending resistances of the cross-sections.

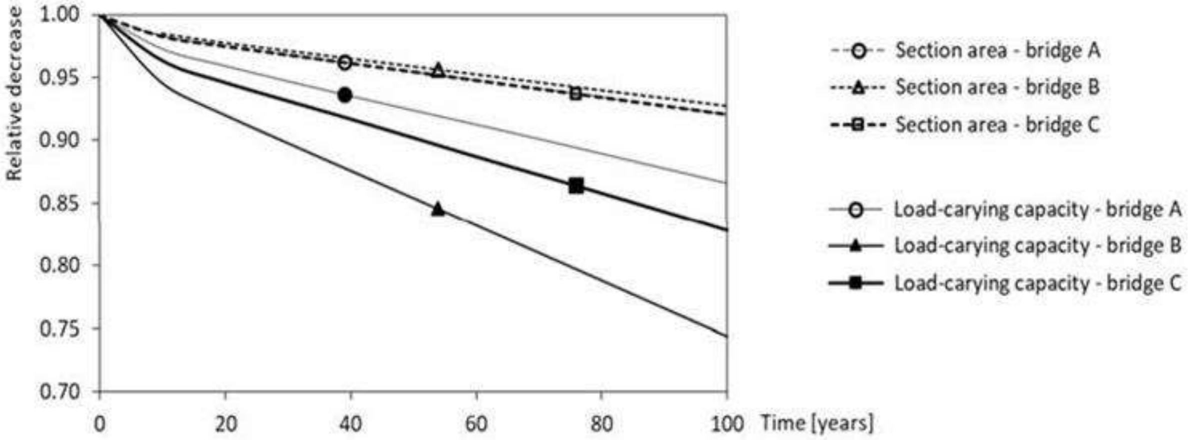

Figure 6

Table 2

Load-carrying capacity Relative decrease of the (comparing *t =0 year)*

Bridge Identification

	year]	[mm/year]	[kNm]	[mm^3]x10^{-3}	[tons]	[tons]	area	modulus	standard	singular
A	0		12867	1943.2	25.9	38.0	1.000	1.000	1.000	1.000
road	10		12656	1910.9	25.2	37.0	0.984	0.983	0.973	0.973
main girder	20		12555	1894.8	24.8	36.5	0.976	0.975	0.959	0.959
14.4 m	**39**	31.73	**12383**	1867.8	**24.2**	**35.6**	**0.962**	**0.961**	**0.937**	**0.937**
rolled and	70		12118	1825.9	23.3	34.3	0.942	0.940	0.901	0.901
welded	100		11852	1783.9	22.4	32.9	0.921	0.918	0.866	0.866
B	0		27750	13223.8	8.3	15.4	1.000	1.000	1.000	1.000
local road	10		27321	13023.8	7.9	14.7	0.985	0.985	0.946	0.958
main girder	20		27122	12928.6	7.7	14.4	0.977	0.978	0.920	0.939
34.2 m	**54**	24.97	**26537**	12652.4	**7.0**	**13.5**	**0.956**	**0.957**	**0.845**	**0.882**
composite	75		26175	12481.0	6.7	13.0	0.943	0.944	0.799	0.846
steel-concrete	100		25745	12276.2	6.2	12.4	0.928	0.928	0.744	0.804
					Z_{LM71} [-]				Rel. decrease of Z_{LM71}	
	0		20738	3954.6	1.205		1.000	1.000	1.000	
C	10		20385	3852.7	1.161		0.983	0.974	0.963	
railway	20		20221	3805.2	1.140		0.975	0.962	0.946	
stringer	40	22.83	19938	3722.6	1.105		0.961	0.941	0.917	
4.9 m	60		19654	3639.5	1.069		0.948	0.920	0.887	
riveted	**76**		**19427**	**3572.7**	**1.041**		**0.937**	**0.903**	**0.864**	
	100		19087	3471.9	0.998		0.920	0.878	0.828	

From the results of the presented study, it can be stated out that the decrease of cross-section areas of the chosen bridge members as well as their load-carrying capacities corresponds to the increase of the corrosion attack D', when after about 15 years, it takes a practically linear course. Interestingly, this conclusion applies to each of the three cases examined with different cross-sectional shapes and different ranges of corrosive attack. The relative decrease of load carrying capacity is stronger than the decrease of the corresponding cross-section area, which is due to the fact that the bending resistance of the cross-section is reduced by other load effects. This phenomenon emphasizes the importance of monitoring the influence of corrosion on the static safety of the bridge structure.

CONCLUSIONS

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 the rapid approximation of especially long-term measurements in less aggressive outdoor environments. However, mapping of corrosion losses and corrosive aggressiveness in the real environment appears to be the most effective in terms of assessing the behavior of metallic materials and their surface treatments. But, even detailed map processing does not take into account local factors resulting from the 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, Křivý et al. (2014).

Results of the case study focused on the influence of the structural steel corrosion on the reliability of bridge structures show a similar virtually linear course of the decrease of cross-section area as well as the load-carrying capacity of the observed bridge structure elements due to the increasing corrosion losses during their service life. The stronger relative decrease of the load-carrying capacity compared to the decrease of the corresponding cross-section area emphasizes the importance of monitoring the influence of corrosion on the static safety of the bridge structure.

Governing criteria for load-bearing capacity may change over time due to corrosion losses, Kayser and Nowak (1989). Neglected inspections can lead to substantial degradation and a consequent decrease of load-carrying capacity; see Odrobiňák and Hlinka (2016). A strong relationship is also between corrosion losses and fatigue resistance, Peng et al. (2017). Thus, only perfect up-to-date protection of steel together with regular periodic inspection and basic routine maintenance can ensure the required life-time and save a lot of money. Underestimating corrosion usually results in poor condition of bridges, requiring major repairs and reconstruction, Ágocs et al. (2004).

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