Influence of microclimate on the sustainability and reliability of weathering steel bridge

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Abstract. Reliability and sustainability of bridge structures designed from weathering steel are influenced by the development of a sufficiently protective layer of corrosion products on its surface. The development of this protective layer is affected by several parameters such as air pollution around the bridge structure, the microclimate under the bridge, the location of surface within the bridge structure and the time of wetness. Design of structural details also significantly influences the development of the protective corrosion layer.

The article deals with the results of the experimental tests carried out on the road bridge located in the city of Ostrava in the Czech Republic. The development of the protective corrosion layer on the surface of the bridge is significantly influenced by the intensive traffic under the bridge construction and the design solution of the bridge itself. Attention is focused mainly on the influence of chloride deposition on the protective function of the corrosion layer. Corrosion samples were placed on the bridge to evaluate the influence of the above-mentioned parameters. The deposition rate of chlorides spreading from the road to surfaces of the steel structure is also measured.

1. Introduction

Steels with increased resistance to atmospheric corrosion, weathering steels, belong to a group of low-alloy steels. The content of alloying elements in such steels does not exceed 2 wt.%. The elementary alloying elements that affect the corrosion resistance of steel are Cu, Cr, P and Ni [1, 2]. Weathering steel is mainly used for structures in outdoor, not only because of its increased corrosion resistance in the air but also with respect to its aesthetic properties. Weathering steel is mainly used in the design of bridge structures, transmission towers, facade of building, but also in the statues and monuments. Increased corrosion resistance of steel is due to the development of a sufficiently protective corrosion layer on the steel surface after 3 to 7 years of direct exposure.

The development of corrosion layers significantly depends on environmental conditions of the structure’s location [3]. One of the basic environmental parameters that affect the development of protective patina is the time of wetness of the metal surface. For the favourable development of the protective patina, it is important to alternately wet and dry the surface. In cases where an increased moisture build-up occurs on the surface of the structure, non-protective, large corrosion products may develop, the presence of which is associated with increased corrosion weakening of the structure bearing elements.

It is therefore obvious that the design of the bridge structure has, in addition to the basic parameters of the environment, a significant influence on the development of corrosion layers [4, 5]. Other environmental factors that significantly influence the development of the protective corrosion
layer are the concentration of corrosion stimulators in the air, especially concentration of SO$_2$ and chlorides. The concentration of SO$_2$ in the air reached maximum values in Europe in the 1970s and 1980s; after this period there was a significant decrease in SO$_2$ concentration [6, 7], see Figure 1. In 1970 in industrial areas of the Czech Republic (Prague, Ostrava, Northern Bohemia), the experimentally measured SO$_2$ concentration in the atmosphere was almost 200 μg.m$^{-3}$. Currently, the SO$_2$ concentration in the air is approximately 20 times lower and ranges around 5 - 15 μg.m$^{-3}$. On the figure 1 there is illustrated decrease of concentration of SO$_2$ experimentally measured in industrial location Kopisty (Czech Republic).

![Figure 1. Changes of concentration of SO$_2$ during 1969-2015 in industrial location Kopisty (Czech Republic)](image)

The decrease in concentration of SO$_2$ is significant and the reason for it is mainly the introduction of desulphurization units into industrial production and the reduction of fossil fuel consumption. In the past, the main corrosive stimulator in the Czech Republic was SO$_2$. At present, due to its low concentration in the atmosphere, the influence of chlorides is increased as a significant corrosion stimulator. In seaside areas, chlorides spread along with the seawater aerosol. In inland areas, sources of chlorides are primarily de-icing salts used in winter maintenance of roads. Therefore, the structures located near motorways with high road traffic are the ones that are most affected by chloride deposition. The negative effect of chlorides not only shows on roads and adjacent structures, but also, for example, on vegetation in a relatively wide area around the road [8].

Increased attention needs to be paid to the development of corrosion processes on bridge structures leading above busy roads. The local microclimate with increased atmospheric corrosivity can be expected mainly in design solutions, creating tunnel-like conditions [9] (see Figure 2). The aerosol and dust raised by the traffic cannot be dispersed in partially tunnel conditions under bridge into the environment, leading to increased settling of dusts on the supporting elements of the bridge structure. These surfaces are not sufficiently ventilated and washed by rain due to closed conditions. The unfavourable development of corrosion products can be expected mainly on horizontal surfaces that are more affected by deposition and retention of dusts with corrosive stimulators than vertical surfaces. In steel structures, these are mainly the upper surfaces of the lower flanges of the main girders of bridge [10].

For design practice, it is very important to predict the development of corrosion processes with sufficient accuracy, both in designing new structures and in assessing the reliability and lifetime of bridges already in use. Workplaces all over the world have been carrying out long-term research projects in this field, where experimental verification of atmospheric corrosivity of the environment and evaluation of the influence of various corrosive agents on the behaviour of corrosion processes...
are carried out [1, 3]. In the submitted article, there are presented and evaluated selected results of experimental corrosion tests carried out on selected bridge structures. In particular, the results of the tests carried out on a bridge in Ostrava, which with its design solution creates the conditions partially corresponding to the conditions in the tunnel, the so-called tunnel-like conditions. The values of corrosion losses after one and three years of exposure of corrosive samples located on typical surfaces of the bridge structure are evaluated and discussed. In addition to the corrosion samples, sampling devices for direct measurement of chloride deposition were installed on the bridge structure. The article presents the measured values of chloride deposition in relation to a particular season of the year. Simultaneously, a comparison of measured values of chloride deposition with a neighbouring bridge located on the same road is performed, which has not been affected by the intensive road traffic under the bridge structure.

![Figure 2. Schematic drawing of tunnel-like conditions under the bridge](image)

**Figure 2.** Schematic drawing of tunnel-like conditions under the bridge

### 2. Methods for experimental testing

The program of experimental corrosion tests includes in total 10 weathering steel bridges [4]. The road bridge above the D1 motorway in Ostrava is the only one bridge from the program that is influenced by tunnel-like conditions. The locality can be characterized in accordance with [11] as an environment with a degree of atmospheric corrosivity C2 to C3. The bridge structure was put into operation in 2001. The steel bridge moves road and tram traffic above the busy D1 motorway. The structure is designed using main girders that are coupled with a reinforced concrete slab. The supporting steel structure is made of weathering steel Atmofix B (S355J2W). The construction design of the bridge structure is shown in Figure 3.

![Figure 3. Views of a tested bridge structure](image)

**Figure 3.** Views of a tested bridge structure

Corrosion test samples and sampling devices for the measurement of chloride deposition were placed on selected surfaces of the bridge structure. Corrosion samples 150x100x1.5 mm (S355J2WP steel), designed in accordance with [12], are intended to monitor the development of corrosion layers on the steel surface over time. The side of the samples adjacent to the steel structure is protected by a special tape in order to develop corrosion products only on the front exposed surface of the sample. Corrosion samples are attached to the steel structure by means of stainless steel clips in such a way
that they fit the evaluated surface of the bridge. A total of three corrosion samples were placed on each selected surface of the bridge, which are supposed to be sequentially removed after 1, 3 and 10 years of exposure. The thickness of the corrosion layer on the samples using a magnetic-induction method is measured continuously for all evaluated surfaces of the bridge, as well as the corrosion loss values. Elemental and diffraction analyses to determine the representation of individual phases in the corrosion layer were also performed on selected samples. Based on the ratio of individual phases in the patina layer, the values of the PA indexes for the evaluation of protective properties of the formed corrosion layer [13, 14] are determined. Selected surfaces of the bridge structure on which the corrosion samples were placed, are shown in Figure 5. Surfaces S8 to S11 are oriented southward (in the driving direction on the motorway under the bridge), the other samples are oriented northward (opposite-direction on the motorway under the bridge).

Sampling devices for chloride deposition measurements were designed in accordance with [15]. The devices for measuring the deposition of chlorides using the wet candle method and the dry plate method have been installed on selected surfaces of the structure. The wet candle method is based on the installation of a bottle made of inert material with prescribed solution. Surgical gauze for the collection of chlorides is wound onto a wick placed in the bottle, which are consequently transferred to the solution in the bottle via the gauze. The dry plate method consists of installing a frame of prescribed dimensions, onto which a special industrial textile for the deposition of chloride-containing dust deposit is stretched out. A small perforation of the textile is important to prevent the textile from being blown through, resulting in collected dust being blown away. As part of experimental measurements, dry plates are oriented both horizontally and vertically. Exposure of the sampling device is one calendar month. Subsequently, the sampling equipment is replaced with a new one and the collected samples are subjected to a chemical analysis to determine the amount of deposited chlorides.

The chloride deposition sampling device was installed on four selected positions on the evaluated bridge (see Figure 4):

- position P1 – outer girder No. I – north (corresponding with surfaces S3 and S4)
- position P2 – inner girder No. III – north (corresponding with surface S12)
- position P3 – inner girder No. III – south (corresponding with surface S9)
- position P4 – outer girder No. XI – south (corresponding with surface S11)

![Figure 4. Tested surfaces with devices for measuring of deposition rate of chlorides](image-url)
3. Results of experimental tests

In order to evaluate the influence of chlorides (or the influence of the specific environment under the bridge structure) on the development of corrosion layers, several fundamental experimental parameters can be used, such as average thickness of corrosion products layer, corrosion losses, chlorine weight content in corrosion products, PA index values, and actual chloride deposition in the air. Due to the extensive character of the experimentally determined data for the purposes of this article, two sets of data have been selected for the microclimate impact assessment under the bridge structure, corrosion losses and chloride deposition.

3.1. Corrosion losses after one and three years of exposure

Corrosion samples were installed on the evaluated bridge structure in 2014. In 2015 the samples were removed after 1 year of exposure and in 2017 after 3 years of exposure. The corrosion loss value was determined using a laboratory analysis in collected samples. Determined corrosion loss values corresponding to selected typical surfaces of a bridge structure are shown in Table 1.
Table 1. Corrosion losses on tested surfaces of bridge after 1 year and 3 years of exposure.

| Tested surface                                         | Corrosion losses [μm] |
|--------------------------------------------------------|-----------------------|
|                                                        | 1 year | 3 years |
| S1 - bottom surface of upper flange – external girder No. I | 8.54  | 12.51  |
| S2 - external wall – external girder No. I              | 14.61 | 19.46  |
| S3 - external wall above bottom flange – external girder No. I | 19.17 | 32.14  |
| S4 - upper surface of bottom flange – external girder No. I | 35.23 | 42.33  |
| S5 - bottom surface of bottom flange – external girder No. I | 10.81 | 18.85  |
| S6 - internal wall – internal girder No. V              | 7.26  | 10.14  |
| S7 - upper surface of bottom flange – internal girder No. V | 27.15 | 38.81  |
| S8 - internal wall – internal girder No. III            | 11.96 | 19.62  |
| S9 - upper surface of bottom flange – internal girder No. III | 27.06 | 41.81  |
| S10 - external wall – external girder No. XII           | 10.50 | 17.40  |
| S11 - upper surface of bottom flange – external girder No. XII | 20.22 | 26.30  |
| S12 - upper surface of bottom flange – internal girder No. III | 24.10 | 43.04  |

From the results shown in Table 1, several interesting observations can be formulated. It is obvious that the course of corrosion processes is strongly influenced by the position and orientation of the surface on the structure. The highest values of corrosion losses were found on the upper horizontal surfaces of the lower flanges of the main girders (surfaces S4, S7, S9, and S12). Significantly lower values of corrosion losses were identified on the horizontal surfaces when viewing them from below (surfaces S1 and S5) and on the walls of the main girders (positions S2, S3, S6, S8, and S10).

The observed corrosion loss values after 1 and 3 years of exposure of corrosion samples have not shown any significant differences between the outer and inner surfaces of the bridge. However, the visual development of patina on corrosion samples and mostly on the surfaces of bridge structure is very different. While compact adhesive corrosion layers have developed on external surfaces, the formation of non-adhesive corrosion layers with visible surface contamination is evident on internal horizontal surfaces, see Figures 6 and 7. The results of chloride deposition measurements described in a later section of the article have shown that there are no significant differences in the deposition of chlorides at the outer and inner surfaces of the bridge. The unfavourable development of the patina near the inner horizontal surfaces is thus caused by a combination of two negative phenomena, namely: (a) high deposition of dust deposits and chlorides from traffic below the bridge structure; (b) limitation of the natural cleaning of the structure’s inner surfaces by rainfall and wind.
Figure 6. Upper surface of a bottom flange of the external girder No. I (left) and of the internal girder No. III (right)

Figure 7. Layer of corrosion products on corrosion samples after 3 years of exposure on the surface S4 (left) and surface S9 (right)

3.2. Deposition rate of chlorides
The sampling devices for chloride deposition measurement were installed on the assessed bridge structure in December 2016. At the time of compilation of the article, results from 10 months of exposure were available including the entire winter season 2016/2017, when de-icing salt for road maintenance was used in the assessed area. The chloride content was analysed in accordance with [15] using the spectrophotometric method. The graphs in Figures 8 to 10 show the deposition rates of chlorides from 12/2016 to 9/2017 for individual measurement methods.

Figure 8. Deposition rate of chlorides measurement by wet candle method
The results of the measurements show a significant influence of the season of the year on the amount of deposited chlorides. High deposition rates were only measured in those months when de-icing salt was used for road maintenance in the assessed locality (December 2016 to February 2017). For the rest of the year (i.e. during a period with no winter road maintenance) the deposition rates of chlorides are low and vary, with a maximum of 3 mg·m⁻²·d⁻¹. Experimentally collected data did not confirm the findings from other research projects [16, 17] when increased amounts of chloride were identified even two months after the end of winter road maintenance. However, for a broader generalization of results, it will be necessary to analyse data from a longer time series of measurements.

The findings show that the external surfaces (P1 and P4) show a slightly higher deposition of chlorides compared to the internal surfaces (P2 and P3). This statement, however, does not apply generally to all measurements made. The observed phenomenon is probably related to the fact that the external surfaces of the bridge are directly exposed to the raised dust deposits and aerosols, the source of which is the traffic under the bridge structure.

Inner surfaces are partially protected from these negative phenomena. However, these surfaces are also protected against natural rainfall and wind cleaning. Despite the lower values of deposition rates, corrosion products that do not meet the requirements for sufficient patina protection have developed on unventilated and unclean horizontal internal surfaces. There are significant differences between the findings concerning deposition rates corresponding to the three measurement methods used. For most measurements, the highest deposition rates of chlorides were obtained by the wet candle method (the maximum measured deposition rate was 90 mg·m⁻²·d⁻¹). In some isolated cases, however, the highest deposition rate of chlorides was measured using a dry plate placed in a horizontal position. The vertical positioning of the dry plate in all cases led to significantly lower values compared to other measurement methods (approximately 3 to 5 times the decrease in the values of the dry plate in the horizontal position).
3.3. Comparison results of two bridges with different microclimate under the bridge  
To evaluate the impact of road transport under the bridge structure, it is possible to compare the experimentally detected data with similar results obtained on the neighbouring bridge structure. The reference bridge is located on the same road as the assessed bridge structure (the distance between the two bridges is approximately 200 m). The design of both bridges is similar – it is a steel bridge with main girders coupled with upper bridge deck in both cases. The second bridge moves road traffic above the railway line and thus cannot be affected by the deposition of dust impurities and chlorides from the transport under the bridge.

Table 2 shows the comparable values of chloride deposition rates obtained using the wet candle method placed on the inner surfaces of both compared bridges. Significantly higher deposition rates were found on a bridge structure constructed above the motorway (in January 2017 as big as a 9 times difference in values was detected). Comparing the results from the sampling devices located on the two reference bridges thus shows the significant influence of the specific microclimate under the bridge structure. It is evident that road transport under the bridge structure is the main source of chloride deposition on bridge bearing elements. The results from the bridge located above the railway show that with a suitable bridge design (a beam bridge with an upper bridge deck and sufficient overhang of the bridge deck above the main girders) the amount of deposited chlorides from the road transport on the bridge is significantly reduced.

| Tested bridge               | Deposition rate of chlorides [mg·m²·d⁻¹] |
|-----------------------------|------------------------------------------|
|                            | 12/2016  | 1/2017  | 2/2017  | 3/2017  |
| Tested bridge above the motorway D1 | 25.8     | 56.4    | 28.1    | 2.8     |
| Tested bridge above the railway          | 9.4      | 6.3     | 5.9     | 1.5     |

The different microclimate under both compared bridges was also reflected in the results of corrosion losses after one and three years of exposure of corrosion samples. The comparable values for inner surfaces of the walls of the main girders in both bridges are listed in Table 3. In the bridge structure above the motorway, the corrosion losses are more than doubled compared to the structure not affected by road traffic under the bridge.

| Tested bridge                 | Corrosion losses [μm] |
|-----------------------------|-----------------------|
|                            | 1 year exposure       | 3 year exposure       |
| Tested bridge above the motorway D1 | 11.96    | 19.62    |
| Tested bridge above the railway          | 5.26     | 8.98     |

4. Discussion of results  
Experimental values of corrosion losses and chloride deposition provide basic information on the influence of a specific environment under the bridge structure on the development of corrosion products on the surface of the structure. From the measured data, several interesting findings can be derived.
4.1. Influence of location and orientation of the surface

The results of the atmospheric tests show that the course of corrosion processes is significantly influenced by the orientation and the placement of the surface on the bridge structure [4, 18]. The development of corrosion products on typical surfaces of the bridge structure can be very different. The greatest differences were observed in corrosion losses measured after one year of corrosion surface exposure (in the tested bridge structure there was nearly 5 times the difference between S4 and S6 surfaces).

The differences after three years of exposure slightly reduced (compared to one year exposure), in that a maximum of 4 times the difference between S4 and S12 surfaces was detected in the tested bridge structure. It is reasonable to expect that during the next exposure, the differences in the corrosion losses of individual typical surfaces of the structure will continue to decrease, yet they will remain significant. In prediction of corrosion losses, it is therefore necessary to consider the influence of the positioning and orientation of the surface within the supporting structure [19], in addition to the general environmental characteristics (expressed by atmospheric corrosivity category of the environment) and microclimatic factors (for example, the influence of traffic under the bridge).

4.2. The bridge design and character of an obstacle to overcome

When designing the load-bearing structure of road bridges, it is necessary to pay increased attention to the choice of design solution with respect to minimization of the effect of adverse phenomena resulting from the use of de-icing salts in winter road maintenance. A suitable construction system is a girder bridge with an upper deck, which has a sufficient overhang over the bridge girders. Measurements of chloride deposition on the bridge over the railway have shown that the upper bridge deck sufficiently protects the steel supporting structure from depositing impurities and chlorides, the source of which is road traffic on the bridge.

Intensive road traffic under the bridge structure can, on the contrary, act as a significant factor contributing to degradation associated with inadequate protection of corrosion products. Raised dust and aerosols containing substances from traffic under the bridge may settle on the elements of the supporting bridge structure. Increased deposition is particularly likely in cases where the design of the bridge does not allow the dispersion of impurities into the area outside the bridge structure. Inappropriate design solutions primarily include the bridges where the supporting system creates conditions similar to those in the tunnels. The combination of intensive road traffic under the bridge together with the environment that does not allow dispersion of contaminated impurities and aerosols is the cause of unfavourable development of patina on the inner surfaces of the lower flanges of the main bridge girders above the D1 motorway in Ostrava. The findings from the locally adverse development of patina on a particular bridge structure can be generalized: the most endangered surfaces are the horizontal areas, the positioning of which within the supporting structure does not allow for regular cleaning by wind and rainfall.

4.3. Influence of the season

Chloride deposition is expected to reach the highest values in the winter. In March 2017 (the climatic conditions in this month did not require the use of de-icing salts in the assessed locality), there was a sharp decrease in a deposition rate regardless of the measurement method. Background values for the rest of the year when winter maintenance is not performed in the locality of the assessed bridge are very low and range up to 3 mg·m⁻²·d⁻¹. It is therefore very important that the bridge maintenance crew perform regular cleaning of the structure with jet water after the winter season ends. With this simple basic maintenance recommended for weathering steel bridges, the adverse effects caused by increased chloride deposition during the winter season can be significantly eliminated.

5. Conclusions

The article presents and evaluates the results of experimental measurements carried out on the bridge structure above the D1 motorway in Ostrava. The research activities carried out on this bridge are part of extensive experimental corrosion testing project carried out on a total of 10 bridge structures designed from weathering steels in the Czech Republic. Details of the whole project can be found, for example, in [4].

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The existing results of the project clearly show that the course of corrosion processes is, in addition to the general characteristics of the environment expressed as a degree of atmospheric corrosivity, significantly influenced by the positioning and orientation of the area within the supporting structure as well as by the specifics of the local microclimate. From the large number of experimentally detected data, more general conclusions can be drawn up about the course of corrosion processes. Significant differences in corrosion processes can be observed between the horizontal and vertical surfaces of the supporting bridge structure; the orientation of the surface outside or inside the bridge is also important.

One of the decisive factors affecting the local microclimate in the vicinity of the bridge is the influence of chlorides, of which deposition on the elements of the bridge structure is mainly due to the traffic on adjacent roads. The source of chlorides is the de-icing salts used in winter road maintenance. The previous results of chloride deposition measurements show some important findings. The measurements show that in the bridges with an appropriate construction design and arrangement, the amount of deposited chlorides, the source of which is the traffic across the bridge structure can be significantly eliminated. A higher chloride deposition may occur due to intensive road traffic under the bridge structure. Currently, there is not enough experimentally validated data available to define specific dimensional and structural requirements that when being complied with, the chloride deposition from the transport under the bridge decreases to a level that doesn’t limit a favourable development of patina on bridge structure elements. Therefore, it is important to adhere to at least the basic principles of designing structures – that is to design the structures allowing the dispersion of raised impurities and aerosol into the surrounding environment, and in particular to ensure the basic maintenance involving regular cleaning of the steel structure after the end of the winter period.

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