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CALCULATION OF CORROSION ALLOWANCES ON WEATHERING STEEL BRIDGES

VÝPOČET KOROZNÍCH PŘÍDAVKŮ NA MOSTNÍCH KONSTRUKCÍCH Z PATINUJÍCÍCH OCELÍ

Abstract

This paper introduces a new method used for calculation of corrosion allowances. The corrosion allowances must be considered when designing bridge structures from weathering steel. The application of the procedure for calculation of corrosion allowances is explained also using certain model example of bridge structure.

Keywords

Weathering steel, corrosion allowances, corrosion, steel structures, bridges, corten.

Abstrakt

V předkládaném článku je uvedena nově vyvinutá metodika výpočtu korozních přídavků, které je potřeba uvažovat při návrhu mostních konstrukcí z patinujících ocelí (oceli se zvýšenou odolností proti atmosférické korozi). Aplikace metodiky výpočtu korozních přídavků je v článku vysvětlena na modelovém příkladu mostní konstrukce.

Klíčová slova

Patinující oceli, korozní přídavky, koroze, ocelové konstrukce, mosty, Atmofix.

1 INTRODUCTION

Choosing a correct type of steel for load-carrying building structures is important in terms of both technology and economy. Considering the time, environment friendliness, economy and technical aspects, it might be a good idea to use steel with improved atmospheric corrosion resistance.

Weathering structural steel has been used for various outdoor load-carrying structures (even without anti-corrosion surface protection) in the world (U.S.A., Germany, Japan, South Korea, France, Switzerland, New Zealand...) as well as in the Czech Republic for about 40 years.

The basic specific property of the weathering steel is its ability to create a protective layer of oxides (patina) on the surface, if suitable atmospheric and structural conditions exist. When designing the load-carrying structures with the designed service life of as many as 100 years, the weathering steel without any corrosion protection can be used as a standard structural material.

The corrosion rate of the weathering steel is considerably lower than that of the standard carbon steel. In spite of this, possible effects of corrosion losses on reliable service of the structure throughout the designed service life T_d [1] should be considered when designing the structures. In

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practice, the effects of the expected corrosion losses are typically eliminated by corrosion allowances which are added to the thickness of the element calculated in static analyses.

The corrosion allowance in foreign standards is typically derived from a single parameter: the classified corrosion aggressiveness of atmospheres [2]. Table 1 shows the recommended corrosion allowances for one exposed surface of construction and for the designed service life of $T_d = 100$ years.

Table 1: Corrosion allowance for the designed 100 year service life pursuant to foreign regulations

Country	**Corrosion allowance for the corrosion aggressiveness ranging from C2 to C4**		
	C2	C3	C4
Germany	0.8 mm	1.2 mm	1.5 mm
United Kingdom	1.0 mm	1.0 mm	1.5 mm
Sweden	0.6 mm	1.2 mm	1.7 mm
Note: The corrosion allowances for Germany, United Kingdom and Sweden were taken from [3, 4], [5], and [6], respectively.			

In the Czech Republic, an internal company standard was used originally when designing weathering steel structures [7]. Calculation of the corrosion allowance [7] depended on several parameters such as the corrosion aggressiveness, quality of material, thickness of the profile, control assurance, maintenance of the structure and compliance of recommended structural principles. This means, it is difficult to compare the corrosion allowances determined only on the basis of the classification of the corrosion aggressiveness in the environment. For that reason, the corrosion allowances pursuant to [7] are not, deliberately, listed in Table 1.

Within the programme [8], most constructions from the weathering steel which were built in the Czech Republic have been inspected and assessed. It follows from the inspection and corrosion tests that more parameters should be taken into account in order to determine more exactly the corrosion allowances, the corrosion aggressiveness only being not enough for this. The new method, if compared with the procedure described in [7], introduces several basic changes, in particular:

- The exposed surfaces are divided into three categories: directly wetted surfaces, indirectly wetted surfaces and surfaces in inside environment.
- The guiding value of corrosion loss is calculated on the basis of the current level of air pollution in the Czech Republic.
- The calculation of the design value of corrosion loss specifies clearly influences of the position and location of the surface in the structure.
- More attention is paid to increased corrosion stress of the structure, if any, caused by neglected maintenance.
- A consistent difference is made between the different quantities: the corrosion loss and the corrosion allowance.
- The minimum corrosion allowance depends not only on the designed corrosion loss, but also on the thickness of the element, on limit rolling tolerances and on static use of the element under assessment.

2 CATEGORIES OF SURFACES LOCATIONS

Considering the place of origin and nature of patina on the structures, three types of the surface exist:

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- <u>Directly wetted surfaces</u> are the surfaces which are located in outdoor environment which are fully exposed to all atmospheric influences. Typically, they are directly wetted by rainfall.
- <u>Indirectly wetted surfaces</u> are those which are located in outdoor environment. They are not, however, directly wetted by rainfall. The surfaces are wetted mostly by air humidity condensation. The indirectly wetted surfaces include, in particular, parts of structures located under "outdoor roofs". In bridge structures, these are the parts located under the bridge deck.
- <u>Surfaces in indoor environment</u> are affected by outdoor atmospheric influences to a limited extent only (they include internal surfaces of closed chamber cross-sections).

Surface of patina in the directly wetted surfaces is rougher than that of the indirectly wetted surfaces. The patina layer is, however, more compact and resistant, see Fig. 1. Corrosion load of the indirectly wetted surfaces is typically lower than that of the surfaces which are directly wetted by rainfall. Exceptions might include situations where limited ventilation does not result in fast drying of condensed water (this risk can be eliminated by a suitable layout and structural design of the construction). If compared with the directly wetted surfaces, the patina is lighter without any flashes, the surfaces are even without any indents. On the surfaces, minor particles of less adhesive corrosion are visible, see Fig. 2. The process of patina creation is lower and protective efficiency of the patina is similar to that created on the directly wetted surfaces. If the inside environment is not perfectly separated from the outside environment, a very thin layer of corrosion products would be created on the surface in the inside environment. The corrosion rate is minimum, if compared with that in the outdoor environment.

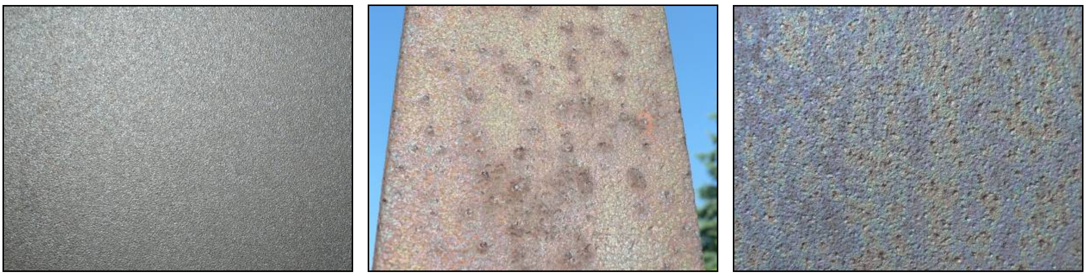

Fig. 1: Appearance of the patina on the directly wetted surfaces (left – patina on the column of a load-carrying structure of a TV mast transmitted in Hošťálkovice, middle – patina on the angle bar of the power grid mast in Ostravice, right – patina on a mast in a crane track in Ostrava-Vítkovice)

Fig. 2: Appearance of the patina on the indirectly wetted surfaces (left – patina on the web of the main girder in a road bridge in Frýdek-Místek, middle – patina on the orthotropic bridge deck in a road bridge in Ostrava, right – patina on the web and lower flange plate in a highway bridge across the Odra River in Ostrava)

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3 GUIDING VALUES OF CORROSION RATES OF THE WEATHERING STEEL

According to ISO 9223 [2] the corrosion aggressiveness is classified by five classes: C1 through C5. The classification is based on the annual corrosion losses of the standard metal after the first year of exposure in given location or on the basis of factors which influence most the corrosion in the environment: (a) pollution by sulphur dioxide (SO_2) and air salinity; (b) wetting time of corroding surfaces expressed as the annual sum of hours when relative humidity exceeded 80 % and temperature was above 0°C.

Acid gas components in the air pollution are only one of main reasons for the material corrosion. Currently, the annual concentration of SO_2 per year in more than 80 % of the Czech Republic is lower than 15 μg/m^3 (the atmosphere with the corrosion aggressiveness being C2). Higher annual concentrations of SO_2 are found in the North Bohemia and Ostrava region (C3 or as much as C4, if close to major sources of pollution). To determine the corrosion aggressiveness it is recommended to contact specialized departments. After several actions had been taken to minimize air pollution, in particular, from stationary sources (such as heating plants or power stations), the main sources of air pollution are small-size stationary sources and mobile sources (cars and trucks). The corrosion aggressiveness in various locations can be found in the map of the corrosion aggressiveness specified in [10], see Fig. 3. The map was created using data prepared for a 2 km x 2 km area. The map does not take into account microclimatic influences or effects resulting from structural details of the buildings.

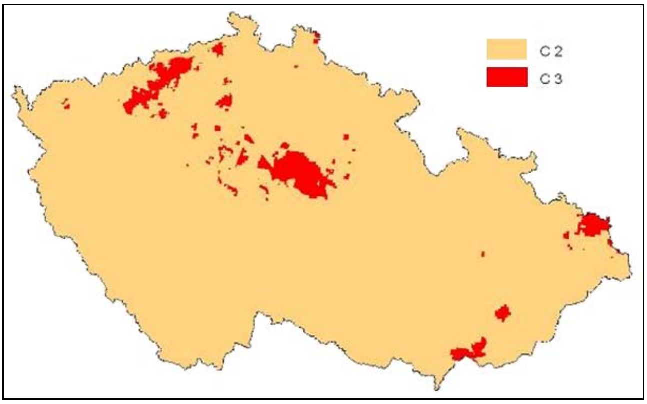

Fig. 3: Map of the corrosion aggressiveness for the weathering steel - SO_2 pollution in the year 2010

The guiding values of corrosion rate of the weathering steel can be estimated from the corrosion rates (r_{av}, r_{lin}) listed in ISO 9224 [9]. See table 2.

Table 2: Guiding values of corrosion rates - weathering steel

corrosivity category	Average corrosion rate during the first 10 years of exposure, r_{av} [μm/year]	Steady state corrosion rate after 10 years of exposure, r_{lin} [μm/year]
C1	≤ 0.1	≤ 0.1
C2	0.1 ~ 2.0	0.1 ~ 1.0
C3	2.0 ~ 8.0	1.0 ~ 5.0
C4	8.0 ~ 15	5.0 ~ 10
C5	15 ~ 80	10 ~ 80

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4 DETERMINING THE GUIDING VALUE OF CORROSION LOSS

The corrosion loss weakens by corrosion a surface of an element in a steel structure. Three methods are available for determining the guiding value of corrosion loss, K_T, throughout the designed service of the construction, T_d:

(a) The guiding value of corrosion loss, K_T, can be derived from the upper limits of the corrosion rates, r_{av} and r_{lin}, which are listed in Table 2 for the respective corrosivity category (to be found in the "Map of the corrosion aggressiveness for the weathering steel” in Fig. 3 above). The guiding value of corrosion loss, K_T, will be calculated as follows:

$$K_T = 10r_{av} + (T_d - 10)r_{lin} \ [\mu m] \tag{1}$$

(b) The guiding value of corrosion loss, K_T, for the designed service life, T_d = 30, 50 or 100 years, can be directly derived from the map in Fig. 4 (intermediate values of the designed service life, T_d, are obtained by linear interpolation).

(c) The guiding value of corrosion loss K_T, or, directly, the design value of corrosion loss, K_{Td}, can be calculated using specialized software (available at www.atmofix.cz).

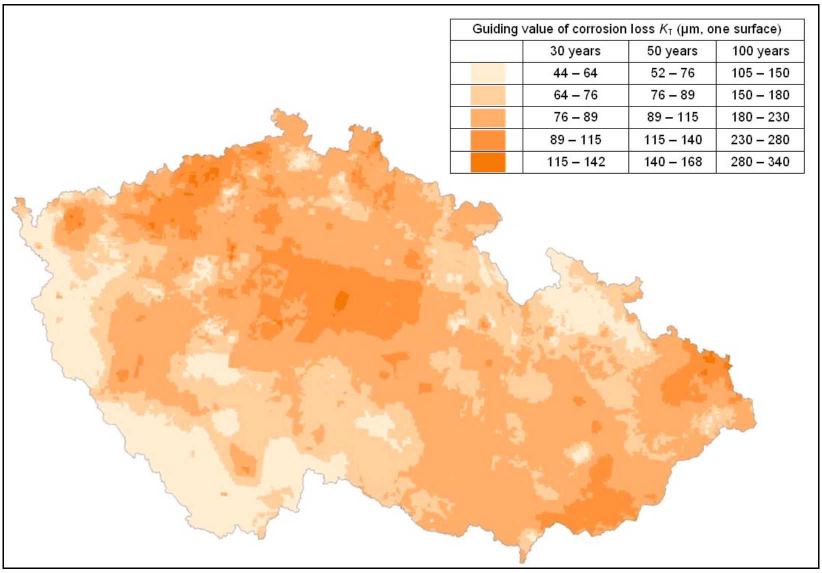

Fig. 4: Map of the guiding values of corrosion losss - SO_2 pollution in the year 2010

5 DETERMINING THE DESIGN VALUE OF CORROSION LOSS

The design value of corrosion loss, K_{Td}, in one surface of the weathering steel in free atmosphere, throughout the designed service life of the construction, T_d, is calculated as follows:

$$K_{Td} = K_T \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 \ [\mu m] \tag{2}$$

where K_T is the guiding value of corrosion loss throughout the designed service life, T_d.

The coefficients, α_1 through α_4, were obtained by an educated guess on a basis of the atmospheric corrosion tests which modelled the situation in bridge structures and from the assessment of bridge structures in the Czech Republic which have been exposed to influences for a long time:

α_1 the coefficient of quality of the material:

- for steel S355J2WP: α_1 = 1.00;
- for steel S355J2W: α_1 = 1.20;

α_2 the coefficient depending on position and location of a surface in the structure, see Table 3;

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α_3 the coefficient of exposure:

- for the directly wetted surfaces: $\alpha_3 = 1.00$;
- for the indirectly wetted surfaces (exposure under outdoor roofs): $\alpha_3 = 0.80$;
- for the indirectly wetted surfaces of bridge structures above roads where chloride sediments may considerably influence the rate of corrosion: $\alpha_3 = 1.30$;

  In particular, these are the bridges with limited ventilation where, in accordance with the Fig. 5, H < 6 m and/or D > B (in unclear situations, it is recommended to contact specialized departments).
- for inside surfaces in box structures: $\alpha_3 = 0.20$;

α_4 the coefficient depending on the correct structural design and maintenance throughout the service life of the structure, see Table 4.

Table 3: The coefficient depending on the position and location of an element in the structure

Description of the surface	α_2	Examples
vertical surfaces	1.0	Webs of main girders (incl. inclined webs of box girders), webs of cross girders and stringers. Cladding of the structures.
horizontal surfaces – from above or from bottom	1.1	Upper and lower surfaces of flanges (main girders, cross girders and stringers). Steel deck plate.
surfaces where water may leak	2.0	Typically surfaces close to deck joints in bridge structures where deicing salt is not used in winter: - In case of a conservative approach, such surfaces are less than 1.5times the height of the steel structure from the bridge deck joint. - If the steel structure is not wetted after the bridge deck joint fails (see Fig. 6), the coefficient $\alpha_2 = 1.0$.
surfaces which might be affected by leaking salt solutions during winter maintenance of the bridges	4.0	Typically surfaces close to deck joints in bridge structures where deicing salt is used in winter: - In case of a conservative approach, such surfaces are less than 1.5times the height of the steel structure from the bridge deck joint. - If the steel structure is not wetted after the bridge deck joint fails (see Fig. 6), the coefficient $\alpha_2 = 1.0$.
web-to-flange fillet weld at the bottom flange	1.5 1)	Web-to-flange fillet welds in main girders, cross girders and stringers.
NOTE 1) If the web-to-flange fillet welds are jeopardized with leaking water, $\alpha_2 = 3{,}00$ (if leaking water does not contain deicing salts) or $\alpha_2 = 6{,}00$ (if leaking water contains deicing salts).		

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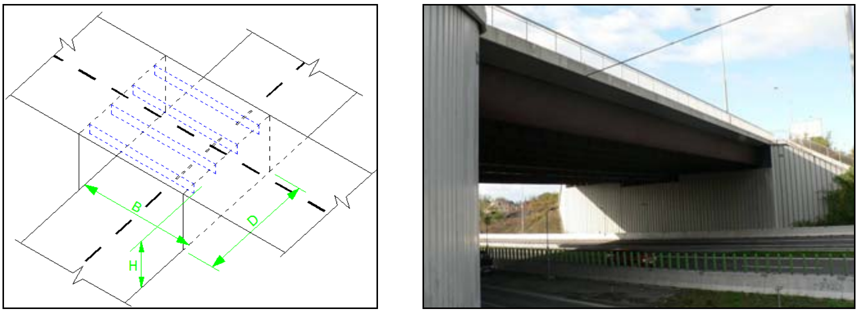

Fig. 5: Bridges with limited ventilation over the road: left - the scheme, right - a typical example of a bridge structure where chloride sediments should be taken into account (road and tram bridges over the D1 Motorway in Ostrava, Czech Republic – built in 2002).

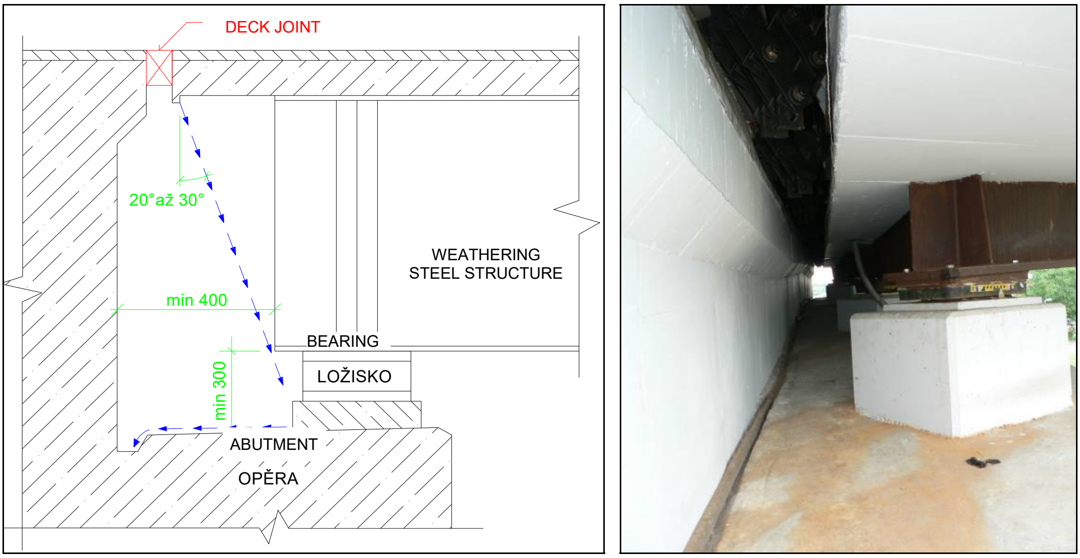

Fig. 6: Acceptable completion of the load-carrying structure of the bridge next to the abutment (no corrosion treatment is necessary): left – recommended dimensions, right – a road bridge in Brno, Czech Republic (built in 2005)

Table 4: Construction maintenance/structural principles coefficient

Fulfilment of the conditions		
Compliance with structural principles	Construction maintenance	α_4
yes	yes	1.00
yes	no	1.50 [1)]
no	yes	
no	no	2.50 [1)]

NOTE[1)] This case comprises unsuitable structural details where construction should be adopted to exclude them pursuant to [10] or structures where necessary maintenance cannot be carried out throughout the designed service life.

6 CORROSION ALLOWANCES

Because corrosion losses in the thickness of the load-carrying elements made from the weathering steel might be rather extensive and might reduce reliability of the structure in case of limit state conditions, it is essential, in accordance with technical standards in force, to add a reasonable corrosion allowance to the initial nominal thickness of the load-carrying capacity.

The minimum corrosion allowance for the thickness of the load-carrying element is calculated as follows:

$$\Delta t_{\min} = t_{d,\min} + K_{Td1} + K_{Td2} - t_{nom} - k_v, \text{ but } \Delta t_{\min} \geq 0 \tag{3}$$

where $t_{d,\min}$ is the minimum thickness of the load-carrying element which is satisfactory for the decisive limit state;

K_{Td1} the design value of corrosion loss of the surface 1;

K_{Td2} the design value of corrosion loss of the surface 2;

t_{nom} the nominal thickness of the element;

k_v the value depending on the thickness and class of the hot rolled steel plate pursuant to Table 5.

Table 5: Values of k_v for calculation of the corrosion allowance

Nominal thickness	classification depending on nominal thickness tolerances pursuant to EN 10029 [11]			
	class A	class B	class C	class D
	k_v (μm)			
5 mm < t ≤ 8 mm	50	150	450	-150
8 mm < t ≤ 15 mm	100	250	600	-250
15 mm < t ≤ 25 mm	150	450	750	-200
25 mm < t ≤ 40 mm	250	750	1050	-100
t ≥ 40 mm	400	1100	1400	100

Note: Values of k_v in the table are derived from the two assumptions given below:

a) Weakening the element by corrosion by 1% of the thickness does not significantly affect reliability of the structure [12].

b) Influence of lower (negative) limit rolling tolerances in class A (being the typically supplied class of the limit rolling deviations) onto reliability of the structure is considered in the partial factor for material property, γ_M, in accordance with [1]. If the difference between class A and class B/C (for more stringent limit values of the tolerances) is taken, this covers the corrosion allowance, without influencing reliability of the structure (effects of various tolerances on reliability of the structure are described in [13]).

It follows from (3) that the nominal thickness of the load-carrying elements should be increased by the positive value of the corrosion allowance, $\Delta t \geq \Delta t_{\min}$, in particular, in following cases:

- in cross-sections of the load-carrying structure which are most loaded and best used, in terms of strength;
- in cross-sections which are most jeopardised in terms of corrosion (such as complex structural details, places affected by leaking water or surfaces jeopardised by salt solutions during winter maintenance of bridges).

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In remaining parts of the structure, the calculated corrosion allowance is, as a rule, negative. In those parts it is, typically, useless and uneconomical to increase the nominal thickness of the load-carrying elements. It does not have any sense either to evaluate and provide the corrosion allowances for the load-carrying elements with the nominal thickness being equal to, or greater then, 50 mm because the corrosion allowances influence the reliable function of the thick-wall elements little only. Extensive studies conducted in Switzerland proved that in Switzerland it is not necessary to provide the corrosion allowance in addition to the thickness of standard load-carrying elements in bridge structures [12].

7 EXAMPLE – CALCULATING THE CORROSION ALLOWANCE

The chapter below gives an example of calculation of the corrosion losses and necessary corrosion allowances for the bridge structure (the calculation is carried out for the web and the upper/bottom flange of the main girder). This road bridge is located on the M1 motorway (Černovická terasa, Brno, Czech Republic). See Figures 6 and 7. The load-carrying structure of the bridge is a composite steel and concrete continuous beam with five spans and the upper bridge deck. The load-carrying steel structure is made from weathering steel, S355J2W. For details about the bridge structure see [14].

The guiding value of corrosion loss for the 100 year designed service life:

$K_{\mathrm{T}} = 230\,\mu m$ (taken from the map in Fig. 4)

The design value of corrosion loss:

$K_{\mathrm{Td}} = K_{\mathrm{T}} \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4$ (the general formula for calculation of the design value)

$\alpha_1 = 1{,}20$ (steel S355J2W)

$\alpha_2 = 1{,}00$ (the web of the main girder which is not affected by leaking water – see Fig. 6)

$\alpha_2 = 1{,}10$ (the upper and bottom flange of the main girder are not affected by leaking water – see Fig. 6)

$\alpha_3 = 0{,}80$ (sufficiently ventilated and indirectly wetted surfaces under the reinforced concrete deck)

$\alpha_4 = 1{,}00$ (compliance with structural principles [10]; the structure can be accessed for maintenance)

Web of the main girder: $K_{\mathrm{Td}} = K_{\mathrm{T}} \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 = 230 \cdot 1{,}20 \cdot 1{,}00 \cdot 0{,}80 \cdot 1{,}00 = 221\,\mu m$

Upper and bottom flanges:

$$K_{\mathrm{Td}} = K_{\mathrm{T}} \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 = 230 \cdot 1{,}20 \cdot 1{,}10 \cdot 0{,}80 \cdot 1{,}00 = 243\,\mu m$$

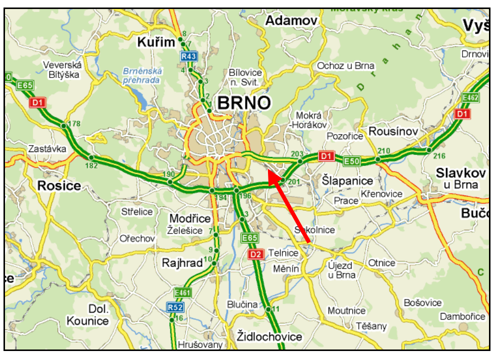

Fig. 7: Road bridge on the M1 Motorway (Černovická terasa, Brno, Czech Republic)

Calculation of the corrosion allowances:

$\Delta t_{min} = t_{d,min} + K_{Td1} + K_{Td2} - t_{nom} - k_v$

(the general formula for calculation of the corrosion allowance)

Web of the main girder:

$k_v = 450\,\mu m$ (The required class of rolling tolerances of the supplied plates is B. The web thickness of the main girder is between 15 and 25 mm).

$\Delta t_{min} = (t_{d,min} - t_{nom}) + K_{Td1} + K_{Td2} - k_v = (t_{d,min} - t_{nom}) + 221 + 221 - 450 =$
$= (t_{d,min} - t_{nom}) - 8\mu m$

The bottom flange of the main girder:

$k_v = 750\,\mu m$ (The required class of rolling tolerances of the supplied plates is B. The thickness of the bottom flange is between 25 and 40 mm).

$\Delta t_{min} = (t_{d,min} - t_{nom}) + K_{Td1} + K_{Td2} - k_v = (t_{d,min} - t_{nom}) + 243 + 243 - 750 =$
$= (t_{d,min} - t_{nom}) - 234\mu m$

The upper flange of the main girder:

$k_v = 750\,\mu m$ (The required class of rolling tolerances of the supplied plates is B. The thickness of the upper flange is between 25 and 40 mm).

$\Delta t_{min} = (t_{d,min} - t_{nom}) + K_{Td1} - k_v = (t_{d,min} - t_{nom}) + 243 - 750 =$
$= (t_{d,min} - t_{nom}) - 507\mu m$

Assessment of the calculation:

It follows from the calculation above that no corrosion allowances are necessary for the element of the load-carrying structure even if the cross-section of the main girder is fully used in terms of statics (the necessary minimum thickness of the load element which is compliant at the decisive limit condition, $t_{d,min}$, is equal to the nominal thickness of the element, t_{nom}). The design values of corrosion loss are sufficiently covered by the more stringent requirements which apply to the negative rolling tolerance in the B class of the limit rolling deviations.

8 CONCLUSION

This paper describes methods used for calculation of the corrosion allowance to be added to the thickness of elements made from the weathering steel. The methods are based on new findings gained during the project work [8]. Calculation of the corrosion losses and, in turn, corrosion allowance, is among specific steps typically for designs of structures made from the weathering steel. For a comprehensive description of steps used when designing the structures made from the weathering steel see the new Directive [10] which is the main outcome of the project [8].

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