THE PROPERTIES OF WEATHERING STEEL IN CONTEMPORARY ATMOSPHERIC ENVIRONMENTS

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Abstract

The mechanical and corrosion properties of weathering steel had been deeply studied in 70 and 80 ties of last century. In this period a lot of structure was built in the Czech Republic. The paper analysis the stage of the existing steel structures made from weathering steels exposed for long-term period in various environments and evaluation of the specific corrosion stress in areas which may affect service life of structures, microclimatic parameters of structures and defect and failure causes. The forming of protective patina layer, initial corrosion rate and other characteristics of weathering steels will be analysed in significantly changed conditions of atmospheric environments in the Czech Republic and in Europe too. As the corrosivity of atmosphere significantly changed during 1995-2005 the corrosion rate was reduced. Paper performed a new data of corrosion rate and comparison of change of weathering steel samples exposed in atmospheric test sites and real bridge structure. The effect of steel structure design was studied too.

Keywords: Weathering steel, properties, corrosion rate

1. ATMOSPHERIC CORROSION BEHAVIOUR OF WEATHERING STEEL

Low alloy steel with improved resistance against atmospheric corrosion, called weathering steel, is one of the atmospheric corrosion resistant material thanks to oxide layer called patina, that create on the surface of the material. Their weather resistance is based mainly on the effects of the alloying elements copper, phosphorus, chromium and nickel - totally ca 2 wt. %. Weathering steel is a material that provides a great potential advantage for use in steel structures like bridges in terms of improved durability and lower construction and maintenance costs.

In 1910 was first reported that carbon steel containing 0.2 percent or more of copper had from 1.5 to 4 times the atmospheric corrosion resistance of carbon steel with a residual copper content [1]. The most significant differences were found in severe industrial atmospheres. The first use of sheets in a building occurred in 1939 and in highway bridges in 1935. Since 1950ties the application of weathering steel for building structures (e.g. JD Company building Moline, Chicago Civic Center, USX Tower Pittsburgh), electrical transmission towers (U.S. Steel plant, Bethlehem Steel plant, Burns Harbour, Virginia Power and Light company) and bridges (New Jersey Turnpike bridge in 1964) started in the USA and then spread around the world. Together with application the study of long-term corrosion behaviour had been performed.

In the former Czechoslovakia the low alloy steel called Atmofix had been developed and use since 1970ties. The program of study the long-term corrosion behaviour of this material was realised on the atmospheric test sites and on real structures too.

The protective oxide film formed on weathering steel adheres tightly to weathering steel in fine, dense grains that are relatively impervious to further atmospheric corrosion, thereby sealing the base metal from the air and further corrosion. The protective oxide film has different colours than the rust on other carbon steels, ranging from a dark reddish-brown to purple grey, depending on the age of the structure, the pollutants in the air, local weather conditions, or the location of the steel within the structure. The appearance, texture, maturity, and anticipated utility of a protective oxide film depends on several factors, e.g. age, degree of exposure, and environment.

The corrosion rates of weathering steel vary with time. During the initial period of exposure, the protective patina develops and stabilises. Under normal weather conditions the patina will form in about 18 - 96 months. After this procedure the corrosion rate is reduced. The time for the rust patina to become effective in controlling corrosion depends upon the specific environmental conditions.

2. LONG-TERM CORROSION LOSS IN THE CZECH REPUBLIC

The first studies of corrosion losses of weathering steel performed in the Czech Republic had been performed in 70 and 80 ties of last century mainly as standardized atmospheric tests on atmospheric test sites and in specific microclimates too. In that time the first steel structures had been built using this type of steel (electric distribution poles, lighting mast, bridges, building cladding, etc. - **Figure 1**) and their corrosion behaviour was followed for 10 years [2 - 10]. After year 1980 about 20 weathering steel bridges were built - their periodical evaluation of the corrosion effects had been performed and causes of defects were defined. In 1990ties the effect of design and local specific pollution had been identified as the main reason for damage of protective patina forming and higher localised corrosion attack of structures [11 - 14].

Figure 1 Examples of steel structures built in 1970ties from weathering steel

Atmospheric corrosivity of the atmospheres in Europe as same as in other industrial developed countries in the past was very high due to high level of acidic pollution, mainly SO_2. In **Figure 2** there is a long-term corrosion behaviour of weathering steel according to the field test performed in period 1970-1995 in the Czech Republic. Long-term exposure realized at 80ties showed the trend of decreasing of corrosion rate to steady state rate after ca 5 years of exposure. Since 1995 and later since 2005 the significant decreasing of SO_2 in air led to decrease of corrosion rate of weathering steel and increase time needs to develop protect patina. In **Figure 2** the comparison of corrosion loss of weathering steel at industrial environments of the Czech Republic is shown in different corrosivity, resp. SO_2 pollution level. There are data from standard flat samples exposed according to EN ISO 9223 at atmospheric test sites. The difference between corrosion rate of mild carbon steel and weathering steel is evident after 15 - 20 year and in environments with SO_2 higher than 10 - 15 μm / m^3.

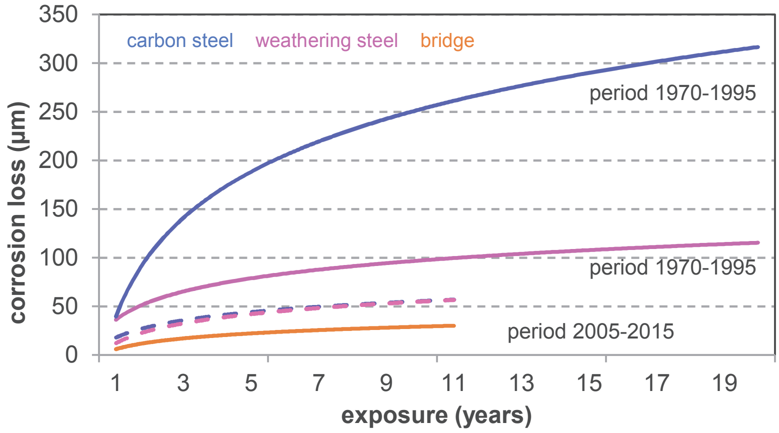


Figure 2 Corrosion of weathering steel in industrial environment of the Czech Republic

The similar effect cannot be seen on real bridge structures. In 1970ties and 80ties the samples had been exposed on bridges at Prague and Brno. Both these bridges are affected by traffic under the bridge. The short-time exposure (1, 2, 3, 4 and 8 years) corrosion loss on Prague bridge are the same in 1980ties and 2010ties - the decreasing of air pollution does no any significant effect but the traffic under bridge shows the dominant effect on corrosion loss/rate. Nevertheless the corrosion loss of samples exposed on bridge structure show lower corrosion loss than samples exposed on test sites.

One of typical parameter of patina layer is its thickness. Average thickness of protective, adherent patina on long-term exposed steel structure (> 25 years) is 175 µm. Mainly on bridges patina thickness is affected by position of beam or flange surface (vertical, horizontal), degree of sheltering and water leakage from bridge deck (**Figure 2**). Thickness of non-adherent, partially protective corrosion product layers was from 350 to 600 µm; layers with thickness over 800 µm were very voluminous and formed o surface affected by leakage of water onto steel structure, in many cases containing chlorides from de-icing salts.

The decreasing of air pollution has also effect on time development of chemical composition of patina. Patinas are made up of compounds of α, β, γ and δ iron oxyhydroxides (FeOOH) and magnetite in different proportion. Their composition, density and morphology depend on the environmental conditions of the place they are formed in. The dominate goethite phase represent the protective patina. In contemporary environment the protective patina formed after 8 years of exposure only at atmospheric test site where the SO_2 is higher than 10 - 15 µm / m^3. At test sites with lower air pollution the corrosion products contain mainly lepidocrocite after this exposure period.

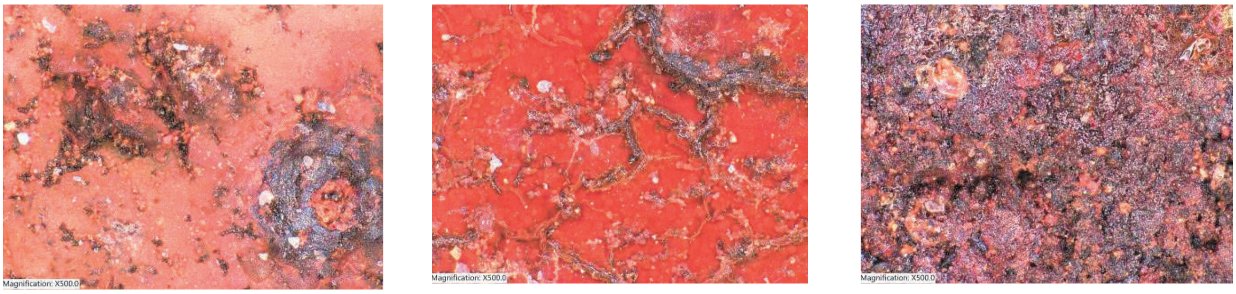
3. THE EFFECT OF SALT DEPOSITION

Weathering steel structures proved long-term service life under conditions of surface alternate wetting and drying. Protective patina does not develop under conditions of:

- surface prolonged dampness - usually wrong design of the structure,
- in excessive exposure to chlorides - a salinity classified interval of S3 according to ISO 9225 shall rule out the use of weathering steel, e.g. 300 mg / (m^{2}d),
- particularly high levels of atmospheric pollution, the maximum limit for SO_2 is classified interval P4 according to ISO 9225, e.g. 90 µg·m^{-3}.

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 could be affected by chloride deposition. This is the environments in the Czech Republic. The difference between weathering steel samples exposed to urban, industrial and traffic environment at test sites with practically the same climate conditions after 8 years exposure in period 2006-16 are shown in **Figure 3**. The effect of de-icing salts is evident on all evaluated corrosion parameters - appearance, thickness, print macrostructure and composition of corrosion products and corrosion loss, too. The chloride deposition rate is about 2.40 mg / (m^2d) at atmospheric test sites in the Czech Republic which are not affected by traffic.

urban test site, 4.6 $\mu g \cdot m^{-3}$ SO_2 | industrial test site, 11.4 $\mu g \cdot m^{-3}$ SO_2 | traffic test site, 2.5 $\mu g \cdot m^{-3}$ SO_2



thickness 75 µm
corrosion loss 20 µm

thickness 130 µm
corrosion loss 55 µm

thickness 115 µm
corrosion loss 40 µm

strong lepidocrocite, weak goethite
AAS analysis - no Cl

strong goethite, weak lepidocrocite
AAS analysis - 0.05 wt. % Cl

very strong lepidocrocite, weak goethite
AAS analysis - 0.25 wt. % Cl

Figure 3 Corrosion of weathering steel in different environment

The effect of de-icing salt is mostly significant for bridge structures made from weathering steel. The tests of effect of deicing salts on weathering steel bridges had been realized mainly in the USA, the UK and Japan [15 - 25]. Based on evaluation of 41 bridges it was recommended to use the weathering steel at environment where the corrosion loss of weathering steel is 0.6 mm after 50 years [25]. Studies indicate the most important factor leading to excessive of corrosion of weathering steel bridges is the runoff of water contaminated with the deicing salts through leaking deck seal, expansion dams or open joints. During the inspection of bridges there were found many defects caused by these functionless, blocked or trimmed elements. In these cases precipitation containing de-icing salts leaked on weathering steel surface and destroyed the protective ability of patina layer. The affected areas are strongly limited and represent only minor areas of construction (**Figure 4**). Realised tests with 25 years old corroded samples with stable, protective patina showed the layer is quickly destroyed by chloride contamination [26].

Since 2013, the program of corrosion specimens installed on 10 weathering steel structures on 97 specific surfaces in the Czech Republic started (**Figure 5**) [27]. The corrosion specimens were installed on the bridge structures in such a way to simulate realistic behaviour of the investigated structural element surface (**Figure 5**). There were choosing typical location, e.g. outside wall of main beam, upper surface of bottom flange and bottom surface of top flange. For structures or parts of structures where the use of de-icing salt is likely to lead to substantial deposits of chloride on steel - on such bridge structures the chloride deposition is measured by wet candle and dry cloth methods according to EN ISO 9225.

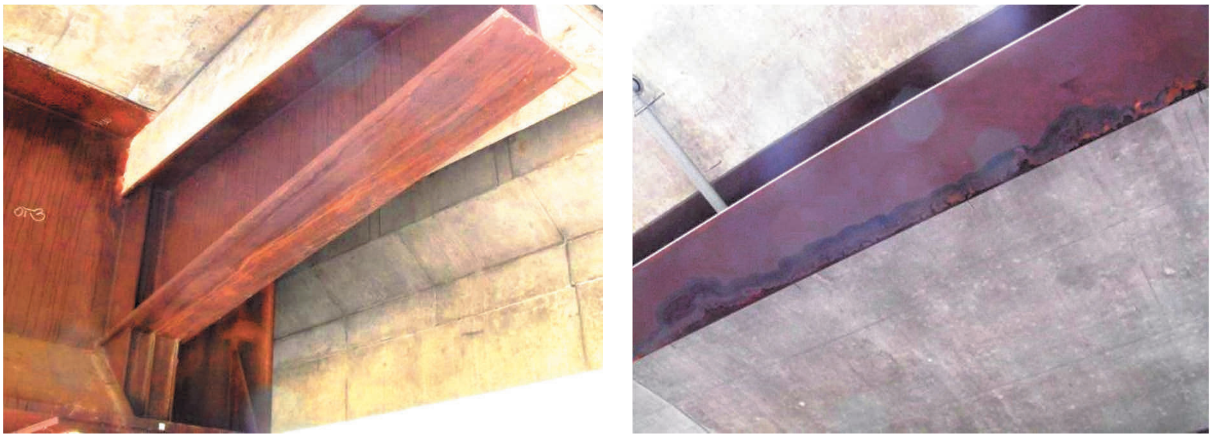


Figure 4 The negative patina appearance in bridge areas affected by leakage from the drainage system (missing gutter has been stolen) after 2 years of exposure

Figure 5 Views of a tested bridge structure

The results of the tests carried out on bridges in the Czech Republic are shown in **Table 1** for 2 specific conditions - bridges without traffic under them and bridges with traffic under bridge, which with its design solution creates the conditions partially corresponding to the conditions in the tunnel, the so-called *tunnel-like conditions* (**Figure 6**). In general higher corrosion loss for all exposed surfaces had been found for bridges with “tunnel effect”, but in both exposure conditions the highest corrosion loss occurred on upper surface of bottom flange.

Table 1 Corrosion loss (µm) of weathering steel specimens exposed at typical areas of bridge structure

Typical areas	**1 year exposure**		**3 years exposure**	
	Bridges without effect of de-icing salts	**Bridges with effect of de-icing salts**	**Bridges without effect of de-icing salts**	**Bridges with effect of de-icing salts**
internal wall	12.0	5.3	19.6	9.0
internal upper surface of the flange	35.2	13.7	42.3	23.8
shelter surface of bottom flange	10.8	11.9	18.9	20.4

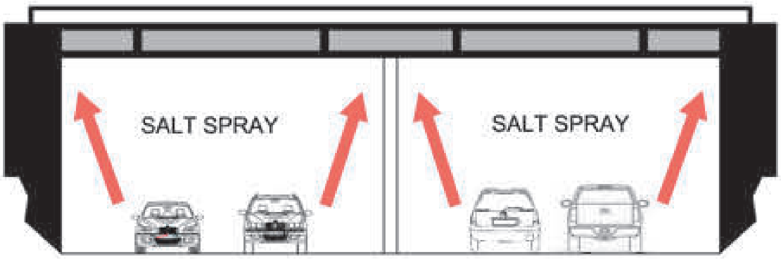


Figure 6 Schematic drawing of *tunnel-like conditions* under the bridge

The chloride deposition on these surfaces is higher only in winter months but during other seasons of the year is practically the same as at atmospheric test sites not affected by traffic - **Figure 7**. The yearly average value on the bridge bottom flange surface (steel structure with the traffic under the bridge) is only 13.1 mg / (m^{2}d).

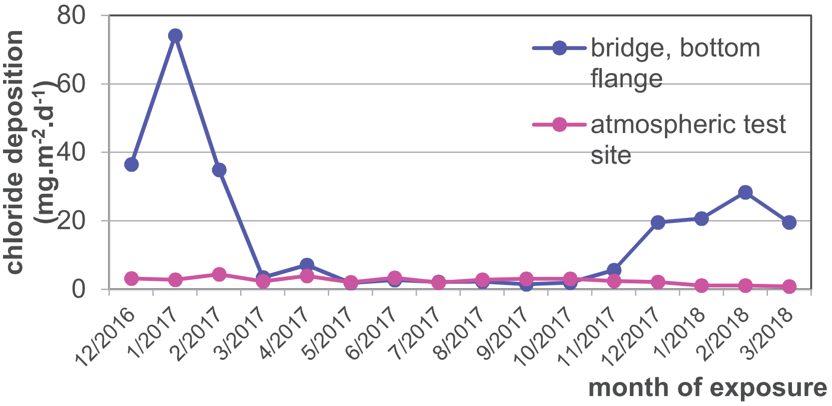


Figure 7 Chloride deposition measured by the wet candle method

4. CONCLUSION

When designing the load-carrying structures with the designed service life of as many as 100 years, the weathering steel can be used as a standard structural material.

Although this is an ongoing project and not much result has come out yet, some observations including those from the pre-investigation are available:

- nevertheless the atmospheric corrosion rate of weathering steel decreased in contemporary environments in the Czech Republic, the corrosion losses of bridge structures are practically the same as in 1970-80ties,
- the corrosion loss of bridge structure surfaces is lower than in atmospheric conditions with only one exception - upper surface of bottom flange in case of bridges affected due to “tunnel effect”.

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