

Prediction of Atmospheric Corrosion of Carbon Steel Bridge Components in a Changing Climate

Istemi F. Ozkan, PhD., PEng
National Research Council Canada
1200 Montreal Road
Ottawa, ON, K1A 0R6
Canada

Jieying Zhang, PhD., PEng
National Research Council Canada
1200 Montreal Road
Ottawa, ON, K1A 0R6
Canada

Dario Markovinovic
National Research Council Canada
1200 Montreal Road
Ottawa, ON, K1A 0R6
Canada

Nafiseh Ebrahimi, PhD, PEng
National Research Council Canada
1200 Montreal Road
Ottawa, ON, K1A 0R6
Canada

Hamidreza Shirkhani, PhD., PEng
National Research Council Canada
1200 Montreal Road
Ottawa, ON, K1A 0R6
Canada

ABSTRACT

This research presents Phase 1 of a study for climate change impacts on the atmospheric corrosion of structural steel components of infrastructure such as bridges. ISO standards that provide quantitative models to calculate corrosion rate as function of key exposure parameters, namely, temperature, relative humidity, chlorides, and sulfur dioxides are used in the evaluation, where the first-year corrosion rate is used to quantify and classify the severity of a corrosive environment. The corrosivity environment of six Canadian cities/locations for carbon steel bridges was modelled for the 1954-2020 period and the next 80 years using projected climatic data up to year 2100. The model was calibrated by the 10-year corrosion field data for these six locations for the 1954-1964 period, where good agreement was observed especially for locations in low and medium environmental corrosivity categories per ISO classification. The results also demonstrated that the methodology can be adopted in Canadian infrastructure standards/codes such as the Canadian Highway Bridge Design Code to enhance the current descriptive environmental exposure with quantitative corrosion rates. This study represented an initial effort and in order to fully implement into a more reliable and quantitative corrosion protection design more research is required.

Key words: Atmospheric corrosion, corrosion rate, infrastructure, climate change

INTRODUCTION

There are more than 47,000 publicly-owned roadway bridges in Canada.¹ Over 25% of these bridges have main structural load bearing components made of structural steel (i.e., truss and steel girder bridges) based

on data from the Ministry of Transportation, Ontario – MTO.² According to Statistics Canada, the condition of approximately 40% of these bridges is rated as either very poor (unfit for sustained service), poor (increasing potential of affecting service), or fair (requires attention).³

It was reported by Koch et al.⁴ that corrosion is one of the main reasons that lead to structural deficiency of steel components of highway bridges. Especially in marine environments, steel bridges are at risk of high rates of corrosion, particularly beyond 15-20 years in service.⁵ This observation can be expanded to locations where the use of de-icing salt is common practice such as urban areas in North America. In addition, future climatic changes that are evident (i.e., change in temperature and relative humidity) may potentially affect the rate of corrosion-induced deterioration and affect the resistance of bridges against various load types throughout their life-cycle.

Current bridge infrastructure management protocols in Canada do not include structural behavior assessment tools for aging bridges, specifically for quantitative remaining capacity assessment. Such tools incorporating quantitative steel deterioration (i.e., corrosion) models that enable prediction of residual capacity and change in failure modes throughout a bridge's service life are believed to be critical information for assessing the climate resiliency. The development of resiliency assessment methods against climate change triggered extreme events and effective bridge management protocols would assist decision makings and allow for allocation of already limited funds efficiently based on potential variation of priorities in our changing climate throughout a bridges life-cycle. One of the most important components in the development of such tools/guidelines is deterioration models with capability to incorporate climate change effects that accurately predict corrosion penetration.

Currently there is a lack of design guidance that provides quantitative corrosion rate prediction models for effective corrosion protection design of steel bridges in Canada. International Organization of Standardization (ISO) was identified to provide standards proposing corrosivity level categorization criterion and methods for quantitative prediction of corrosion rates/penetrations (ISO 9223 and ISO 9224). The criteria proposed in these standards may potentially be applicable to Canadian environment and infrastructure and may be adopted in the development of the guidelines mentioned above. The main objective of this paper is to demonstrate the applicability of the ISO standard – ISO 9223⁶ – to Canadian environments for corrosion rate/penetration prediction in a changing climate as the first step in the development of the guidelines mentioned above.

FACTORS AFFECTING ATMOSPHERIC CORROSION

There are five main forms of corrosion.⁷ These include atmospheric corrosion, pitting corrosion, galvanic corrosion, crevice corrosion, and stress corrosion. General atmospheric corrosion accounts for the largest percentage of the corrosion types for steel bridges, which lead to gradual thinning of the members. Atmospheric corrosion of steel is generally uniform and occurs when steel exposed to the atmosphere is wet by a thin film of moisture. The time of wetness is a major factor in determining the severity of atmospheric corrosion.⁸ The primary cause of the atmospheric corrosion is the accumulation of water and chlorides (i.e. salt) on bridge steel.⁷ The amount of these substances may vary due to the effects of a changing climate which in-turn may affect corrosion rates. In addition to accumulation of chlorides and water, other parameters that may affect atmospheric corrosion are temperature, carbon dioxide, relative humidity, wind, rainfall, and pollution.⁹

IMPACT OF CLIMATE CHANGE ON CORROSION

Literature reviews on the impact of climate change on corrosion of steel structures/bridges demonstrated that studies in this area are limited. Such a study to predict the effect of climate change on atmospheric corrosion rates of steel structures in Canada was not found. Currently, available studies are mostly from Australia and the U.K.⁹⁻¹² Various studies^{11, 12} suggest that although projected future climatic changes will

affect the extent of general corrosion, it may be argued that it is currently very difficult to quantify this effect. In their study, Nguyen et al.⁹ reported that the change in corrosion rates was highly dependent on the conditions of the city/region considered as well as the global climate prediction models (GCMs) used. Whereas some regions showed an increase in corrosion rates associated with climate change, other regions showed a decrease. For instance, for two coastal cities in Australia, Brisbane and Melbourne, a 14% increase and a 14% decrease in their corrosion rates, respectively, were predicted over a 100 year span (1990 and 2090). By using the corrosion rate change predictions of this study; Ozkan et al.¹³ demonstrated that governing failure modes may change throughout the service life of a bridge at negative moment regions and significant capacity reductions may be experienced due to the effects of corrosion.

ISO CORROSION MODELS

ISO 9223 Corrosivity Categories

According to Mikhailov et al.,¹⁴ the ISO 9223 Standard, namely “Corrosion of Metals and Alloys – The Corrosivity of Atmosphere – Classification”, that was developed in the 1970s and 1980s became the first classification system quantitatively defining the corrosivity categories. This was unlike all the precedent classification systems that had only qualitatively described the corrosivity of rural, urban, industrial, and marine atmospheres to metals. The database for the development of the model/classification was based on tests conducted at 52 points located in Europe, Argentina, Canada, New Zealand, USA, and Japan.¹⁵⁻¹⁷ After recognizing that the data was not adequate for very cold climates and tropical zones, more data was collected/included from Central and Southern America^{18, 19} and the cold/very cold regions of Eastern Russia.^{20, 21} The standard is extensively used in optimizing the selection of structural materials, protective coatings, and methods to prevent corrosion as well as for developing other international and national standards. It has also been accepted and incorporated into other normative documents by ISO/TC 107, ISO/RC35/SC 14, CEN/TC 262 and CEN/TC 240 Technical Committees.¹⁵ International standard ISO 9223⁶ proposes a classification system for the corrosivity of atmospheric environments based on the first-year corrosion rate of standard specimens. Table 1 outlines the corrosivity categories as defined by the standard (i.e., C1, C2, etc.) and corresponding corrosivity (i.e., very low, low, medium, high, very high, and extreme). It also provides examples for typical outdoor environments for each category. It should be noted that the extreme effect of chloride contamination (i.e., local corrosion attacks with rates higher than typical atmospheric corrosion rates for the environment under consideration), which is typical of marine splash or heavy salt spray, is outside of the scope of this international standard.

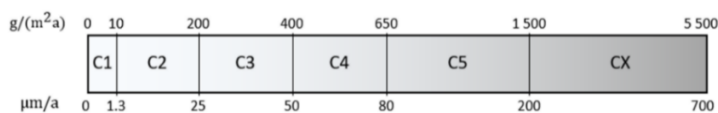
Table 1: Atmospheric Corrosivity Categories according to ISO 9223

Corrosivity category	Typical outdoor environments - Examples
C1 – Very low	Dry or cold zone, atmospheric environment with very low pollution (SO_2 practically equal to 0 $\mu\text{g}/\text{m}^3$) and time of wetness, e.g. certain deserts, Central Arctic/Antarctica
C2 – Low	Temperate zone, atmospheric environment with low pollution ($\text{SO}_2 < 5 \mu\text{g}/\text{m}^3$), e.g. rural areas, small towns Dry or cold zone, atmospheric environment with short time of wetness, e.g. deserts, subarctic areas
C3 – Medium	Temperate zone, atmospheric environment with medium pollution ($\text{SO}_2: 5 \mu\text{g}/\text{m}^3$ to $30 \mu\text{g}/\text{m}^3$) or some effect of chlorides, e.g. urban areas, coastal areas with low deposition of chlorides Subtropical and tropical zone, atmosphere with low pollution
C4 – High	Temperate zone, atmospheric environment with high pollution ($\text{SO}_2: 30 \mu\text{g}/\text{m}^3$ to $90 \mu\text{g}/\text{m}^3$) or substantial effect of chlorides, e.g. polluted urban areas, industrial areas, coastal areas without spray of salt water or, exposure to strong effect of de-icing salts Subtropical and tropical zone, atmosphere with medium pollution
C5 – Very high	Temperate and subtropical zone, atmospheric environment with very high pollution ($\text{SO}_2: 90 \mu\text{g}/\text{m}^3$ to $250 \mu\text{g}/\text{m}^3$) and/or significant effect of chlorides, e.g. industrial areas, coastal areas, sheltered positions on coastline

CX – Extreme	Subtropical and tropical zone (very high time of wetness), atmospheric environment with very high SO ₂ pollution (higher than 250 µg/m ³) including accompanying and production factors and/or strong effect of chlorides, e.g. extreme industrial areas, coastal and offshore areas, occasional contact with salt spray
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ISO 9223⁶ also proposes a classification system based on corrosion rates following the first year of exposure, r_{corr} , which is often measured by the corrosion mass loss or corrosion penetration depth after the first year of exposure, and it is summarized in Figure 1 for carbon steel in terms of g/(m²*year) and µm/year.

If testing is preferred to determine the first-year corrosion rates, it is recommended by the standard to start the one-year corrosion penetration tests during the most aggressive time in climates with marked seasonal differences, which is the case for most of Canadian regions. It is also specified that the first-year corrosion penetration results cannot be extrapolated for the prediction of long-term behavior, but is used to classify the corrosivity of an environment. For the long term corrosion rate, thus long term corrosion penetrations, additional information and prediction models are provided in ISO 9224.²²



NOTE 1 The classification criterion is based on the methods of determination of corrosion rates of standard specimens for the evaluation of corrosivity (see ISO 9226).

NOTE 2 The corrosion rates, expressed in grams per square metre per year [g/(m²·y)], are recalculated in micrometres per year (µm/y) and rounded.

NOTE 3 Corrosion rates exceeding the upper limits in category C5 are considered extreme. Corrosivity category CX refers to specific marine and marine/industrial environments (see Annex C).

Figure 1: Corrosion rates for the first year of exposure for the different corrosivity categories

Figure 2 presents the plot for the boundaries between the corrosivity categories and a distribution of some Canadian cities within these categories for tests that had been conducted by Gibbons²³ and Albrecht and Naeemi.²⁴ Representative cities from certain regions of Canada can be observed on the plot, i.e., Halifax (Atlantic), Ottawa/Montreal, Saskatoon (Prairies), Esquimalt (Pacific), and Norman Wells (Subarctic). It appears that the Canadian cities with available corrosion data mostly fall between categories C2 and C3. Only marine/industrial areas of Halifax are C5. CX is not included in the chart as there were no Canadian cities with corrosion rates at that level; however, it should be noted that potential direct sea water or traffic splash may increase the corrosion rates to extreme levels. It should also be noted that the atmospheric corrosion of the carbon steel bridges may have increased considerably after the accumulation of de-icing salts after they were first applied in some of the locations in 1950s, and thus the corrosivity categories may have changed considerably. These aspects are out-of-scope of this paper.

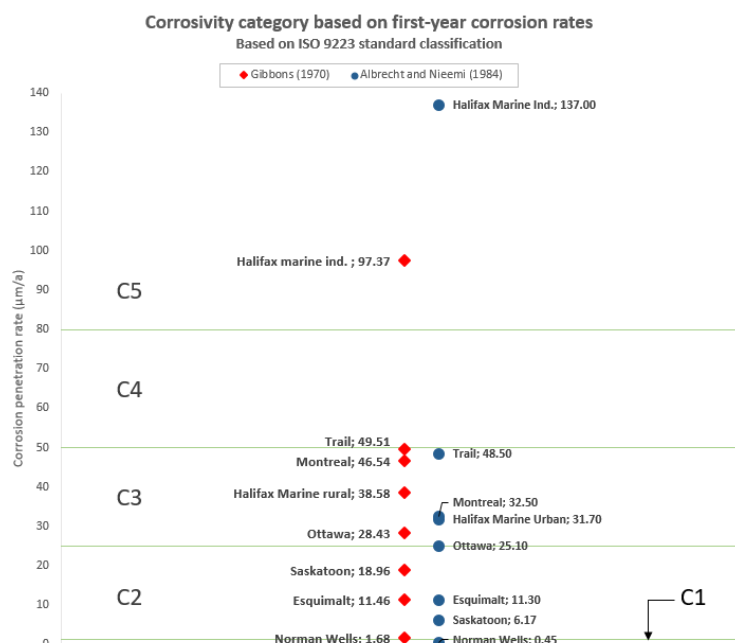


Figure 2. ISO 9223 corrosivity categories and corrosion penetration levels as tested by Gibbons (1970) and Albrecht and Nieemi (1984)

ISO 9223 Corrosion Penetration Estimation Model

Based on the data collected in the regions described previously, ISO 9223⁶ specifies the key factors for the first-year corrosion as chloride content (S_d), sulfur dioxide content (P_d), annual mean relative humidity (RH), and annual mean temperature (T) and proposes a first-year corrosion loss of carbon steel equation as a function of these parameters (i.e., Dose-response function in Equation 1 from ISO 9223⁶). The correlation coefficient, R^2 , for the equation was 0.85 for 128 specimens (N). The applicability intervals for each parameter of Equation 1 are presented in Table 2.

$$r_{corr} = 1.77 * P_d^{0.52} * \exp(0.020 * RH + f_{St}) + 0.102 * S_d^{0.62} * \exp(0.033 * RH + 0.040T) \quad (1)$$

$$f_{St} = 0.150(T - 10) \text{ when } T \leq 10^\circ\text{C}; \text{ otherwise } -0.054(T - 10)$$

where:

r_{corr} is first-year corrosion rate of metal, expressed in micrometres per year ($\mu\text{m}/\text{year}$);

T is the annual mean temperature, expressed in degrees Celsius ($^\circ\text{C}$);

RH is the annual mean relative humidity, expressed as a percentage (%);

P_d is the annual mean SO_2 deposition, expressed in milligrams per square metre per day [$\text{mg}/(\text{m}^2 \cdot \text{d})$];

S_d is the annual mean chloride deposition, expressed in milligrams per square metre per day [$\text{mg}/(\text{m}^2 \cdot \text{d})$].

Table 2: Applicability intervals for the dose-response function parameters

Symbol	Description	Interval	Unit
T	Temperature	-17.1 to 28.7	$^\circ\text{C}$
RH	Relative humidity	34 to 93	%
P_d	SO_2 deposition	0.7 to 150.4	$\text{mg}/(\text{m}^2 \cdot \text{d})$
S_d	Cl^- deposition	0.4 to 760.5	$\text{mg}/(\text{m}^2 \cdot \text{d})$

The sulfur dioxide (SO_2) values determined by the deposition method, P_d , and volumetric method, P_c , are equivalent for the purposes of this International Standard. The relationship between measurements using both methods may be approximately expressed as $P_d = 0.8 P_c$ [P_d in $\text{mg}/(\text{m}^2 \cdot \text{d})$, P_c in $\mu\text{g}/\text{m}^3$].

NOTE: All parameters are expressed as annual averages.